Clean Energy Innovation Policies in Emerging and Developing Economies

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Abstract

Emerging developing economies have a major stake in tackling the climate challenge, including through the innovations needed to underpin the clean energy transition. In recent years, energy, climate and development policies in many emerging economies have included ambitious innovation objectives for clean energy technologies. The economic opportunity is large, and strengthening energy innovation systems in these countries is important for the pace of global energy transitions. However, the statuses and forms of these innovation systems vary widely today.

Government policies play an essential role in clean energy innovation, and it is the combination of a broad range of measures that makes them effective. Emerging economies have a wealth of policy and innovation experience to share, and all countries have much to learn about their specific challenges and commonalities.

This report presents 11 new case studies of national experiences with policy development and implementation in support of energy innovation in emerging and developing economies. The case studies, authored by national experts, cover a range of technologies and highlight distinct aspects of the energy innovation process across diverse settings in Argentina, Brazil, China, Colombia, India, Kazakhstan, Kenya, Mexico, Morocco, Nigeria and South Africa. A comparison of the case studies reveals seven key findings and a set of insights for governments, intergovernmental bodies and other partners to work on effective policy packages and stronger clean energy innovation ecosystems globally.

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The case study chapters were contributed by the following national experts: Soukaina Boudoudouh (L'Institut de Recherche en Énergie Solaire et Énergies Nouvelles), Edilaine Camillo (State University of Campinas), Diana Canales (Conahcyt), André Tosi Furtado (State University of Campinas), Carina Guzowski (Universidad Nacional del Sur), Zhangjin Huang (School of Political Science and Public Administration, China University of Political Science and Law), María María Ibañez Martín (Universidad Nacional del Sur), Abhishek Malhotra (World Bank), Loveline Muluh (University of Cape Town), Vivian Ogechi Nwadiaru (University of Massachusetts Amherst), Vincent Ogaya (Kenya Climate Innovation Center), Serik Orazagaliyev (SDSN Kazakhstan and Graduate School of Public Policy, Nazarbayev University), Olufolahan Osunmuyiwa (Chalmers University of Technology), Rodrigo Palacios (Conahcyt, Iniciativa Climática de México), Clara Ines Pardo Martinez (Universidad del Rosario), Britta Rennkamp (University of Cape Town), Ambuj Sagar (IIT Delhi), Aliya Sembayeva (SDSN Kazakhstan, Nazarbayev University), Stella Tsani (Department of Economics, National and Kapodistrian University of Athens), Stefanos Xenarios (SDSN Kazakhstan and Graduate School of Public Policy, Nazarbayev University and CSIRO Environment, Australia), María Florencia Zabaloy (Universidad Nacional del Sur), Regina Zamora (Universidad Nacional Autónoma de México), Fang Zhang (School of Public Policy and Management, Tsinghua University).

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Executive summary and insights for policy makers

Emerging market and developing economies (EMDEs) have a major stake in tackling the climate challenge, including through the innovations needed to underpin the clean energy transition. The pathways taken by emerging economies to increase their energy supplies to meet rising demand and boost economic development will be fundamental to achieving energy transitions globally. Given the role of new and improved energy technologies in achieving clean energy goals, technological innovation is critical to addressing the climate challenge for all countries. Without it, energy and climate goals will remain out of reach. According to IEA analysis, 35% of the energy sector emissions savings that are needed to achieve net zero CO_2 emissions globally by mid-century must come from technologies that are not yet commercially available on the market. As well as continued improvements to products already on the market, there is therefore a need for concerted global efforts to successfully demonstrate emissions-reducing technologies that are known, but not yet proven at scale.

Energy and climate policy in emerging economies increasingly targets ambitious innovation objectives. The case studies in this report demonstrate that many countries have put in place substantial policies and programmes to advance a clean energy transition domestically, in a manner that realises the developmental benefits of such a transition. This includes expectations to develop, own, produce or optimise the technologies that they deploy, and to shape domestic markets to the capabilities and aspirations of the local population. In some cases, energy or climate policy documents state a vision of becoming an exporter of technologies in this area.

The economic opportunity is large, but EMDEs face multiple challenges to fully reap its benefits. The emergence of a new clean energy economy, led by mass-market solar PV, batteries and electric vehicles, is bringing the economic opportunities of clean energy transitions into focus for governments, including in developing economies. Nurturing new technologies to maturity can create local economic prosperity, and clean energy transitions will offer market opportunities for all economies in the coming decades. But emerging economies face specific challenges to be overcome in order to take advantage of these opportunities, including constrained public budgets, competition between immediate social needs and longer-term innovation goals, a lack of cutting-edge research infrastructure, high costs of capital for risk-taking enterprises, weak intellectual property enforcement and small or uncertain domestic markets for innovative technologies.

Investment in clean energy and spending on innovation is unevenly distributed. The trend towards higher spending on clean energy is visible all around the world, but most of the spending is in advanced economies and China. For every dollar invested in battery storage in advanced economies and China in 2023, only one cent was invested in other emerging markets. This falls far short of the amounts needed to ensure full access to modern energy and to meet rising energy demand in a sustainable way. Spending on energy innovation also reflects this imbalance: In 2023, just 6% of public energy R&D spending, 3% of corporate energy R&D spending and 9% of energy venture capital was in EMDEs outside China. Considering the active role these countries need to play in energy transitions and the importance of technologies that are a good fit with local markets and contexts, their limited investment participation is a concern.

Policy plays an essential role in clean energy innovation. Governments have a key role to play in enabling and accelerating technology deployment through different policy tools such as financial incentives, regulations and research support. Interest in identifying effective policies to catalyse innovation is growing worldwide, backed by expectations that clean energy technologies can be commercialised almost anywhere – especially mass-manufactured technologies like batteries or solar panels. In many cases, governments and the networks of institutions they co-ordinate, including state-owned enterprises, are the only actors with the influence and overview to bolster and shape innovation ecosystems in EMDEs. Elsewhere, other governments, investors and philanthropists are asking what they can do to support emerging economies to enter a virtuous cycle of technology deployment, learning, research, manufacturing and process improvement, boosted by further deployment or exports with higher local content. Innovation can also help countries more quickly reach tipping points at which the advantages of clean energy to the domestic economy clearly outweigh the benefits of continuing along a higher-emissions pathway.

Effective innovation policy combines a broad range of measures. While most governments channel funding to innovators to guide them towards national technology priorities, countries that are more successful in clean energy innovation support four key policy pillars: resource push (a sustained flow of R&D funding, capital for innovators, skills and research infrastructure); knowledge management (the free exchange of information between researchers, academia, companies, policy makers and international partners); market pull (creation of expected market value for the new product or service that makes the R&D risks worthwhile); and socio-political support (broad cross-society support for new products or services and the tests needed to develop them into commercial products). The case studies confirm that countries struggle to translate research into technological change without action under each pillar. Developing economies typically do not have an extensive legacy of energy innovation, and an energy innovation ecosystem in a developing economy may look very different from that of an advanced economy. It might be mainly composed of the skills, institutions and incentives to evaluate, adapt, manufacture and deploy a technology that is unfamiliar in the country context. These ecosystems are “innovation-ready” platforms that can foster incremental improvements to technologies and grow into more sophisticated communities of innovators at a later stage.

Emerging economies have a wealth of innovation experiences to share, and all countries have much to learn from them. Many already have extensive experience in technology R&D and deployment, whether for energy or in adjacent areas, but it is rarely considered collectively. Examples of global technology leadership in these countries are more plentiful than is often recognised, and include biotechnology in India, nuclear power in Argentina, synthetic fuel synthesis in South Africa, biofuels in Brazil, financial technology in Kenya, fertilisers in Morocco and building materials in Mexico.

The heterogeneity of EMDE country contexts means that sharing policy lessons and successes is more valuable when it accounts for local context. The case studies in this report cover 11 countries, yet the variations among them are broad. While they all illustrate effective policy approaches to boosting clean energy technology capabilities despite relatively low per capita wealth, the institutional, infrastructure and private sector contexts vary widely. These contextual aspects are of particular importance to examining policy design and effectiveness in EMDEs. It is therefore necessary to look not only at the details of the policy documentation, but also at the policy’s origins within the broader national priorities and the factors that shaped the choice of measures, assessment and learning.

Findings from a set of 11 case studies

This report presents 11 new case studies of national experiences with policy development and implementation in support of energy innovation in EMDEs. The case studies cover a range of different countries and key technologies, and highlight distinct aspects of the energy innovation process across diverse settings. Each case study was authored by national experts with deep experience of the energy innovation landscape in their countries.

Common to all of these case studies is the aspiration of governments to engage in the clean energy transition, even in the face of resource constraints. A comparison of the case studies reveals a number of key findings that demonstrate the strengths of energy innovation in the countries under consideration:

1. **Clean energy innovation has risen high up the policy agenda in developing countries, just as it has in advanced economies.** The potential for economic development is a key motivating factor, as is the need to boost energy security and respond to the climate challenge. Countries including Argentina, Colombia, Kazakhstan, Nigeria and South Africa issued new national energy strategies that referenced clean energy innovation shortly after publishing their nationally determined contributions (NDCs) as part of the Paris Agreement process. However, since around 2020, industrial development and inward investment have become equally strong drivers for action.

2. **Innovation policy can build upon and reinforce broader trends to catalyse technological change**. Energy innovation outcomes are more easily achieved when they align well with national visions for economic and social development. In India, energy efficiency was boosted by the government's priority of maintaining access to electricity for a growing population despite financial challenges for utilities. In Colombia, hydrogen technologies have the potential to address a range of emergent and pressing policy issues.
3. **There are multiple ways to set innovation in motion**. In many cases, successes at the national level have emerged through different configurations of private sector-led research, expert interaction through knowledge networks, strategic funding and policy tools, and partnerships with foreign technology suppliers. In Kenya, for example, a new cohort of producers of solar home systems were borne from a funding programme for off-grid solar PV that rewarded innovative means of adapting services to local consumers' needs.

4. **Institutional history exerts a powerful influence on policy choices**. South Africa's "just transition" policies have their roots in a long social and institutional history. Successful innovation policy interventions work in harmony with the existing policy landscape, and it is important that international partners are sensitive to the institutional history. Overall, the state typically plays a more prominent role in the energy sector than it does in advanced economies, and, as illustrated by nuclear innovation in Argentina, there is less reliance on market forces and private sector R&D.

5. **Existing technical expertise can provide a springboard, including from adjacent sectors**. For example, Kazakhstan's energy technology plans promote areas that require transferable skills from the oil and gas sector, such as sustainable liquid fuels. Kenya, by contrast, became a leading innovator in solar home systems due to its prior expertise in digital finance technology. Mexico is building on its manufacturing expertise to enter technologies related to solar PV.

6. **There are demonstrated ways to make the most of limited resources.** International co-operation – whether through financial support or knowledge sharing – is a key feature across the cases. Limited resources demand prioritisation of technology options that match local capacities. Morocco has developed tools and expertise for exploring potential technologies and identifying gaps to be targeted by policy. Nurturing the innovation ecosystem and maintaining connections with international innovators is also important. The earliest solar PV manufacturing in China benefited from individuals with strong international networks and connections to diasporas.

7. **Few countries have well-established and comparable processes for evaluating outcomes against the original policy goals.** Evaluating innovation policy is complex for all governments, but it should be built into policy design at the outset, to support the process of learning. Mexico is an exception in this regard: its General Law on Climate Change mandates the evaluation of climate change policies through INECC, an institution within the Environment Ministry.

Table ES.1 The 11 case studies

Country	Case study
Argentina	Innovation in nuclear energy technology and energy efficiency policies
Brazil	Policy directed to the development of domestic technical capacity in the new wind energy sector and nearly 100 years of policy, industrial and technological change in the bioethanol sector
China	Ultra-high-voltage (UHV) technology and solar PV
Colombia	Renewable energy support and hydrogen ambitions
India	Energy efficiency policy
Kazakhstan	Energy and industrial transitions, and Kazakhstan’s sovereign wealth fund
Kenya	Off-grid solar PV and geothermal energy technology
Mexico	Solar PV distributed generation
Morocco	New technology-related renewable energy institutions in Morocco
Nigeria	Innovation-oriented projects in the context of rural electrification
South Africa	The Renewable Energy Independent Power Producer Procurement Programme and South Africa’s Just Energy Transition Partnership

Insights for policy makers

Strengthening energy innovation systems in EMDEs is important for the pace of global energy transitions and enhancing clean energy technologies more generally. However, the statuses and forms of these innovation systems vary widely today. While China's experiences with clean energy innovation policies in the early 2000s provide an instructive case study, the country has since built a sophisticated innovation ecosystem that it has the capacity to maintain. Developing economies with less mature innovation ecosystems will benefit from "innovation co-operation" with advanced economies as well as other EMDEs. We find there is considerable scope for partnerships and knowledge exchange among EMDEs. Shifting the discourse towards "innovation co-operation" may help alleviate some of the setbacks in the political arena that have been encountered by a narrower focus on technology or policy transfer. In this context, roles can be identified for all governments, intergovernmental bodies and other partners to work on effective policy packages and stronger clean energy innovation ecosystems in EMDEs.

For domestic policy makers

As in advanced economies, the importance of fostering predictable and durable domestic demand cannot be overstated. A dependable market for clean energy technologies within a given sector creates the incentives for innovators to take risks and improve existing products. Markets can start small but should reward suppliers of products and services that are a particularly good fit with local needs, as well as those that have higher performance and lower costs.

The lack of an extensive institutional and technical legacy in clean energy may often be a weakness, but also creates an opportunity for creative policy. Enabling policies do not need large R&D budgets – although R&D budgets remain valuable. New agencies to co-ordinate clean energy technology expertise can be established with the responsibility to inform policy. Networks for learning and sharing are also important, and state-owned enterprises, including research institutes, can play a central organising role if their aims are aligned with those of the broader network. Well-designed incentives for domestic procurement can foster competition and technology adaptation, and they can start at relatively small scales, for example by targeting installation and assembly. Encouraging innovation in digital technologies, which require lower capital for development, can be as impactful as much larger R&D budgets.

International engagement can help build domestic energy innovation ecosystems more rapidly if it is targeted towards key national challenges. This strengthens the case for mapping exercises that identify gaps in capacity and policy that hinder the development and take-up of new technologies. Depending on the needs, there are various forms of international co-operation that can be pursued simultaneously. These include participation in international fora (such as Mission Innovation, the IEA technology network and UN bodies); collaboration on tailored studies of opportunities; exchanges of experiences with countries facing similar challenges; multilateral financing of technology deployment programmes and technical capacity building; joint R&D programmes; and financial support to actors in the innovation ecosystem, including incubators and testing facilities.

In countries with limited public R&D budgets, domestic technology innovation advances more quickly when it leverages existing industrial expertise and aligns well with national visions of future socio-economic development. It is therefore important to carefully prioritise technology areas. The skills and capital requirements required to scale up mass-manufactured or digital technologies differ considerably from those required in sectors like carbon capture, hydrogen production, nuclear or biofuels. Examples of countries entering an entirely new technology area and quickly establishing technological leadership are rare, even in advanced economies. To mobilise broad support, the choice of policy measures in support of new technologies should account for societal objectives such as energy access, inclusiveness, affordability and accessing higher added-value production.

For international partners

In the medium-to-long-term, the interests of all countries will be well-served by faster transitions to clean energy in EMDEs and more clean energy technology innovation overall. International engagement on clean energy can promote stronger energy innovation ecosystems in EMDEs and do so within programmes related to the development of clean energy markets, deployment of clean energy technologies, or social and economic prosperity more broadly. Bilateral R&D programmes play an important role in such collaborations, and could be expanded, while also co-funding projects that enhance the innovation ecosystems of the partners in areas tailored to their strengths.

International initiatives related to clean energy should continue to include EMDE priorities in their work programmes. For projects involving several countries, including on R&D and technology demonstration, being at a relatively low level of technological maturity should not be a barrier to participation but requires upfront discussion of expectations and mutual benefits. Consortia of partners from countries with stronger and weaker clean energy innovation ecosystems, but which face similar challenges, could be assembled.

There is scope and need for the technical and market requirements for clean energy transitions in EMDEs to be more highly prioritised within the R&D programmes of the broader international community. Given the considerable economic and infrastructure challenges of shifting away from fossil fuels in key sectors such as transport, industry and power generation, and adopting more energy-efficient building designs, global net zero emissions targets will be out of reach without available and appropriate technologies for EMDEs.

Using development finance to help establish durable demand for clean energy technologies can have a catalytic effect on innovation provided it also supports competition, entrepreneurship and domestic capabilities. Such programmes can facilitate policy experimentation that would be difficult within the existing institutional architecture of the country, or could attract international companies to deploy novel technologies in projects they would otherwise not prioritise. Project loans, technical assistance with standards and regulations, finance for incubators, seed investments and capacity-building grants are just some of the ways in which international capital can spark large changes.

1. Introduction

The urgency of meeting the climate challenge cannot be overstated. While advanced economies have a leading and central role to play in the clean energy transition that is the mainstay of climate action, emerging market and developing economies (EMDEs) are also integral to achieving this transition as they grow their economies and energy supplies to meet their developmental aspirations. And given the role of new and improved energy technologies in underpinning this transition, energy innovation is critical to addressing the climate challenge for all countries. Without enhanced energy innovation, energy and climate goals will be out of reach.

It is also important to recognise that nurturing new technologies to maturity can create local economic prosperity, and clean energy transitions will be a major market opportunity for all economies during the course of the 21st century. Countries around the world are striving to be the home of the next breakthrough clean energy technology company or host world-class clean energy supply chains, with good reason.

Policy plays an essential role in clean energy innovation. Governments have a hand in shaping innovation outputs and ecosystems by funding R&D projects, providing tax breaks and using market regulation to incentivise improvements to product design and reductions in costs, and by applying appropriate policies and other incentives that enable and accelerate deployment. Interest in identifying effective government policy for clean energy technology innovation is spreading rapidly, with higher expectations that clean energy technologies can be commercialised anywhere in the world – especially true for mass-manufactured technologies like batteries, electrolysers, modular reactors, sensors, solar panels and vehicles.

Governments and other stakeholders are especially interested in how to catalyse clean energy innovation in EMDEs. Governments in these countries recognise the potential economic benefits of home-grown products in a world that is scrambling to deploy as much renewable and other low-emissions energy as quickly and cheaply as possible. In addition, outside these countries, other governments, investors and philanthropists are asking what they can do to help EMDEs into a virtuous cycle of technology deployment, learning, research, manufacturing and process improvement, boosted by further deployment or exports with higher local content. As well as accelerating the global pace of technological change, innovation can help countries more quickly reach tipping points at which the advantages of clean energy to the domestic economy clearly outweigh the benefits of continuing along a higher-emissions pathway.

However, the understanding of clean energy innovation and the specific policy challenges in EMDEs is limited. This hinders sound decision-making in these countries and makes it harder for the international community to provide support and guidance. Governments possess a range of strengths beyond their ability to provide grant-based financing to help clean energy innovators overcome barriers. These strengths include operating world-class laboratories, building trusted reputations and extensive networks, and developing a capacity to target suitable technologies – those that are widely agreed to be important for the future, but which are not yet viewed by investors as having near-term profitability. Governments can also choose to selectively target underrepresented social groups and social policy objectives by prioritising low-cost technology development for clean cooking, biomass conversion and off-grid electricity access.

Many EMDEs already have extensive experience in technology R&D and deployment, whether for energy or in adjacent areas, but it is rarely considered collectively. Examples of global technology leadership in these countries are more plentiful than is often recognised, and include biotechnology in India, nuclear power in Argentina, synthetic fuel synthesis in South Africa, biofuels in Brazil, financial technology in Kenya, fertilisers in Morocco and building materials in Mexico. Each country has a different history and national context, but in aggregate their successes and disappointments in fostering energy technology innovation point to how they differ from advanced economies and how progress can be accelerated despite their limited financial resources.

This report takes a case study approach to illuminating some of these experiences in 11 countries around the world. It is intended as a resource for policy makers in EMDEs who are seeking to develop new measures or improve those already in place. It should also serve as a useful resource for governments, philanthropists and multilateral agencies to inform their bilateral and multilateral engagement around clean energy innovation as they co-operate to promote development. The aim is not to be comprehensive or to prove which approaches are most effective, but rather to present a set of coherent examples from different country contexts that can both provide insights and inspire action.

Technology's role in tackling climate change

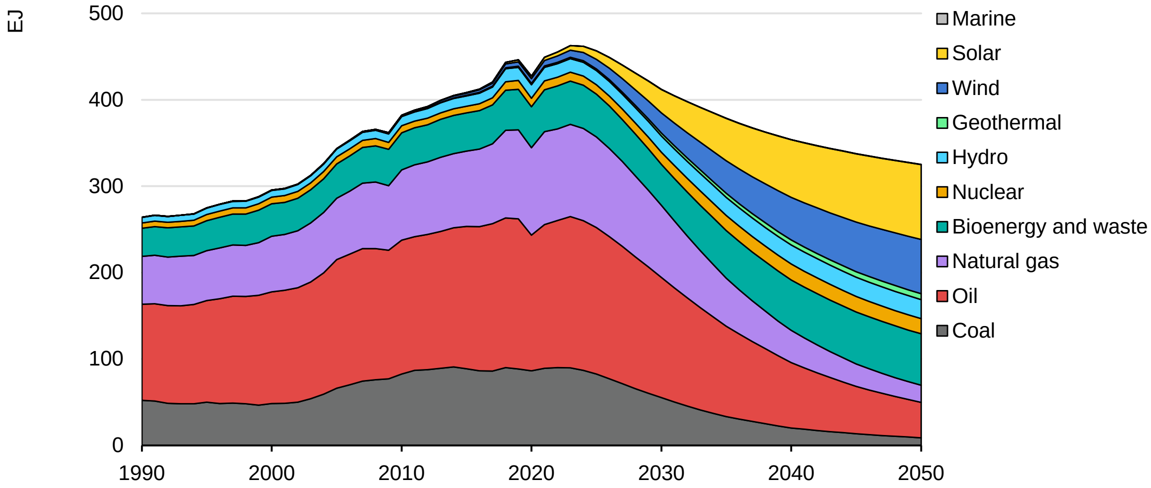
Technology and development are important components of orderly, just and secure energy transitions

The case for rapidly transforming the global energy system to clean energy has never been stronger. May 2024 was the twelfth successive month to break its temperature record. The impacts of climate change are increasingly frequent and severe, and scientific warnings about the dangers of the current pathway have become stronger than ever.

Global carbon dioxide (CO_2) emissions from the energy sector reached a record high of 37.4 billion tonnes (Gt) in 2023, 1% above the previous year. The global mean temperature rise above pre-industrial levels stands today at around 1.2 °C., and there is about a one-third probability of warming exceeding 2.6 °C if no additional policy measures are taken to curb emissions. However, the speed of the roll-out of key clean energy technologies means that the IEA now projects that demand for coal, oil and natural gas could all peak this decade on the basis of the policy measures that governments have already implemented or implement those that are already in the legislative process. This is encouraging, but not nearly enough to meet the goal of limiting warming to 1.5 °C globally, or even 2 °C. To do this requires governments, companies and, in some cases, citizens to take additional measures, to change the direction of energy sector investment and the ways that energy is supplied and consumed. Reducing fossil fuel combustion will have to be a main target of such measures, but not the only one. Under the IEA scenario that provides a 50% chance of limiting temperature rise to 1.5 °C, nearly two-fifths of the reduction in warming compared with the current direction comes from lower emissions of methane from energy and non-energy sources.

For net emissions from fossil fuel use to fall to zero, renewable energy sources would be expected to meet around three-quarters of the world's final energy demand, up from 18% today (Figure 1.1). This is enabled by much more efficient use of energy, especially in advanced economies, which allows continued economic development around the world. In such a scenario, EMDEs' share of world gross domestic product (GDP) rises from around 53% today to around 65% in 2050, with the People's Republic of China's (hereafter "China") share remaining constant at around 20% of the total. For comparison, their demand for energy – electricity, heat, oil products for transport and fuels for heating and cooking – is around 63% of the global total today and would rise above 70% in such a scenario (of which China's share of the global total would decline from nearly two-fifths to below one-third).

Figure 1.1 Evolution of the sources of final energy consumption in the IEA Net Zero by 2050 Scenario, 1990-2050



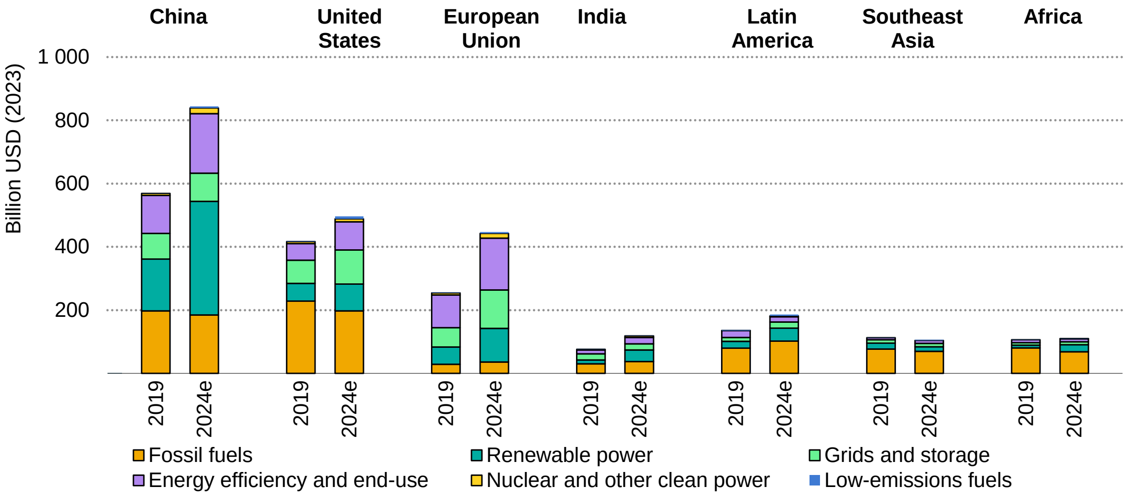
Note: To show the sources of final energy, electricity, hydrogen, ammonia and synthetic fuels production are split into their primary energy shares.
Source: IEA (2023), Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach.

Clean energy investment is growing, but is unevenly distributed

As countries have bounced back from the global pandemic, the trend towards a new energy economy based on clean energy sources has been more pronounced. Investment in clean energy has accelerated since 2020, and spending on renewable power, grids and storage is now higher than total spending on oil, gas and coal. Global energy investment is set to exceed US dollars (USD) 3 trillion for the first time in 2024, with USD 2 trillion going to clean energy technologies and infrastructure. In 2015 the ratio of investment in clean power to investment in unabated fossil fuel based power generation was roughly 2:1. In 2024 this ratio is set to reach 10:1. However, it takes time to transform a country's fuel mix and introduce the necessary changes in infrastructure, industrial assets and consumer goods. Investment in fossil fuel supplies continues in response to the vast existing fossil fuel-based systems in the world's economies. Fossil fuel investment is set to rise by 2% in 2024, nearly back to 2019 levels.

While the trend towards higher spending on clean energy is visible all around the world, there are major imbalances in the volume of investment by region (Figure 1.2). EMDEs outside China account for only around 15% of global clean energy spending. As an example of how concentrated this spending is, for every dollar invested in battery storage in advanced economies and China in 2023, only one cent was invested in other EMDEs. Many of the least-developed economies are being left behind (several face acute problems servicing high levels of debt). Both in terms of volume and share, clean energy investment in EMDEs is far below the amounts that are required to ensure full access to modern energy and to meet rising energy demand in a sustainable way.

Figure 1.2 Annual energy investment by selected country and region, 2019 and 2024e



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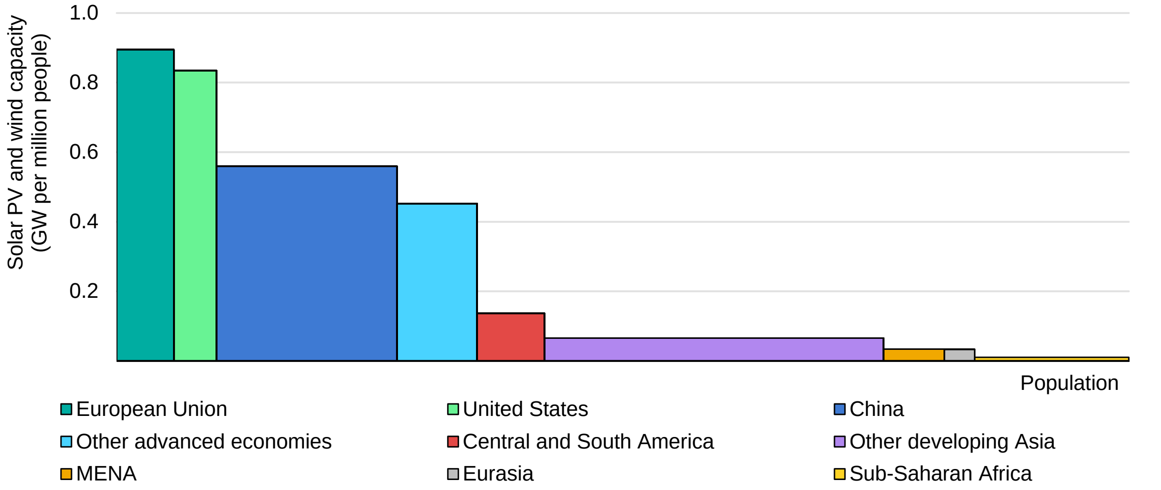
Note: 2024e = estimated values for 2024.
Source: IEA (2024), World Energy Investment.

Achieving net zero emissions by the middle of this century or in the following decades requires every country, every organisation and every individual around the world to contribute to the clean energy transition. Energy consumption per capita is highly unequal between countries, and clean energy consumption even more so. Among the countries for which the IEA has comprehensive energy statistics, the current Gini coefficient of energy inequality[1] is 0.39 for all sources of energy consumption and, at 0.46, shows more inequality for clean energy consumption. Half of all the clean energy supplied is used by 15% of the global population, the majority of whom live in advanced economies. Within societies, there is a risk that the less well-off will see fewer benefits from the transition unless supportive policies are put in place for a people-centred transition.

Advanced economies and China combined have nearly 2.5 times more solar PV and wind capacity in operation per person than the global average. Wind and solar deployment per capita are particularly low in Africa (Figure 1.3). In 2022, the Netherlands had more solar PV capacity installed than the whole of Africa, for example.

[1] The Gini coefficient is a measure of inequality typically used to measure income inequality, which has been adopted here to evaluate inequality in energy consumption. 1 indicates perfect inequality (where one group or one individual consumes or receives all the resources) while 0 indicates perfect equality.

Figure 1.3 Solar PV and wind deployment normalised for population by region, 2022



Source: IEA (2023), Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach.

EMDEs have a major role to play

Over half of global investment in clean energy assets to 2050 is in EMDEs in the IEA Net Zero Emissions by 2050 Scenario. This share could be even higher when considering investment to secure and process supplies of critical minerals. This investment, which underpins economic growth, will only be directed to low-emissions technologies if they are available, affordable and well-adapted to local contexts. While this is a significant innovation challenge domestically and internationally, it is aided by the ever-closer links between clean energy, such as renewable power, and manufacturing opportunities.

Clean energy transitions offer major opportunities for growth and employment in new and expanding industries. The global market opportunity for key mass-manufactured clean energy technologies would be worth nearly USD 1 trillion a year by 2030 – more than three times today's level – if countries worldwide fully implement their announced energy and climate pledges. Related clean energy manufacturing jobs would more than double from 6 million today to nearly 14 million by 2030, with over half of these jobs tied to electric vehicles (EVs), solar PV, wind and heat pumps. As clean energy transitions advance beyond 2030, this would lead to further rapid industrial and employment growth. Continued market growth thereafter represents a major economic opportunity for countries that can capture some of this value by producing cutting-edge goods for domestic or export markets.

Every country needs to identify how it can benefit from the opportunities of the new energy economy, defining its industrial strategy according to its strengths and weaknesses. Diversity of supplies will be an important consideration for many countries and companies, as concentration at any point along a supply chain makes the entire supply chain vulnerable to incidents, be they related to an individual country's policy choices, natural disasters, technical failures or company decisions. Partnerships between countries are already emerging to raise environmental, social and governance standards across the clean energy sector, from mining and processing to components and final product manufacturing.

These opportunities for development and growth through clean energy will only be realised where investment and national priorities are well aligned, and where governments address questions such as future impacts on society, energy access needs, structural economic concerns and energy security. International partnerships that seek to boost clean energy investment in EMDEs will be most successful where this alignment is strong, or can be quickly fostered.

Technology innovation is needed to meet global climate goals

Technology is central to these efforts. According to IEA analysis, 35% of energy sector emissions needed to achieve net zero CO_2 emissions globally by mid-century relies on technologies that are not yet commercially available on the market. This illustrates the need for concerted global efforts to successfully demonstrate emissions-reducing technologies that are known, but not yet proven at scale. These technologies are predominantly in areas such as heavy industry, long-distance transport and low-emissions fuel production.

In addition, for technologies that are already being deployed, the net zero goal will remain costly or out of reach without continuous R&D and creativity to keep their costs on a steep downward trend and adapt their attributes to new areas of application. These include the specific needs of customers in EMDEs, whose use patterns, price sensitivity and climatic conditions can differ substantially from the markets in wealthier regions where uptake is already underway.

Energy innovation spending is rising, but concentrated in a handful of countries

In recognition of the technology needs of clean energy transitions and the economic opportunity they represent, spending on R&D is rising. Public spending on energy R&D grew by 10% in 2022, taking it to nearly USD 44 billion, over USD 10 billion more than five years before. Corporate energy R&D also rose 10% in 2022, with competition and regulation in the push towards electric vehicles fuelling much of this growth. For earlier-stage innovators, venture capital investment in energy start-ups has grown more rapidly, by 340% in the five years to 2022 to reach USD 40 billion. A wave of ambitious innovation-related policies has also been announced in recent years, including the US Infrastructure

Investment and Jobs Act, Japan's Green Technologies of Excellence, the EU Innovation Fund, China's Made in China 2025 strategy and Australia's Towards Net Zero Mission.

This spending is concentrated in a relatively small number of advanced economies, plus China, but there are ambitions to change this picture. In 2023 leaders of the G7 countries stated that they will "keep supporting the research, development, and deployment of clean technologies as a critical enabler of an accelerated clean energy transition in low- and middle-income countries (LMICs). In 2024 the Brazilian presidency of the G20 took up this issue in the G20 Research and Innovation Working Group. These support measures complement and add to the work of the IEA Technology Collaboration Programmes (launched in 1976), the United Nations Framework Convention on Climate Change (UNFCCC) Technology Mechanism (launched in 2010), Mission Innovation (launched in 2015), the UNFCCC Global Innovation Hub (launched in 2021) and the UNIDO-GEF Global cleantech programme (launched in 2018).

Energy innovation in EMDEs

Technology innovation in EMDEs can accelerate energy transitions

Many countries, including some that previously had little or no stake in clean energy technology development and deployment, are evaluating opportunities to develop new industries and enter new value chains, with plans to move up these chains over the longer term to access or manufacture technologies with higher levels of added value. This is especially the case for internationally traded goods, such as equipment for producing renewable energy, energy-efficient consumer goods, low-emissions materials or new types of fuels.

The opportunity is not limited to high-tech laboratory research. Participation in energy innovation encompasses a wide range of technical activities, including basic R&D for transformational technologies and also relatively minor adjustments to techniques for installing imported products. In addition, it may also involve the development of deployment models that are suited to the local socio-economic or geographic context. And it may involve creative approaches to harnessing climate finance. All these types of endeavour can lead to new business for local firms or entirely new businesses that attract capital and other resources for their competitive products and services. In a developing economy, during the early period of emergence of a new sector – such as solar mini-grids, clean cooking and electric mobility – deployment of imported technologies is typically linked to more sophisticated ambitions for manufacturing and foreign direct investment in the sector. In this formative phase it is often small innovations by installers and handlers that foster local technical capabilities. However, even modest levels of clean energy innovation are hard to nurture without building domestic capacity for planning, handling, deploying and maintaining technologies that are new to the country or region.

If successful, harnessing the innovative capacity of EMDEs will accelerate clean energy transitions. Above all, this is because these countries have a large pool of educated talent in science, engineering and business. Only by fully integrating them into international technology development efforts can the world benefit from their ideas and discoveries to inform the next generation of clean energy equipment and products; at the same time, it would also ensure these countries make full use of their burgeoning clean energy deployment opportunities. There is therefore a global interest in maximising the level of effort devoted to clean energy technology innovation in EMDEs and enhancing the connections between experts in these countries with those in other parts of the world.

In addition, people in EMDEs bring a special perspective to technology innovation because they understand the needs of local consumers and the local operating conditions to which the technologies will be exposed. The "localisation" of clean energy innovation is a pressing concern given the extensive need for deployment of non-polluting products in rapidly developing economies before they lock themselves more deeply into unabated fossil fuel infrastructure. This localisation process can be formal – through market-specific customisation and patenting – or informal via local adaptations to marketing, financing, installation and maintenance. Lastly, successful clean energy innovation generates domestic companies and products that will be the beneficiaries of stronger climate policy in a particular country. Knowing that the investment related to climate policies will largely flow to the local economy can make them politically easier to pass into law.

Since the establishment of the UN Framework Convention on Climate Change in 1992, UN mechanisms have recognised the importance of engaging EMDEs in technology discussions. From this framework the Expert Group on Technology Transfer (EGTT) was created in 2001 and replaced in 2010 by the Technology Executive Committee and the Climate Technology Centre & Network. In addition to facilitating discussion between country experts, these bodies also support countries wishing to undertake national Technology Needs Assessments (TNAs). To date, 74 TNAs have been completed in the area of climate change mitigation, including energy. However, much less focus has been devoted to recognising the important contributions that innovation in these countries could make to global climate goals.

National strategies include ambitious technology goals, but they face multiple challenges

More than 90 countries and the European Union have announced targets to achieve net zero emissions, with nearly all of these pledges made since 2020. As it stands, more than 85% of global energy-related emissions and nearly 90% of global GDP come from places that are covered by a net zero emissions pledge. Most commitments from advanced economies target 2050 or earlier, while some of the targets (but certainly not all) stated by EMDEs are for 2060 or 2070. Whether the objective is to reduce energy-related emissions to near zero (while balancing the remainder with permanent carbon removals) by 2050 or 2070, the task is an ambitious one. Achieving these goals requires a full portfolio of technologies to be available and affordable in the next one or two decades to meet growing demand for energy services without unabated fossil fuels.

Many EMDE governments draw an explicit link between their climate pledges and energy technology innovation objectives. For example, Nigeria's 2021 Climate Change Policy outlines a priority of pursuing "an alternative and sustainable path to industrialisation that takes advantage of innovations, technologies and business models for improved energy efficiency" by supporting "financial services entities with appropriate policies to play an adequate role of providing the financial and de-risking products needed to fund innovations necessary for climate actions". Kenya's 2015 Green Economy Strategy and Implementation Plan promoted the creation of "green-tech" start-ups through innovation and replication, while its 2019 Energy Act specifically highlighted the need to stimulate innovation in renewable energy technology. Morocco's NDC, submitted as a signatory to the Paris Agreement on Climate Change, says that "supporting the emergence of an innovative Moroccan industry specialising in the development of renewable energies and energy efficiency is a matter of the utmost urgency".

The challenges faced by EMDEs to enhance their clean energy innovation ecosystems include:

- Constrained public budgets and competition between immediate social needs and longer-term innovation goals.
- A lack of cutting-edge research infrastructure and testing facilities, which are expensive.
- Poor understanding of energy R&D needs and efforts.
- Shallow pools of hands-on expertise in academic, public and corporate research institutions.
- Perceptions of small or uncertain domestic markets for future sales of the fruits of innovation, with underdeveloped business models for the local context as a result.
- High cost of debt and equity capital for risk-taking enterprises.

- Weak intellectual property enforcement.
- Limited understanding of and data on technology performance, including requirements for the local context.
- Weak linkages between actors in local innovation ecosystems, including researchers, government officials, investors and established businesses.
- Few existing linkages into global supply chains for clean energy technologies.
- Limited experience with innovation policy design and implementation in government institutions and a lack of institutional continuity in some cases.
- Weak bargaining power to ensure that the results of technology projects undertaken with international partners are retained in the local economy.

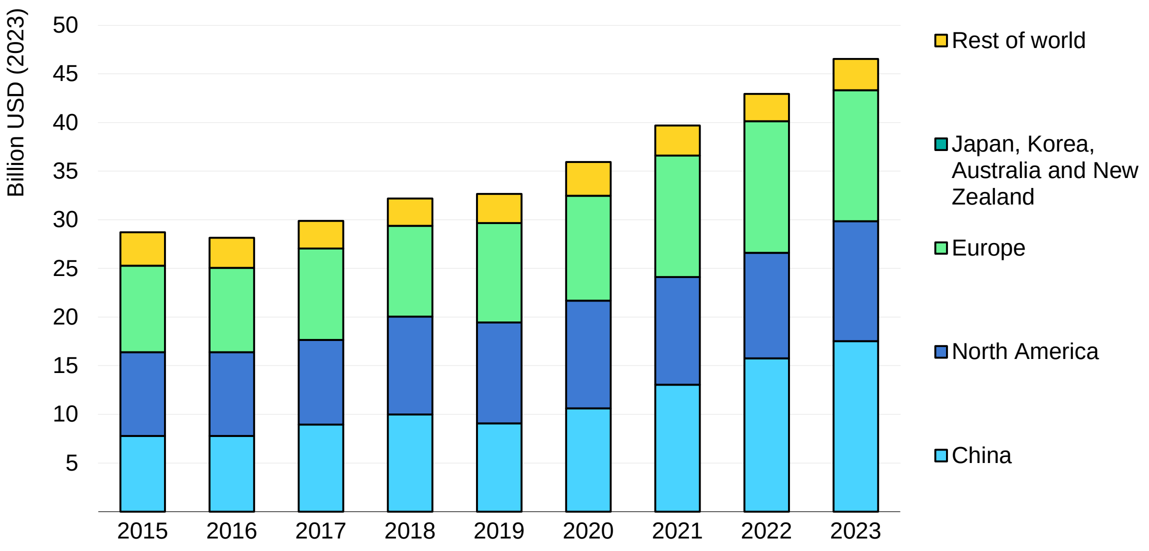
While it is not possible for all of these challenges to be overcome quickly, effective strategies for energy innovation in EMDEs must take realistic account of this starting point. The only feasible way to meet countries' long-term aspirations for knowledge-driven economic growth is to initiate appropriate projects and institutions that will grow, strengthen and attract more funding over time.

Energy innovation ecosystems in EMDEs need strengthening

There is a common misconception that policy support for technology innovation is merely a matter of making public funds available for technical R&D activities at public institutions or in the private sector. In fact, the complexities of successful innovation require many more types of support to overcome the considerable risks and inertia encountered by hopeful developers and marketers of new products hoping to substitute or transform the incumbents. This is more pronounced in the energy sector than in many other industries due to the highly networked nature of the infrastructure, the large amounts of capital invested in individual installations, the near-monopoly nature of some of the business activities and the strategic political and economic importance of avoiding supply disruption. Therefore, government has a set of important roles to play to establish incentives for researchers, entrepreneurs and established businesses that will drive them to innovate, for example by setting a clear strategy for the future and by ensuring that competitive advantages can be rewarded by higher market shares in priority technology areas. There are also non-technical roles for government in reducing the risks and costs associated with knowledge acquisition, technology testing and market entry, for example by setting standards, supporting technology demonstrations, reducing financial risk, facilitating collaboration and upholding property rights.

In each of these areas, EMDEs often tend to have weaker or less sophisticated policies and institutions. National innovation capacity is a product of a web of institutions, expectations, resources, networks and expertise. It takes time to build an effective innovation ecosystem, including laboratories, financial know-how, market understanding, testing facilities, peer-to-peer support and customer feedback. Developing economies typically do not have an extensive legacy of energy innovation, whether at the frontier of scientific development or for tailoring existing technologies to local users. Therefore, an energy innovation ecosystem in a developing economy may look very different from traditional conceptions in advanced economies. A well-functioning energy innovation ecosystem in a developing country might be mainly composed of the skills, institutions and incentives to evaluate, adapt, manufacture and deploy a technology that is unfamiliar in the country context. These ecosystems are "innovation-ready" platforms that can foster incremental improvements to technologies and grow into more sophisticated communities of innovators at a later stage. If EMDEs are to participate more fully in international efforts to develop and commercialise cheaper and higher-performing clean energy technologies in the coming decades in line with their aspirations, it is important to speed up the capacity building process.

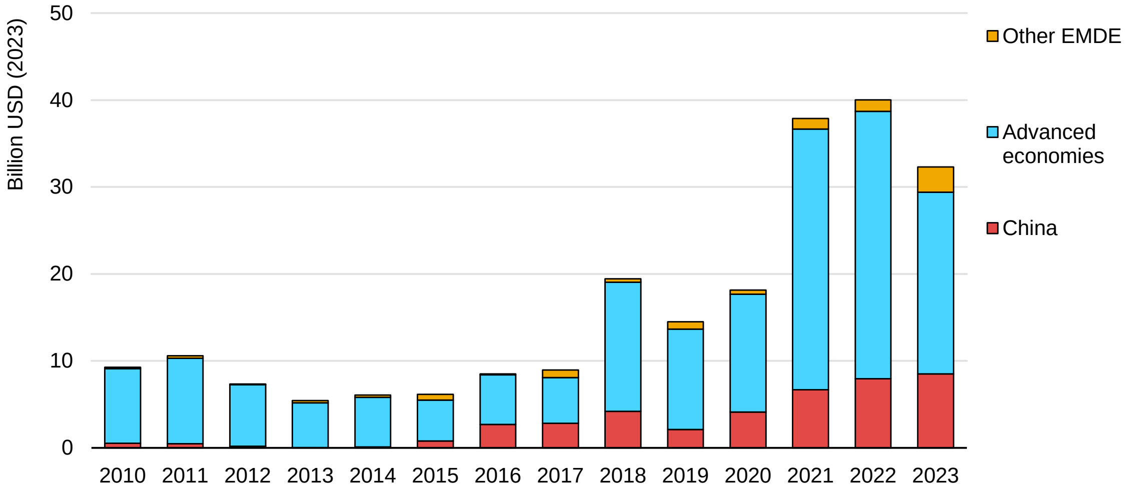
Figure 1.4 Government spending on energy R&D by region, 2015-2023



Source: IEA (2024), World Energy Investment.

In terms of funding alone, the resources that EMDEs can direct to energy R&D are small, and the technology needs of EMDEs are not generally prioritised by other, wealthier countries. In 2023 the EMDE share of global corporate energy R&D spending (excluding China) was 3%, the share of global public energy R&D spending was 6% and the share of global energy venture capital investment was 8% (Figures 1.4 and 1.5). Of the 24 members of Mission Innovation, an international initiative to foster co-operation between countries on clean energy innovation, just six are not members of the European Union or the Organisation for Economic Co-operation and Development (OECD), and one of these is China. There is considerable scope to increase these numbers.

Figure 1.5 Venture capital funding for energy-related start-ups, 2010-2023



Note: Regional data are presented by headquarters of start-up.
Source: IEA analysis based on Cleantech Group (2024) and Crunchbase (2024).

For funding efforts to be successful and expand, they will need to be rooted in the local context, considering local priorities, resources, and technical, financial and institutional capabilities. In most cases, governments and the networks of institutions they co-ordinate, including state-owned enterprises, are the only actors with the influence and overview to bolster and orchestrate the various functions of innovation ecosystems in EMDEs.

The main functions of clean energy innovation systems can be grouped under four headings:

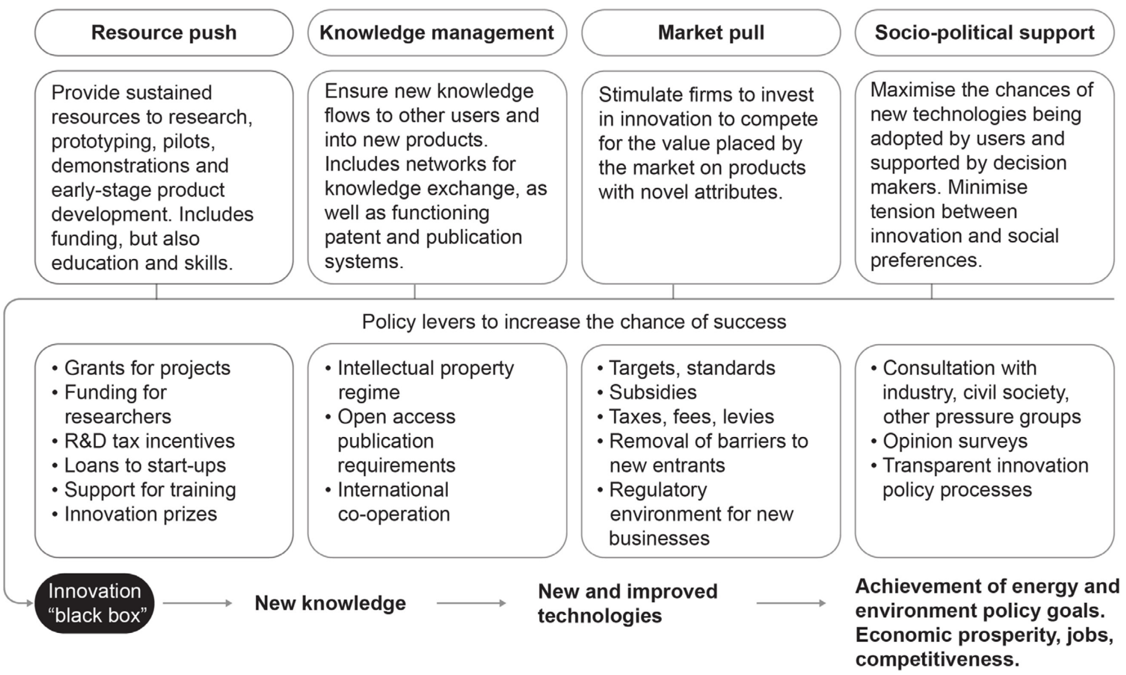
- **Resource push:** a sustained flow of R&D funding, capital for innovators, a skilled workforce (e.g. researchers and engineers) and research infrastructure (laboratories, research institutes and universities) are required. These resources can come from public or private sources, including philanthropic, and can be directed to specific problems or basic research.
- **Knowledge management:** it must be possible for knowledge arising to be exchanged easily between researchers, academia, companies, policy makers and international partners.
- **Market pull:** the expected market value of the new product or service must be large enough to make the R&D risks worthwhile, and this is often a function of market rules and incentives established by legislation. This includes support for

competition between firms and ease of entry for newcomers, as well as measures to grow the market to its full potential. If the market incentives are high, then much of the risk of developing a new idea can be borne by the private sector.

- **Socio-political support:** there needs to be broad socio-political support for the new product or service, despite potential opposition from those whose interests might be threatened.

While most governments put more resources and efforts into the first of these – especially the channelling of finance to researchers and innovators to guide them towards national technology priorities underfunded by the private sector – all four pillars play a role. An innovation system will struggle to translate research into technological change without action under each of these headings. In this report we use this framework to present the actions of different governments, and the gaps in their policies, in a consistent manner.

Figure 1.6 Four policy pillars (functions) of effective energy innovation systems



Note: For ease of use, these four functions group together the longer list of functions developed within the Technological Innovation Systems framework (for example in Bergek et al., 2008).
Source: IEA (2020), Energy Technology Perspectives 2020 – Special Report on Clean Energy Innovation.

“Innovation co-operation” between countries can help strengthen innovation systems in EMDEs

The case for strengthening clean energy innovation systems in EMDEs includes the significant benefits for all countries around the world. Advanced economies have a stated interest in encouraging faster energy transitions to minimise the impacts of climate change. Faster transitions will grow the global markets for clean energy technologies from all sources more quickly. They are a more likely outcome if greater efforts are dedicated to clean energy innovation in the countries that face greater challenges in adopting existing renewable and other low-emissions technologies. In addition, a greater diversity of researchers and entrepreneurs working on clean energy technology problems is likely to produce a more varied and resilient technology portfolio. With more firms and countries entering clean energy value chains, there is a higher chance of supply chain security and equitable outcomes.

In the longer term, co-operation between advanced economies and EMDEs could aim to level up their capabilities to the extent that knowledge and ideas flow as much through so-called "south-to-north" and "south-to-south" channels as "north-to-south". This is already happening in some cases: EMDEs have been a main source of the world's innovation in, for example, mobile finance and vehicle battery swapping. However, in the shorter term, international partnerships will continue to be a conduit for expertise in advanced economies to spread to EMDEs. In some cases, this might be characterised as "technology transfer", though such outcomes are rarely in the gift of governments that do not own the intellectual property, and in others it will involve soft skills and seed capital. Broadening the perspective from "technology transfer" to "innovation co-operation" has the benefit of encompassing a range of activities (beyond the narrowly technology-centred ones) that are necessary to support effective innovation, and the advantage of a more equitable framing where knowledge can flow in multiple directions.

For innovation co-operation to be effective, complementary efforts on multiple fronts are needed by both parties. Advanced economy partners (whether donors, knowledge entities or others) ought to have a holistic understanding of the needs, space and application context of the recipient region so they are able to develop and implement programmes that are appropriately designed and resourced. Developing economies need to ensure a genuine demand for technology backed by enabling policy frameworks and appropriate innovation ecosystems. To enter meaningful partnerships with external actors, developing economies have an opportunity to use their knowledge as inputs in joint innovation and in return gain from the partners' skills. In many cases, this requires upgrading their capacity to engage in such projects on a reciprocal basis. Such mutual commitments need to be deep and sustained, and the expectations of the partners need to be reflexive, flexible and built on trust; they must evolve with the changing demands of the context. This demands a degree of mutual trust.

Understanding energy innovation policy in EMDEs: A case study approach

In this report, we use a case study approach to explore EMDE's experiences with fostering clean energy innovation, looking at the institutional processes by which key policies came into existence and were implemented in practice. We identified four steps in the policy process to help guide our case study research in a consistent manner:

- envisioning
- choice-making
- implementation
- assessment and learning.

In addition, we analysed the nature of the policies themselves using the four policy pillars (or functions) listed in the previous section.

Each time a government takes an action in pursuit of a policy objective it can choose from a wide range of possible instruments and various means of implementation. The choices that it makes are conditioned by the institutional framework that it has developed over many decades and the familiarity of policy makers and stakeholders with certain types of interventions. Some governments have rich experience of seeking to achieve policy goals through careful planning, setting targets and guiding state-owned enterprises. Other governments' tools are dominated by regulating the behaviour of companies or individuals, or transferring government funds to companies, institutions or the public. In many cases, governments will also use their resources to provide information and education. Each of these main branches of policy design contains further choices, such as whether to allocate government funds via grants, tax incentives or debt, and how to select the recipients.

Energy technology innovation policy packages may combine different measures towards a single objective or multiple objectives. In some cases, successful energy innovation outcomes may emerge from policy packages that do not explicitly target technology development, but stimulate private sector activity.

The case studies

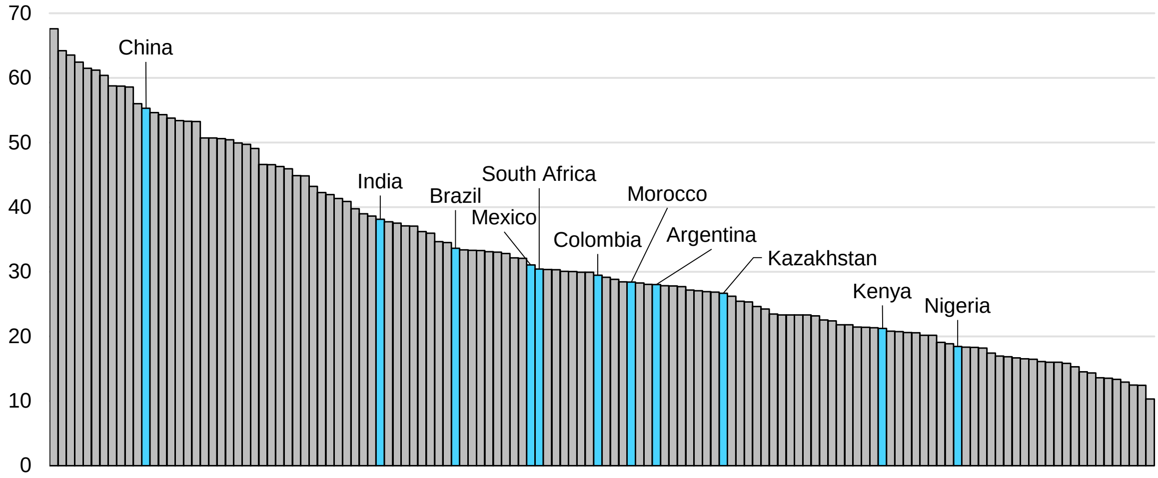
The 11 case studies developed for this report cover a range of different country contexts and focus technologies. While they do not represent a comprehensive set of policy experiences in EMDEs – indeed, they do not even present a comprehensive view of the energy policy landscape in the case study countries – they do provide insights into the factors that shape energy technology innovation outcomes in countries that face similar socio-economic challenges. When read as a group, they reveal commonalities that can better inform EMDE governments and international partners as they make decisions on clean energy innovation.

Table 1.1 The 11 case studies

Country	Focus
Argentina	The challenge for an emerging market economy of maintaining leadership in a high-tech sector such as nuclear energy The importance of international cooperation and complementary policy measures to foster a new market and innovation for energy efficiency
Brazil	Policy design to support a nascent wind energy manufacturing sector Building on a multi-decade process of innovation leadership for sugarcane bioethanol to push forward cellulosic bioethanol
China	UHV electricity transmission in China gained political legitimacy and became a global trailblazer for the technology The importance of private sector competition to innovation for solar PV in China
Colombia	Applying the experience of renewable energy policy development to industrial development of hydrogen energy systems
India	Building a new energy efficiency ecosystem through institutional design and market formation
Kazakhstan	Harnessing the influence and capacities of a sovereign wealth fund to deliver a national vision for energy sector transformation
Kenya	How creative policy design for off-grid energy access brought solar PV from the periphery to the centre of Kenyan energy strategy
Mexico	Synergies between solar PV plans for distributed generation and Mexico's manufacturing strengths
Morocco	The value of a national co-ordinating institution for renewable energy technology for informing policy and incubating new economic opportunities
Nigeria	Fostering solar PV by integrating it into established planning processes and establishing effective institutional responsibilities
South Africa	Applying a just transition framework to enhance the domestic value of renewable energy deployment, and innovation in newer technologies

The case studies were selected to cover some of the largest economies in Africa, Asia and Latin America that have stated aspirations to foster new clean energy technologies. These countries represent a range of different energy sector contexts, social development situations and innovation capacities (Figure 1.7). Each case study author is a national expert with deep local knowledge of the key issues and experiences in their country. The strength of the work lies in the co-ordination among the authors, via video calls and an in-person meeting between 2022 and 2024, which frequently revealed unexpected common features among the national contexts.

Figure 1.7 Global Innovation Index scores of the case study countries among 132 assessed countries, 2023



IEA and IITD. CC BY 4.0.

Source: IEA analysis based on WIPO (2023), Global Innovation Index 2023.

Each case study considers a major policy or set of policies that have significantly influenced the clean energy innovation trajectory of the selected country in the past decade. Each one characterises the four steps in the policy-making process that led to the observed outcomes, and the types of policy instrument that were chosen or overlooked by government processes. In some cases, the policies in question did not have a stated R&D or innovation objective upfront, which raises questions about why this did not feature in the policy process and how it could have been integrated at the outset.

The report should therefore be read as a compendium of narratives that shed light on the process of clean energy technology innovation policy making in EMDEs, and its strengths and weaknesses, a topic that is underexplored yet important to the achievement of international climate goals. Much remains to be studied in greater depth and more cases could be presented. Nonetheless, the key findings that emerge from this comparison of 11 cases can inform not only EMDE governments about how to strengthen their clean energy innovation processes, but also other country governments, multilateral agencies, philanthropies and other actors around the world that wish to support energy technology innovation in EMDEs and help decision-makers to design projects and policies with a better understanding of the factors that can reinforce or stymie success. The work for this report reveals that these factors are not always obvious and sometimes arise from outside the typical boundaries of energy and innovation policy.

Steps in the policy process

We consider four stages of policy development that are strongly conditioned by the local institutional and political landscape.

Table 1.2 Four steps in the policy process

Step	Description
Envisioning	The way in which national visions of the future socio-economic development trajectory shape the nature and ambition of clean energy innovation policies and processes. Envisioning includes how technological innovation is explicitly or implicitly considered (or not) by influential actors and institutions for achieving energy, economic and social policy goals. It also includes how shared visions of energy technology priorities (for R&D, import or export) are constructed and communicated.
Choice-making	The ways in which decisions about policy goals and policy instruments are made, including legal and institutional constraints, influential stakeholders, formal planning processes, consultations and impact assessments.
Implementation	The organisational means of implementing a policy measure or funding programme, including institutional responsibilities, inter-institutional co-ordination, selection of funding recipients, enforcement of rules and engagement with international partners.
Assessment and learning	The mechanisms by which choice-making and implementation are adapted over time to incorporate new knowledge, including through independent evaluations, transparency of governance, expert consultations and reviews of international practices.

Source: Sagar, A. D., & Klinsky, S. (2022). Negotiator Briefing: Needs-Based Assessment and Capacity Building.

Key findings from 11 case studies

The salient insights from across the 11 case studies can be generalised into seven groupings that demonstrate the surprising strengths of energy innovation in these countries as much as they highlight weaknesses. While innovation ecosystems are on the whole much weaker in most of the studied countries than in advanced economies, and formal institutions for policy learning and planning are often weak or absent, pockets of cutting-edge thinking and practice have thrived, for example where the absence of a prevailing practice allowed flexibility in a fast-moving area like digital products. The socio-economic priorities of the countries strongly influence their visions and choices, especially in relation to energy access and affordability, which can open major opportunities for experimentation in initiatives that align with visions for socio-economic development, while closing off pathways that do not reinforce these political preoccupations.

But what perhaps stands out the most from the case studies are the impressive aspirations of these governments to engage with the opportunities offered by clean energy transition. This high level of aspiration is contrasted by their often-limited capacities to achieve their objectives, especially in the face of resource (human, technical, financial, institutional) constraints, volatile macroeconomic conditions and political realities. However, through the use of appropriate and affordable interventions, while drawing on existing national strengths and international partners, some of these gaps between aspiration and capacities can be closed over periods of years rather than decades.

1. Clean energy innovation has risen high up the policy agenda in developing countries, just as it has in advanced economies

- In recent years, most of the countries studied have stated new ambitions to develop and produce competitive clean energy technologies. This has captured the attention of heads of state in countries including China, India, Morocco, South Africa. There are multiple factors that drive this change, but foremost among them are economic opportunity, employment and industrial development. In a cleaner energy system that will reward renewable resources, low-cost manufacturing, technical ingenuity and decentralisation, EMDEs can find many advantages. One example of this is the youth of the workforce and the latent demand for jobs in technical sectors, something that is behind Nigeria's establishment of more educational curricula in renewable energy technologies.
- The commitments that these countries have made under the Paris Agreement to reducing their GHG emissions have emphatically elevated these plans. These widely advertised pledges, often including a commitment to reach net zero emissions in the next three to five decades, have focused attention in two ways: they have convinced leaders that the market for clean energy technologies is sustainable, global and a key part of future growth; and they have compelled high-level decision-makers to think about the role they want their countries to play in clean energy technology supply chains. Countries including Argentina, Kazakhstan, Nigeria and South Africa issued new national energy strategies that referenced clean energy innovation shortly after publishing their NDCs as part of the Paris Agreement process.
- In some EMDEs, the current emphasis on the opportunity for clean energy innovation derives from existing capabilities that can find new markets. Kenya's technological capabilities in geothermal energy, developed over several decades, are translating into opportunities to supply services abroad and diversify into adjacent sectors such as CO_2 storage. Argentina and Brazil have identified potential global demand for their expertise in nuclear and bioethanol, respectively.
- Higher ambitions for the adoption of clean energy technologies in these countries are, in turn, influencing expectations for the relative roles of the public and private

sectors in the energy system. The need to rapidly learn about cutting-edge technologies and identify effective ways to adapt and adopt is encouraging some of the studied governments to give more responsibility for policy delivery to non-state actors than in the past, including start-up entrepreneurs. This is especially true where the technology targets are small scale or decentralised, such as solar PV, batteries or EV chargers and it can be seen in policy developments in China, India, Kenya and Nigeria.

2. Innovation policy can build upon and reinforce broader trends to catalyse technological change

- There is clear evidence from the case studies that energy innovation outcomes are more easily achieved when they align well with national visions for economic and social development. Although there is broad agreement in the value of R&D and other forms of innovation, it is often hard for governments to mobilise substantial resources given the opportunity costs related to pressing shorter-term policy priorities.
- The catalytic impact of recent climate change policy commitments is a striking example of this in our case study countries, but it is also apparent for other policy priorities. In South Africa, clean energy innovation has received a political boost from the country's "just transition" agenda. In China, a major policy drive to reduce air pollution provided the momentum needed to invest in UHV transmission R&D. In India, energy efficiency was propelled by the government's priority of maintaining access to electricity for a growing population despite financial challenges for utilities. In Kazakhstan, energy technology innovation intersects well with the country's push to diversify its economy and find new sources of export revenue. The provision of universal energy access remains a prominent policy concern in several of the case study countries and it opened opportunities for policies in Kenya and Nigeria that were supportive of technology innovation.
- Multiple overlapping policy objectives can help raise the priority of energy innovation but can also complicate institutional co-ordination between ministries. In China, clean energy innovation is closely associated with climate change, air pollution, export revenue, modernisation and energy security agendas. In Brazil, bioethanol innovation is supported by regional development, agricultural, energy security and climate change considerations.
- As demand for clean energy technologies grows, especially in advanced economies, energy innovation policy in EMDEs can focus on technologies of interest to their main trading partners. Recent policies in the European Union and United States give preferential treatment to clean energy equipment imported from partners with free trade agreements and this confer competitive advantages on innovators in their partner countries. Morocco's innovations in batteries may become integrated into electric vehicles for the EU market. Mexican innovators may identify similar opportunities vis-à-vis the United States.

- It can also be the case that international trends can hamper innovation in EMDEs. These countries often do not have large enough domestic markets to influence international standards and their products tend to have to comply with the norms of their trading partners. Any fragmentation of requirements between countries or uncertainty about the prevailing standards and regulations abroad can significantly increase the risk of developing new products, and this is noted as a challenge in Argentina, Kazakhstan and Morocco.

3. There are multiple ways to set innovation in motion

- R&D budgets in most of the case study countries remain small and well below 1% of GDP for public and private research spending combined. While there is no one-size-fits-all recommendation for the level of R&D spending, especially when accounting for wide variations in national situations, countries that aspire to be among the innovators in the new clean energy economy should seek to raise R&D budgets to the level of the highest spending countries in their regions and income level classes.
- However, the case studies strongly confirm that innovation policy is much broader than R&D funding programmes and the guidance of state-led of research facilities. Indeed, many of the successes related to domestic technology development or production have come through other channels, though local researchers have in some cases played a role. In Brazil, commercial flex-fuel vehicles emerged from the private sector, which responded to the incentives of the policy-led bioethanol market. Kenya's cohort of new producers of solar home systems were borne from a funding programme for off-grid solar PV that rewarded innovative means of adapting services to local consumers' needs. China's world-class solar PV manufacturers innovated to compete for market share by cutting costs. India's energy efficiency policies embedded technical expertise in LEDs and industrial processes within testing facilities and service providers, creating an innovation ecosystem for adapting and installing imported products. While these types of innovation are harder to track than R&D budgets and patents, they need to be included in any conception of how policy can stimulate energy technology innovation.
- Local content requirements are insufficient on their own to stimulate domestic manufacturing and innovation. Furthermore, they need to be carefully designed to reap the benefits of inward investment without creating risks of higher costs, slower deployment and lower incentives to innovate. Brazil's local content requirements for wind energy evolved over time and were opened up to more competition and responsiveness to global market developments. They benefitted from existing relevant industrial skills in Brazil, parallel scale-up of manufacturing outside Brazil and the availability of concessional finance. In South Africa, local content requirements for renewable energy equipment were designed to address additional policy goals related to inequality, and they generated valuable lessons about the need for clear and swift implementation.

- Energy innovation ecosystems are generally much weaker in most of the studied countries than in advanced economies, and they take different forms. Despite having fewer researchers, technology developers and formal institutions for innovation policy and learning, there are examples of countries that support the skills and capacities necessary to evaluate, adapt, manufacture and deploy a technology that is new to the country. India, Morocco and Kenya are notable examples of this among the case studies. In fact, the absence of a strong and formalised innovation ecosystem can allow for more responsive and creative approaches to policy. In the Kenya case, this is apparent in the speed with which digital tools transformed finance for solar PV, something that may have taken longer in a larger ecosystem with more inertia. In India, the government led programme facilitated imports to meet a need to offer the technology at lowest cost, but also incentivised a domestic innovation ecosystem through support for skills and manufacturing in the value chain. By fostering a network of technical skills around a technology that is new to the country the chances of domestic innovation are increased. These skills can be in any stage of the value chain, including manufacturing of components, assembly of systems, installation, maintenance or testing. If the participants in these technical tasks can exchange ideas, interact with other experts and access capital, these networks can seed new businesses and ideas even if the initial policy encouraged imports.
- Countries are not all alike and optimal technology or project configurations differ between markets. Products and processes often need adaptation to local conditions to be smoothly integrated with infrastructure and consumer preferences. This relies on local knowledge and understanding that in many EMDEs must be fostered in parallel to the uptake of a new technology, for example via technical education. Morocco strategically invested in renewable energy know-how for the evaluation and procurement of technologies that were new to the country, including concentrating solar power (CSP), solar PV and hydrogen. This investment has supported government decisions, including for directing energy R&D. By contrast, in Argentina energy efficiency regulations were not initially complemented by technical capacity to test and certify performance. In Kenya, the KOSAP programme experienced challenges with technical enforcement of safety and product quality for solar PV equipment.
- Hosting large-scale demonstration projects involving foreign technology suppliers is a means of entering a less mature clean energy area at the technology frontier. Morocco was able to achieve this for CSP, while Argentina, Brazil, Colombia, and South Africa have similar plans for hydrogen production. Such projects, if well designed, can facilitate rapid transfer of knowledge to local entities and seed new industries, but also carry risks due to the large levels of capital involved and the uncertainties over market readiness and technology performance.

4. Institutional history exerts a powerful influence on policy choices

- The case study countries are following different pathways in terms of the modes of governance and roles of state-owned enterprises in their energy systems. The case studies on Brazil and South Africa show that it can take a long time to change the institutional landscape, for example to increase the level of economic liberalisation. In Brazil's case, the government institutions for regulation and R&D that grew alongside the sugarcane and hydropower industries in the early 20th century continued to shape energy innovation policy choices for many decades. South Africa's "just transition" policies have their roots in a long social and institutional history. In Colombia, the policy support for solar PV and wind energy was designed to fit an electricity market that was liberalised in the 1990s and therefore sought to attract private investment and competition. This approach was then copied to support hydrogen energy, a much less mature sector. Successful innovation policy interventions work in harmony with the existing policy landscape, and it is important that international partners are sensitive to the institutional history.
- In EMDEs, the state typically plays a more dominant role in the energy sector and there is less reliance on market forces and private R&D. Large energy companies frequently play an outsize role in the economy and these tend to have a level of state ownership. In some EMDEs – including Argentina, Brazil, China, Colombia, India, Kazakhstan, Mexico and Nigeria – the government owns major fossil fuel extraction companies and their financial health is a consideration in policy design for clean energy transitions. Policymakers in countries with a tradition of state planning and control generally use key national planning documents to signal the value and direction of energy technology innovation. In the cases of UHV and solar PV in China, the rising expectations for developing the technologies featured in successive planning documents, giving administrators and investors confidence in providing their support. A similar pattern can be observed for solar PV in Nigeria, where the existence of a formal planning body in the form of the Energy Commission of Nigeria was important for establishing common expectations. However, the paperwork must also be complemented by sustained implementation efforts, something that has sometimes been lacking across administrative changes in South Africa.
- State-owned enterprises typically have more financial resources than other domestic companies and close connections to government decision-makers, which can allow them to take risks on innovative projects. In many cases they also have trusted relationships with local communities. State-owned enterprises can therefore be a resource for governments wishing to test or learn about a technology. Petrobras in Brazil played a significant role in the scale-up of bioethanol. The State Grid Corporation of China was central to the developments of capital-intensive UHV technology. In Colombia, Ecopetrol is involved in many of the large-scale hydrogen projects in development. In Kazakhstan, Samruk-

Kazyna is uniquely placed to formulate a strategic plan to diversity and decarbonise the economy, and co-ordinate its implementation across multiple state-owned enterprises in different sectors. Its use of fossil fuel revenues to undertake this programme to reduce transition risks shows a potential pathway for other state-directed fossil fuel exporting economies.

- In some EMDEs, state-owned utilities are a means of providing below-cost electricity prices to consumers, which reduces the incentives of energy users to innovate. These utilities can sometimes also oppose new clean energy technologies that do not complement their existing assets and expertise. However, as the case studies for Kenya and Nigeria show, off-grid energy access and rural electrification programmes can support innovation outside the centralised electricity system. In these cases, the demonstration of the costs and potential of solar PV in this policy niche led to the technology being adopted into the planning for the main utilities.
- Political upheavals and disruptive changes to macroeconomic policy tend to me more prevalent in the recent histories of our case study countries than for OECD countries. These changes are not neutral with respect to energy innovation. In Brazil liberalisation policies in the 1990s unwound bioethanol innovation ecosystems that were not compensated by the private companies that maintained the country's industrial base thereafter.

5. Existing technical expertise can provide a springboard, including from adjacent sectors

- Countries with limited financial resources to build entirely new sectors can nonetheless leverage skills and expertise within the country by selecting technologies with familiar attributes. Kazakhstan's energy technology plans do not promote digital technologies but rather emphasise carbon capture, utilisation and storage (CCUS) and sustainable liquid fuels, two areas that require transferrable skills from the oil and gas sector. Kenya, by contrast, became a leading innovator in solar home systems due to its prior expertise in digital finance technology. This enabled solar PV providers to integrate mobile payments, microfinance and app development, and also benefit from the healthy start-up ecosystem that had built up around the fintech sector in the previous decade. A similar pattern was established in Nigeria and in Colombia, the state-owned oil company has considerable direct experience and R&D facilities that are relevant to hydrogen but were not so valuable for renewable electricity. In Argentina, IMPSA, a manufacturer of hydropower parts developed products for the nuclear and renewable energy sectors.
- Synergies with existing technical expertise is not always so direct. In Brazil, extensive experience with aerospace manufacturing meant that it was easier to get started in wind turbine production. Countries such as Argentina, Mexico, Morocco and South Africa that already have internationally oriented mass manufacturing of high-tech products, including auto parts, have a foundation that

can facilitate foreign direct investment in clean technology manufacturing. In turn, such a manufacturing platform can be used to attract local suppliers, corporate R&D and investors in spin-off businesses.

6. There are demonstrated ways to make the most of limited resources

- The case studies cover countries that do not (or did not at the time of the case) have extensive resources to invest in energy R&D and other innovation policies. For EMDEs, innovation budgets come with opportunity costs of less spending on near-term social priorities. Energy-related companies in EMDEs are less likely to have significant R&D budgets as they often specialise in less sophisticated parts of the value chain or are local subsidiaries of firms with research programmes overseas. The case studies offer valuable insights about how governments in these countries have made the most of limited resources.
- International cooperation emerges as a key feature across the cases, whether based on financial support or knowledge sharing. Programmes developed with multilateral donors, were transformative for solar PV and wind power in Kenya, Morocco, Nigeria and South Africa. The example of the Kenya Climate Innovation Center (KCIC) and Kenya Off-grid Solar Access Programme shows how World Bank Group finance created the space for smart policymaking that supported new and technically innovative approaches. In Nigeria, a range of bilateral, multilateral and philanthropic support programmes have targeted energy innovators with grants, training and business development support. In Morocco, bilateral relationships with European research institutes helped government institutions to study opportunities in the area of hydrogen. Given the investment risks associated with clean energy innovation, and the potential future climate benefits, the case studies make a compelling argument for allocating a share of international climate finance to support domestic energy innovation ecosystems. There is scope for further analysis of effective approaches and international lessons learned in this area.
- Being a solo trailblazer country in a selected technology area is especially challenging for EMDEs, with the possible exceptions of China and, more recently, India. The case studies show that it can be possible, for example in the case of Brazilian bioethanol and flex-fuel vehicles, but development costs will be lower if there is knowledge exchange with practitioners working in parallel overseas. While this can raise the risks of being left behind by wealthier countries, it also opens opportunities to specialise as a regional leader or competitive manufacturer. The presence of regional leaders in clean energy has led to so-called south-south co-operation: Kenya supplies geothermal services in the Rift Valley area; Morocco has set up renewable R&D programmes with the Ivory Coast; India's EESL provides expertise and lighting technologies to Southeast Asian countries. Argentina and Brazil's cooperation in nuclear seeks to expand their joint market to reduce risks.

- Limited resources demand effective prioritisation of technology options. Morocco has developed tools and expertise for exploring potential technologies and identifying gaps to be targeted by policy. Argentina has specialised in nuclear technology, Brazil has focused on biofuels, Colombia seeks leadership in hydrogen and Kazakhstan is exploring CCUS. In India, energy efficient lighting and appliance technologies were initially prioritised for their relevance to pressing social and economic challenges. Early successes in this area enabled expansion of energy efficiency policy in India to other technology areas. In general, it is important to match local capacities and budgets to the technology type: digital technologies, as developed for Kenyan and Nigerian solar PV, have much lower entry costs than larger-scale technologies like CCS, CSP, fuel production or nuclear.
- New, dedicated energy innovation institutions can play highly valuable roles as a hub that ensures efficient knowledge exchange within the energy innovation ecosystem. Such institutions can also be given a mandate to inform policymakers about new technologies, thereby reducing expenditure on international consultants, and co-ordinate international co-operation. The Researchers for Mexico programme funds scientists and innovators to be embedded in the federal government for a fixed period to facilitate knowledge exchange in both directions. In some countries, issues of institutional continuity between government administrations can be helped by arm's length institutions. Among the case studies, IRESEN in Morocco is the clearest example of such an approach. However, RenovaBio and EPE in Brazil, Samruk-Kazyna in Kazakhstan, KCIC in Kenya, REA in Nigeria, and BEE in India share some of the same attributes. One common attribute is that these institutions have designed policies that are not only outside the traditional approach of the country but also novel in global terms. As EMDEs encounter energy innovation policy challenges it is often for the first time, and they are unencumbered by the institutional traditions that can stymie policy creativity in advanced economies.
- Consensus building can be especially important for ensuing that limited resources are impactful. The China case study illustrates the use of iterative formal and informal processes to align stakeholder's visions of the future, highlighting the importance of gaining socio-political support for innovation policies. In Kenya, involving key stakeholders in project execution and tariff collection helped build trust and a shared vision of the co-existence of national grid, mini-grid and stand-alone systems.
- The case studies also show the importance of being responsive to opportunities and maintaining international connections with innovators. Opportunities to develop a new technology domestically or secure foreign-direct investment are less frequent in EMDEs and can be easily lost due to administrative delays for entrepreneurs or a lack of networking between investors, users and innovators. In some cases, innovators have left EMDEs to seek support and facilities abroad but successful efforts have been made to help them keep a presence in their home country. In the relatively small energy innovation ecosystems of many EMDEs,

individuals with strong international networks and connections to diasporas can play outsize roles, as was the case with the earliest solar PV manufacturing in China.

7. Few countries have well-established and comparable processes for evaluating outcomes against the original policy goals

- An important final finding from the case studies is that the studied countries had few examples of policy evaluation for technology innovation outcomes. Additionally, while the case studies include many examples of policy papers that state high-level ambitions for energy technology development, few of them articulate the ambitions in a way that can be evaluated for lessons learned after their implementation. Mexico is an exception in this regard: its General Law on Climate Change mandates the evaluation of climate change policies through INECC, an institution within the Environment Ministry. In Colombia, the World Bank supported a thorough review of the Science, Technology and Innovation Fund, which is capitalised with 10% of the royalties from the exploitation of energy and mining resources, and this led to significant revisions to the programme.
- While innovation policy evaluation is a challenging area for all governments, it is important that it is built into policy design and, ideally, reflected in a corresponding impact assessment at the time of policy development. Given the wide differences between countries, internal evaluation is essential to the process of learning by which governments can improve their policy choices and implementation over time. Within a country the lessons may be transferrable to different technology areas, ensuring that new areas can be entered in the most efficient way. Furthermore, public records of evaluations and participation in international discussions – for example via international initiatives such as Mission Innovation – can help countries facing similar challenges to learn from one another.

Implications

Collectively, the case studies reinforce several messages that are pertinent to policy makers in EMDEs and also in advanced economies and international organisations. They highlight that a rising share of EMDEs have put in place substantial policies and programmes to advance a clean energy transition domestically, and their aim has been to do so in a manner that realises the developmental benefits of such a transition. This increasingly includes expectations to develop, own, produce or optimise the technologies that they deploy, and shape domestic markets to the capabilities and aspirations of the local population. In some cases, energy or climate policy documents state a vision of becoming an exporter of technologies in this area.

However, there remains a gap between countries' significant ambitions and their capacities to fully deliver them. The opportunity therefore exists for domestic policy makers, as well as international actors, to contribute to building capacity in EMDEs that will allow them to accelerate their clean energy transitions in line with their economic transformations. By harnessing clean energy technology innovation, they have a greater chance of making these transitions inclusive and equitable over the longer term.

The case studies show that policies must be carefully designed to realise the significant potential synergies between the development, adaptation and deployment of clean energy technologies and other developmental goals, including industrial and economic development, improved livelihoods and energy security. There is clearly much that can be learned and shared among the countries covered by the case studies. They face a range of similar challenges and have adopted diverse approaches to fostering clean energy technologies, each with some success and some learnings for improvement.

One such learning is that advancing clean energy innovation to underpin the clean energy transition requires a focus on more than just technology R&D. Supporting effective innovation also requires paying attention to the other dimensions, such as aligning clean-technology imperatives with the national vision for development. There is considerable opportunity for EMDE governments to work together to exchange experiences on this topic (i.e. "south-south" co-operation), potentially mediated by international institutions, as a complement to their existing co-operation with advanced economy entities and opportunities to engage in initiatives such as Mission Innovation and UN bodies.

As well as R&D, domestic policy makers should focus on building capability across the innovation cycle. A range of factors determine effectiveness, including fostering domestic markets, harnessing existing industrial strengths, building technical expertise within government, creating networks of know-how (including with international experts) and, rather than being constrained by national budgets, finding synergies with the objectives of international donors. The last point is important because, however efficient the policy design, there are costs involved in testing new technology options, funding R&D and building the expertise required to be an "informed buyer". Another strong insight that emerges from the case studies is the importance of not working directly against the incumbent businesses and institutions. In most of the countries studied, the ministries and enterprises that manage the existing fossil fuel and electricity assets wield considerable power and can delay attempts to disrupt their market rapidly. The case studies show two approaches that can effectively address this challenge:

- Make a state-owned enterprise or institution responsible for leading and creating value from the new technology, backed by a consensus-building process that elevates the accountability to the highest levels of government.
- Incubate the new technology area in a part of the energy system that is outside the concerns of incumbent institutions that may not prioritise the success of the new technology, for example by securing international finance to build capacity in off-grid energy access that can then be transferred to centre ground of energy policy making if successful.

In each of these simple archetypes, creative institutional design can be as effective as higher budgets or ambitious targets in policy documents. It is important that these institutions are sustained and strengthened and evolve over time. The capacity for supporting clean energy innovation is built up in a cumulative fashion and the importance of learning from experience cannot be overstated. If EMDEs are to realise fully their ambitions in one or two decades from now, the foundations must be laid in the near term.

International governments and other actors, such as multilateral institutions and philanthropies, have several crucial roles to play. The case studies underline how influential international engagement has been on clean energy technology progress in EMDEs. They also highlight ways in which greater international attention to the needs of EMDEs would help catalyse more rapid advances. These include:

- Continue to include EMDE priorities within international initiatives – including the IEA technology Network, Mission Innovation and UN initiatives – and encourage their participation in such forums to share experiences and expectations.
- Identify the technical and market needs for greater uptake of clean energy technologies in EMDEs and prioritise these within R&D programmes in advanced economies.
- Co-fund co-operative projects that seek to raise the innovation capabilities of EMDE partners in strategic areas, while tailoring support to their existing strengths. One potential approach is to create consortia that include partners from countries with weaker clean energy innovation ecosystems in projects that support a country with similar challenges but more mature capabilities, an approach that is often precluded by typical bilateral agreements.
- Use development finance strategically to help create markets for clean energy technologies while simultaneously supporting domestic skills and entrepreneurship. This could be through combinations of project loans, finance for incubators, seed investments to attract more venture capital, capacity-building grants, technical assistance with standards and regulations, or helping international companies to bring their technologies to projects they would otherwise not prioritise.

- Help to shift the discourse towards "innovation co-operation" by broadening out the scope from a narrow focus on technology or policy transfer, which frequently encounters setbacks in the political arena, to a collaborative approach to building long-term capabilities based on mutual interests.

2. Nuclear energy and energy efficiency in Argentina

María Florencia Zabaloy, María María Ibañez Martín and Carina Guzowski (Universidad Nacional del Sur)

Nuclear energy has a long history in Argentina, backed by sustained government intervention and support that has made it a dynamic sector of the economy. Argentina is now at the centre of nuclear innovation, as one of the leading countries in the development of small modular reactors (SMRs).

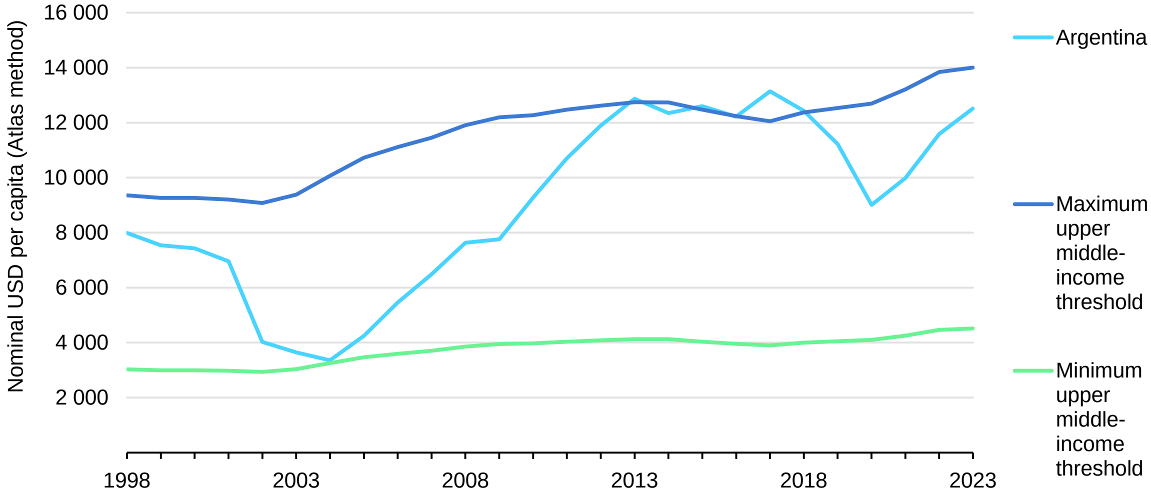
In contrast, energy efficiency only became a policy target in 1999. Since then, there have been several measures aimed at different sectors, but these have largely been "stop-go" policies, strongly dependent on the economic cycle. Beyond the nuclear industry, there has been limited sustained focus on clean energy technological innovation, the creation of specialised institutions or human resources. While public sector bodies in the oil and gas sector have well-developed research capabilities, the technical know-how does not overlap strongly with nuclear, buildings energy efficiency or mass-manufactured clean energy products. However, it could nonetheless be a platform for innovation in adjacent areas such as hydrogen or carbon capture if they became a domestic priority.

Policies in the two spheres, nuclear energy and energy efficiency, have followed very different paths, not least in terms of their duration, and comparing them can help deepen understanding of how energy policy is formulated and how it affects innovation. However, both policy approaches share the aim of developing domestic industry and increasing the share of national components in the value chain of the goods and services involved in the energy sector.

Country context

Argentina, Latin America's second-largest country by size, has undergone significant political shifts over the past century, vacillating between periods of economic growth and economic contraction. It has fluctuated between income classifications and, while it has been considered an upper middle-income country for most of this century, it has met the high-income definition at times and also come very close to being a lower middle-income country (Figure 2.1). Despite these fluctuations, it remains a member of the G20 group of advanced economies. Inflation has also risen steeply since 2021. In 2023 annual inflation was 254%, with monthly inflation recorded at more than 25%.

Figure 2.1 Gross national income per capita, and thresholds for income level classification, Argentina, 1998-2023



Sources: IEA analysis based on World Bank (2024) GNI per capita, Atlas method (current US$) - Argentina and World Bank Country and Lending Groups.

The Argentinian economy is characterised by significant external indebtedness, which in 2020 reached more than 60% of gross national income, and the country has defaulted on its international sovereign debt several times in the past two decades. In 2022, ahead of a general election in October 2023, the government secured a deal with the International Monetary Fund to restructure its debt of more than USD 44 billion.

In addition, its trade balance with the rest of the world has shown a sustained deficit over the years, with the exception of the period between 2002 and 2009. In the most severe years, the current account deficit within the balance of payments has reached 5% of the country's GDP. In 2022 Argentina's current account deficit stood at USD 4.3 billion. Argentina is ranked 26th globally for industrial production, and 45th in per-capita terms. The industrial sector (including construction) accounts for 24% of GDP.[1]

Argentina is currently classed as an upper middle-income country by the World Bank. Although the UNDP ranks the country as having “Very High Human Development”, Argentina has serious problems at the macroeconomic level due to high productivity volatility, cycles of significant expansion and contraction, an international position as a supplier of products with low added value, high inflation rates, exchange rate volatility, institutional instability and problems with corruption,

[1] Estimated based on data from the World Bank World Development Indicators according to constant manufacturing value added at 2010 prices, averaged over 2010-2022.

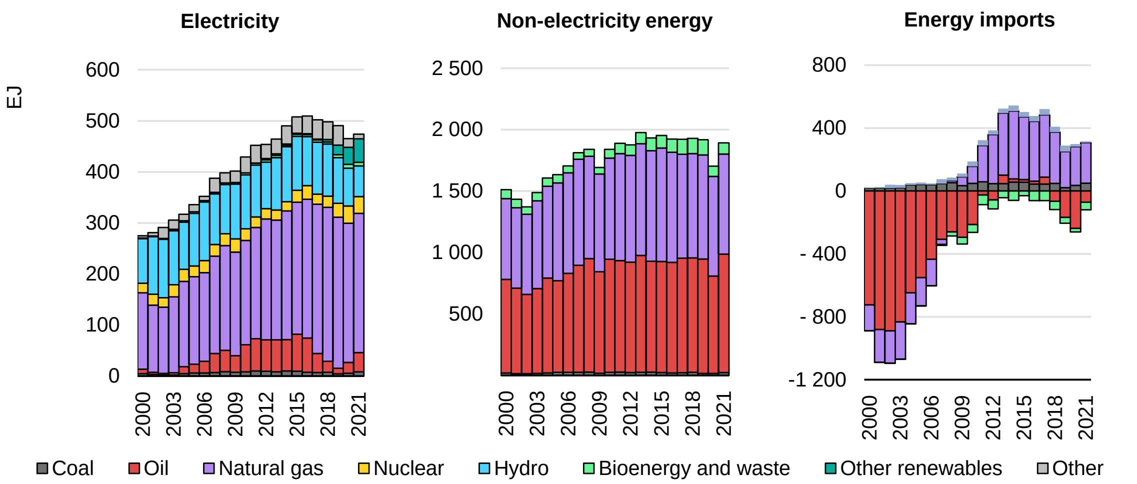
among other issues. Evidence points to significant inequality of income distribution and the worsening of already high rates of poverty after the Covid-19 pandemic.

Faced with this fragile economic outlook, the government that took office on 10 December 2023 is implementing a policy and stabilisation plan that encompasses a range of monetary, exchange rate, productivity and fiscal measures.

Energy sector context

Argentina's energy consumption increased steadily between 1970 and 2016, but has since slightly decreased. The energy mix is highly dependent on fossil fuels, especially natural gas and oil, and also relies on nuclear power and hydropower, albeit to a far lesser extent. The promotion of solar and wind energy began in the 1990s, with the results only becoming visible in the energy supply data from 2010. They currently represent only a small share of primary supply. In 2021, 24% of electricity generation was from renewables, of which half was large hydropower. Energy intensity remained relatively stable over the same period.

Figure 2.2 Energy sources for electricity and other uses, and level of imports, Argentina, 2000-2021



Notes: Electricity and non-electricity energy are shown on a final consumption basis. Imports are shown net of exports. "Other" refers to imported or exported electricity.
Source: IEA (2024), World Energy Balances.

In 2022 Argentina ranked 33rd in the world for total CO_2 emissions, producing 184 Mt CO_2. However, in terms of total GHG emissions, Argentina ranked 27th with 383 Mt CO_2-eq, reflecting the significant impact of the agricultural and livestock sectors, which contribute 37% of the country's GHG emissions, well above the global average of 12%. In terms of per-capita CO_2 emissions from fossil fuels and industry, Argentina ranked 92nd in the world with 4.3 t CO_2 per capita.

Argentina ratified the Paris Agreement in 2016 and numerous policies have been initiated to support the transition to a cleaner and more flexible energy system in recent years, and to increase the transparency of information on the energy sector. In its latest NDC, submitted in 2021, Argentina committed to emit no more than 359 Mt CO_2-eq in the year 2030.

Notable policy initiatives include the Energy Scenarios 2030 initiative, which is led by the Undersecretary of Energy Planning. This began in 2016 with the aim of setting a long-term vision for energy policy. More recently, the Guidelines for an Energy Transition Plan to 2030 have shaped Argentina's vision for energy policy. When the Energy Transition Plan 2030 (which was based on the guidelines) was approved in 2023, it set targets to:

- Not exceed net emissions of 349 Mt CO_2-eq in 2030.
- Reduce energy demand by 8%.
- Reach more than 50% renewable energy as a proportion of electricity generation.
- Achieve EV penetration of 2% of the vehicle fleet.
- Reach 1 GW of distributed renewable power capacity.
- Increase the high-voltage electrical transmission network by 5 000 km.

The plan also includes qualitative goals such as local development of the clean energy technology value chain and job creation, a reduction in energy poverty, and promotion of a just energy transition. Energy efficiency, clean energy and the development of national technological capacity account for three of the nine strategic lines included in the plan.

Innovation context

Argentina has a dynamic scientific sector, predominantly based in public institutions, and the number of full-time researchers has tripled in the past decade. Articles in scientific and technical publications in Argentina increased by 40% between 2008 and 2018.

According to the World Intellectual Property Organization, Argentina ranked 73rd in the Global Innovation Index Globalin 2023, and 6th at regional level. It ranked 18th among the 34 economies in the upper middle-income group – a relatively low result given its level of development. However, it performs above the regional average on human capital and research, infrastructure, business sophistication, and knowledge and technology products. Various indexes note that Argentina has a strong skills base, market size and ability to innovate, although poor macroeconomic stability and the functioning of markets and institutions negatively impact its overall competitiveness.

In 2019 investment in R&D in Argentina was Argentine Pesos (ARS) 96 664 million (equivalent to USD 1.6 billion as of 31 December 2019), of which 39.1% was accounted for by public science organisations, 22.3% by public universities, 36.1% by private companies, and the remaining 2.5% by private universities and non-profit entities. Total investment represented 0.46% of GDP in the same year (0.28% public investment and 0.18% private investment). In 2021 the Law on Financing National Science, Technology and Innovation proposes to gradually increase public investment in R&D to 1% of GDP by 2032.

Since 2003 science and technology policy at the national level has focused on priorities for economic development, such as renewable energy, the rational use of energy and technological advances in oil and gas. The Green Productive Plan, launched in 2021, aims to develop domestic business in the green economy, and the Productive Argentina Plan 2030, launched in 2022, sets out to develop the green economy for a just environmental transition. Although national government generally defines the direction of innovation policies, priorities are also determined at the provincial level.

The National Agency for the Promotion of Research, Technological Development and Innovation (Agencia I+D+i) is a decentralised body reporting to the Ministry of Science, Technology and Innovation, and has a key role in determining the direction of innovation through its funding calls. In addition, Y-TEC, a research company created by the National Scientific and Technical Research Council (CONICET) and the majority state-owned YPF oil and gas company, focuses on technology development in the oil and gas and chemicals sectors and plays a key role in directing investment in energy innovation. In recent years, Y-TEC has launched initiatives in the areas of carbon capture, utilisation and storage (CCUS), hydrogen and lithium-ion batteries

The case of innovation in nuclear energy technology in Argentina

Innovation in nuclear energy technology has a long history in Argentina, dating back to the formation in 1950 of the National Atomic Energy Commission (CNEA), created to promote R&D related to the peaceful use of nuclear energy. In addition, the Balseiro Institute, founded as the Instituto de Física de Bariloche in 1955, has been a locus for physics and nuclear energy research in Argentina ever since.

Building technological and innovation capacity in the nuclear sector has received sustained policy support and been regarded as an engine of economic development. With the exception of a short period in the 1990s, Argentina has had a remarkable degree of continuity in nuclear energy policy in spite of volatility in the economic and political landscape.

The nuclear sector is one of Argentina's most sophisticated technological clusters, making it a leader within the Latin American region and the wider world. This has served different purposes, including the development of research reactors, large nuclear power plants, satellites, radars, the first prototype of the SMR, irradiation plants for industrial uses, uranium dioxide conversion, and nuclear medicine centres, among others.

One of the main aims of development in the nuclear sector has been to diversify the energy mix to support decarbonisation and improve energy security.

Historical milestones in nuclear energy innovation

Between the 1950s and 1970s a nuclear ecosystem began to take shape at CNEA scientific and technological facilities located across Argentina. CNEA started South America's first operational experimental reactor, the RA-1 Enrico Fermi, in 1958, built mainly using local technologies. The RA-1 pioneered the production of radioisotopes for medical and industrial use in Argentina, and is still used today for scientific purposes, including the testing of nuclear reactor materials and the development of medical therapies.

In 1968 construction began on what was to become Latin America's first nuclear power plant, Atucha I (Lima, Province of Buenos Aires, 362 MW), which was inaugurated in 1974. This was followed by Embalse (Córdoba, 648 MW) in 1983, and finally Atucha II (Lima, Province of Buenos Aires, 745 MW) in 2014. Construction of Atucha II began in 1980, but was halted between 1994 and 2006, when it was restarted as a result of renewed presidential support for nuclear development. All three nuclear power plants are pressurised heavy water reactors (PHWRs) operated by Nucleoeléctrica Argentina (NA-SA), which is majority owned by the Ministry of Economy and the CNEA. The reactors were built using technology imported from Germany (Siemens) for Atucha, and from Canada (CANDU) for Embalse. Local industry was behind most of the civil engineering, some of the assembly work and a small share of supplies; NA-SA prioritised using Argentine suppliers whenever possible and imported technology only when necessary. To facilitate this, it certified national companies to international standards, which also enabled them to bid for international tenders afterwards. The contract with the Canadian company, CANDU Energy, included technology transfer to the Argentine company IMPSA.

A key objective of nuclear innovation policy in the early years was to become self-sufficient by developing all the necessary technologies for the industrial production of key inputs in the nuclear fuel development cycle, including enriched uranium. This became a particularly pressing objective following the entry into force of the Nuclear Non-Proliferation Treaty in the 1970s.[2] Argentina's uranium enrichment plant was constructed by the public company INVAP for the CNEA and became

[2] Argentina signed the treaty in the 1990s.

operational in 1983, using gaseous diffusion technology, but was stopped in the late 1990s. In 2015 Argentina reactivated the plant, two decades after production was initially halted, but production ceased again in 2018. The plant has not been used for commercial or export purposes since.

In the 1970s Argentina began to evaluate the possibility of constructing an industrial plant to produce heavy water to supply PHWRs. The CNEA was authorised to start construction of a such a plant in 1979, and work began with the expectation of completion in 1983. However, the need to reduce the fiscal deficit in the 1980s put a halt to the project, which required a total investment of USD 1 billion. The plant was later commissioned in 1994 by ENSI (Empresa Neuiquina de Servicios de Ingeniería). This allowed Argentina to meet domestic demand for heavy water, which was also exported to Australia, Canada, France, Germany, Korea, Norway, Switzerland and the United States. In 2006, when Argentinian nuclear development again became a policy priority, the plant underwent improvement after years of budget restrictions. However, it has been idle since 2017 due to financial difficulties, and in 2021 Argentina imported heavy water. Most of the plant's workers have now left. Pre-commissioning or restarting the plant would be costly but would reduce import needs and open up export potential, including for heavy water needs in medical applications. Alternatives under consideration include converting the plant to produce ammonia-based fertilisers, including the possibility of using low-emissions hydrogen in the future.

Public participation in nuclear energy innovation

One of the distinctive characteristics of technological development and innovation in the Argentinian nuclear sector is the central role of the state in financing and promotion. This has led to the creation of a large number of public institutions, organisations and public–private partnerships within the sector. One key player is INVAP, a public company created in 1976 to commercialise knowledge developed in CNEA research centres. INVAP is owned by the province of Rio Negro and aims to be self-financing, but a large part of its activity is driven by requests from the CNEA. INVAP has established itself as a major exporter of nuclear research reactors, including multipurpose and medical research reactors, and has exported them to Algeria, Australia, Egypt and Peru. In January 2018 INVAP won an international tender worth USD 400 million to manufacture a research reactor for the Netherlands – the first time this type of technology had been exported to an EU member state. Large nuclear power plants are managed by NA-SA, which is state-owned. Research and development continues to be led by the CNEA, and since 1994 regulation has been overseen by the Nuclear Regulatory Authority.

Argentina has built significant research and innovation capacity in the nuclear sector, most prominently through the Balseiro Institute, a public institution, which specialises in training scientists and technologists in the peaceful use of nuclear science. Student scholarships, funding and training opportunities have also helped to build a skilled workforce.

In 2022 a financing opportunity for companies active in the nuclear sector was added to the existing National Programme for the Development of Suppliers (PRODEPRO), which aimed to develop domestic supply in strategic sectors. Projects could receive grants of up to ARS 100 million (approximately USD 274 000), up to a limit of 75% of all financing.

A new era for nuclear innovation targets exports

The launch of the Argentina Nuclear Reactivation Plan in 2006 marked the start of a renewed push for nuclear innovation. The plan was behind the completion of the Atucha II nuclear power plant, and the extension of the Embalse plant's lifespan. The latter project, which began in 2015 and was completed in 2019, directly employed more than 3 000 people and fostered the development of highly qualified national suppliers of goods and services. The plant's useful lifetime was extended by 30 years.

Looking to the future, the plan also included a proposal to build the first prototype of an SMR, called CAREM, designed to produce 32 MW, or 9% of the capacity of the Atucha I plant. When construction began in 2014, led by the CNEA, the CAREM pressurised water reactor (PWR) was the first SMR project in the world to move from design to construction, demonstrating the strength of technological innovation in the Argentinian nuclear sector. In addition, unlike Argentina's existing nuclear power plants, CAREM would be entirely designed and developed domestically, using low-enrichment uranium as fuel, and light water as coolant and moderator, in a first for the country. As of 2024 the research prototype is expected to start operating between 2028 and 2030. The advances made to date are a result of a process of constant technological innovation in the national industry, from the development of the pressure vessel, classified and non-classified components, fuel, heat exchangers and overhead cranes and engineering work. It is expected that around 70% of inputs, components and related services will be provided by Argentine companies certified under the international quality standards supervised by the CNEA.

The Productive Argentina Plan 2030 sets out the aim of exporting the SMR technology at a scale of up to 100-120 MW for the international market. In addition, the CNEA is already working on a commercial design that, using the same technology, will integrate four 120 MW reactors in a medium-sized plant with a total capacity of 480 MW. This commercial model of CAREM is expected to cost USD 1.5 billion and to require two years for construction. The CNEA estimates that the commercial module will be able to produce energy at USD 80 or

USD 90 per MWh. This type of reactor could potentially bring grid-connected electricity to regions and places that are traditionally off-grid, as well as boosting the reliability of the power grid, especially for energy intensive sectors.

Despite having had government support since 2003, the CAREM project has faced interruptions in funding. This has resulted in uncertainty about completion, overall cost, the participation of the national industry and, above all, the probability that the CAREM prototype can be reproduced on a commercial scale. CAREM has two major challenges. One is technological, and relates to completing the prototype and demonstrating that the technology is scalable to a commercial model of four reactors. The other is to make the medium-sized 480 MW plant commercially viable by producing 1 MWh at a competitive cost. More than 80 SMR designs are under development by several companies worldwide, but only two are operational: one in the Russian Federation (hereafter "Russia") Russia (70 MW) and another in China (210 MW). While some reactors are under construction in Russia and China, most SMR technologies worldwide remain in the design phase, with around 22 GW planned as of Q1 2024, led by the United States with nearly 4 GW. In July 2024 Rolls Royce SMR advanced to stage 3 of the three-step Generic Design Assessment for its 470 MW SMR design in the United Kingdom. There SMR field includes prominent incumbents such as NuScale's light water SMR (United States, 77 MW per module), GE-Hitachi's BWRX-300 (United States/Japan, 300 MW), Nuward (France), Holtec International (United States, 300 MW) and Westinghouse AP300 SMR (United States, 300 MW), as well as numerous start-ups pursuing innovative designs. Both established players and emerging companies would be in direct competition with CAREM.

The Argentina Nuclear Reactivation Plan also set out to investigate the feasibility of a fourth nuclear power plant in order to expand the share of nuclear generation in the energy supply. Argentina has since begun negotiations to purchase a large 1 150 MW Hualong-type PWR plant from China, which would be called Atucha III. In 2014 the governments of Argentina and China signed a framework agreement to co-operate on economic initiatives, including the aforementioned nuclear power plant, but negotiations stalled, and in 2018 were cancelled by Argentina due to fiscal constraints. More recently, in 2022 Argentina signed a co-operation agreement in which China agreed to finance 85% of the project, representing an investment of USD 8 billion. However, this has not yet been implemented, with Argentina negotiating for China to finance a larger share of the project and to grant a licence to produce nuclear fuel domestically, ensuring subsequent knowledge transfer.

Technological leadership and international co-operation as a driver of development

Argentina's nuclear sector has become a paradigmatic example of the results of public policy focused on the accumulation of technological and innovative capacity. This has been underpinned by a Latin American perspective on science, technology and development that, since the late 1960s, has emphasised the need for states to strengthen scientific and technological infrastructure through active funding and infrastructure policies. This approach sought to align scientific and technological efforts with the interests and developmental objectives of the countries of the region, by advocating the co-ordination of three fundamental elements: government, industry, and scientific and technological infrastructure.

The success of this approach can be seen in the favourable environment created for the formation of a nuclear industrial complex in Argentina, and the establishment of scientific and technological institutions and specialised capacity to train experts in the field. Over the years, this has fostered an ecosystem of companies and institutions capable of producing components and final products with international nuclear certification, positioning Argentina as a leader in the nuclear sector both in Latin America and globally. Despite the macroeconomic challenges faced by Argentina and the implementation of fiscal adjustment measures since the mid-1980s, which led to cutbacks and interruptions in the nuclear industry, the country's strong skills base, the maintenance of a degree of autonomy and continuity of nuclear institutions and a forward-looking approach, both domestically and outwards, have enabled the nuclear industry to continue to progress.

In the 1970s Argentina and Brazil competed for regional leadership in nuclear technology, but in the 1980s their relationship began to shift towards co-operation. In 1985 the creation of the Argentine-Brazilian Permanent Committee on Nuclear Policy (CPPN) marked a turning point in bilateral nuclear relations. This co-operation deepened in 1991 with the creation of the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC), the world's only bilateral and supranational safeguard organisation dedicated to the mutual verification of the peaceful use of nuclear materials. Taking their partnership further, the Binational Commission on Nuclear Energy (COBEN) was created in 2008 to promote bilateral co-operation on the development of multipurpose reactors. The evolution from competition to co-operation between Argentina and Brazil underscores a comprehensive integration in policy (CPPN), control (ABACC) and innovation (COBEN), characterised by sustained political dialogue, technical exchanges and mutual inspections of nuclear facilities, which together have transformed their nuclear relationship into a unique model of bilateral co-operation, including in innovation, with a combined weight that the two countries may not have achieved on their own.

The case of energy efficiency policies in Argentina

Energy efficiency in Argentina has gained support at a political level only relatively recently. Until the late 1990s energy policy largely centred on exploiting and exporting fossil resources. The first signs of a broader vision for energy policy appeared in 1999 with Resolution 319, which promoted appliance efficiency standards and labelling. Later, the Rational Use of Electric Energy Programme (PUREE), launched in 2004, and the National Programme for the Rational and Efficient Use of Energy (PRONUREE) launched in 2007, further contributed to shaping a national vision for energy efficiency in Argentina.

However, the economic crisis of the early 2000s had knock-on effects for energy supply, and when PRONUREE was launched, energy efficiency was thought of as just one of many measures to alleviate the energy crisis, and the programme faced implementation problems. Consequently, energy efficiency slipped off the agenda when the crisis was over.

Only in 2015 did energy efficiency begin to appear as a central axis of long-term public policies. The period of greatest transparency was between 2015 and 2018, at which time the Undersecretary of Energy Saving and Efficiency existed and periodically published reports on its activity.

Implementation

PRONUREE constitutes the general framework for the promotion of energy efficiency in Argentina. In the case of the residential sector, the main lines of action proposed by the programme in the short term were: promotion of an energy efficiency labelling regime and the implementation of minimum standards for the sale of equipment; education, awareness and information campaigns; and the replacement of incandescent light bulbs. As a result of the latter, 18 million low-energy light bulbs were distributed and 23 million incandescent light bulbs collected.

Different objectives were established for the medium and long term, including the decision to work with the Ministry of Science, Technology and Productive Innovation to promote development and technological innovation in materials and methods of construction for new housing. Improving construction materials has therefore become a primary policy target for innovation on energy efficiency in the medium and longer term. In general terms, the promotion of energy efficiency policies in the building sector is relatively recent. Appliance design has not been a major focus of energy efficiency policy, as appliances are typically imported or dependent on imported parts. Despite this, there have been equipment replacement programmes such as the Programme to Promote the Production and Marketing of Energy Efficient Household Electrical Appliances (RENOVATE).

Different instruments have been used to promote energy efficiency policies, such as demand pull, knowledge management and resource push. However, energy efficiency policies have often been isolated actions that have not served to accelerate the overall effective improvement of energy efficiency.

Appliances, standards and labelling

Resolution 319, which was passed in 1999, only came into force (at least partially) in 2007 through a provision to establish the characteristics and minimum standards of energy efficiency for lighting. This delay in implementation was due to the lack of recognised testing laboratories capable of carrying out the required certification. Since 2007 the National Directorate of Internal Trade has validated different points of the resolution.

Within the framework of PRONUREE, in May 2010 the Argentine Institute of Standardization and Certification (IRAM) developed the IRAM Standard 11 900 "Heating energy efficiency label for buildings". This establishes a methodology for calculating the level of energy efficiency of the building envelope that can be heated, with information presented on a label.

Based on the interest in improving the thermal envelope of buildings, the National Housing Labelling Programme was launched in October 2016. This has the objective of introducing energy efficiency labels to provide information on the energy performance of a dwelling, to support consumers looking to buy or sell their homes or undertake renovations. This programme is currently under development, with pilots in a few provinces.

Financial incentives

In the case of residential buildings, between 2004 and 2016 PUREE offered bonuses for those who reduced their electricity consumption. However, the programme was unsuccessful in creating incentives to save energy because electricity rates remained frozen from the start of the programme until 2007, and because it did not have an appropriate advertising campaign. In 2016 this initiative was replaced by a stimulus plan (Plan Estímulo), which aimed to incentivise energy saving.

Some fiscal incentives and soft loans provided by the government to industry are designed to improve the level of energy efficiency of industry in terms of its energy use. This means that they are usually not designed to promote improvements in materials or energy efficiency inputs. In many instances, industries belonging to the construction sector are not eligible for funding. One such example is the

Argentine Energy Efficiency Fund (FAEE), which was in force between 2014 and 2017 with the aim of enabling credit for technology improvements at manufacturers and processors of industrial products, service providers, agricultural and agro-industrial undertakings, and in the commercial, mining and tourism industries. However, some loans are available to the construction sector, such as a financing line from the Ministry of Productive Development for strategic investments aimed at medium-sized and large companies that want to acquire fixed assets, build or improve facilities to develop new products and create new production lines.

Looking ahead, industries in the construction sector will need access to financing in order to innovate and design new products that in the long term will help to optimise the country's energy consumption. This issue is due to be addressed by the current Green Productive Development Plan, which includes the consideration of measures to improve the energy efficiency of equipment and building sector materials, and deploy more smart devices.

Another recent initiative with the strong participation of government in public financing is the Competitiveness Support Programme for Micro, Small and Medium-sized Enterprises (PAC Empresas). The government grants a non-reimbursable contribution to cover a maximum of 70% of the project and up to ARS 3 million for business development projects that incorporate improvements in digital transformation, sustainable development, quality, design and innovation or export development. The sectors eligible comprise agriculture, manufacturing industry, trade, construction and services, but companies in the construction sector are assigned lower scores in the selection process. A specific area of innovation promoted by the programme is related to design, products and processes.

Support from international development banks has also encompassed energy efficiency initiatives. For instance, the Energy Efficiency Project funded by the Global Environment Facility (GEF) was approved in 2009, consisting of a donation of USD 15 million through the World Bank. In the context of a growing market for energy efficiency services and equipment, this project aimed to increase efficiency in the use of energy, and to contribute to the reduction of GHG emissions through the application of alternative energy sources. Some of the actions were aimed at replacing incandescent lighting with compact fluorescent lighting in the residential sector, as well as standardisation and labelling.

Participation in national and international initiatives to promote knowledge sharing

Argentina participates in several international alliances relevant to energy efficiency. It has been an associate member of the International Energy Agency since 2022 and participates in the Clean Energy Ministerial (CEM). It is also a member of the Renewable Energy and Energy Efficiency Partnership (REEEP), International Partnership for Energy Efficiency Cooperation (IPEEC), and Three Percent Club for Energy Efficiency.

At the national level, the Portal of Energy Efficiency in Argentina network exists to link interested parties and spread information about events; any interested party can register.

Within the building sector, the innovation platform Transform and Innovate the Building Industry (TIIC), created by the Argentine Chamber of Construction, provides a forum for entrepreneurs and startups to present projects and ideas that can provide innovative solutions to problems in the construction industry. TIIC brings together companies in the construction industry with startups, universities and scientific centres, governments and venture capital funds. Its current call includes the area of sustainable construction. Some of the goals of the call are to achieve greater sustainability in conventional materials and to promote the development of new materials and techniques.

Argentina is also working with the European Union on several initiatives to promote knowledge-sharing. The project Mitigation of greenhouse gases and adaptation to the impacts of climate change in Latin America, funded by the EUROCLIMA+ programme, aims to strengthen policy and practice on energy efficiency through the transfer of knowledge between Argentina and Chile. The National Energy Efficiency Plan (PlaneeAR), which was first published in 2021, began in 2018 through co-operation between the European Union and the Secretary of Energy of Argentina. The plan includes guidelines for promoting energy efficiency actions in the industrial, transport and residential sectors, in line with emissions reduction targets for 2030/2040.

Assessment and learning, and next steps

Energy efficiency is a central pillar of Argentina's energy policy, although progress towards policy objectives is less easy to identify. Nevertheless, there has been an improvement in the enabling conditions for energy efficiency in recent years.

Massive public awareness campaigns have been carried out in the past decade, and awareness is growing, but public support remains weak. Energy efficiency is beginning to gain prominence in the private sector, and the Secretary of Energy now publishes a list of energy efficiency consultants. Nevertheless, the market is only just emerging. There are no energy service companies (ESCOs) in Argentina, due to the presence of high subsidies that delay the payback date of investments and the lack of a clear norm for ESCOs, including their accreditation.

However, within the framework of the Argentina 2030 Productive Plan, policy instruments are now being designed to promote the production of goods and services linked to energy efficiency.

Energy efficiency policies have, to date, incorporated more regulatory instruments than economic and voluntary measures, largely due to economic and financial barriers. In turn, there are institutional barriers and boundary conditions that hinder the development of energy efficiency measures.

For example, implementing energy efficiency policies for buildings requires co-ordinated effort from national and subnational governments. While federal policies can provide a comprehensive framework and set broad standards, subnational governments play a critical role in ensuring compliance. Challenges include ensuring regulatory consistency among regions, allocating adequate resources, adapting policies to diverse local contexts, and a lack of co-ordination among all stakeholders involved. For example, measures aimed at improving the thermal envelope of buildings, both existing and new, have made very little progress in Argentina, mainly due to the lack of centralised regulation that would provide municipalities with the enforcement capabilities to implement this type of policy. The norms of thermal conditioning of buildings fall into the jurisdiction of local government. In addition, policies launched through presidential decrees (as was the case with the PRONUREE), rather than legislative decision-making bodies, can be particularly affected by a lack of co-ordination between local decision-making bodies and the ministries, secretariat and programmes of the national government.

In contrast, more progress has been seen with regard to appliances used in the residential sector, which have shown a substantial improvement in energy efficiency indicators. In this case, centralised co-ordination was based on the gradual but sustained incorporation of minimum energy performance standards (MEPS), combined with an increase in consumers' real wages in the first half of the 2010s, which led to a relatively rapid replacement of appliances.

There is still a lot to be done regarding construction materials. To date, there have been no significant initiatives to improve the energy efficiency performance of construction materials, though this could change in the medium term as a result of policies currently being designed.

In contrast to the case of promoting nuclear energy innovation, the enabling conditions for energy efficiency are notably different: Argentina has no specialised institutions, has made no great advances in human resource training and has no overall legal framework for policies. Instead, there is a presidential decree that functions as a general framework for the promotion of energy efficiency. In addition, there is only one declared national industry development objective: the development of innovative materials for buildings in the PRONUREE programme.

Another difference relates to interest groups and the national policy agenda. In the case of the long-established nuclear sector, there has been some learning about the need to have continuity in policy to promote the national industry and develop the market. The development of energy efficiency policy is not yet at an advanced stage, but there is a possibility that it will be strengthened in the coming years given that it is part of the objectives of the Productive Argentina 2030 industrial development plan. The primary mission of this plan relates to the development of a green economy for a just environmental transition. Interventions on appliances and smart devices are prioritised, while interventions to improve innovation in materials are considered secondary actions.

Finally, regarding monitoring and evaluation, there is a clear political desire to develop better indicators and data. Alongside the interactive platform for Argentina’s GHG inventory is a tool to monitor the different strategic lines of the Energy Transition Plan. However, this platform currently only has results for renewable energy policies. No data are available in the case of energy efficiency or other strategic lines.

Findings

Argentina's ongoing commitment to fostering innovation in the nuclear sector has yielded positive outcomes, showcasing the effectiveness of a public policy approach that prioritises the accumulation of technological and innovative capabilities. This strategy, which has its roots in a Latin American perspective on science, technology and development since the 1960s, emphasises the need for states to actively strengthen their scientific and technological infrastructure as a means of promoting development. Argentina's continued political support for nuclear innovation over seven decades, coupled with its strong skills base, has created a favourable environment for the emergence of a robust nuclear industry. Specialised research institutions, companies and training programmes have positioned Argentina as a regional and global leader in the nuclear sector. The evolution of Argentina's nuclear relationship with Brazil, from competition to co-operation, highlights the potential of South-South international co-operation to enhance technological leadership and achieve a combined impact greater than either country could achieve independently.

Argentina's nuclear innovation demonstrates the value of a long-term vision supported by dedicated institutions. The CNEA and INVAP have been instrumental in maintaining Argentina's leadership position, enabling the country to develop and export advanced technologies, including research reactors and medical applications. However, Argentina's nuclear leadership faces significant challenges in a volatile macroeconomic environment, particularly as the global market for emerging technologies such as SMRs is becoming increasingly competitive. With over 80 SMR designs currently in development worldwide and intense competition from major economies with greater domestic demand and financial resources, the success of Argentina's nuclear industry will depend on its ability to leverage its technological strengths and secure stable funding for projects such as CAREM. The country could be at risk of losing its position in nuclear innovation if economic difficulties persist. In this context, it is crucial to allocate resources effectively to priority areas, particularly in a highly regulated sector such as nuclear, where the state plays a significant role in R&D and innovation. Argentina's longstanding prioritisation of nuclear energy has been a significant factor in its success in innovation. The country should identify specific nuclear-related technology components in which it can maintain a competitive edge. This approach recognises that innovation success extends beyond reactor exports to encompass niche technologies with the potential for spillover into sectors such as medical applications.

In comparison, energy efficiency policy in Argentina has followed a more fragmented path, characterised by a lack of continuity, institutional support and strategic alignment with broader economic and environmental goals. In contrast to the nuclear sector, energy efficiency lacks the dedicated institutions, long-term financing mechanisms and regulatory frameworks that are essential for sustained progress. The implementation of recent initiatives to improve energy efficiency has been hindered by regulatory gaps, inconsistent implementation and limited engagement with the private sector. Argentina's experience with appliance efficiency standards demonstrates the challenges faced in this area. The lack of significant local innovation has been due to the country's relatively small manufacturing base and, at the outset of the promotion of energy efficiency, by the lack of infrastructure to support compliance, such as testing laboratories.

Economic and institutional barriers also hamper the implementation of energy efficiency measures, particularly in the building sector, where a lack of co-ordinated national and sub-national efforts has restricted progress. While there is a clear need for investment in building materials, the lack of adequate financial and regulatory support has slowed the adoption of energy-efficient practices. Energy efficiency innovation in Argentina would benefit from enhanced inter-jurisdictional collaboration and economic instruments aligned with policy objectives.

Monitoring and evaluation are key to ensuring progress in both sectors. Argentina's nuclear sector benefits from well-established monitoring and data collection mechanisms, which have contributed to its sustained success. However, there is currently no comparable monitoring system in place for energy efficiency policies, which limits the ability to assess policy effectiveness and hinders the refinement of initiatives. Improved data transparency and accountability in the energy efficiency sector would significantly enhance Argentina's capacity to achieve its energy transition goals.

Argentina's contrasting experiences in nuclear energy and energy efficiency demonstrate the importance of strategic long-term planning, prioritisation, institutional support and international co-operation in fostering technological innovation. To maintain Argentina's leadership in nuclear innovation and advance its energy efficiency agenda, it is essential to address macroeconomic instability, promote private sector participation and maintain political stability regarding clean energy priorities with institutionalisation of certain long-term goals that achieve broader societal consensus.

3. Bioethanol and wind in Brazil

Edilaine Camillo and André Tosi Furtado (State University of Campinas); Pedro Ninô de Carvalho (International Energy Agency)

Brazil is one of the largest emerging market economies and has been active in energy technology innovation over many decades. Its technological achievements in the areas of electricity generation and bioenergy were built up during a period of central planning, promotion of independence from energy imports and investment in public institutions between the 1950s and 1980s. Since then, changes to Brazil's political system and economic performance have strongly affected the nature of technology innovation support and its innovation ecosystems. However, as the case study on bioethanol technology shows, the combination of technical expertise, environmental concern and the importance of the sugar cane industry have sustained this clean energy sector in Brazil through several economic crises. When environmental concerns came to the forefront of energy policymaking in the late 1990s, Brazil's legacy of industrial achievement in the mid-twentieth century led it to adopt clean energy technology policies that were more ambitious than those of many advanced economies and integrated ambitions for innovation and industrial development. The case study on support to wind energy describes how Brazil was a pioneer in targeting non-hydro renewable electricity as early as 2002 and was able to build on skills in adjacent sectors. However, the two case studies also show how weak investment in a foundation of technical expertise and limited incentives for private sector innovation make it difficult for an emerging economy to establish domestic technology supply chains and international innovation leadership. Iterative improvements to policy design for cellulosic bioethanol and local content requirements for wind turbines have been coupled with strengthened support for R&D and public-private partnerships in the past decade. Overall, Brazil's clean energy innovation efforts have had mixed success so far, but Brazil has nonetheless improved its ability to contribute to global clean energy innovation by combining an appetite for reform – including regulatory creativity, policy fine-tuning and data collection – with approaches that are a good fit with its institutional traditions – including forward planning, a strong national development bank, state-owned research institutions and support for domestic production over imports.

Country context

Brazil is the largest country in Latin America in terms of its population of 214 million, its land area and its GDP, which is the ninth largest in the world. The country has been a member of the G20 group of large economies since the G20's foundation in 1999. Brazil's GDP per capita places it within the category of upper middle-income countries, where it currently sits roughly between the lower and upper bounds for the category. However, its per-capita GDP is around 4% lower than it was in 2013, a year when it was briefly at the lower threshold for high-income countries. Inequality in Brazil is an important policy issue, with the wealthiest 1% of the population owning nearly half of the nation's household wealth and 62.5 million people living in poverty in 2021, including 17.9 million in extreme poverty. Among those living in poverty, the number of black and mixed-race individuals is almost double that of white persons, and a higher share of people live in poverty in the north and northeast of the country. Overall inequality, as measured by the Gini index, fell steadily from the mid-1990s to 2015, but has since been relatively volatile and in 2022 was at roughly the same level as in 2015.

Brazil's economic development has followed various stages with specific characteristics. The 1950s and early 1960s can be characterised as a period of rapid economic growth underpinned by policies, including trade restrictions, to promote import substitution and domestic production. In that period, key institutions such as the national development bank (BNDES) and national research institutions were established, along with the energy-related state-owned enterprises Electrobras and Petrobras. The 1970s is often referred to as the period of the "economic miracle", a time when GDP growth rates reached over 10% and major public infrastructure investments were made under the military dictatorship, including hydropower plants and expansion of the national electricity grid. However, this was also a period of rising inequality.

Since the 1980s Brazil's development has continued, but has been punctuated by several periods of political and economic instability, as well as high inflation and public debt. Economic liberalisation reforms in the early 1990s aimed to stabilise the economy, reduce state intervention and promote growth by opening the Brazilian market to foreign investment, thereby incentivising capital inflow. In this period, 90% of foreign direct investment flowed to the automobile, beverage, cement, chemicals and electronics sectors. The monopolies of some state-owned enterprises were ended at this time, including in the oil and gas and electricity sectors. These reforms did attract foreign capital and were successful in stabilising the currency and local prices. However, capital inflow was aided by high interest rates, which has had downsides for the national balance of payments, cost of debt, exchange rates and competitiveness.

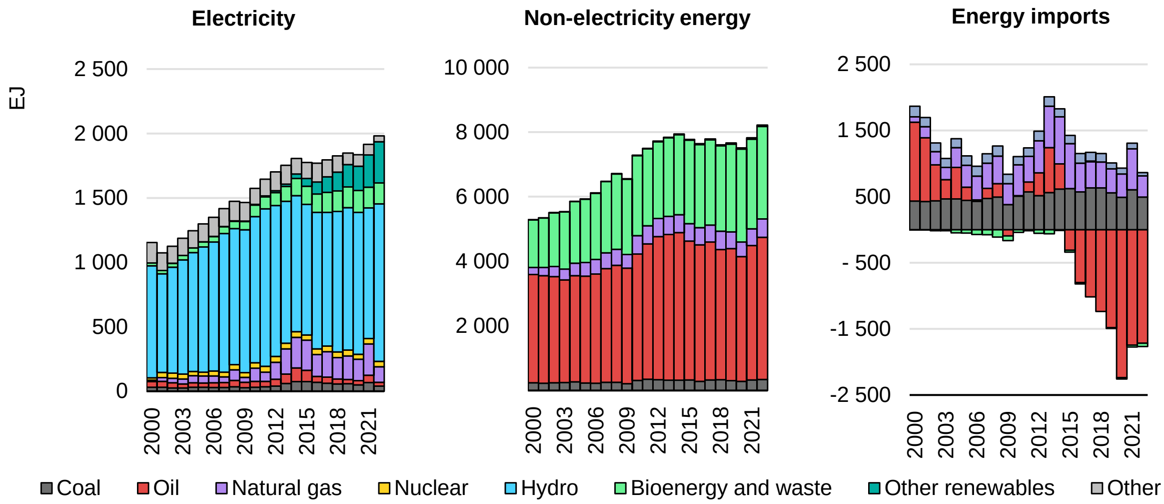
The period since the 2008 financial crisis, which significantly dented the economy, has been more focused on public investment and spending, exports, household consumption and social policies, including a minimum wage. However, the macroeconomic impacts of the global pandemic and its aftermath have counterbalanced progress in recent years. Manufacturing, in particular, has stagnated and accounted for 11% of GDP in 2021, compared with 36% in 1985, while exports of primary and semi-finished goods have risen in a trend that has been referred to as "deindustrialisation".

Energy sector context

Brazil's energy sector has already undergone several significant changes this century. These include expansion of renewable power (apart from large-scale hydropower), the widespread introduction of biodiesel into the road freight sector and the exploration and production of oil from the technically demanding offshore "pre-salt" fields. The latter development has transformed the country from an oil importer into a major exporter (Figure 3.1). This has coincided with a period, since around 2015, when domestic energy demand has stagnated due to slower economic growth, pushing up the amount of oil that is exported. However, due to a lack of domestic refining capacity, Brazil remains dependent on imports of oil products such as gasoline and diesel. The government is committed to further investing in oil and gas extraction and processing as a means of improving energy security. Development licences have been issued to oil developers in the Brazilian Amazon.

Despite increased oil production in its offshore fields this century, Brazil's electricity and transport fuel mixes are shaped by many decades of efforts to reduce reliance on imported fossil fuels. In the electricity sector more than half of Brazil's demand is met by hydropower, its national system having among the lowest greenhouse gas intensities in the world. For road transport fuel, the share of biofuels, at almost one-quarter, is the highest in the world (see the case study below on bioethanol). This has helped suppress oil imports in a country that this highly reliant on long-distance road transport for moving goods.

Figure 3.1 Energy sources for electricity and other uses, and level of imports, Brazil, 2000-2022



IEA and IITD. CC BY 4.0.

Notes: Electricity and non-electricity energy are shown on a final consumption basis. Imports are shown net of exports. “Other” refers to imported or exported electricity.
Source: IEA (2024), World Energy Balances.

Since the early 2000s energy policy in Brazil has paid more attention to the inclusion of all members of the population, with the objective of ensuring the affordability of tariffs. As of 2024 incomplete energy access is still a concern in some Brazilian communities, but significant progress has been made in recent years. Since the National Programme for Universal Access to and Use of Electricity, Light for All, was established in 2004, more than 3.6 million connections have been made to the national power grid, benefiting more than 17 million people and achieving a connection rate of 98.6% of the population. In 2021, 212 isolated and small electricity systems serving 3 million consumers in the Legal Amazon region remained. These systems, which are mostly supplied by thermal power plants, have higher power prices than the rest of the country. They also have high emissions, responsible for 9% of electricity-related CO_2 emissions despite supplying just 0.6% of national demand. A further 990 000 people have no connection to electricity grids and rely on diesel or gasoline generators without access to government policies or regulatory protections.

While it is still a major contributor to Brazil’s electricity supply, challenges face its hydropower sector. In 2000-2010 hydropower met over three-quarters of the country’s electricity demand, but it has declined sharply in the past decade. Rainfall patterns have been affected by climate change and the main options for new hydropower investment are in environmental conservation areas, making it hard to maintain sufficient reservoir capacity to meet energy demand or the historical levels of output.

At the same time, there have been significant efforts to increase the share of non-hydropower renewables in recent years, and wind and solar PV has grown rapidly to become 17% of electricity supply in 2022, from less than 1% in 2012. There is an opportunity to deploy solar PV instead of natural gas-fired plants under the 2020 More Light for the Amazon programme to extend full energy access to isolated and unconnected parts of the population. Expansion of non-hydro renewables is in line with the National Policy on Climate Change (PNMC) and Brazil's NDC under its commitment to the Paris Agreement. Its 2023 NDC update commits to achieving net zero greenhouse gas emissions by 2050, with remaining emissions from fossil fuel combustion balanced by carbon sequestration in forests and other forms of biomass. Brazil has already exceeded the 45% renewable energy target set for 2030 in its first "intended" NDC in 2016.

Two topics that have received considerable attention in the past few years are hydrogen and the production of aviation biofuels. These technologies offer options for meeting long-term domestic emissions reduction goals and, potentially, as a source of economic development and exports. The 2031 Energy Plan, the Action Plan for Neo Industrialisation 2024-2026 and the Ecological Transformation Plan emphasise hydrogen produced from renewable electricity and sustainable aviation fuel (SAF). These planning documents also identify SAF and hydrogen-related technologies as an innovation opportunity for Brazil, which is keen to attract investment for clean energy manufacturing. In the transport sector, this manufacturing objective is reflected in the tax recently imposed on imported electric vehicles, a source of public revenue that the government aims to spend on financing a transition of the Brazilian automotive industry to electric vehicle production.

Innovation context

Formal R&D institutions in support of industrial development have existed in Brazil since the 1950s and were considerably strengthened and provided with a higher level of funding during the period of military government in the 1960s and 1970s. State-directed firms in sectors such as aerospace, chemicals, hydropower, oil and sugar production made contributions to advancing technology performance internationally. The funds available for R&D and industrial investment were lower in the 1980s and 1990s, when privatisation of state-owned enterprises led to a reduction in the R&D spending of large firms that were no longer guided to invest in technological capabilities or work with public research institutes. Public laboratories likewise lost their connections to industrial technology users and faced financial challenges due to the loss of contracts with these companies.

Since 2000 the government has made significant efforts to boost technology innovation in Brazil. In 2023 Brazil ranked 49th among the 132 countries in the Global Innovation Index, and 6th within the upper middle-income category. The number of researchers in Brazil with a doctorate in 2017 was five times the level in 1999 and in 2018 Brazil published the 13th highest number of academic journal articles in the world. However, its total national R&D spending as a share of GDP, at 1.15% in 2020, was less than half of the level of China, which is the top-ranked country in the upper middle-income category. In fact, Brazil's R&D spending as a share of GDP has dipped from 1.37% in 2015, the number of invention patents filed in Brazil has grown only modestly in the past decade, with a rising share of applications from higher education institutions, and high-tech exports have fallen from 14%-16% of manufactured exports between 2015 and 2020, to 9% to 11% in 2021 to 2022, the lowest value in fifteen years.

Some of the challenges facing policy makers are structural and will take time to address. Historically, Brazilian industrial R&D has been strongly led and predominantly funded by the government. While this has made the system of technological development and adoption one of the most effective among emerging market economies in some sectors, when compared with many advanced economies it has not nurtured as much entrepreneurial innovation or responsiveness to arising technological opportunities in the private sector. A national survey showed that the share of total spending on R&D in Brazil by the private sector actually declined between 2000 and 2017, from 38% to 34%. In the United States this share stands at around 70%. Among private companies that reported receiving public funds for technological improvements, most were funded to buy equipment rather than to undertake R&D projects. One reason for this is that Brazilian enterprises reliant on cutting-edge technology, and also large infrastructure investments (such as in the energy sector), have traditionally been the most dependent on government R&D funding. During periods of economic crisis, these Brazilian firms have experienced cuts to government spending on R&D. The large subsidiaries of foreign multinationals that are also active in these sectors tend to rely on their R&D capabilities in their home countries or other regions. In other sectors that are major contributors to Brazil's GDP, including primary resources and low-tech manufacturing, there is less need to develop or adopt new technology.

Measures that have been taken by the government to stimulate technology innovation since 2000 include a range of dedicated institutions, regulations and funds. Key institutions include the Brazilian Innovation Agency (Finep), the National Council for Scientific and Technological Development (CNPq), and the Co-ordination for the Improvement of Higher Education Personnel (Capes). Finep, Capes and CNPq were all established in the 1990s to fund and encourage private sector innovation and have been significantly expanded in recent years. Finep is an especially important funder of R&D, and its grants, which typically require private sector co-funding, are often made available together with finance from BNDES. While Finep mostly funds projects with the participation of companies, Capes and CNPq generally fund researchers at research institutions. Notable regulations include the Innovation Law, Good Law and Biosafety Law. Expanded funds included the, Investment Sustainability Programme (PSI-Inovation) and Inova Empresa.

None of the aforementioned institutions, regulations or funds are dedicated to energy. However, two regulations passed in 2000 use a novel legal approach to raising R&D spending by regulated entities in the electricity and oil and gas sectors. These regulations were developed as part of the programme of so-called Sectoral Science and Technology Funds in the late 1990s. Electricity utilities and oil production licence holders are mandated to spend 1% of their revenue on R&D, around one-third of which must be channelled into publicly managed funds. Given that this new system did not drive much faster introduction of new technologies among the regulated companies, the electricity regulation was revised in 2022 to widen the scope of eligible expenditure to include innovations closer to market and metrics to evaluate impacts. In addition, the Brazilian government has undertaken a review of its energy R&D system since 2019 and launched an online platform for tracking data and performance in this area.

The case of wind energy: Policy directed to the development of domestic technical capacity in a new sector

Electricity supply security was the main policy objective that drove the introduction of financial support for non-large-hydro renewable energy in the early 2000s in Brazil. Declining output from the existing hydropower fleet due to changing rainfall patterns and a lack of attractive locations for expanding hydropower capacity began to constrain Brazil's electricity supply outlook from the late 1990s. Given expectations of electricity demand growth alongside economic growth, any supply shortfall was a major concern. The option of importing liquefied natural gas was limited and costly at the time. It has been suggested that there had been a lack of strategic planning of electricity resources in the preceding years despite the creation of the National Council of Energy Policy (CNPE) in 1997.

In 2002 the Incentive Programme for Alternative Sources of Electricity (PROINFA) was passed into law and provided operators of wind, biomass and small hydroelectric power plant operators with:

- A 20-year offtake contract with Electrobras at a fixed price.
- A 50% discount on electricity network charges.[1]
- Access to concessional loans from BNDES for power plant construction.

[1] This provision was created in 2003 in a separate regulation.

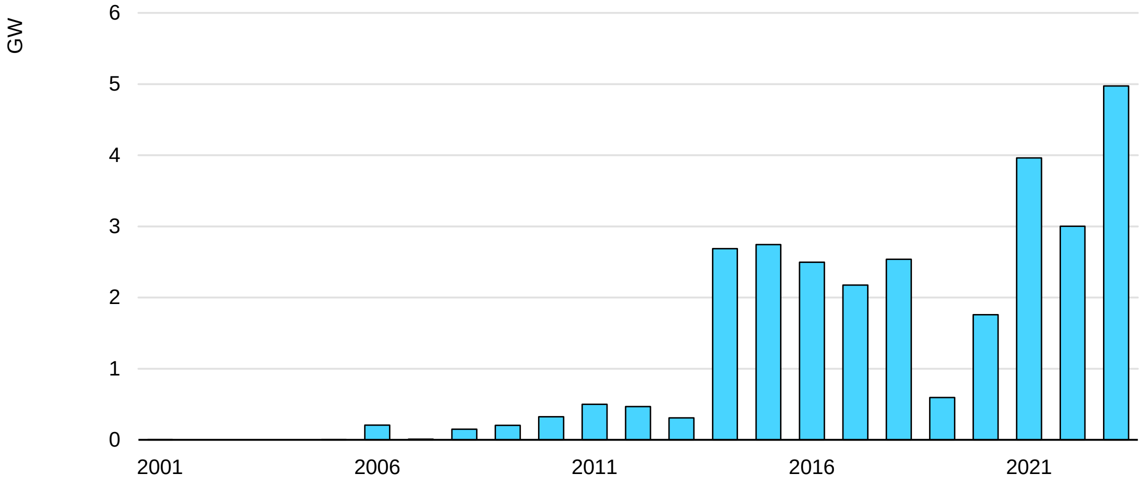
This type of support policy for renewables was at the forefront of government activity internationally. Germany's Renewable Energy Sources Act, with its feed-in tariff for utility-scale renewable energy, was passed in 2000. The United Kingdom's Renewables Obligation was introduced in 2002. China's Renewable Energy Law came into force in 2006. California's renewable electricity feed-in tariff, the first in the United States, was approved in 2008. Among the various policies worldwide, Brazil's was among the most ambitious, with a goal of installing 1.1 GW by the end of 2004. At the start of 2002, Brazil had around 4.4 GW of bioenergy-fired power plants and 1.3 GW of small hydropower plants, but only about 21 MW of wind energy,

From the outset, Brazil linked the development of a new electricity source in the country to domestic industrial investment. PROINFA included a requirement that projects bidding for offtake contracts would only be eligible if at least 60% of the value and the mass of the equipment and services were procured from Brazilian suppliers. This provision was in line with Brazil's longstanding tradition of minimising imports in strategic sectors and supporting manufacturers in the electricity sector, which had been dominated by Brazil's hydropower industry in the prior century. It was also a means of attracting foreign direct investment that could help address the trade deficit at a time when the government was reconsidering the value of industrial policy measures that had been dropped during the economic liberalisation of the 1990s. In addition, it was an approach that was well aligned with the Industrial, Technology and Foreign Trade Policy (PITCE) of the government of President Lula, who came to power in 2003. The PITCE policy aimed to stimulate more manufacturing and more innovation in Brazil and included renewable energy among its priority technology areas. However, the main measures to implement PITCE were not in place until after 2004.

A slow start to wind investment in Brazil under PROINFA

Annual installations of wind energy did not rise quickly after the introduction of PROINFA despite the attractive tariff conditions. It was not until 2006 that more than 5 MW was connected to the grid in a single year (Figure 3.2). One reason for this was that the local content requirements could not immediately be met for large projects. There was no existing wind energy manufacturing business that could quickly be scaled up, as the prior installations had all been smaller turbines for research or off-grid purposes. These were built with a mixture of imported and local components, with local assembly that did not use industrial-scale manufacturing practices or employ the latest international techniques, to keep costs down. Another reason was the lack of expertise in connecting variable renewable power sources to the grid.

Figure 3.2 Annual capacity additions of onshore wind energy in Brazil, 2001-2023



Source: IRENA (2024), IRENASTAT Online Data Query Tool.

The PROINFA regulation was not accompanied initially by any measures to support technical capacity building or foster local wind energy supply chains. Before 2002 there had been no dedicated national R&D funds or technology guidance for wind energy, nor programmes targeting utility-scale grid-connected wind turbines in Brazil. The research activities that had been undertaken as part of programmes at the electricity market regulator, ANEEL, focused on modelling the wind potential and the impacts of variable power generation on the grid. Just one project had researched megawatt-scale wind turbines. One of the ways in which ANEEL raises and distributes R&D funds in the electricity sector is via a regulation passed in 2000 under which regulated utilities must allocate 1% of their revenues to research, some of which is transferred to the Sectoral Fund of Electrical Energy (CT-Energy). However, while this succeeded in raising R&D spending in the early 2000s, the system inevitably favoured the immediate challenges faced by the regulator and the utilities in technology areas with which they were already familiar. The investment needs of the existing hydropower infrastructure, with its low emissions intensity, and the objective of operating it for as many hours as possible, likely made it hard for the utilities to see wind energy as an attractive complementary technology.

Institutional changes were made in 2004 that helped pave the way towards more investment in wind energy manufacturing and installation. The Ministry of Mines and Energy, which has responsibility for the administration of PROINFA, created a new energy planning body – the Energy Research Office (EPE) – tasked with developing medium- and long-term plans for Brazil's energy sector. The intention has been to establish a body with stable funding and staffing dedicated to building the knowledge needed to support energy policy formulation, including strategically guiding the evolution of electricity transmission infrastructure.

Faster progress with a more supportive investment environment for local suppliers and more mature global supply chains

With the creation of EPE came a new regulatory approach from the government that had come to power the year before. This emphasised new sources of renewable electricity, but replaced PROINFA with an auction mechanism to minimise government expenditure and the costs passed on to consumers. Both existing and new power plants became subject to auctions to win supply contracts with guaranteed offtake conditions that would reduce risks for investors, similar to those of PROINFA. When the first auctions for new power plants were held in 2005, the offtake contracts were signed by distribution companies rather than Electrobras, which had competing interests as an electricity generator itself. This was followed by 2009 by a resolution to extend the transmission grid to bridge network gaps, some of which hindered the availability of locations for wind projects, and to institute a new contractual model to manage power plant operator risk. One wind-only reverse-auction was held in 2009, which secured 1.8 GW of capacity, and further PROINFA auctions were held in 2010 in which wind competed against other technologies an only projects the windiest regions of Brazil succeeded.

Under the new system, the local content requirements of PROINFA applied only to the concessional loans available to auction winners, which were not a necessary condition for building projects. As a result, projects with 60% or more of their costs (and weight) allocated to Brazilian equipment and services would have access to low-cost finance, but would not be insulated from international competitors who chose not to take the BNDES loans. Rather than take protective measures to disadvantage imports, a special tax regime was established to facilitate interstate trade and imports of renewable energy components to help project developers scale up more quickly. Imported wind energy equipment faced lower taxes than that produced domestically.

Another favourable institutional factor that was supporting wind energy deployment by 2006 was the level of co-operation between regulators, ministries and industry stakeholders. The good relationships that were cultivated by ANEEL, EPE, MME and other bodies derived from the central government's strategic prioritisation of attracting investment into the emerging renewable energy sector. Institutional learning was also evident in the private banking system, which became more familiar with wind energy projects once a few had been built and then were able to offer credit alongside BNDES.

However, the experience in Brazil highlights the importance of synchronising scale-up with other countries. In hindsight, it appears unlikely that Brazil could had achieved significant expansion of its wind sector from 2006 without the benefits of cost reductions and learning in parallel with other regions of the world. Costs for utility-scale wind projects fell significantly between 2004 and 2006, and then the financial crisis of 2008 led to a fall of 15% in the cost of wind turbines – a major component of project costs – almost overnight. Several major turbine manufacturers overseas began to look to Brazil as a growing market that could help compensate for slower than expected demand in their home regions. This made Brazil more attractive as a location for investing in assembly plants than would otherwise have been the case.

It was also important that BNDES made changes to how the local content requirements were administered based on experience. The first of these changes, in 2009, enabled BNDES to negotiate plans for progressive levels of localised production with each wind energy developer or manufacturer that received a concessional loan. This relaxed the need to meet the local content requirement from the outset. The next change, in 2012, introduced a weighting per component rather than a fixed 60% share across the whole project value and mass. This action was taken to address the outcome that project developers had initially only located the production of the least technologically complex parts in Brazil – these were the towers and blades, which accounted for roughly 50% of the cost and 50% of the weight. Manufacturing of blades in Brazil was not a major technological leap for a country with a history of aerospace manufacturing. Embraer, the world's third-largest producer of civil aircraft, was founded in 1969 as a state-owned enterprise and still has some government ownership, including golden shares with veto power. The most technically sophisticated part of the wind turbine, the nacelle, was typically imported from the United States.

From 2012 BNDES set detailed and progressive targets for local content for all major wind turbine components, something that it had previously done for other sectors of the economy. The targets accounted for the materials, complexities and weights of towers, blades and nacelles, as well as the capabilities of domestic supply chains in industry at the time of contracting. Blades, for examples, required higher levels of local content that nacelles initially, but the levels for nacelles were set to progressively tighten. In 2013 only one subcomponent of a nacelle needed to be locally made, and the nacelle assembled in Brazil. In 2016 it was expected that 12 subcomponents would be locally made for projects receiving concessional finance.

At the same time, in 2012 changes were made to the availability of R&D funding for wind energy. ANEEL's R&D projects began to include research into the major components of large wind turbines, including complex electronic components. In 2013 Finep launched the Inova Energy Joint Action Plan to co-ordinate R&D funding and financing for new energy technologies between ANEEL, BNDES and Finep. It was agreed that the three institutions would provide Brazilian reais (BRL) 3 billion (USD 1.4 billion) up to 2016 in three areas: smart grids and UHV transmission; solar PV, concentrating solar and wind; and hybrid vehicles and vehicle energy efficiency. This led to a high point in Brazilian public renewable energy R&D funding in 2014, which has since declined. In fact, while the share of Brazilian public energy R&D devoted to renewable energy dropped from 21% in 2013 to 14% in 2018, the share for oil and gas rose from 55% to 64% over the same period. Consequently, since 2014 the level of "resource push" funding for technology innovation in wind energy – including R&D, pilot projects, large-scale demonstrations and product development – has not significantly grown. This stands in contrast to developments in China and India, where "resource push" and "market pull" instruments have grown and complemented one another.

As investment in the sector scaled up, especially from 2014, a supply chain for wind turbine components and assembly emerged. By 2017, 235 manufacturers of parts and components for wind turbines were accredited in Brazil, a level that was 50% higher than in 2013. The additional manufacturers included ten that were active in the production of transformers, cables and other accessories, areas that were not represented in 2013. The number of companies active in areas including subcomponents of axes and gearless turbines also grew. By 2016 local manufacturing was able to meet around 80% of blade demand and a similar share of towers, bearings and castings However, the representation of more technical elements of the nacelles remained very limited. Nacelle production in Brazil met only 4% of national demand in 2019, partly due to economic crises that curbed BNDES' budget. Furthermore, many of the companies are subsidiaries of overseas suppliers, which produce their standardised international products without any adaptation to the local context.

Overall, the expansion of Brazil's wind energy sector has been largely positive. It has helped demonstrate the potential for non-large-hydro renewables to contribute to both electricity security and emissions mitigation. It has to some extent vindicated the government's belief that an emerging market economy's transition to new energy sources can support local industrial development and not simply increase import dependency. As a result, the outlook for renewables in Brazil has been enhanced in successive policy planning documents. Wind energy features strongly in the 2009 National Climate Change Policy, the 2012 10-Year Plan for Energy Expansion, and the 2015 intended NDC to the Paris Agreement (which pledged to cut emissions by 36-39% by 2020).

Facilitation of technology progress and innovation by promoting manufacturing

As described in the preceding sections, Brazil's government took a decision in the early 2000s to grow the share of wind energy in the electricity mix rapidly, and to do so by building up a domestic industrial base to supply the projects. The government wanted local manufacturers to be internationally competitive and operate at the forefront of wind turbine technology. The policy measures it put in place incentivised investment in domestic manufacturing without first developing local technologies or skills via R&D. While this approach was not successful at first, it was adapted to account for ongoing learning, adjust to international markets and accommodate new institutional planning frameworks.

In terms of technology innovation, this approach could be described as one in which an industrial foundation for innovation was created primarily by attracting international suppliers in the blade, tower and subcomponent segments. As a location for investment in manufacturing blades, Brazil benefited from its existing skills and experience in aircraft production. Brazil now exports wind turbine blades to the United States among other countries. The presence of manufacturing of cutting-edge technological items in a region inherently generates incremental innovation via learning-by-doing. Its participants identify gaps in the market and opportunities to launch or spin off a new product line for cheaper or improved subcomponents. However, the approach has been much less successful at securing a leading position for Brazil in supply chains for more complex components to date.

More than 20 years after the launch of PROINFA, Brazil now has an opportunity to capitalise on this industrial base to address emerging challenges in wind energy. The first of these relates to the logistics of delivering turbines to remote areas, for which shipping costs have increased in recent years due to fuel prices and international maritime bottlenecks. Local technology and production can help avoid high transport costs, and could also position the country as a supplier to the region more generally. There is also scope to incrementally improve the cost-effectiveness of wind turbines in Brazil by supporting local manufacturers to undertake R&D into adaptations to local climate conditions, including installation methods for remote regions and turbines optimised for high wind speeds, typhoons and ice. Other R&D challenges that are not locally specific include lighter and smarter rotors, enhanced controls and more efficient power electronics. Although it has proven to be a difficult manufacturing sector to break into technologically, Brazil may be able to gain an advantage in advanced generators due to its rare earth metal resources and international concerns about the concentration of supplies of these material for powerful generator magnets.

Brazil plans to move from onshore to offshore wind energy, which brings an additional set of technology challenges. Brazil's offshore conditions can be more severe, with very high wind speeds and waves that damage materials and make maintenance expensive. With its existing industrial base, Brazil could be well-positioned to become a global hub for developing technology for such conditions, something that has already happened with technology development for Brazil's distinctive pre-salt offshore oil production industry. In this case, the strength of Brazil's wind energy innovation system may lie in the presence of major international wind energy companies in Brazil, who could be financially supported to collaborate with local research institutes on R&D, rather than fostering Brazilian national champions. Robust certification procedures for wind turbines and their components are important for a pioneer country in a frontier technology area.

The case of bioethanol: Nearly 100 years of policy, industrial and technological change

In 2021 almost half of the fuel demand from gasoline-powered cars and other light-duty vehicles in Brazil was met by bioethanol produced domestically. This is a notable example of technological success in an emerging market economy, and one that evolved over many decades. Brazilian government interventions in favour of converting sugarcane to bioethanol fuel began in the 1930s. Since then, bioethanol has become a major industrial sector and the country relies on this renewable fuel for transport and to reduce its oil import bills. By encouraging technological innovation in the private sector – including in the automotive sector – and by directing public research institutions, Brazil has generated many of the technical advances that are used in the bioethanol industry globally today. In the 21st century, attempts have been made to diversify away from sugarcane towards non-food feedstocks as the basis for production – so-called advanced bioenergy – but these have been less successful technically and economically.

The development of sugarcane bioethanol from 1930 to present

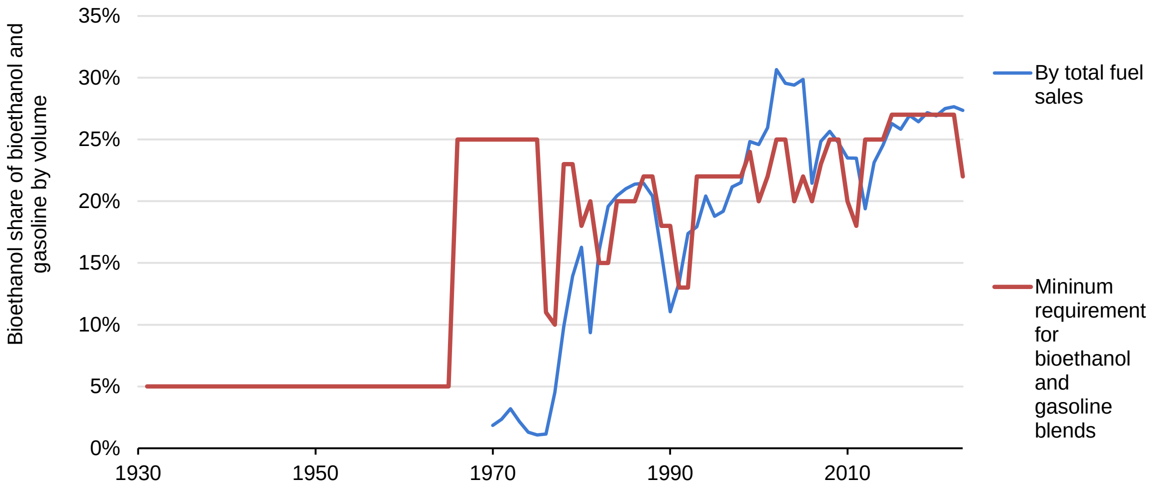
From its earliest days, support for bioethanol in Brazil had its foundations in a strong linkage between the national vision for a world-leading sugar industry and the broad consensus in favour of greater industrial independence. Sugarcane was the first major industrial sector in Brazil in the 16th century and has been closely associated with its national identity and economic development ever since.

The story of bioethanol in Brazil can be traced back to the stock market crash of 1929 and the resulting sudden loss of income from Brazil's sugar exports. The technology to make ethanol from sugar via fermentation was already well known globally and had been promoted in the first two decades of the 20th century as an alternative to gasoline. To support agricultural producers and redirect gasoline to the military, tax incentives were available in the United States for bioethanol as a vehicle fuel up to 1907. To create a new market for its sugarcane production, the Brazilian government implemented a mandatory blend of 5% bioethanol in gasoline in 1931 (Figure 3.3).

Policies to support bioethanol demand have been in place since then, and were strengthened considerably to counter the economic impact of oil price spikes caused by the 1973-1974 oil crisis. At that time, 80% of Brazil's oil demand was met by imports. To enhance energy security, the government convened representatives of research institutions, the automobile industry, sugar refineries and ethanol distilleries to develop a programme to boost the production and use of ethanol as a fuel. Secondary objectives of the resulting Programa Nacional do Álcool – the Pró-Álcool programme – were job creation, increasing domestic industrial activity, restarting idle mills and distilleries, and reducing equality between the regions of Brazil. Pró-Álcool increased the mandated blend share to 20% and complemented this with payments and tax breaks to spur corporate investment and make retail prices competitive with gasoline. From 1975 to 1979 annual bioethanol production rose on average by around 46% per year to 2.5 billion litres. As the sector expanded, Brazilian companies identified synergies between different steps in the value chain and opportunities for technical improvements, making Brazilian bioethanol production the largest in the world.

A second phase of the Pró-Álcool programme in the late 1970s – after the second oil crisis – facilitated the infrastructure for retailing pure bioethanol (E100), not just blended bioethanol. Due to the economic support for ethanol production and high oil prices, E100 had a lower retail price than petroleum fuels and from 1979 cars were marketed with engines that could run on E100. Between 1979 and 1988 ethanol production grew at an average annual rate of 19% to 11.6 billion litres per year.

Figure 3.3 Bioethanol content of Brazilian retail gasoline for road transport, 1930-2007

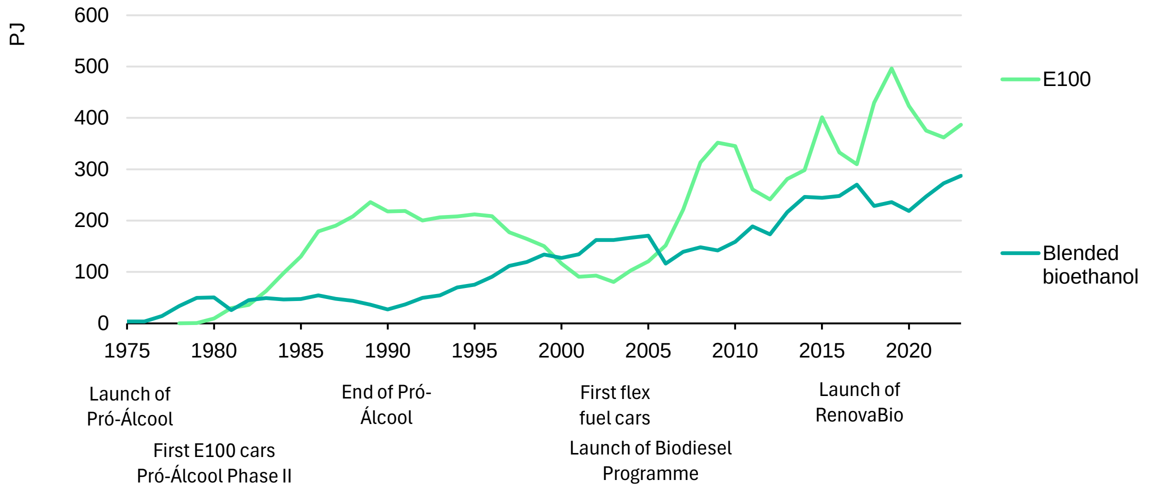


Sources: Mendes Souza, G. et al. (eds.) (2015), Bioenergy & Sustainability: bridging the gaps (p. 235); National Agency for Petroleum, Natural Gas and Biofuels (2018), ANP Resolution No. 758 of 23/11/2018, 27 November 2018; Puerto Rica, J. A. (2007), Programa de Biocombustíveis no Brasil e na Colômbia: uma análise da implantação, resultados e perspectivas.

From the late 1980s until the early 2000s government blending mandates for bioethanol were relaxed and subsidies for producers decreased. This was initially to reduce budget expenditure amid economic crisis, and then the Pró-Álcool programme was ended as part of liberal economic reforms and in response to lower oil prices and higher sugar prices in the 1990s. Sugarcane producers shifted away from ethanol production, causing shortages that left many drivers unable to fuel their cars in the early 1990s and reducing public support for bioethanol. Higher ethanol prices led to a decline in sales of ethanol-powered vehicles.

The most recent phase of policy support for bioethanol in Brazil relates to efforts to reduce fossil fuel consumption for environmental reasons, notably to address climate change. In the early 2000s tax breaks for the sale of ethanol-fuelled cars were introduced, which boosted declining sales. The government established a biofuels policy – RenovaBio – in 2017 as part of broader national energy policy in the context of Brazil's commitments under the Paris Agreement. RenovaBio is designed to guarantee predictability in the fuel market, something that had undermined ethanol sales in a world of volatile oil prices in the past. Since the introduction of RenovaBio, the ethanol market has continued to grow, with E100 sales rising with oil prices before the global pandemic, and blended bioethanol gaining market share as they fell during 2020 (Figure 3.4).

Figure 3.4 Sales of biofuels in Brazil and selected policy and technology milestones, 1975-2023



Sources: Brazil, Ministry of Agriculture, Livestock and Supply (2013), Statistical Yearbook of Agrienergy 2012.

In 2021 energy derived from sugarcane was the second-largest source of primary energy in Brazil, after oil. Nearly 55% of all sugarcane harvested was used for bioethanol, and 335 mills produced 30 billion litres of bioethanol, 62% of which was sold as E100. Including the burning of the bioethanol by-product "bagasse", sugarcane also met 6% of electricity demand. The National Energy Research Office has indicated that sugarcane production could be as much as 55% higher in 2050.

Institutional and policy design to support sugarcane bioethanol

To encourage investment in bioethanol deployment, Brazil primarily used regulatory measures from the outset, notably a blending mandate. Regulatory requirements, state ownership of key industries and price controls are all tools the country has used in a number of sectors to support domestic production and these were adapted for bioethanol. Brazil has long used state planning and certain industries to pursue policy objectives, and until 1990 medium- and long-term expansion plans for the sugarcane sector were governed by an overarching agency, the Sugar and Alcohol Institute.

The blending regulation has remained in place for nearly a century, indicating a political consensus surrounding the policy. The level of the mandate has, however, been changed according to the international energy security and domestic economic outlook, including refining capacity and sugarcane harvests. In addition, the government has influenced the market with price controls on oil products – via the state-owned oil company – and a fixed price ratio between gasoline and ethanol. This ratio was removed in the 1990s as part of reforms, but differential taxation of the two fuels remains, with bioethanol buyers paying around 24% in comparison to 39% charged for gasoline in 2023. Some state fuel taxes also significantly favour bioethanol, especially in sugarcane producing regions. Another policy tool that has been used is a tax incentive for flex-fuel and E100 car purchases.

Brazil's national development bank (BNDES) has also played a key role in enabling the investment necessary to expand bioethanol mills since 2000. BNDES provides concessional financing linked to national priorities.

The RenovaBio policy of 2017 took a different direction, given its broader objective of tackling emissions. It takes a green certificate approach that sets annual CO_2 emission targets for hydrocarbon fuel distributors, which must source tradeable decarbonisation credits (CBIOs) to meet their obligations. CBIOs are generated by suppliers of bioethanol, biodiesel and biomethane that choose to opt into the scheme and cover the costs of certification. The number of credits issued relates to the carbon intensity of the fuel, including the origin of the biomass. To generate credits, biomass produced in Brazil must come from land with an active or pending Rural Environmental Registration (CAR) and must not involve the displacement of native vegetation. In 2022 the required emission reduction was 17.6% compared to fossil fuels alone and credit prices roughly tripled in response, adding Brazilian Reais (BRL) 0.09 to a litre of gasoline.

Support for innovation in sugarcane bioethanol

Policies designed to stimulate the market for sugarcane bioethanol, a known and mature fermentation technology, have also raised the competitiveness of firms in the sector and created strong incentives to innovate. In particular, policies like RenovaBio that incentivise improved environmental sustainability as well as cost-competitiveness have initiated projects to innovate in the water, land and energy efficiency performance of sugarcane. Brazil has also provided dedicated support for technological development with the aim of being more technically self-sufficient and efficient.

In 2005 the Brazilian government commissioned research by the state-owned Centre for Management and Strategic Studies (CGEE) into the bottlenecks preventing faster expansion of bioethanol. The resulting three-year study identified technological challenges and a lack of Brazilian innovative capacity to overcome them. In response, the government created a new research centre to aggregate existing capabilities in 2009, firstly as the Brazilian Bioethanol Science and Technology Laboratory (CTBE) and then, from 2019, as the Brazilian Biorenewables National Laboratory (LNBR), which integrates more industrial biotechnology expertise and encompasses non-fuel products. These institutions work via partnerships with key private sector business, national laboratories and other actors.

The government has also supported the establishment of intellectual property in the sector. New varieties of sugarcane are protected by the Ministry of Agriculture's plant variety system, including 225 registrations of Scharum L. belonging to several Brazilian organisations. Unicellular microorganisms and biotech substances such as enzymes are protected by Brazilian legislation and registered by the national patent office (INPI). Most applications have been by foreign companies.

Co-ordination between public and private actors has been intentional and important to R&D efforts and the introduction of new technologies. However, despite a well-established set of research entities in Brazil, an overarching body that helps guide public and private efforts has been lacking since the Sugar and Alcohol Institute was dissolved in 1990. Analysts have highlighted a lack of co-ordination between federal ministries, administrations, state governments, science and technology institutes, and market-based policies.

Technological leadership outcomes in sugarcane bioethanol

Most of the government-directed research relating to sugarcane bioethanol has focused on plant varieties, many new versions of which have been successfully developed. However, their adoption has been limited, with the main association of sugarcane mills and distilleries (UNICA) engaging only weakly with the innovation agenda of the government. Despite this, the main varieties currently grown in Brazil are products of dedicated national research efforts. The strength of the Brazilian sugarcane industry lies primarily in its strong capital goods industry, producing reliable equipment for distilleries and agricultural machinery. This industrial strength can be attributed to the scale of the industry and Brazil's first-mover advantage globally. This first-mover advantage was cemented by considerable state planning and the involvement of state-backed finance in the early decades. Petrobras, the state-owned oil company, was solely responsible for purchasing, blending and distributing bioethanol nationwide for several years and thereby helped establish and consolidate the infrastructure that increased the efficiency of the Pró-Álcool programme's efficiency. In the 1970s and 1980s technological efficiency was spurred by co-operation between major industrial players and state research institutions. Even since liberalisation, the industry has generated incremental but effective learning-by-doing that has helped Brazilian companies to continue to dominate Brazil's own supply chain.

Perhaps the most impactful Brazilian technological contribution arising from the country's sugarcane bioethanol programmes was the new vehicle engines that could run exclusively or flexibly on E100 (Box 3.1). This innovation was not initially directed by the government and was unrelated to the production of bioethanol itself.

Box 3.1 Brazilian leadership in the development of flex-fuel vehicles

In the 1970s Brazil was at the forefront of the development of engines that could run on E100, and then in the late 1990s of engines that could run on gasoline, E100 or any blend of the two, allowing drivers to choose the most economic fuel. Both technologies were designed for the unique nature of the Brazilian market, with the high availability and competitive pricing of bioethanol. While the innovation was led by private sector efforts in the 1970s, there was more government involvement in the 1990s' achievements.

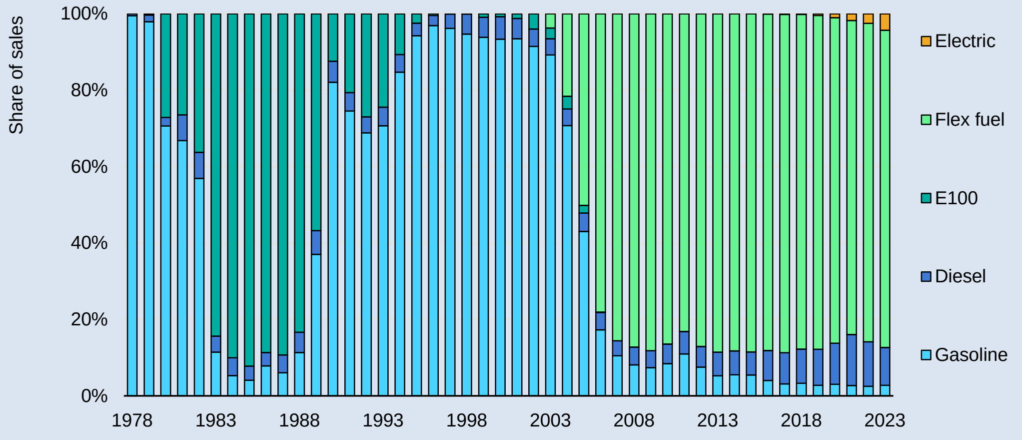
The first E100 vehicle hit the market in 1979, a version of the Fiat 147, which was produced in the state of Minas Gerais from 1976 until 1987. The augmented compression ratio worked well and the car outperformed expectations, becoming a big seller.

Sales of bioethanol and E100 cars declined in the 1990s, and by 2000 the Brazilian government was concerned about the environmental impacts of rising sales of gasoline, especially greenhouse gases. Following discussions between the government, the automobile industry and engineering experts, international carmakers and parts suppliers identified the possibility of flex-fuel vehicles as a way to protect Brazilian consumers from volatile or high oil prices. While the government was initially sceptical, once the technology was demonstrated it encouraged further development as a means of increasing bioethanol sales above the limits of blending with gasoline. In 2002 the government reduced the tax on flex-fuel vehicles.

Volkswagen completed work on the Gol 1.6 Total Flex, which in 2003 became the first car to be able to run on any mix of ethanol and gasoline. Consumers rapidly accepted flex-fuel vehicles and the fuel choice they provided. In just a few years, flex-fuel vehicles grew to 78% of new light-duty vehicle sales, much faster growth than carmakers had expected. Volkswagen brought to the market the Polo E-Flex car in 2009 as the first flex-fuel vehicle that did not need an auxiliary gasoline tank for cold start. Another notable innovation of Brazilian flex-fuel technology was avoiding the need for a dedicated sensor to monitor the ethanol-gasoline mix. By 2011, 12 companies were making flex-fuel vehicles for the Brazilian market.

Technology developed in Brazil is now used in flex-fuel vehicles elsewhere in the world. It marked a new era for bioethanol sales in Brazil by reviving a flagging sugarcane bioethanol industry. Flex-fuel technology also affected bioethanol policymaking more generally, as adjustment of the blending mandate to absorb sugarcane production or dampen gasoline prices no longer had the same impact: if the price ratio between E100 and gasoline-ethanol blends changed markedly then consumers could simply switch from one fuel to the other.

Registration share of new light-duty vehicles in Brazil, by fuel type, 1978-2023



Source: ANAFAVEA (2024), Brazilian automotive industry yearbook 2024.

Support for advanced bioenergy from 2010

In the 2010s poor sugarcane harvests due to a changing climate increased pressure on the bioethanol fuel sector from increases in international sugar prices. The sector was also affected by the global financial crisis (which occurred at a time when sugarcane companies had high levels of debt), political intervention to reduce gasoline prices and a downturn in private investment in new mills and agricultural productivity. Declining productivity of traditional sugarcane plantations means more land per unit of output, which increases the risk of deforestation to expand the land available and potentially raises competition with food production. While corn as an alternative feedstock to sugarcane had entered the Brazilian market (corn met 12% of Brazil's bioethanol output in 2020), it has a higher environmental impact than sugarcane.

One of the government's responses was to promote the development of advanced bioenergy. Advanced bioenergy does not rely on food inputs and includes cellulosic bioethanol, which is the product of fermentation of the sugars present in woody biomass. These sugars are more difficult to extract than those in sugarcane or corn.[2] Analysis at BNDES highlighted the potential for cellulosic bioethanol to be the basis for future biofuel growth. However, the difficulty of extracting the sugars means that cellulosic bioethanol has higher production costs than sugarcane bioethanol even though the fermentation part of the process has already been optimised by Brazilian and international innovators.

The government launched its first initiative in this area in 2011, called Support for Innovation in the Sugar-Energy and Sucrochemical Sectors (PAISS), which made USD 1 billion in finance available via BNDES and the Brazilian Innovation Agency (Finep). The public research institute LNBR addresses advanced bioenergy and now works on microorganisms and enzymes for cellulosic bioethanol. Analysis from BNDES projects that cellulosic bioethanol could underpin future bioethanol growth.

Two industrial plants and a demonstration unit for cellulosic bioethanol have been funded since 2010, the funders including BNDES. These plants aimed to use bagasse – a by-product of sugarcane refining – and straw as feedstock, thus integrating advanced bioethanol with sugarcane bioethanol. While some major and costly technical difficulties had to be tackled, the company Raizen is planning

[2] Cellulosic bioethanol is a type of novel advanced biofuel – sometimes called a second-generation biofuel – that can use the skins, stems, leaves and husks of food crops, non-food crops such as switchgrass, jatropha and miscanthus, and waste, including wood chips and pulp. Some of these inputs can be grown on land not suitable for food or alongside food in a way that raises land productivity. Others contribute to waste reduction.

three new plants. This would make Brazil a global leader in the technology, which has encountered significant technical challenges that have prevented scale-up in Europe and North America.

However, with the exception of Raizen's investments, the innovation ecosystem for cellulosic bioethanol is notably weaker than that for sugarcane bioethanol. This can be attributed to its lack of alignment with the vision of influential stakeholders, which, for sugarcane, rested on the desire of the large sugar industry to diversify into products that hedge its exposure to sugar export markets. Given the political importance of the states involved, this translated into a continuous tailwind for bioethanol policies. To a greater or lesser degree, depending on the macroeconomic and political situation, this offset the interests of the state-owned oil company and other institutional actors. There is no similarly powerful advocate for cellulosic bioethanol. The sugarcane industry association, UNICA, has not robustly advocated cellulosic feedstocks and has mostly defended its preference for expansion of non-cellulosic sugarcane bioethanol.

At an institutional level, there is also inertia in favour of non-cellulosic sugarcane bioethanol. A think tank of the Ministry of Science and Technology, CGEE, has published several studies to demonstrate the potential of cellulosic sugarcane bioethanol, but financing from BNDES for non-cellulosic sugarcane bioethanol mills continued to grow until 2013, when macroeconomic conditions worsened.

Brazil currently has no additional market-pull incentives for cellulosic bioethanol besides those available to other biofuels. This contrasts with the United States where additional measures exist. The result is investors' heavy reliance on financing from BNDES and few examples of private sector willingness to engage in the government's programme to scale up the technologies.

Insights from the bioethanol case

The development of sugarcane bioethanol in Brazil demonstrates the feasibility of creating a world-leading position in a clean energy technology if political and industrial interests, as well as resource availability, are well aligned. Remarkably, Brazil achieved this success despite very little attention to bioethanol elsewhere in the world for much of the 20th century and despite not being in the top tier of advanced economies. The bioethanol case study shows how industrial expansion, especially in the supply chain for a new technology, can drive unforeseen endogenous technological innovation, such as the flex-fuel vehicle. This can further be augmented by the allocation of public resources to strategic basic and applied research, such as cutting-edge biotechnology for new plant varieties and fermentation enzymes. However, it is also a reminder that these processes play out over many decades and will be affected by cycles of macroeconomic and political influences. A key strength of the expansion of sugarcane bioethanol in

Brazil was its deep roots in an industry that is politically important in several large states, which helped the support policies survive political changes. It can therefore be understood in terms of growth and modernisation of an existing industry as much as an emergence of a new one.

While market support for sugarcane bioethanol has relied on a number of different government incentives, especially since the creation of Pró-Álcool, it has also survived cycles of political uncertainty. In this sense, there has nonetheless been a lack of continuity over time, especially in the co-ordination of technological innovation. With most of the research resources routed through public research institutions, private industry's uptake of cutting-edge technical progress was not guaranteed. The stagnation of sugarcane production in the 2020s may partially have its roots in the failure to test and adopt new varieties in the decades preceding recent droughts and climatic threats. It also reflects the challenge of investing in the level of innovation needed to keep Brazil consistently at the international innovation frontier when the macroeconomic and political situation has been volatile for several decades. The lack of capital is one reason Brazil has struggled to raise more export revenue from bioethanol and its equipment.

Shifting from sugarcane to cellulosic feedstocks for continued bioethanol expansion brings economic and environmental opportunities, but also points to a separate set of challenges. In this case, the lack of alignment between the long-term visions of the government, academic experts and major industrial players has made it much harder to support a new technology in its nascent, more costly stages. In particular, the absence of a politically important industrial stakeholder – and some opposition from the incumbent sugarcane sector – suggests that much more public sector effort will be required than was the case for sugarcane bioethanol before 2000.

The Brazilian bioethanol case illustrates an important aspect of technology innovation in emerging economies, where high-skilled job creation is primary driver. Some of the innovations in Brazil have been positive for working conditions, such as the adaptation of imported boiler technology to avoid traditional straw burning during harvesting. The improved competitiveness of the sector contributed to its expansion and thereby helped reduce inequality between regions of Brazil. However, the encouragement of this type of technology development for mechanisation led to job losses among unskilled workers, jobs that were not replaced by higher-skilled opportunities for the affected communities.

Findings

Although the wind energy and bioethanol cases are very different, they both demonstrate how an emerging market economy can occupy a leadership role in clean energy technology development. In both cases, the policy objectives of ensuring energy security with domestic resources and directing industrial investment to new value chains were paramount. From the late 1990s, these were joined by climate-related policy objectives. Compared with experiences in some other emerging market economies, these objectives have been complemented well by the government's efforts to make Brazil an attractive destination for foreign direct investment and a clean energy technology hub. In neither case did local technology innovation feature strongly at the outset, but the creation of an industrial base provided a platform for innovation that was subsequently supported by government R&D policy. These platforms provide the capabilities to move into arising and unanticipated technology areas (a type of so-called "technology spillover"), such as flex-fuel vehicles, cellulosic bioethanol and offshore wind. However, in both cases, policy tensions between cost, sustainability and R&D budgets hindered Brazil's success at innovating in the more complex and high-value technology areas.

Several overarching insights can be highlighted from these case studies:

- Encouraging foreign direct investment in manufacturing is an approach to building technology innovation capacity, However, local content rules are insufficient on their own and are likely to be counterproductive if set too strictly or inflexibly. Brazil's linking of local content requirements for wind energy to eligibility for cheaper finance rather than eligibility for grid connections, as well as the adaptation of the rules to the evolving situation, helped the policy secure investment while remaining open to the competitive benefits of international exposure. In addition, BNDES is an institution with experience of administering such rules, which can be very complicated and create considerable burdens for inexperienced institutions that can add to total costs.
- Technology pathways are strongly influenced by the history of the sectors. In the case of sugarcane, the historical connection of the sugarcane industry to the national vision has its roots in the 16th century. In the wind energy case, the government's choices were influenced by the country's experience with hydropower, a domestic renewable electricity resource around which it had structured the power grid. In both cases, the supportive relationships between MME, regulators, research institutes and major companies – including the current and former state-owned enterprises of Electrobras, Embraer and Petrobras – were crucial to creating consensus around new technologies. These types of companies are also often able to take a long-term perspective. Existing adjacent industries that already have skills and stakeholders in place are highly valuable to nascent industrial sectors and can help reduce risks. In the bioethanol case study, transport fuel was an opportunity for portfolio diversification for sugarcane mills, and not a threat. Without relevant existing industrial capabilities, or where

incumbent companies are threatened by the new technology area, the financial and political costs of enabling investment are likely to be considerably higher.[3]

- In Brazil's electricity and transport sectors, the market structure has changed several times under different political circumstances, and these changes are not neutral with respect to innovation. For example, the privatisation of state-owned companies cost Brazilian innovators access to laboratories and testing facilities, and also broke longstanding linkages between government R&D programmes and industrial strategy. On the other hand, pro-competition policies in the 1990s and 2000s helped make Brazil an attractive location for foreign direct investment, which has spurred technology transfer. But it is only in the past 15 years that efforts have been made to address some of the gaps left by the loss of integrated sectoral planning after the 1980s and improve the business environment for technology innovators. Without a dependable environment for planning and investment, innovation policy efforts have limited impact. These efforts include the integration of innovation into the responsibilities of strategic planning and research institutions like EPE, co-ordination between institutions involved in clean energy R&D, and an increase in funding for research, demonstration projects and commercialisation programmes.
- It is important to adapt to international developments in technology costs, maturity and policy. In its use of blending mandates, biofuel emissions credits, renewable capacity auctions and local content rules linked to finance, Brazil has been a global pioneer. However, it also benefited significantly from factors such as the maturation of the global wind industry, experiences overseas with feed-in-tariffs, global equipment supply chains, and R&D into cellulosic biofuels in advanced economies. The ability to export wind turbine blades derives from Brazil's integration into intra-American trade. Effective adoption and adaptation of technologies by emerging market and developing economies relies on awareness of international developments and the flexibility to adapt to them.

[3] Indeed, in 2005 Brazil's government funded a pilot solar PV manufacturing plant on university premises with associated R&D activities. Processes for solar PV production were developed and the first cells and modules produced in 2009, but in the absence of synergies with existing industries – Brazil did not have semiconductor manufacturing, for examples, or a supportive industrial base for local solar PV production, the pilot went no further. The first assembly plants for imported solar PV cells started in 2012, but announcements of commercial investments in solar cell production in Brazil were not until the early 2020s.

4. UHV and solar PV in China

Fang Zhang (School of Public Policy and Management, Tsinghua University), Zhangjin Huang (School of Political Science and Public Administration, China University of Political Science and Law)

Clean energy innovation policymaking should actively engage diverse stakeholders to foster broad consensus and support for clean energy innovation activities. Aligning clean energy innovation with national strategies at the macro level can effectively garner political support for clean energy policymaking and break policy impasses. Where state-owned enterprises play a large role in energy technologies, governments can incentivise them to take on more clean energy innovation, leveraging their financial capacities and abilities to forge political and social consensus. In China, state-owned enterprises play a pivotal role in advocating clean energy technologies in policymaking and fostering clean energy innovation. Private actors face challenges in influencing clean energy policymaking and innovation in China, necessitating additional support from governments. Top-down intervention can help to break political deadlock and advance clean energy policymaking once there is a clear national vision.

Country context

China is the world's second-largest economy. At around USD 18 trillion in 2023 (market exchange rate basis), its GDP is around two-thirds that of the United States. However, on a purchasing power parity (PPP) basis, which takes into account the price of goods in each country, its GDP is 20% higher than that of the United States. Annual GDP growth averaged an impressive 10% between 1980 and 2010, driven by investment in industrial and infrastructure expansion as well as exports, much of which was powered by coal and accompanied by limited environmental protections. Between 2010 and 2022 the rate slowed to 6.9% on average and is expected to be around 5% in 2024. The government's 14th Five-Year Plan for the country, which runs from 2021 to 2025, charts a shift towards higher environmental protection and more high-tech output.

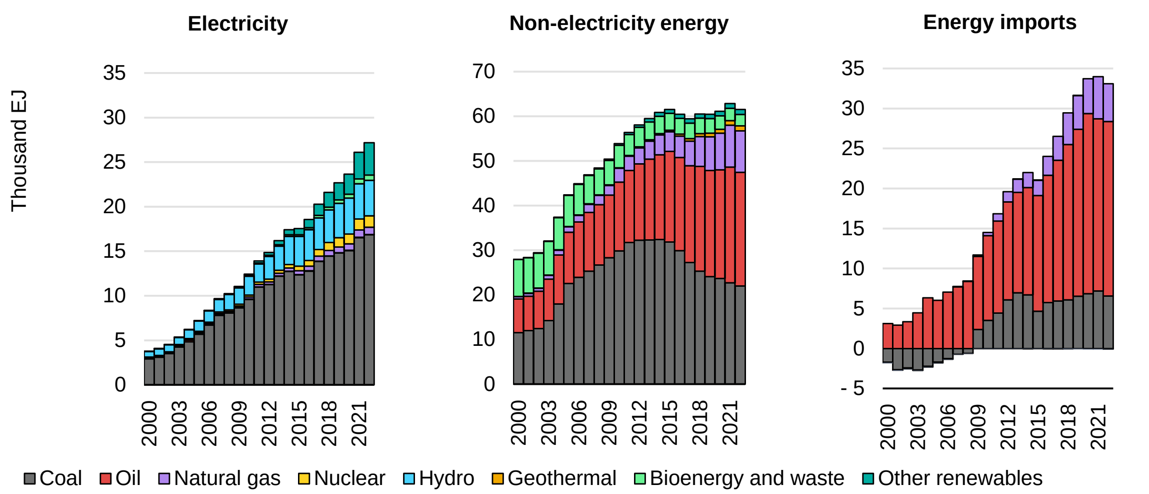
The government aims to reposition China from being a middle-income country to the high-income country by 2035. Its GDP per capita in 2022 was 2.9 times the minimum threshold for a lower-middle income country, and just 7% below the minimum threshold for a high-income country. However, it is one-sixth of the level of the United States (which has a car ownership rate five times higher) and one-third that of the European Union. In China's case, these national averages belie stark differences between regions and population groups, with the urban population enjoying per-capita disposable income that is 2.5 times that of rural residents. Through its "common prosperity" initiative and initiatives like the Solar Energy for Poverty Alleviation Programme, the government aims to narrow this gap.

Energy sector context

China's energy demand is the highest in the world, and it leads global consumption of several individual energy sources, including coal (56% of global demand), wind (35%), solar PV (32%) and hydropower (30%). It is the second-largest user of oil and nuclear after the United States, and the third-largest user of natural gas after the United States and Russia. Unlike GDP, which grew strongly in the latter decades of the twentieth century and through to 2010, China's final energy consumption grew most strongly between 2000 and 2010 – at an average annual rate of 8% – a period characterised by particularly energy-intensive development. Since 2010 this rate has slowed to 2.5% on average as GDP growth has dipped.

The high share of coal in meeting China's final energy demand, at 44% in 2022, contributes to the country's high CO_2 emissions, which have more than tripled since 2000. In 2006 China became the country with the highest CO_2 emissions from fuel combustion, being 40% higher than those of the United States in 2021. In 2020 President Xi Jinping committed China to reaching peak CO_2 emissions before 2030 and achieving carbon neutrality before 2060. China has an interim target to increase the share of non-fossil primary energy to 25% by 2030, from around 13% today.

Figure 4.1 Energy sources for electricity and other uses, and level of imports, China, 2000-2022



Notes: Electricity and non-electricity energy are shown on a final consumption basis. Imports are shown net of exports. "Other" refers to imported or exported electricity.
Source: IEA (2024), World Energy Balances.

One of the factors that has spurred China's pursuit of nuclear power, renewables and electric vehicles in recent years is its reliance on imported oil and natural gas (Figure 4.1). Net imports account for 75% of China's oil demand and 40% of its natural gas demand.

China achieved universal electricity access before 2000 and, unlike many emerging market and developing economies, this issue is not among its energy policy priorities.

Innovation context

Technology innovation is a central pillar of China's economic development strategy and this is emphasised at the highest levels by the change in strategic focus from "Made in China" to "Innovation in China". Its spending on R&D, at USD 433 billion in 2021, represents 2.4% of GDP and is second only to the United States in absolute terms. However, 2.4% remains below the OECD average of 2.7% and the level of 5% reached by Israel[1] and Korea. Nonetheless, the higher spending on R&D in recent years has driven up China's patenting activity and it now accounts for 47% of global patent applications, having overtaken the United States as the largest source of applications in 2011.[2] Since 2012 China has risen from 34th to 12th place in one international ranking of innovation performance, and produced the most-cited scientific research papers in 2021.

Clean energy innovation is one of China's top national priorities, alongside other strategic areas including artificial intelligence, semiconductors, quantum computing and synthetic biology. The government of China spends more on energy-related R&D than any other country. It seeks to compete with other countries to produce the most cutting-edge energy-related equipment in a range of areas, including advanced batteries, electrolysers for hydrogen and electric vehicles. Its manufacturers are already exporting high-quality lithium-ion batteries and solar PV modules designed in China. Critically, China's contribution to lowering the global price of these items lies partly in technology innovation related to manufacturing processes and not just input costs. By one estimate, China produced more research outputs in clean energy between 2001 and 2020 than any other country.

Choices about technology development in China are often characterised as being the result of decisions taken and applied in a top-down manner, but this

[1] The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

[2] While the impressive quantity of filings is undeniable, many analysts conclude that the quality of China's patents is not as high as those of other regions.

oversimplifies the unique systems in place that encourage rapid innovation. These systems have several features that are largely unmatched in their nature or scale worldwide:

- Mobilising large budgets for strategic national missions.
- Devolving responsibility for innovation to state-owned enterprises.
- Empowering provincial and municipal governments to experiment and compete.
- Reaping the benefits of the country's vast domestic market to spread risks and sustain competition.
- Negotiating international partnerships to accelerate domestic learning, especially between firms.

The case of UHV technology in China

Since UHV transmission technologies were first proposed in China in 2004, it has successfully managed to catch up with the global innovation frontier and achieve leadership status in terms of deployment. The term UHV is applied to any power transmission line, whether alternating current (AC) or direct current (DC), that can operate above 800 000 volts for AC or DC. For long-distance transmission, higher voltages are more efficient and can carry several multiples more electricity compared with equivalent cables at 500 000 volts. While there are some examples of the technology being used experimentally over relatively short distances in Japan and longer examples in the former Soviet Union in the 1980s, no country other than China has deployed significant lengths of UHV lines. However, the path to successful operation was not a smooth one and UHV remains a contested technology in China.

When UHV was proposed in December 2004 it was not in line with the national vision for the economy and energy, mainly for two reasons. Firstly, as UHV technology was costly, central government was reluctant to invest in the UHV technology innovation using national finance. Secondly, there was a lack of practical international experience of UHV technology to learn from, with developed countries' research on the technology remaining at the laboratory stage and not put into practical application. At that time the maximum voltage of power transmission lines that the country could build independently was no higher than 750 000 volts.

This misalignment changed early in the next decade. China experienced some of its worst pollution and air quality from coal combustion near major cities, leading the State Council to issue an Action Plan for Air Pollution Prevention and Control in September 2013. This plan made combating air pollution a top priority for central government and was followed by a strategy of "electricity as substitute", which referred to replacing inefficient coal and oil power plants near population centres with remote power generation in distant provinces and long-distance power transmission. This initiative gained support from central government, and UHV was included as part of the technology options.

Between 2005 and 2018 UHV was highlighted in a series of national strategies, moving it from an innovation or sectoral topic to the centre of national industrial policy:

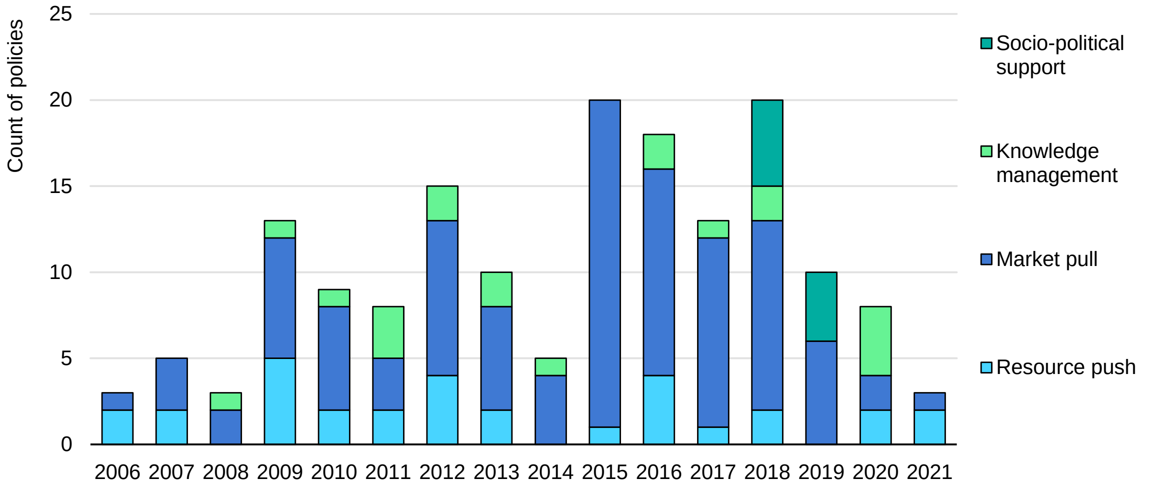
- The 2005 National Programme for Medium- and Long-term Scientific and Technological Development
- The 2011 12th Five-Year Plan for National Economic and Social Development
- The 2014 Work Plan for Strengthening Air Pollution Prevention and Control in the Energy Sector
- The 2018 Communiqué of the 2018 Central Economic Work Conference.

Alignment of the UHV innovation agenda with national and international visions for the energy sector were further strengthened towards the end of the 2010s as long-distance efficient power transmission became closely identified with renewable energy. The ability to bring electricity from diverse regions with solar and wind resources to power distant urban areas is central to most stakeholders' visions of how China will realise its 2060 carbon neutrality goal. In September 2020, when the Chinese carbon neutrality goal was articulated, UHV was emphasised as an important channel for delivering clean energy power generation.

UHV policy development through consultation and debate

China's central government issued 163 UHV-related policy documents between 2006 and 2021, covering different elements of innovation policy. Policies in the resource push and market pull categories were most frequently used, with less focus on knowledge management and socio-political support (Figure 4.2). From the outset, the successful scaling up of UHV – a technology that had not previously been effectively used commercially anywhere in the world – was far from certain and the policy approach had to evolve as more was learned about the technology and its fit with policy objectives.

Figure 4.2 Policy instruments used to support UHV technology by year of implementation, 2006-2021



Source: Government Document Center of the School of Public Policy and Management of Tsinghua University.

From 2004 to 2010 the focus was on funding basic research, demonstrations and pilots. This began in 2004 when State Grid Corporation of China (SGCC) – the largest state-owned power grid operator – independently conducted early UHV technology R&D to support its advocacy of the technology to the National Development and Reform Commission (NDRC), which is responsible for the macro-level direction of China's energy policy and must approve any major projects. SGCC allocated R&D funds specifically for UHV research, mandating its subordinate research institute, the China Electric Power Research Institute, to undertake the technological research. It also assembled a group of international experts to assess the status of the technology.

The period after 2004 was marked by several distinct debates about whether UHV technology should be developed and to what extent UHV power lines should be promoted. These debates were largely transparent and involved multiple stakeholders, including but not limited to a powerful state-owned enterprise as the lead advocate for UHV. Critics raised concerns about technical security, economic cost and effectiveness. These opponents were mainly retired officials and experts, some of whom were very senior power industry experts and had extensive experience of working in government sectors. This made it easier for them to gain access to central government leadership and gave their discourse significant influence. They jointly wrote a report on the problems relating to, and their recommendations for, developing UHV power grids and sent it to Premier Wen Jiabao.

In response to the report, Premier Wen Jiabao instructed the NDRC to carefully examine the feasibility of the UHV project. The NDRC brought together more than

200 experts from China's top think tanks to discuss UHV in June 2005. SGCC's research team presented a report at this meeting that aimed to cover almost all foreseeable technical concerns. The strong opposing views of some well-known power sector experts, researchers and senior government officials that were voiced at the meeting were recorded, including an expert from the former Ministry of Electricity (now National Energy Administration, NEA) and an expert form the Investment Association of China. Without a consensus at the meeting, demonstrations of the technology were approved with the support of delegates from Shanxi province, a coal-rich part of China. However, as central government was reluctant to provide finance from the central budget, these demonstration projects were funded by SGCC. They comprised a 1 million volt AC line from Shanxi Province to Hubei Province and the first DC line of around 800 000 volts from Sichuan Province and Yunnan Province to Shanghai.

The debate did not fully subside, however. In 2010, 23 power industry experts requested in a letter to Premier Wen Jiabao that the State Council stop UHV technology development and delist it from the 12th Five-Year Plan. While the Premier asked for a response from the NEA and SGCC, UHV projects continued. The critics then turned to Former Premier Zhu Rongi. whose protests that the approval of UHV projects did not meet procedural requirements managed to delay implementation until October 2013. Then, in April 2014 China Central Television (CCTV), the national broadcaster, devoted an episode of "Dialogue" on its financial channel to a nationally broadcast show entitled "Debating UHV". This episode brought much more attention to UHV as opposing sides presented several critiques of the UHV decision-making process, which related to: the administrative procedure for project approval; safety and security; cost; the considerable influence of SGCC as a monopoly; and whether UHV could realistically mitigate the air pollution problem.

In the end, the successful demonstration projects did much to convince the opposition and facilitate the politics of the policymaking process. In May 2014 the NDRC, the NEA and the Ministry of Environmental Protection jointly issued the Work Plan for Strengthening Air Pollution Prevention and Control in the Energy Sector, which proposed to increase the scale of UHV power transmission. Later, the NEA included nine UHV projects in priority locations for long-distance transmission corridors to help relocate coal combustion and reduce local air pollution impacts. From this point, the policy instruments evolved quickly to incentive investment via market pull. Concessional loans, simplified administrative approvals and financial subsidies for deployment were all offered.

UHV policy and project implementation through iteration

The implementation of UHV on a large scale was not monolithically imposed by central planning. Rather, it involved a wide variety of government institutions, and in a way that adapted to local contexts and societal concerns.

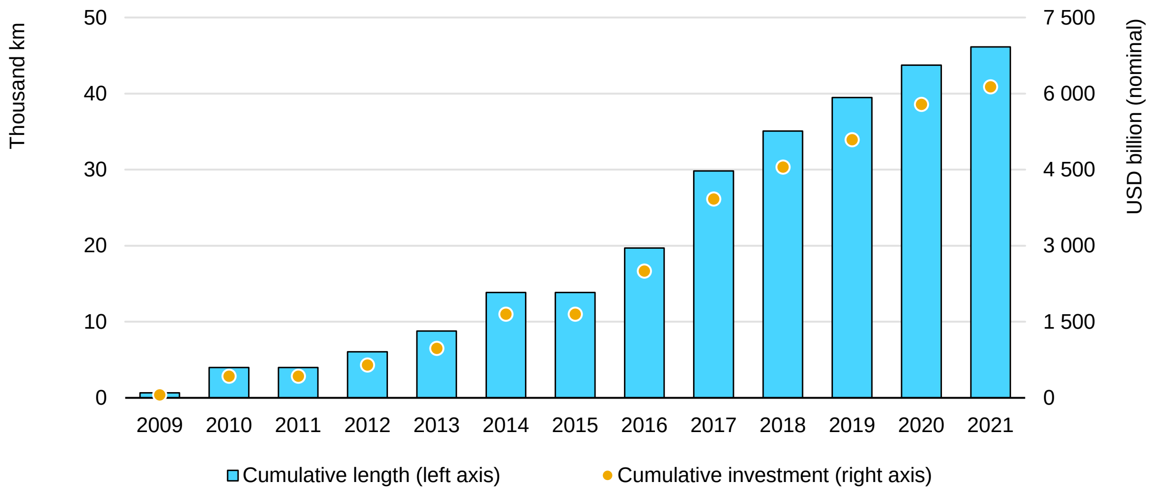
The policy framework designed at the highest level by the State Council and NDRC specified roles for different ministries, departments and local governments. The NEA is responsible for auditing the route of UHV power lines as part of its oversight of energy planning, development, management and regulation. The Ministry of Science and Technology (MOST) is responsible for planning the R&D and development of UHV technology and its applications. Local governments assist and support SGCC's provincial subsidiaries by handling local approval for land acquisition, finance and engineering. The NDRC co-ordinates interaction between ministries, departments and local governments along the UHV power line routes. When the UHV power lines are completed, the NDRC and NEA both have responsibilities for monitoring project acceptance and undertaking evaluation by government institutions and external experts.

Various actors in the implementation of UHV policy had to adapt their approaches due to the evolving knowledge base and public perception of UHV technology in the period after 2014. For example, central government introduced more supervision and regulatory instruments, including the supervision of engineering, safety, quality, the market and costs. From 2014 this included a strong focus on environmental supervision, with mandatory environmental impact assessments for all UHV construction projects. SGCC had to react to several setbacks, including a request for it to suspend its USD 77 billion UHV investment plan in 2011 after its first demonstration projects initially underperformed. Among its responses, it pledged to help insurance companies, large-scale industrial funds and state-owned investment platforms in the regions covered by UHV projects to participate, thereby creating financial benefits for local communities. These measures played an important role in fostering socio-political support for the new technology and reducing potential barriers to further scale-up.

The value of combining state-owned enterprise innovation with checks and balances

By the end of 2021 China's cumulative operational UHV transmission distance exceeded 45 000 km (Figure 4.3). UHV-related patent applications to the national intellectual property office reached 7 206 in 2021, and these came from an array of companies and research institutions beyond SGCC. With China being the only country active in UHV deployment, a whole industry of equipment suppliers and experts has arisen alongside. State-owned enterprises such as China Xidian, NARI Technology and Pinggao Electric, and private enterprises such as TBEA and Beijing Sifang Automation, all generate revenue in this new area. The innovation process of UHV transmission is, however, not entirely closed; international partners (such as ABB) also participate and contribute to its success.

Figure 4.3 Installation of UHV lines and corresponding investment, 2009-2021



Source: guangfu.bjx.com.cn (2023), Inventory – 2023 UHV Project Approval, Construction and Commissioning.

The advocacy of a large, well-capitalised state-owned enterprise is central to the narrative of UHV in China. SGCC and its subsidiaries supply 26 provinces that together cover more than 88% of China's land area, making it one of the most important players in China's energy planning. In 2022 SGCC budgeted a record USD 75 billion for 2023, and spent around USD 22 billion on UHV initiatives alone in the second half of 2022 and the start of 2023. It is difficult to conceive of the rapid build-out of UHV in China without SGCC's ability to fund technology R&D, exploit its links with universities and research institutes, plan UHV lines, finance projects and mandate its provincial companies to conduct engineering and construction.

However, the story of UHV in China shows the importance of independent and critical institutions alongside SGCC. The influence of government and other experts on the trajectory of technology development demonstrate that state-owned enterprises like SGCC do not operate in isolation and are influenced by critical debate as much as they influence it themselves. The result was a slower pace of development, testing of the company's hypotheses and claims, and greater enforcement of environmental principles.

The case of solar PV in China

China's solar PV industry is a manufacturing and installation powerhouse and much has been written about how cells, panels and modules first came to be manufactured in China and then scaled up to world-leading levels. The country has become a pioneer of innovative designs and production techniques that continue to contribute to declining global prices. This section outlines Chinese central government solar PV policy and the factors that spurred technology innovation. It draws a contrast with the UHV case because of the central role played by private companies rather than state-owned enterprises.

When solar PV technology first became an industrial activity in China, it came from outside the state planning system and was misaligned with the national vision of the future Chinese energy system. For example, MOST delayed its manufacturing demonstration project scheduled for 1998 due to an uncertain domestic market and weak support for solar PV in China. It eventually came online five years later, in 2003, and was operated by the private company Yingli Solar, which went on to become a global leader in solar module production. By that time, another small manufacturing line had been started in 2002 by Suntech Power, which also went on to become one of the world’s largest PV manufacturers before its bankruptcy in 2013. Suntech Power was founded in 2001 by a Chinese student of solar technology returning from Australia and its factory was backed by private equity financing. At this time, there was no expectation among senior decision makers that solar PV would become either a significant source of electricity or revenue for China. It was considered too expensive for Chinese consumers and utilities. The technology for these facilities was purchased or brought in from overseas. The output mostly found its way to Europe and other export markets, where market pull policies were stronger.

In the early 2000s solar PV was an R&D topic at MOST and funded via the so-called 863 and 973 Programmes, but few efforts were made to develop Chinese innovation capacity in the technology. Furthermore, the key linkages between policy makers, including MOST, the NEA and NDRC, and the main state-owned electricity enterprises, were underdeveloped for solar PV. Core technology and policy developments were concentrated in Europe, Japan and North America.

It was not until 2010 that the State Council identified solar PV as a strategic emerging industry. It included solar PV in the national vision for economy and energy because of an appreciation that it could generate numerous jobs and also be one of the ways to reduce reliance on coal. In 2009 an important document, “Several Opinions of NDRC and Other Nine Departments on Curbing Overcapacity and Redundant Construction in Some Industries to Guide Industries’ Healthy Development” had been published to hasten the construction permits for polysilicon production plants, a core material for the solar PV industry.

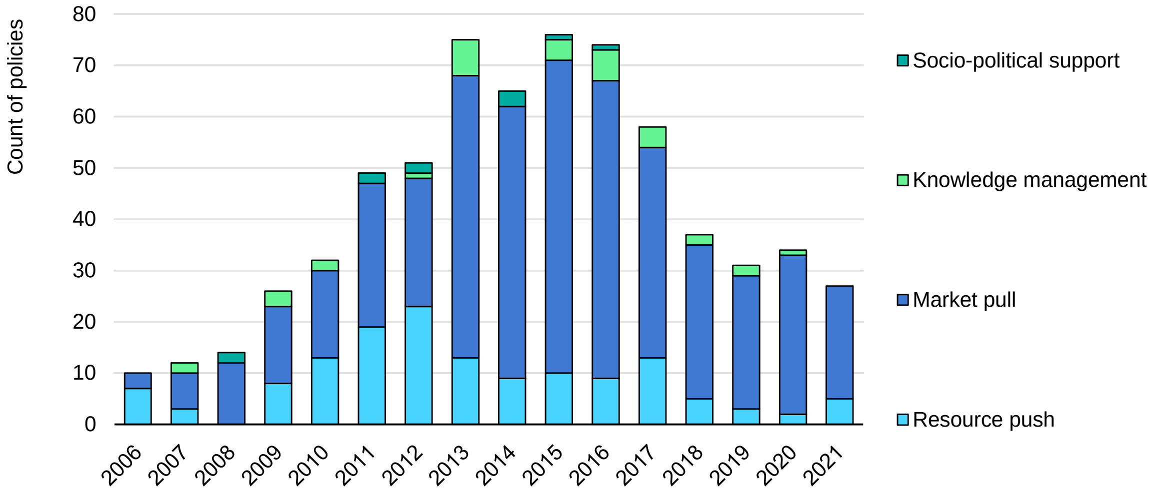
The evolution of policy choices as the market grows

To demonstrate the evolution of policy as the sector scaled up, we have identified 671 central-level policy documents targeting solar PV between 2006 and 2021 (Figure 4,4). In numerical terms, these ramped up rapidly after 2009, and mostly covered domestic deployment rather than manufacturing. Notably, the period from

2009 to 2013 contained the most resource push policies that supported R&D. These included demonstrations and pilots financed from the national budget, including the Solar Rooftop Programme, to which the Ministry of Finance (MOF) and the Ministry of Housing and Urban-Rural Development allocated USD 190 million for 111 projects with a total capacity of 91 MW nationwide. Technology innovation was also encouraged via knowledge management instruments that included awards to recognise excellence and disseminate high-potential advances.[3]

To start building demand for solar PV technologies, a sequence of policies was implemented between 2009 and 2013. These included the MOF and NEA Golden Sun Demonstration Project, which covered 50% of the costs of solar PV power plants (70% in remote areas), and the NEA solar PV concession projects, which funded 16 solar PV projects via competitive bidding. It was not until 2011 that China's first national power production subsidy for solar PV was introduced via a feed-in-tariff,[4] as it took some time to reach consensus around budget implications and institutional perspectives. For example, the NEA expressed concern that individual technologies should not be protected from competition as that would reduce their incentives to innovate. The policy was introduced after a series of internal dialogues.

Figure 4.4 Policy instruments used to support solar PV technology by year of implementation, 2006-2021



Source: Government Document Center of the School of Public Policy and Management of Tsinghua University.

Since around 2010 solar PV has received an increasing level of socio-political support in China, with the technology being highlighted in an increasing number

[3] The government organised a range of awards, including patent awards, science and technology awards, engineering design awards, university scientific research awards and basic research awards. Some of these came with financial rewards.
[4] Prior to this, renewables support since 2006 had been allocated mostly to wind energy.

of national strategies (Table 4.1). These publications are widely used in China to signal political support and build consensus around a path of action. In these documents it is possible to see solar PV move from being a technical curiosity to a topic that is mentioned by non-energy government departments in relation to national innovation competitiveness, jobs and the rural economy. The 12th Five-Year Plan for Solar Power Development set a goal of 21 GW of installed solar power capacity by the end of 2015, a level that was around four times higher than installed capacity in China and equivalent to 25% of all global installations at the time of its publication. In the end, the target was exceeded and installations reached 43 GW. In the 2015 Work Plan on the Implementation of PV-based Poverty Alleviation Project, promotion of solar PV is described in relation to the development of local agriculture, jobs and social benefits. Likewise, by 2015 the NEA's Solar PV Leader Plan took into account enhanced targets for moving the country to less polluting forms of energy and encouraging innovation to improve the quality of domestically manufactured solar PV. While this increased alignment with the national policy vision for the economy, manufacturing of solar PV was not an explicit policy goal – as it has been in other countries – but rather an implicitly expected outcome given China's manufacturing strengths.

Consequently, at the central level the focus on promoting the deployment of solar PV was not matched by an equivalent focus on supporting investment in manufacturing capacity. The production of solar PV equipment was largely left to the private sector and support from provincial governments. This support, for example via access to cheap capital and land, can be substantial but might not be targeted at specific industries. In total, direct and indirect support to firms to pursue a variety of industrial policy goals in China has been estimated to have been equivalent to 1.7% of GDP in 2017-2019.

Table 4.1. Selected socio-political support documents of China's central government related to solar PV

Year	Document
2012	12th Five-Year Plan for Solar Power Development
2014	Work Plan on the Implementation of PV for Poverty Alleviation Project
2015	State Council Leading Group Office of Poverty Alleviation and Development (OPAD) Listed Solar PV for Poverty Alleviation as One of Ten Major Projects for Targeted Poverty Alleviation
2015	Solar PV Leader Plan
2016	13th Five-Year Plan for Solar Power Development
2018	Notice on Matters Related to Photovoltaic Power Generation in 2018

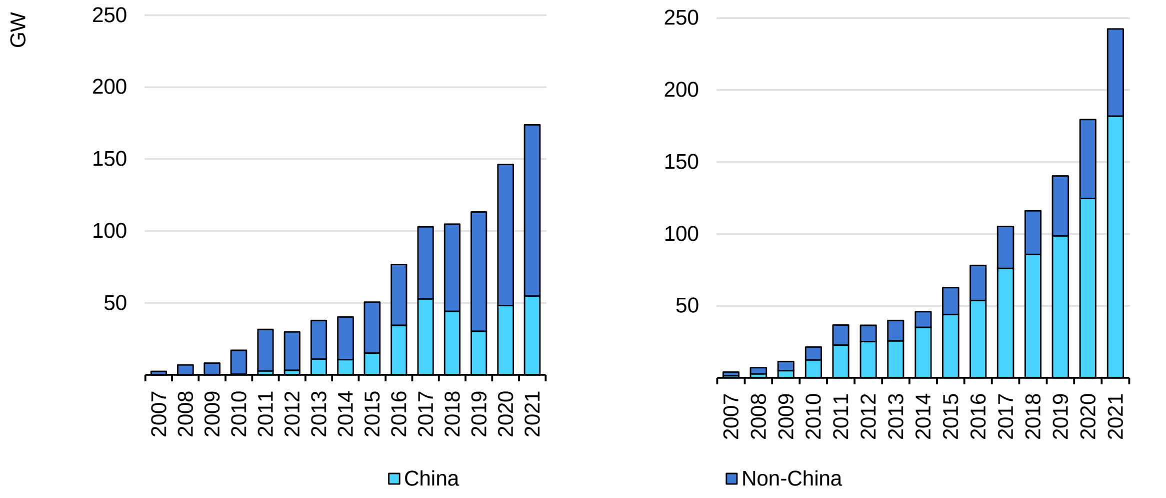
Sources: NEA (2012), Solar Power Development Twelfth Five-Year Plan; NEA and OPAD (2014), Notice On The Work Plan Of Photovoltaic Poverty Alleviation Project; OPAD (2015), China Promotes the Implementation of the Top Ten Projects of Targeted Poverty Alleviation; NEA (2015), Opinions on Promoting the Application of Advanced Photovoltaic Technology Products and Industrial Upgrading; NEA (2016), Solar Energy Development 13th Five-Year Plan; NEA (2018), Notice on Matters Related to Photovoltaic Power Generation in 2018.

In the period from 2013 to 2018 market pull and socio-political support policies dominated. Annual solar PV deployment targets were issued by the NEA each year for utility-scale and small-scale projects. Support policies for uptake in specific sectors multiplied, and included agriculture, water conservation, civil aviation, poverty alleviation in rural and western regions, and use in public institutions and enterprises. Market development was aided by the establishment of standards, quality control and monitoring, including for equipment, land use, corporate bonds and environmental impacts. It was during this period that market pull policies expanded to also encourage technological leadership and industrial investment in module production.

However, subsidy measures came to an end on 31 May 2018 when the NDRC, MOF and NEA jointly issued the Notice on Matters Related to Photovoltaic Power Generation in 2018 (the so-called “5.31 new policy”). Among the factors behind this decision were the challenges that rapid expansion of solar PV was causing for electricity grid integration and for public budgets. Another reason was the increasing belief that solar PV technologies were approaching grid parity. Due to constraints on grid infrastructure and market structure (whereby many coal plants were given priority access to the network), the rate of solar PV curtailment rose in northwest China by between 20% and 32% in 2015 to 2017. This significantly increased the cost per unit of solar electricity consumed, and MOF’s Renewable Energy Development Funding could not keep up with the subsidy bill from the flourishing installations. By the end of 2017 the cumulative budget shortfall was almost USD 15 billion despite a tenfold increase in the levies imposed on electricity consumers to help fund the cost.

As the price of solar PV generation dropped towards the fixed price paid to coal-fired power generators – a threshold it passed in 2021 – deployment continued apace (Figure 4.5). Every step of its market expansion has been accompanied by a corresponding growth in its solar PV manufacturing output, which has continuously been larger than any other country for polysilicon, wafers, cells and modules since at least 2010. Among the top 20 solar PV manufacturing companies in 2022, 17 were Chinese and many of these have operations around the world.

Figure 4.5 Global solar PV installations (left) and module production (right), 2007-2021



Source: IEA (2021), PVPS trends reports.

Achieving this level of output and dominance at the same time as continual dramatic cost reductions would not have been feasible without technology innovation. Economies of scale played a significant role, but advances in cell design and assembly techniques were also fundamental in lowering costs. While early output was based on overseas technology, Chinese researchers have become a significant source of international patents in solar PV. While their rate of patenting lags that of Europe, Japan, the United States and Korea in most areas, they account for more than 10% of the total in areas including power conversion and organic PV cells. In 2016 Trina Solar set the world efficiency record of 19.9% for a laboratory version of a multi-crystalline solar module, though it has since been beaten. Jinko Solar and Longi reported record efficiencies above 25% for variants of n-type and p-type monocrystalline cells in mid-2021. In 2023 Longi achieved records of 27.1% and 33.9% combined efficiency for silicon heterostructures (HIT) and hybrid tandems. Nanjing University reported a record efficiency of 29.1% for perovskite tandem cells in 2022 and the University of Science and Technology of China reported 26.1% for perovskite cells in 2023. These results demonstrate how Chinese corporate and university laboratories have followed government laboratories and universities in shifting their R&D focus to next-generation solar PV designs. However, most of the PV efficiency records set in recent years have been by German, Japanese, Korean and US firms.

Notable features of the solar PV case

By comparing the different routes by which China achieved global leadership in solar PV and UHV, notable features of the solar PV case emerge. They include the participation of more private companies, a more diverse set of accountable ministries, the importance of international co-operation, and the challenges of regulating mass-manufactured products. These are each discussed in turn:

1. The influence of private companies and market competition.

China's solar PV manufacturing industry initially became established outside the central planning system, with private companies setting up factories to manufacture imported technology designs. These companies had government backing, but it was from provincial and municipal administrations and their banks. Suntech Power, for example, raised USD 2.9 billion in Jiangsu province in 2010. Several important dynamics resulted from this situation:

- At the outset, the companies were reliant on markets outside China and experienced boom-and-bust cycles due to external policy changes. There were a number of high-profile bankruptcies, including Suntech Power.
- With support from different provinces and no involvement of national state-owned enterprises, competition between these firms was intense. This was especially the case during periods when the global market cooled down, but in this commodity business the margins have been persistently thin and competitive. This incentivised innovation to stay competitive without needing dedicated government R&D policy.
- Once central government stepped in to support and promote solar PV in response to various national and international trends, the main private players were already established. Policy support from central government provided market stability, but entrenched the competition between private firms and provinces. To stay competitive, industrial clusters emerged around the main manufacturing companies with a relatively open exchange of knowledge and expertise between universities, component suppliers and the finance community. This spurred more effective innovation.

2. Policy experimentation was facilitated by the involvement of multiple ministries.

As a sector straddling energy, manufacturing, environmental and rural development policy, there was considerable diversity among the government departments with a stake in solar PV. For example, ten departments including the NDRC and the Ministry of Industry and Information Technology co-issued a 2009 opinion on how to address overcapacity in polysilicon production resulting from changes in overseas policies. These departments had different opinions on issues such as whether solar PV support should prioritise utility-scale or small-scale projects, or whether state support should be via administrative approval or competitive processes. The outcome of the lack of consensus was more diversity of policy. The Solar Rooftop Programme of the Ministry of Housing and Urban-Rural Development targeted small-scale projects, the Golden Sun Demonstration Projects of MOST and the NEA targeted utility-scale grid-connected projects using the administrative approval approach, and the solar PV concession projects launched by the NEA targeted utility-scale grid-connected projects using the competitive bidding approach. This level of policy experimentation was magnified by interventions at the provincial and municipal levels, which included various combinations of production subsidies, demand subsidies and innovation support measures.[5] It has been shown that production subsidies were frequently combined with innovation support at the subnational level between 2006 and 2022, and these policies were most successful at stimulating patenting and capacity expansions.

3. International partnerships can be key to knowledge exchange and launching a new sector.

In the early days of solar PV in China, rapid technology learning was facilitated by joint ventures and licensing of intellectual property. In 2008 Shandong Solar Technology licensed technology from Johanna Solar Technology, a German company. In 2012 Tianjin Zhonghuan Semiconductor formed a joint venture with Sunpower, a US company that went on to form other joint ventures with Dongfang Electric Company and two other Chinese companies. The value of access to China's large domestic market gave Chinese companies a negotiating edge, but non-Chinese were generally keen to enter such partnerships to improve the competitiveness of their manufacturing activities, which would benefit from access to cheaper finance and labour in China. Some Chinese companies also acquired foreign competitors and progressively absorbed their R&D activities. For example, Hanergy Group acquired Alta Devices, a US company, in 2013.

Several Chinese companies established partnerships with universities overseas, such as Trina Solar's tie-up with the Australian National University in 2011, and put in place special programmes to hire skilled labour and executives with academic and professional experience abroad, with a focus on Chinese nationals working abroad. According to the patent data, a relatively high share (13%) of all co-inventions between innovators from at least two different countries involved Chinese entities in 2000-2009. Compared with a state-owned behemoth such as SGCC, the flexibility and freedom to engage in such a variety of international partnerships is likely to have made it easier for private companies in an internationally growing segment such as solar PV. However, these interactions appear to have slowed after 2015, with growth in patents by Chinese-only innovators and no growth in co-inventions.

[5] Production subsidies are those that provide financial support to firms building new manufacturing lines. Demand subsidies are those that provide financial assistance to the users of solar PV for generating electricity or to their customers who purchase electricity. Innovation support measures include R&D funds but also, as in Guilin city in 2011, payments to reward firms if their R&D centres achieved provincial-level certifications.

4. Regulating mass-manufactured technology from multiple producers brings challenges.

In contrast to the centralised and large-project nature of UHV, policy implementation for solar PV was hampered by quality control and monitoring in a fast-moving technological environment. MOF allocated over USD 700 million to the Golden Sun Demonstration Projects in 2009, but some recipients never constructed the promised plants or used substandard equipment, leading to the cancellation of 54 MW of capacity, including projects owned by well-regarded firms such as Wuxi Suntech, AT&S and BP. Another 11 firms were found to have defrauded MOF of USD 35 million in other ways. For the following phases of policy, the quality control and monitoring regulations were tightened.

Findings

The two cases explored in this chapter reveal different types of policies and dynamics that can help emerging market economies to achieve their ambitions for domestic clean energy innovation. China is in many ways a unique case, given its vast domestic market, large national budget and range of socio-economic contexts – from high-tech engineering towns to low-wage industrialising provinces. Nonetheless, several insights stand out from the UHV and solar PV cases. These may be especially relevant to other countries that have a high degree of centralisation of economic and social development planning, dominant state-owned enterprises and devolution of policy implementation to subnational levels.

One emerging finding is that centralised systems still face tensions among powerful departments and stakeholders. Contrary to some external perceptions, it is not sufficient in such a system for a single government department to issue a diktat in the expectation that everyone will toe the line. The processes by which consensus is built and agreement on how to proceed are vitally important in China. This was especially the case for UHV technology. The two cases both show the need to foster consent and actively engage diverse stakeholders through consultation and co-ordination, highlighting the importance of socio-political support for innovation policies.

China's clean energy policymaking process included prominent consensus building activities in both the case of UHV and solar PV. They covered consultation meetings, expert reviews and collective drafting of key strategic documents that involved some of the most senior politicians in the country. The time and effort required by these processes should not be underestimated. In both the UHV and solar PV cases, institutional stakeholders were given space to test technology or policy approaches that could then be appraised by a cross-departmental group. In the UHV case, setbacks had to be navigated, while in the solar PV case it was necessary to negotiate an end to support policies that had shared responsibilities among departments. The UHV case demonstrates the benefits of transparency and inclusivity in terms of consultation for highly visible and high-cost infrastructure projects. In the solar PV case, institutional dialogue was less public, perhaps arising from the challenges of co ordinating and integrating the views of a larger number of smaller private companies in the nascent sector. Overall, however, an iterative process is often necessary to ensure the commitment of all stakeholders to a course of implementation and requires patience.

In both cases, the socio-political support of consensus building gave way to the socio-political support of strategic planning as the technology scaled up. The technologies were increasingly integrated into sectoral and national strategies that were aligned with the national vision, first for energy and then for the wider economy and society. In 2006 UHV technology was included in the influential National Programme for Medium- and Long-Term Scientific and Technological Development (2006-2020), thereby placing it in a special category of technologies of national strategic priority. Likewise, solar PV was classified as a strategic emerging industry. In this way, technology maturity (i.e. policy makers' confidence in its effectiveness and suitability to solve policy problems) was accompanied by a move from the political periphery to the centre of national policy in a stepwise fashion. China could potentially have moved into PV even earlier if it had been better aligned with the national vision.

Another clear finding is that different clean energy technologies benefit from different approaches to innovation policy. The role of SGCC as an advocate and then implementer of UHV technology policy would not have been appropriate for solar PV. Because of its substantial financial capacities, SGCC does not need public R&D funds. What it needs most is the permission to innovate. Solar PV was already established as an effective technology abroad, it had several competing designs and it would be adopted by a variety of different customers if it could be manufactured at sufficient scale and quality in China. China's existing manufacturing excellence in other sectors helped it to move quickly into PV. An approach to solar PV that gave a single company the type of preferential access to central government leadership enjoyed by SGCC would have been unlikely to yield the benefits of technological competition, a plurality of international partnerships and local industrial clustering. However, the private solar PV companies suffered from being outside the policy process and vulnerable to policy changes and funding gaps in a way that SGCC never needed to worry about for UHV. Where state-owned enterprises have significant resources and close connections to the centre, governments can incentivise them to take on more clean energy innovation, leveraging their financial capacities and abilities to forge political and social consensus. Private entities and new entities outside existing regimes may require additional financial and political support to foster innovation. Policy makers should consider providing necessary resources and interventions to facilitate their participation and contribution.

Finally, key individuals and networks are important, especially if they have international connections. It can be observed that in both cases it was critically important for Chinese companies to be familiar with the latest international technological developments, but that this did not happen via a government–government process. The six main ways that Chinese companies established a foothold in the new technology areas would be very familiar to any major international technology developer:

- joint ventures between private companies
- technology licensing from private companies
- engagement of foreign technology suppliers as contractors
- acquisition of foreign companies and integration of their R&D capabilities
- research partnerships with overseas universities
- relocation of human capital from overseas universities and companies to become founders or employees of Chinese firms.

While these six approaches can be considered as specific to the Chinese case of a rapidly growing economy with a large population in the period studied, they indicate ways of thinking about domestic innovation in emerging economies even if other countries were unlikely to find some of the exact policy instruments as easy or effective to implement.

5. Renewable energy and hydrogen in Colombia

Clara Ines Pardo Martinez (Universidad del Rosario)

Colombia is a fossil fuel producing country that is acting on its commitment to make a transition to clean energy. This commitment shapes key policy documents and strategies at all levels of government. Over the past decade, the government has made considerable progress in policy development to support private investment in solar PV and wind energy, despite starting from a low base of expertise in these technologies. A range of fiscal, financial and regulatory measures have been used to tap into the country's considerable renewable resources to help address the challenges of electricity security and electricity access. However, it has not all been smooth: the auction system had to be adjusted in 2019 and issues related to social acceptance were encountered. In addition, the policy approach favoured technology imports and the entry of foreign firms to develop projects. Nonetheless, when Colombia decided to move decisively into the even less mature area of hydrogen energy in 2020, experiences with the solar PV and wind policies were highly valuable. While it is too early to judge whether Colombia's ambitious hydrogen roadmap targets will be fulfilled, it has a solid foundation to attract investment and foster innovation. Notably, the extensive experience with fuel production and handling from Colombia's established oil and gas sector is a good fit with hydrogen project development, including the possibility of using carbon capture. The role of Ecopetrol, Colombia's largest firm and a state-owned oil company, is likely to be crucial in this regard, especially considering its corporate commitment to net zero CO_2 emissions by 2050. Despite this, there remains much uncertainty about the future of hydrogen, and the investments that the roadmap would require represent a major undertaking for Colombia. To capitalise successfully on the opportunity to become a regional leader in hydrogen, strategic international partnerships and a strong innovation ecosystem will be required.

Country context

Colombia is the second-largest country in Central and South America by population, after Brazil and before Argentina. However, it is the third largest by GDP,[1] given that its GDP per capita is just 60% of that of Argentina and the

[1] In market Exchange rate terms.

populations are similar. However, Colombia's GDP per capita grew rapidly between 2004 and 2014, enabling it to pass the lower threshold for an upper middle-income country in 2008. This trend was in part driven by rising fossil fuel exports. The period of rapid growth came to an end in 2014, as oil prices dipped and Colombia's rising domestic demand for energy reduced the amount available for export. Subsequent economic challenges, notably the Covid-19 pandemic, have kept GDP per capita around 30% lower than the 2014 peak.

The Colombian economy is reliant on the service sector, which represents around three-quarters of GDP. Outside the oil and mining sectors, the country is not heavily industrialised and, with 42% of people living below the national poverty threshold, has considerable scope for further development to improve livelihoods.

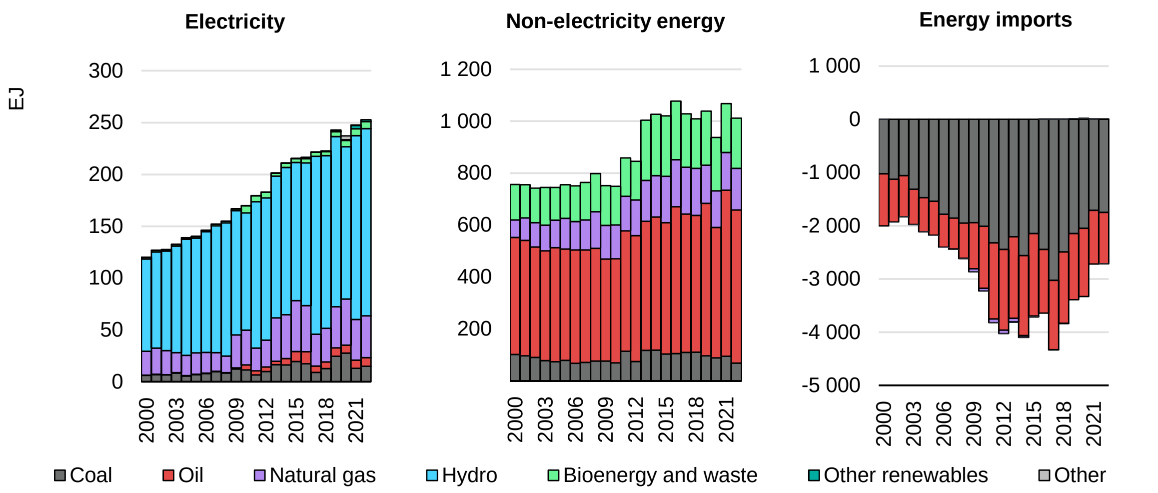
In 2021, the government announced an Economic and Social Recovery Policy, establishing an investment equivalent to 12.5% of Colombia's GDP distributed in five commitments on: job creation; clean and sustainable growth; vulnerable households; rural areas and peace and legality; and health care. This spending, coupled with privatisations, boosted economic growth between 2020 and 2022. However, economic activity has since slowed and the economy is expected to undergo another year of modest growth, at 1.8% in 2024, before picking up by 2.8% in 2025. In April 2020, Colombia joined the Organisation for OECD.

Energy sector context

Revenues from the production and export of oil, gas and coal remain important for the country's GDP. The oil sector has contributed an annual average of close to 2% of GDP and 13% of total government revenue in the last 10 years from tax revenues, dividends and royalties. Ecopetrol, Colombia's publicly traded state-owned oil company, is the country's largest company, and the rest of the country's top five firms are composed of oil refining, oil product distribution and coal mining companies. Almost 90% of Colombia's coal production is exported, securing a large part of the state budget.

For two decades, the energy transition has been a stated policy goal for Colombia and the country has made progress towards achieving it. It also has a very good resource endowment: Colombia has abundant natural renewable energy sources, a highly decarbonised electricity mix, with 72% from hydropower, and consumes more renewable energy in its final consumption than many other OECD countries. Colombia's daily average solar radiation of 4.5 kWh/m^2 is well above the global average of 3.9 kWh/m^2, its wind speeds in La Guajira are twice as high as the world average. However, while solar and wind energy make up one-quarter of projects in planning that are registered with the Mining and Energy Planning Unit of the Ministry of Mines and Energy, these sources represented less than 1% of the electricity mix in 2022.

Figure 5.1. Energy sources for electricity and other uses, and imports, Colombia, 2000-2021



Notes: Electricity and non-electricity energy are shown on a final consumption basis. Imports are shown net of exports. “Other” refers to imports or exports of electricity.
Source: IEA (2024), World Energy Balances.

Colombia’s energy strategy is aligned with the sustainable development agenda of the nation. The latest National Development Plan (PND) for the period 2022-2026, under the theme of “Colombia, World Power of Life (Colombia Potencia Mundial de la Vida)”, was approved in May 2023 after a country-wide consultation process with Congress, the unions and civil society, including binding regional dialogues across the national territory. The PND supports five socio-economic transformations: 1) territorial planning in line with the availability of water; 2) human security and social justice, 3) human right to food, 4) productive transformation, internationalisation and climate action and 5) regional convergence.

The PND sets priorities for investments in the country’s energy transition under the dedicated pillar on ‘Productive transformation, internationalisation and climate action’ with the following priorities: diversification of exports (a targeted share of 56.3% to come from non-mining exports), reindustrialisation and technology investment (with a targeted share of 0.5% in the GDP dedicated to R&D), the promotion of new mechanisms for the generation of 2 GW of non-conventional renewables, sustainable transportation, a 20% reduction of deforestation, and the restoration of the country’s ecosystems.

In addition to the PND, Colombia has a long-term national energy plan (PEN), last published in 2020 and based on scenario planning to 2050, electricity generation plans and electricity transmission expansion plans. The legal bases for its energy transition activities are the Energy Transition Law (2099/2021), the Climate Action Law (2169/2021) and sectoral climate change management plans (so-called PIGCC), including for the energy sector (PIGCCme).

Colombia's interconnected electricity grid reaches one-third of the territory and provides electricity to approximately 96% of the population. In the remaining two-thirds of the territory – mostly in the east where much of the land is impassable by road and sparsely populated – electricity is mainly provided by small diesel generators, many of which suffer from poor maintenance, or by renewable energy. Colombia's grid plays an important role in regional energy integration, with connections to Ecuador and Venezuela.[2]

The government started to financially support the development of non-hydropower renewable energies in 2014. It currently does so through auctions for long-term power purchase agreement contracts (PPAs). The current national target is to increase the installed capacity of these electricity generation sources on the national grid by 670% by 2026, from 300 MW in 2022. The President has proposed creating a fund that would use royalties and taxes from the fossil fuel sector to finance clean energy initiatives.

In 2021, 3% of Colombia's population, or 500 000 users, did not have access to electricity and 1 million families used wood for their heating and cooking needs. By 2030, the government aims to halve this lack of coverage by connecting 100 000 families to electricity supplies and providing 200 000 families with clean cooking per year.

Colombia's GHG emissions are relatively low in per capita terms due to the high share of hydropower in the electricity mix and limited industrial and transport fuel demand. Nonetheless, they have been rising over the last decade and reaching emission targets will depend on progress with renewable electricity and technological change in the transport and manufacturing sectors, as well as the fight against deforestation. Colombia's updated NDC to the Paris Agreement, to which it is a signatory, includes a reduction of its GHG emissions by 51% compared to the business-as-usual scenario by 2030. In June 2021, the President announced Colombia's Long-term Strategy "E2050", which has an integrated vision of resilience and progressive emissions reduction towards carbon neutrality by 2050. Though a carbon tax was recently introduced, it is currently set at a

[2] Exports to Venezuela were stopped in 2019.

comparatively low level, and covers only 25% of domestic emissions. The revenues it raises are similar to the amount the government spends on fossil fuel subsidies.

Innovation context

Colombia has a well-developed research system relative to many of its peers in South America. It is currently ranked 70 out of 132 countries in the Global Innovation Index – below Brazil, Chile and Uruguay, and above Argentina – and 15 among 33 upper middle-income countries. Its score balances a higher ranking for business and market development with a lower ranking for human capital and R&D. The government is directly responsible for just over one-quarter of the national R&D budget, with the rest of the finance coming from companies (including state-owned enterprises), universities and 7% from the international community. Given the large role of oil companies in the national economy, energy R&D enjoys a significant share of total R&D in Colombia, with 5% of researchers working on energy sector issues.

The Ministry of Science, Technology and Innovation is responsible for maintaining funding for R&D, technical training and innovation activities, allocating responsibilities and determining priorities in line with national socio-economic objectives, including those for manufacturing and trade. The government targets an increase in R&D spending as a share of GDP from 0.26% to 0.5% between 2021 and 2026. The National Policy of Science, Technology and Innovation seeks to increase the contribution of science, technology and innovation to the social, economic, environmental and sustainable development of the country, with a differential, territorial, and participatory approach. This includes action plans that link energy policy with innovation through the aims of (1) increasing the inclusion of human capital in science, technology and innovation, and those with high-level training in the labour market, including the energy sector, and (2) increasing the transfer of knowledge and technology to the productive sector through green technologies to improve competitiveness and innovation, which are key in the energy sector.

Colombia supports energy R&D through the following general (non-energy specific) funding instruments:

- National financing fund for science, technology and innovation – the "Francisco José de Caldas Fund". This fund is the main financing mechanism for science, technology and innovation and provides financial support for the development of RD&D projects aimed at developing and validating new technologies for the energy transition. The fund is sourced by the general government budget, as well as resources from other public and private entities, donations, and international co-operation.

- The Science, Technology and Innovation Fund (FCTeI), which is funded by using 10% of the royalties from the exploitation of energy and mining resources. It is intended to increase the scientific, technological, innovation and competitiveness capacity of the regions across priority sectors not limited to energy.
- Tax benefits granted by the National Council of Tax Benefits to companies that carry out science, technology and innovation projects, in association with an actor acknowledged by the Ministry of Science, Technology and Innovation.
- Fiscal credits for small and medium-sized enterprises.
- The Fund for Unconventional Energies and Efficient Energy Management (FENOGE), created in 2014 (although in operation since 2018), which can finance projects across all the technology development stages, including research, innovation and demonstration. The fund was developed to support projects to improve energy efficiency and develop unconventional energy sources, but Law 2099/2021 allows the fund to support hydrogen projects as well.

Overall, however, the research community on energy technologies is quite small (around 100 research groups). With half of the funding provided by the World Bank, USD 36 million was spent between 2018 and 2022 to support a network of co-operation and training among experts in the area of sustainable energy (called SÉNECA), co-ordinated by universities and involving the private sector.

As a response to a Commission of Experts, the Ministry of Science, Technology and Innovation; the MME; and Ecopetrol have established a co-operation agreement within the Francisco José de Caldas Fund to develop science, technology and innovation activities to address energy transition issues. The first call (USD 1 million) to develop projects on renewable hydrogen and carbon capture, utilisation and storage (CCUS) has been announced. In addition, as part of Ecopetrol's "2040 Strategy, Energy to Transform", more than USD 240 million was earmarked for innovation, technology and digital transformation projects in 2022-2024. This scope for this spending included cybersecurity, supply chain optimisation, sustainable water production and management, and CO_2 capture. In addition, the plan included resources to boost human resources and skills.

Presidential Directive No. 6/2021, which defined the mining-energy sector as a benchmark sector and established that the sector must make an investment in R&D of at least 7% of the total investment from 2022, also established that the National Planning Department and the Ministry of Science, Technology and Innovation will provide technical assistance to entities for defining the investments for them to fulfil this investment goal in accordance with their competencies.

As of 2023, Colombia did not have a formal system to track public spending on energy RD&D or evaluate progress, but evaluations have been used in recent years with positive outcomes. The National Administrative Department of Statistics collects information from companies through the Technological Development and Innovation Survey, with the most recent being from 2018.

However, the results are not disaggregated to the level of energy. A public expenditure review for science, technology and innovation was piloted by the National Planning Department (DNP) and World Bank in 2015-2016, with assessments of 129 programmes managed by eight agencies. In 2018, the methodology was applied to the FCTeI (which is funded with oil and mining royalties) with guided interviews and focus groups. In total, 166 projects in 12 project portfolios (corresponding to 12 departments) were analysed in 10 areas, including budget, partnership types, economic activity, intervention mechanisms, economic results, objectives and beneficiaries. Portfolios of projects were also evaluated for functional performance in terms of design, implementation, and governance. The process led to significant changes to programme design and policy strategy co-ordination across stakeholders. This included creation of a digital Innovation Portal to provide detailed information about different instruments supporting R&D, innovation and entrepreneurship and about overall policy strategy. In addition, the FCTeI project cycle was amended to have a portfolio approach to departmental priorities, more defined terms of reference for calls, and to enhance department R&D and innovation strategies. The use of FCTeI resources toward credit lines through second-tier banking and was also enabled and the overall number of instruments reduced to help agencies sharpen the focus of their programmes and limit administrative costs.

The case of renewable energy support measures

The legal basis for Colombia's support to non-hydropower renewable energy was established in 2014 by Law 1715, which sets out the policy objectives. These objectives include:

- sustainable economic development
- the reduction of greenhouse gas emissions
- security of energy supply
- supply non-interconnected regions

These aims reflect the government's recognition of several coincident factors: the stress on the hydropower system caused by extreme weather events, the importance of diversifying the economy away from fossil fuel exports, which had peaked, the need to provide electricity to unconnected communities, and commitments to tackling climate change. These factors constituted a strong national vision for the development of the economy and Colombian society.

The law references innovation in its stated intention to "stimulate investment, research and development for the production and use of energy from Non-Conventional Energy Sources, mainly those of a renewable nature, through the establishment of tax, tariff or accounting incentives and other mechanisms that stimulate the development of such sources in Colombia."

Selection of measures to foster private investment in renewables

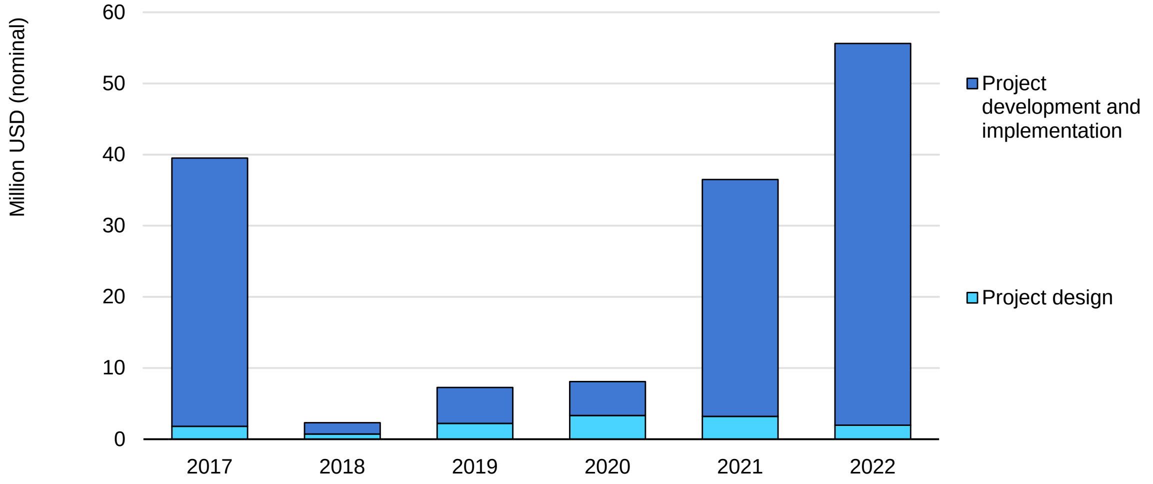
Since 2014, the main policy measures adopted by the government have been chosen to incentivise investment by the private sector rather than direct investment in publicly owned renewables projects. In this regard, policy choice was constrained by the institutional history of energy governance, which included the liberalisation of the electricity market in the 1990s and separation of the functions of power generation, transmission and retail. The selected approaches adopt a variety of different policy tools (Table 5.1).

Table 5.1. Selected measures to foster investment in non-hydropower renewables in Colombia, 2014-2021

Name	Measures
Law 1715 (2014)	A dedicated fund (financed by wholesale electricity sales or other sources, including international finance) to support projects with reimbursable or non-reimbursable finance. Income tax deduction of 50% of investment value for up to 50% of taxable income for up to 5 years. Exclusion of projects from sales tax on the acquisition of goods and services. Accelerated depreciation of assets. Net metering for small-scale generators. Harmonisation of environmental requirements, including environmental impact assessments. A rapid assessment process for renewable energy projects.
MME Resolution 40791 (2018)	Established competitive double-sided sealed-bid auctions for 10–20-year PPA contracts (for energy, not capacity) as the main mechanism for funding projects.
Law 2036 (2020)	Provisions for the use of the National General Budget and the General System of Royalties to support the participation of territorial entities in alternative renewable energy generation projects.
MME Resolution 40060 (2021)	Required power traders to source 10% of their annual energy purchases from non-hydropower renewables.
Law 2099 (2021) "Energy Transition Law"	The tax incentives for projects were extended and expanded to include exemption from import duty for equipment for projects.

Non-hydropower renewable energy projects in receipt of the incentives, including tax exemptions, must be certified with the regulatory agency. From 2017 to 2022, investments in such projects, and the number of projects developed, increased in isolated regions (Figure 5.2). The majority of these were based on solar PV.

Figure 5.2. Estimated investments in non-hydropower renewable energy projects in non-Interconnected areas under Institute for the Planning and Promotion of Energy Solutions mechanisms, 2017-2022



Notes: 2022 data reflects the year to May 2022.
Source: Institute for the Planning and Promotion of Energy Solutions for Non-Interconnected Areas (IPSE).

In December 2023, the Colombian government launched Latin America's first offshore wind auction, for which the winners will be named in August 2025 . Temporary eight-year licences will be awarded to successful bidders in December 2025 to assess the viability of offshore sites. Awardees will then have the opportunity to convert them into longer-term concessions for the construction and operation of offshore wind farms.

To complement the measures to support deployment, the Ministry of Science, Technology and Innovation developed two "resource push" innovation programmes. One programme involved included annual calls between 2014 and 2021 for R&D projects within the National Program of Energy and Mines and funded by the National General Budget, resulting in 35 projects by universities, largely focused on solar PV, biofuels and wind technologies. The other involved the use FCTeI funds for 19 projects across 20 different regions from 2012 to 2021, including projects to improve laboratories and research centre capabilities.

Experiences with policy implementation

The choice to use competitive auctions to distribute funding for renewable energy projects is intended to minimise taxpayer costs and consumer prices. However, implementation has not been entirely straightforward. The first auction in 2019 failed to award contracts because bidders did not meet the specified criteria. In response, changes were made for the second auction later that year as follows:

- The energy supply commitment was changed to a daily rate from an annual rate.
- Documentation requirements were reduced.
- The winning bid was chosen using a simpler algorithm that prioritised consumer costs rather than also including competition elements.
- Contract durations were extended from 12 years to 15 years.
- Electricity buyers assumed the obligation of paying the contracted amount to generators regardless of consumption, with any difference settled on the spot market rather than on a yearly basis.
- The costs of commitment bonds for participation in the auction were reduced.

Another challenge that emerged related to tensions within the communities where projects were located. Confidence-building and consultation exercises had to be established and routinised by project developers. Capacity within the public institutions to manage the various policy elements also needed to be built quickly and was a challenge for Colombia. For some communities, access to electricity is hindered by complex regulatory requirements.

By encouraging the private sector to bid for long-term contracts competitively, supported by tax exemptions that help make Colombia an attractive location to invest in the region, Colombia has diverse corporate participation in its solar PV and wind sectors. The active companies are a mix of local firms (such as EPM Group, Celsia, ISAGEN and AES Colombia), local subsidiaries of overseas firms, and multinationals. For wind projects, most of the main international equipment suppliers are present, including GE, Siemens Gamesa and Vestas.

Interaction between national and international companies has increased knowledge-sharing and creates a potential foundation for innovation. For example, EPM Group has two decades of experience of renewable energy R&D in Colombia, including building the country's first pilot wind farm in La Guajira in 2004, but did not have the technical resources to scale up quickly without partnerships. In 2019, it partnered with US firm Invenergy. ISAGEN built an alliance with US-based project developer Atlas Renewable Energy to develop, build and operate 1 GW of renewable energy capacity in Colombia. These partnerships have connected Colombian entities, and the research institutes with which they have longstanding relationships, with international supply chains. On the other hand, the majority of the equipment and technical know-how has been imported and there are few mechanisms in place to keep as much of this know-how as possible in the country. This is a potential downside of a policy that seeks deployment at lowest cost, including through exemptions from import duties, and encourages participation of the largest firms.

Across the whole value chain in Colombia, networks of developers, promoters, marketers, manufacturers of components operation and maintenance specialists, consultants and financers have emerged in response to the renewables support policies. This has undoubtedly strengthened skills and competences in the labour market and supported adaptations of installations to the local context. Colombia has developed formal and informal education programmes to provide further support to workers: there are 77 technical and technological education programmes up to doctoral level, accounting for 1% of formal education. However, the country still has gaps in the energy workforce for non-hydropower renewables, partly owing to a historic focus on fossil fuel topics in university engineering programmes.

The deployment of solar PV and wind in Colombia has generated new markets for complementary innovation. The Renewable Energy Integration Programme, launched in 2023 with support from the multilateral Climate Investment Funds, includes up to USD 70 million to support electricity system access, flexibility and resilience energy through technologies such as batteries, hydrogen and smart grids, which are at an earlier stage of development in Colombia.

The case of Colombia's hydrogen energy roadmap

In 2017, the topic of hydrogen as a clean energy carrier was first introduced into Colombia's legal and regulatory framework. Law 1964/2017, on electric mobility, did not contain any specific objectives or support measures for hydrogen production or use, but it included hydrogen-powered vehicles using fuel cells within the definition of electric vehicles. This made such vehicles eligible for lower tax rates, designated road space and other incentives for electric vehicles introduced by regional authorities.

It was in 2020 that hydrogen became a more strategic topic in Colombia's energy planning. With support from the UK government and Inter-American Development Bank, the government began preparing a roadmap document for hydrogen energy, which was published in mid-2021. In parallel, definitions for low-emissions hydrogen production were included in the Energy Transition Law published in 2021.

A vision for hydrogen that is aligned with selected national priorities

Columbia's hydrogen roadmap sets targets for investment of USD 2.5 billion to USD 5.5 billion and the creation of 7 000 to 15 000 direct and indirect jobs in hydrogen-related fields by 2030. The 2030 targets for installed capacity are 1 GW to 3 GW of water electrolysis and sufficient carbon capture capacity to produce 50 thousand tonnes of hydrogen from fossil fuels with low emissions. The 2030 cost target for electrolysis hydrogen from renewable electricity in the lowest-cost areas of Colombia is 1.7 USD/kg, a level that had not been reached elsewhere in the world. On the demand side, the main potential users of low-emissions hydrogen are stated to be in the oil refining, fertiliser and transport sectors initially, and expansion into aviation, maritime uses and electricity storage thereafter. A 2030 target of 40% low-emissions hydrogen in total industrial hydrogen consumption is stated alongside a target for 2 500 to 3 500 vehicles on the road by 2030.

Achieving each of these targets would represent a major expansion of industrial investment and expertise in the country and a significant element of overall economic activity this decade.

The emergence of hydrogen as a topic of strategic importance reflected shifts in the national vision for energy and development since the start of the non-hydropower renewables programmes in 2014. In 2020, the following developments had risen up the agenda:

- Colombia had made a national commitment to reducing emissions when it ratified the Paris Agreement in 2017. This focused attention on the transport and industrial sectors, given that emissions from electricity generation were already quite low.
- Progress with solar PV and wind energy, among other measures, had eased some of the political pressure to focus on non-grid-connected electricity customers.
- Seasonal and inter-seasonal variability of hydropower was increasing for climatic reasons and penetration of solar PV and wind energy showed a future need for electricity storage technologies.
- After two decades of encouraging natural gas consumption, Colombia's proven gas reserves were not keeping pace with demand and were in decline. Between 2010 and 2020, reserves declined by 45% and at the end of 2022 the reserves to production ratio stood at 7.2 years. The government was looking for options for replacing natural gas supplies to consumers with minimal disruption and without increasing imports.
- Declining fossil fuel exports were creating a possibility of higher future energy imports, something that the government wished to avoid. Hydrogen could allow the use of Colombia's considerable fossil fuel and renewable resources in ways that would avoid the need for more fuel imports while being consistent with climate goals, and potentially support exports of hydrogen given the potential for competitive hydrogen production costs in Colombia.
- Expectations for improved technologies, lower-cost hydrogen production and significant global hydrogen demand had grown quickly around the world in the preceding few years. Colombia's expertise in oil and natural gas handling and processing gives it a potential advantage as a technology developer for hydrogen,

which requires similar skills, which could be realised if the country was one of the "first movers" in the region. This proactive stance towards hydrogen fit well with the government's pursuit of technology and innovation-driven economic growth.

However, as an area of energy technology, low-emissions hydrogen in 2020 was at a much less mature state of market readiness than solar PV and wind energy in 2014, in both technical and cost terms. A much higher contribution of R&D, demonstration and innovation spending would be required than was needed than for non-hydropower renewables. As a molecular fuel technology, the importation and installation of hydrogen equipment requires more local expertise and operational skills than solar PV and wind energy. This implied greater risks for the public budget in the near term, which was a challenge to the country's finances.

Support measures for hydrogen build on the existing framework for renewable energy

The roadmap foresees "market pull"[3] support measures for hydrogen innovation that draw from the same toolbox as applied to non-hydropower renewable electricity. In parallel to the roadmap publication, the Energy Transition Law added hydrogen produced from renewable electricity and fossil fuels with CCUS to Colombia's legal definition of Non-Conventional Energy Sources, making them eligible for the same fiscal incentives as solar PV and wind. It also extended the scope of the fund for directly financing Non-Conventional Energy Sources to include "viable projects in the [low-emissions] hydrogen value chain, regardless of the point in the chain […] prioritised according to their impact on emissions reduction […] and the creation of wealth and jobs." Such projects are projected to include 50 to 100 public access hydrogen refuelling stations by 2030.

Further "market pull" measures were introduced after the roadmap's publication. These include the Climate Action Law (2169/2021), which establishes projects for the production and storage of hydrogen from renewable electricity as having public utility and social interest; a classification that eases project development and sets certain public interest conditions. Decree 1732/2021 and CONPES document 4075/2022 enable a "regulatory sandbox" approach for the electricity grid operator to exempt certain hydrogen projects from the full range of regulatory risks to facilitate limited real-world tests. Decree 1476/2022 establishes competencies for standards, regulation and support to hydrogen in the Colombian energy system. Decree 895/2022 and Decree 2235/2023 extend the definition of Non-Conventional Energy Sources to include hydrogen extracted directly from geological sources.

[3] See Colombia, Ministry of Mines and Energy, Colombia's Hydrogen Roadmap, Chapter 1.

A central role for the country's oil and gas sector

At the same time as the publication of the hydrogen roadmap, Ecopetrol became the first oil and gas company in Latin America to announce a commitment and plan to achieve net zero CO_2 emissions by 2050. The company aims to reduce its emissions by 25% by 2030 compared with a 2019 baseline. Today, over 80% of hydrogen produced in Colombia is used in oil refining and produced from fossil fuels, making a large contribution to Ecopetrol's total emissions. With the impetus behind the roadmap including challenges in Ecopetrol's business areas – declining natural gas reserves and fossil fuel export revenues – and the roadmap's expectation that oil refining would be the first sector to use low-emissions hydrogen, Ecopetrol is strongly implicated in the roadmaps implementation. In addition, it, and other oil and gas companies in Colombia, possess much of the technical expertise needed for large-scale hydrogen projects.

In 2022, Colombia's first pilot project for hydrogen production from renewable electricity was commissioned by Ecopetrol and Promigas, following the contribution of government funds to the 50 kW electrolyser project. Hydrogen is produced and injected into the natural gas distribution grid that supplies households and industrial customers. It was designed to provide information on the operation, maintenance, reliability and scalability of the technologies used. The electrolyser was supplied by an international manufacturer. Ecopetrol also hosts Colombia's first hydrogen refuelling station, which was built by a consortium including Ecopetrol and Fanalca, a Colombian automotive component maker.

Ecopetrol plans further projects to explore hydrogen use in four applications: oil refining, road transport, blending hydrogen with natural gas for combustion and possible hydrogen-based products for domestic industry and export. It has forged cooperation agreements with six international corporate partners and developed a strategic plan that anticipates annual investments in hydrogen-related activities of close to USD 140 million to 2040.

Of the 33 known hydrogen supply projects in development or operation in Colombia by mid-2024, Ecopetrol is formally involved in 11 of them. Of the remainder, five count oil and gas companies among the consortium partners.

Inclusion of dedicated innovation support

To date, there are fewer specific interventions related to "resource push" for hydrogen technology innovation than "market pull", but those that exist are more targeted towards innovation outcomes. Decree 1476/2022 establishes the responsibility of the Ministry of Science, Technology and Innovation to "establish science, technology and innovation programmes to promote the formation of scientific, technical and technological capacities for research, technological development and innovation, related to the technologies linked to the hydrogen industry value chain", in co-ordination with the Ministry of Mines and Energy. Decree 1732/2021 provides for a regulation that facilitates the development of business models that leverage and boost the high-value economy, including support for experimentation and founding of micro, small and medium-sized enterprises.

As part of Ecopetrol's strategic plan for hydrogen, it has joined forces with the Inter-American Development Bank, the national business association ANDI, the incubator iNNpulsa Colombia, the Cartagena Chamber of Commerce, the national training centre SENA and several universities to create the first dedicated Innovation and Technology Centre in the Caribbean region. It will be located near an Ecopetrol refinery and will work on technical challenges facing energy transitions, including for the petrochemical sector and with a primary focus on hydrogen and access to an electrolyser. The centre is to be part of Colombia's network of institutions to support entrepreneurs, called C-Emprende, launched in 2019.

Initial projects related to hydrogen use in road transport have supported Colombia's Marcopolo Superpolo bus making company to develop a fuel cell bus. With public R&D and investment support, the firm is planning to move into hydrogen bus production to help fulfil the transport and innovation targets of the roadmap.

In terms of "knowledge management" for hydrogen innovation, Colombia participates in the International PtX Hub with financial support from the German government. This initiative has developed a programme of technical capacity building for government and other stakeholders in the country as well as facilitating exchanges of experiences with international partners.

In terms of "socio-political support" for innovation in hydrogen, the roadmap itself, including the consultation process that preceded it, provides a solid foundation that will need to be maintained over time.

Findings

Colombia's approaches to solar PV and wind in 2014-2020 and hydrogen energy in 2020-2024 differ markedly in their emphasis on technology innovation. In part, this reflects differences in the technologies themselves, but it also represents an evolution of the national vision of how Colombia wishes to participate in clean energy transitions to address its changing socio-economic challenges. Nonetheless, Colombia is building its clean energy ecosystem from a relatively weak basis and will need to carefully channel resources to achieve its ambitious goals.

Colombia's policy choices in relation to non-hydropower renewable electricity were shaped by the country's institutional history, especially the liberalisation of the electricity sector in the 1990s. This led it to adopt more measures to bring in the private sector – including international firms – through fiscal and financial incentives, coupled with competitive auctions. Although it has been slower to adopt solar PV and wind than some other Latin American countries, its hydropower, coal and natural gas resources made diversification of the electricity mix a less pressing concern before 2014. In addition, the lack of a strong manufacturing sector in Colombia limited the opportunity for the government to support a domestic industry for the equipment in the solar and wind value chains. As a result, renewables deployment policies in 2014-2020 addressed social issues related to non-grid connected communities but were not accompanied by major innovation programmes for long-term prosperity.

Hydrogen energy is a very different proposition. The overlap between Colombia's technical capabilities, long-term economic interests and hydrogen projects is much larger. In addition, the learnings from the implementation of renewable energy support policies provide a solid foundation for moving into hydrogen-related fields. In 2021 and 2022 the government was able to quickly establish incentive programmes for hydrogen simply by extending the existing regulations for non-hydropower renewables to include low-emissions hydrogen value chains. The flexibility with which Colombia adjusted its auction system to make it more effective in 2019 will be valuable experience for navigating the uncertain path towards the hydrogen roadmap goals. While hydrogen technologies are at a more immature stage than solar PV and wind energy in 2014, and the costs are highly uncertain for a range of other factors including electricity prices, a number of major international private companies have already been attracted to Colombia's nascent hydrogen sector.

To help the government adjust to evolving conditions, nationally and internationally, the hydrogen roadmap establishes responsibilities for overseeing implementation, including a monitoring committee comprised of ministry representatives and representatives of other organisations, both public and private. The monitoring and assessment of the hydrogen roadmap will be carried out based on a series of indicators, analysed every 3 years as a minimum frequency, and will report on progress across the various components and make recommendations for the next period. At the same time, a balance will need to be found between attentive regulation, including control of how limited resources are distributed, and a milder approach that avoids constraining an emerging sector with standards and regulatory costs too early.

Colombia has many of the ingredients to attract investment in hydrogen projects and capitalise on the related technology opportunities through R&D and innovation. It could become a regional leader in clean energy technologies, including hydrogen. These ingredients include the national commitment to reducing emissions and a well-established university system for training engineers and researchers. However, much of the energy-related engineering capacity and skills have traditionally been dedicated to fossil fuels and there is a need to diversify, not only into the related hydrogen and CCUS technologies, but also other electrification technologies in case the hydrogen roadmap is not implemented, for example if hydrogen technologies are outcompeted by other low-emissions options.

Building on the expertise and commitment of Ecopetrol, as an internationally established and well-resourced state-owned actor, appears critical to success. However, this also brings challenge of managing the transition of the oil and gas sector to new businesses related to hydrogen and CCUS if there is a prolonged period over which fossil fuel revenues decline, whether due to lower output or climate regulations (regulations that may be needed to support hydrogen at the expense of traditional business lines). In a country such as Colombia, with limited financial resources to spread across various urgent socio-economic priorities, continual attention to the alignment of stakeholders behind a common vision is likely to be essential to successful projects.

The investment needs to implement the roadmap will be large. The USD 5.5 billion of investment envisaged in the roadmap over 8 years would represent more than 5% of all the foreign direct investment in Colombia in the past 8 years. This investment in hydrogen does not include all the infrastructure that will be needed to upgrade the electricity grid and build terminals if the hydrogen is converted to fuel or fertiliser products for export. Colombia’s energy and transport infrastructure has weaknesses that could slow down project development. International partnerships will therefore be critically important to success in the hydrogen and associated non-hydrogen projects alike. However, attention should be paid to ensuring that the knowledge acquired in development of Colombian hydrogen projects remains with the Colombian project partners. Ensuring that investments and benefits are shared with the wider population to raise the national prosperity can be enshrined in such partnerships and a key principle.

6. Energy efficiency in India

Abhishek Malhotra (World Bank) and Ambuj Sagar (Indian Institute of Technology Delhi)

This chapter examines India's clean energy innovation policies and institutions, focusing on energy efficiency programmes. India's ambitious clean energy programmes, in the face of rapid economic growth and increasing energy demand, have made it a crucial case study for understanding the challenges and opportunities of clean energy transitions in emerging economies. The study explores how India has implemented energy efficiency policies and programmes, including the Standards and Labelling (S&L) programme, the Perform, Achieve and Trade (PAT) programme, and the UJALA programme, to reduce energy consumption and mitigate climate change. It analyses the factors that have influenced policy choices, including the national vision, data collection, international experiences and stakeholder engagement. It also highlights the importance of institutional innovation and the role of the Bureau of Energy Efficiency (BEE) and Energy Efficiency Services Limited (EESL) in driving energy efficiency adoption. By examining India's experiences, this case study aims to provide valuable insights for other emerging economies seeking to enhance clean energy innovation and achieve sustainable development goals.

Country context

Between 2003 and 2023 India’s annual GDP grew on average by 6% per year in real terms, which raised it from a low-income to a lower middle-income country on a per-capita GDP basis in 2008. Over this period, GDP growth was primarily driven by growth in the services sector, which comprised about 50% of India’s economy in 2023. The country has also made significant progress in bringing down the share of the population living below the poverty line, from 33% in 2009 to 13% in 2021, and reducing the share of its population living in moderate poverty (USD 3.65 per person per day) to 44%. The country managed to make this progress while keeping inequality in consumption at relatively stable levels, with a Gini index between 33 and 36 over the past 20 years.

These developments were supported by a range of macroeconomic, fiscal, tax and business environment reforms starting in 1991, when India began its transition towards a market-based economy. The country continues to implement reforms to improve the ease of doing business and attract foreign direct investment. More recent reforms include a new inflation targeting framework, energy subsidy reforms, reinstatement of fiscal deficit reduction targets, strengthening of fiscal federalism, improvements in the quality of government expenditure, efforts to improve the business environment and ease inflows of foreign direct investment, the introduction and strengthening of an insolvency and bankruptcy framework, widening access to financial services, promoting digital payment systems, and the implementation of a harmonised GST code. There is also a recent trend of increased investment in infrastructure, with federal government spending on infrastructure rising from less than Indian rupees (INR) 3 trillion (USD 44 billion) in FY2017/18 to a projected INR 11 trillion (USD 133 billion) in FY2024/25.

Despite these positive developments, India will have to overcome several challenges to sustain progress along its development pathway. The government's vision of achieving a poverty rate of 5% by FY2030/31 and middle-income status by 2047 will require inclusive and sustained high growth rates for the next three decades. The challenges include confronting demographic and structural challenges. Although India's growing working-age population holds the promise of a demographic dividend to drive this growth, the rate of growth of India's working-age population outpaced the rate of employment growth between 2000 and 2023. Thus, over this period, the share of the total working-age population in employment declined by around 2 percentage points, falling to around 60% in 2023. In 2022 agriculture and its allied sectors employed 43% of India's total population and formed the major source of livelihood for 70% of all rural households, contributing 20% of India's GDP. Creating a higher share of non-agricultural jobs therefore appears to be a prerequisite for high and sustained economic growth, yet service sector jobs, which currently drive much of India's GDP growth, require highly skilled workers and have only a limited capacity to employ India's large pool of unskilled workers. While India has promoted the development of manufacturing, its share of India's economy stagnated at around 13-18% between 1990 and 2020.

Energy sector context

India's GDP growth has been accompanied by increasing energy consumption and, concomitantly, greenhouse gas emissions. Between 2009 and 2021 India's total final energy consumption increased at 3.5% on average per year, just over half the rate of GDP growth. However, high levels of inequality and poverty mean that India's per-capita primary energy consumption remains one-third of the global average.

Historically, energy access has been one of the most important priorities for energy policy in India, with a prominent emphasis on electricity access in rural India. At the time of enactment of the Electricity Act in 2003, just 65% of India's population had access to electricity, yet by 2019 it was announced that 100% had been achieved. This can be attributed to the greater emphasis on increasing electricity access in the Electricity Act and subsequent policies, including the National Electrification Policy in 2005, the Rural Electrification Policy in 2006, and a series of schemes allocating public funds towards investment in infrastructure for electricity access, including the 2005 Rajiv Gandhi Grameen Vidyutikaran Yojana, 2014 Deendayal Upadhyaya Gram Jyoti Yojana and 2017 Pradhan Mantri Sahaj Bijli Har Ghar Yojana. In parallel, the Indian government has made efforts to improve access to fuels, specifically kerosene and liquefied petroleum gas (LPG), by providing them at subsidised rates through the public distribution system. Efforts to displace the use of traditional biomass for cooking with LPG received a boost under the 2016 Pradhan Mantri Ujjwala Yojana, which aimed to distribute 50 million LPG connections.

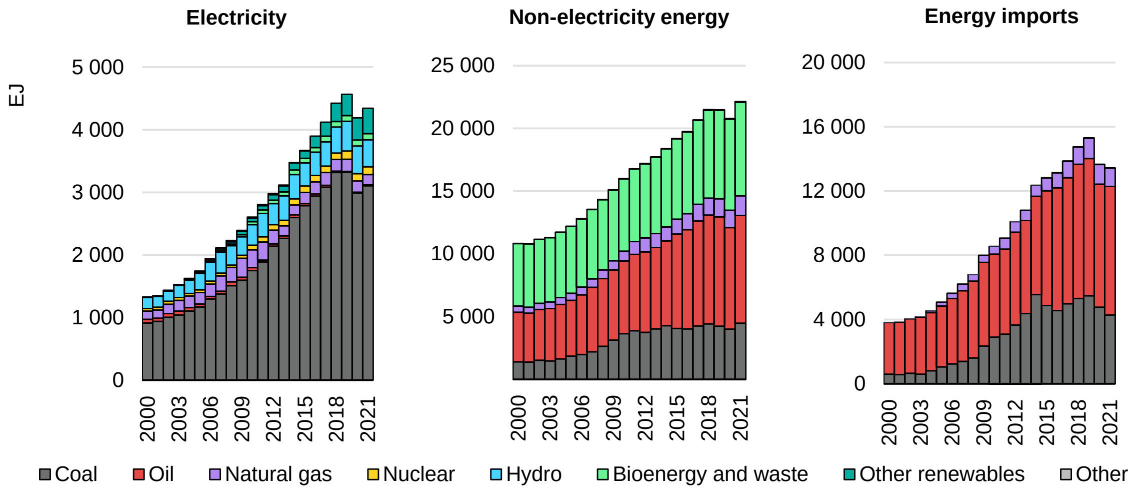
Energy security and affordability have also been major historical drivers of Indian energy policy. India's energy sector is highly regulated, with price controls for electricity, oil and gas. In the electricity sector, energy security has largely been achieved through the exploitation of India's cheap and abundant coal and hydropower resources, which together constituted 83% of power generation in FY2022/23. In addition, affordability for end users has been ensured through a combination of regulated tariffs, direct subsidies for distribution utilities, and cross-subsidies for residential and agricultural customers. Despite the high degree of energy independence in the electricity sector, India has been largely dependent on imports for oil and gas for transport, industry, heating and cooking, as well as for energy technologies. India has made efforts to enhance its energy security by supporting domestic production of fossil fuels through the Hydrocarbon Exploration and Licensing Policy (HELP) and building up a strategic petroleum reserve. Oil imports continue to be the largest use of India's foreign exchange reserves. While historically petrol and diesel in India were subsidised, subsidies have been gradually phased out since FY2014/15, partly by capitalising on the window of opportunity provided by low global oil prices. Today, the excise duty charged on petroleum is one of the largest contributors to India's indirect tax revenue, accounting for over 45% in FY2020/21.

In the last three decades, reforming the power sector has also been a major policy objective, with the goal of increasing the efficiency of electricity supply, and unlocking private sector participation and investment to meet India's growing energy needs. The 2003 Electricity Act directed India's state governments to unbundle their vertically integrated utilities and to corporatise the resulting companies. It also allowed for private sector participation in power generation and distribution and directed distribution utilities to procure power competitively. As a result, India's power generation capacity grew by 300% to 440 GW between 2002 and 2024. Private sector participation in power generation, which was below 5% in 1992, reached 25% in 2012, and 51% in 2023. In 2015, India's power generation was larger than its demand for the first time, alleviating blackouts and load shedding. However, further expansion is needed, and the government estimates that India will require around 818 GW of power generation capacity by FY2029/30, and may need to add generation capacity equal in size to that of the European Union by 2040.

India's energy sector is the largest and fastest-growing source of GHG emissions in the country, contributing 71% of its emissions in 2021, and almost all of the growth in emissions over the period 2010-2020. India's GHG emissions almost tripled from 0.98 gigatonnes CO_2 equivalent ($GtCO_2$-eq) to 2.83 $GtCO_2$-eq between 2002 and 2022, representing 7.6% of the global total, and making India the third-largest GHG emitting country in the world. Even though India's per-capita income and emissions are very low – 19% and 36% of the global averages, respectively – it still needs to decouple economic growth from carbon emissions. Thus, climate change mitigation is a further key policy priority for the energy sector, as demonstrated by India's targets for renewable energy and energy efficiency. India aims to achieve net zero emissions by 2070, 500 GW of renewable electricity generation capacity by 2030, 50% of energy from renewables by 2030, and a 45% reduction in the emissions intensity of GDP by 2030. Renewable energy and energy efficiency have been identified as key policy priorities as they can play a crucial role in not only meeting India's growing energy needs, but also reducing its dependence on fossil fuels, including for transport, mitigating their environmental impact, and creating jobs in environmentally sustainable sectors.

India has taken several measures to support the renewables sector. The Jawaharlal Nehru National Solar Mission was launched in 2009 with the ambitious target of deploying 20 GW of solar PV by 2022, achieving grid parity by 2030, and setting up 4-5 GW of solar PV manufacturing capacity by 2020. Its success in achieving cost reductions resulted in the deployment goal for 2022 being revised upwards in 2015 from 20 GW to 100 GW. 2021 saw a greater push to promote manufacturing through a production-linked incentive scheme, under which INR 18.5 billion in government support is being provided to a total manufacturing capacity of 48 337 MW. As of November 2023 India's solar electricity generating capacity was 72.31 GW, a 30-fold increase in just nine years. India has also made progress in deploying wind power, ranking fourth in terms of installed capacity globally. Overall, as a result of its efforts to promote renewables, India has made remarkable progress in the past two decades. Its installed non-fossil fuel capacity has increased by roughly 400% in the last 8.5 years and stands at 180 GW (including hydropower and nuclear), about 42% of the country's total capacity in 2023.

Figure 6.1 Energy sources for electricity and other uses, and level of imports, India, 2000-2021



Notes: Electricity and non-electricity energy are shown on a final consumption basis. Imports are shown net of exports. "Other" refers to imported or exported electricity. In 2021 India exported 0.1 EJ of electricity, and between 2010 and 2014 it was a net exporter of up to 3 EJ per year of bioenergy and waste.
Source: IEA (2024), World Energy Balances.

Innovation context

India has long emphasised the importance of science, technology and innovation, and has promoted it nationally. India developed its first science policy in 1958 – one decade after independence – called the Scientific Policy Resolution, to "foster, promote and sustain" the "cultivation of science and scientific research in all its aspects – pure, applied, and educational". In parallel, under India's second and third five-year plans (1956 to 1966), there was an emphasis on nationalising and investing in heavy industries through the public sector, and the imposition of high tariffs and strict import licensing to bring about import substitution in key sectors of the economy. It was in this period that India's public R&D and technical education institutions were strengthened, and the role of state-owned enterprises in indigenising the production of capital and consumer goods was cemented through licensing and technology transfer agreements with other countries.

Easing of the licensing regime and increased participation of the private sector in the Indian economy began in the 1980s with the relaxation of the Monopolistic and Restrictive Trade Practices Act (1969) and the announcement of the Industrial Policy Statement (1980).[1] This process was accelerated in 1991 when India started economic liberalisation. These developments in economic policy were reflected in three updates to innovation-related policy in India – the Technology

[1] It allowed for automatic expansion of licensing capacities and "broadbanding" of licences, which now allowed firms to produce other goods within the same broad industrial category.

Policy Statement in 1983, Science and Technology Policy in 2003, and Science Technology and Innovation Policy in 2013. This acknowledged the role of a broader set of stakeholders in the innovation process (including the private sector), highlighted the importance of making innovation inclusive – by improving access, availability and affordability of solutions for as much of the population as possible – and orienting it toward national sustainable development challenges, including but not limited to climate change.

However, despite policy attention to innovation, India still scores low on several key metrics, including R&D investment, research personnel and patenting activity. India's public and private spending on R&D was equivalent to only 0.64% of its GDP in 2021 and the country ranked 40th in the 2023 despite having the third-largest national economy (on a purchasing power parity basis) and the second-largest population. Not only is this spending low compared to the global average of 2%, but it is also lower than that of other major emerging economies, such as Brazil (1.3%), Russia (1.1%), and China (2.4%). Furthermore, India's R&D spending is skewed towards the public sector (36.4% is from the private sector, compared with a global average of 71%), and more patent applications are from publicly owned entities, unlike in most other developed and emerging economies. In addition, the university system plays a less prominent role, with 85% of India's public R&D spending going to public autonomous research institutes. Overall, India has a relatively weak industrial innovation system, with weak ties between R&D institutions (research labs and universities) and industry, leading to a low rate of translation of research to commercial application. India's spending on industrial R&D is concentrated in the pharmaceutical, software and automobile sectors.

Entrepreneurship is seen by policy makers as a means of generating employment, connecting academia with industry and promoting innovation. In the past three decades, policy support for entrepreneurship has expanded significantly. A growing and dynamic entrepreneurial ecosystem and venture capital sector has emerged, focusing largely on e-commerce, healthcare, financial technologies, education, travel, artificial intelligence and customer services. Today, India has the third-largest startup ecosystem in the world, with USD 141 billion in funding raised in 2023 and a total valuation of USD 450 billion.[2] There are early signs of the emergence a high-tech manufacturing start-up ecosystem, including in defence, aerospace, mobility and energy.

The case of energy efficiency policy

In the late 1990s energy efficiency in India was impeded by many obstacles typical of energy efficiency markets, including financing, awareness, technical and

[2] For comparison, start-ups in the United States raised USD 2.5 trillion and those in China raised USD 816 billion in 2023.

capacity barriers. In response, the government undertook a series of policy, regulatory and institutional steps to address these barriers. In 2001 India enacted the Energy Conversation Act, which empowered the government to:

- Enact standards and labelling for energy-consuming appliances and machinery.
- Prescribe and enforce energy conservation norms for a specified list of energy-intensive industries.
- Prescribe guidelines for building energy efficiency codes, which would then be implemented by state governments.
- Specify procedures for the training and certification of accredited energy auditors.

The act also established the Bureau of Energy Efficiency (BEE), which has helped develop policies and strategies, and exercises the powers given to it under the act since 2002.

In 2009, Energy Efficiency Services Limited (EESL) was launched as a publicly-owned "super ESCO" in 2009 to address the challenges of financing, awareness, technical capability and skills facing energy efficiency.. In 2019 BEE laid out a strategy and vision document for Unlocking National Energy Efficiency Potential and in 2022 India amended the Energy Conservation Act to expand its scale and scope.

India saved 50.81 mtoe (2.1 TJ) in FY2022/23, an amount valued at over USD 22.8 billion. The government estimates that achieving its target of net zero GHG emissions by 2070 will require an increase in the rate of improvement of the energy intensity of India's GDP of 5% per year.

Promotion of energy efficiency technologies aligned with the national vision for economic development

India does not have an explicit vision for how energy innovation can support its socio-economic goals, but expectations for energy technology innovation have been lifted by a national consensus around economic growth (including via import substitution) and climate change at different times in the past half century. However, only in the past few years have these two policy pressures coincided and reinforced one another.

Energy efficiency can help achieve cost savings while mitigating GHG emissions and reducing energy consumption. As early as 1970, the government was cognisant of the need to manage India's domestic energy resources efficiently to meet the country's increasing energy demand, and to reduce its dependence on oil imports to reduce pressure on its foreign exchange reserves. Starting in the mid-1960s, the government appointed committees and commissioned studies at regular intervals to analyse issues related to fuel substitution and energy efficiency (also referred to as energy conservation in government documents), keeping in mind targets for GDP growth, income distribution, regional economic balance and balance of payments.[3] Energy efficiency was promoted as a means to reduce the need for capital investment in energy infrastructure, meet India's growing energy demand in a more cost-efficient way, and strengthen energy security.

In 1970 the government set up the Fuel Policy Committee to project India's energy demand up to 1990/91, explore options for fuel switching away from oil, and estimate the potential for higher fuel efficiency. Its recommendations, published in 1974, were heavily influenced by the first oil shock of 1973, and included guidance on the substitution of imported oil by domestic coal, the promotion of higher energy efficiency in the electricity sector, and the promotion of indigenous R&D in energy technologies. The committee also suggested measures to systematically integrate India's energy planning into national economic development planning. This suggestion was taken up in 1980 by the Advisory Board of Energy under the Planning Commission of India, which published multiple reports on India's energy outlook and energy conservation and whose findings acted as inputs for India's five-year plans.[4]

While the passage of the Energy Conservation Act created the first legal and institutional framework for energy efficiency in India, only in the late 2000s was energy efficiency articulated as a national priority. This occurred when India published its National Action Plan on Climate Change in 2008, which declared climate change adaptation and mitigation as national priorities and was partly in response to increasing global momentum to address climate change. This plan identified eight priority "missions", including the National Mission on Enhanced Energy Efficiency, which announced four new initiatives to complement those under the Energy Conservation Act (2001). The four initiatives were:

- A market-based mechanism to incentivise energy efficiency in energy-intensive sectors.
- Measures for energy efficiency in appliances.
- Demand-side management.
- Fiscal instruments to support energy efficiency.

In 2016 this priority was reinforced in India's NDC to the Paris Agreement, which it signed in 2015. The NDC promotes energy efficiency as a priority area and includes the target of reducing the emissions intensity of GDP by 33-35% by 2030 from the 2005 level. This target was further raised to 45% in the 2022 NDC update.

[3] Examples of government-led energy modelling exercises for policy include the Energy Survey Committee (1965), the Fuel Policy Committee (1974), the Working Group on Energy Policy (1979), and the Integrated Energy Policy Committee (2006).
[4] See, for example, Ramesh, J. and J. N. Maggo (1985), "Towards a perspective on energy demand and supply in India in 2004/05", Advisory Board on Energy.

The need to intensify efforts related to tackling climate change helps explain how energy efficiency policy came to the forefront of the government's priorities. However, technology innovation was not included as a core part of this until an amendment to the Energy Conservation Act in 2022 empowered BEE to promote or undertake R&D in the field of energy conservation. The recommendations relating to R&D and indigenous technology made by the Fuel Policy Committee in 1974 were not repeated in the first national climate change policy documents, which focused more on the benefits of technology transfer to India from other countries and capacity building. For example, the National Mission on Enhanced Energy Efficiency was concerned with raising awareness of energy efficiency technologies, upgrading technical knowledge, and improving the ability of the financial sector to appraise energy efficiency investments. One reason for this was that the national vision for mitigating climate change emerged in the framework of an international negotiation that included consideration of responsibility for past emissions, an area in which India stressed its lack of responsibility to date. As a result, many poorer countries downplayed their opportunity to innovate for a new clean energy economy and instead stated that advanced economies bore more responsibility for investing in clean energy technologies as well as transferring them to developing economies, given that these economies had been primarily responsible for reducing the remaining "carbon budget", i.e. the headroom for any future emissions from all countries.

India's energy efficiency policy choices reflect the maturity of the available technologies

Decision-making for energy efficiency policy in India takes place in the context of limited public sector resources and a need to prioritise efforts. This has involved the selection of specific energy end uses – such as lighting, appliances, buildings and industry – for policy support, as well as the types of policy tools used to target them.

To identify priority sectors, India has a history of data collection and analysis, which have guided technology choices. In 1981 the government's Interministerial Working Group on Energy Conservation and the National Productivity Council audited energy use in 12 different energy-intensive industries and other sectors. The resulting report showed that investment in energy efficiency in industry, transport and agriculture could save capital and energy expenditure two and a half times the cost of the interventions. Similarly, in the early 2000s, when several energy efficiency programmes were being scaled up, the relative prioritisation of areas for support was guided by studies on energy demand, projected growth and savings potential. For example, one market study showed that lighting was the fastest-growing contributor to residential and commercial electricity demand, and that refrigerators and air conditioners consumed the most energy in India among home appliances. Accordingly, lighting, refrigerators and air conditioners were designated as early areas of focus. Since then, BEE has developed internal capacity for gathering the data to monitor and evaluate its programmes in these areas.

The choice of energy efficiency policy tools in India has been strongly influenced by technology availability. Lighting efficiency policies were enabled by the international availability of tubular and compact fluorescent lamps (CFLs), which had been shown to reduce lighting energy consumption by 80%, yielding savings worth more than the initial capital outlay. The 2008 Bachat Lamp Yojana or "Savings Lamp Scheme" therefore focused on CFLs, which were eligible under the Clean Development Mechanism of the Kyoto Protocol for the sale of emissions reduction certificates. These allowed the government to sell the more costly CFLs at the same price as cheaper incandescent bulbs. This approach changed in 2014, when light-emitting diode (LED) bulbs were shown to have greater efficiency than CFLs and were available to upgrade the streetlighting infrastructure of Puducherry and rebuild that of Visakhapatnam after a cyclone. These policies, and the nationwide Unnat Jyoti by Affordable LEDs for All (UJALA) scheme that followed them in 2015, operated via bulk procurement and distribution of LEDs. UJALA targeted the sale of 770 million LED lightbulbs in the residential sector by early 2019. This scheme was implemented by EESL, which has the ability aggregate demand, negotiate prices and deliver a uniform set of financing and other services. It also had a mandate to support and grow the private sector ESCO market.

Similarly, the emergence of inverter-based air conditioners, which are more efficient across a wider range of ambient temperature as compared to fixed-speed models, stimulated significant adaptations to air conditioner testing and certification protocols, energy efficiency standards and manufacturers' product mix. For example, the Indian Seasonal Energy Efficiency Ratio (ISEER) was defined in 2015, which defines the energy efficiency of air conditioners across a range of temperatures rather than at a single temperature. This values the better performance of inverter-based models and accelerated technological change by providing an incentive for manufacturers to adopt and manufacture the new technology, driving down its cost and resulting in the majority of air conditioner sales in 2020 being inverter-based models.

Learning from international experiences and ensuring buy-in from key stakeholders when designing policies has also contributed to the successful adoption and adaptation of energy efficiency technologies. Bilateral aid agencies (such as Germany's GIZ) and private consultancies (such as CLASP) were engaged for their technical expertise and their familiarity with experiences elsewhere and technology options. Both entities were involved in the design of BEE's Standards and Labelling (S&L) programme for energy-efficient equipment and appliances in 2006. Consultative approaches involving multiple stakeholders from government, industry and civil society were also used. The S&L programme was voluntary for an initial trial period from 2006 to 2009 to ensure buy-in from appliance manufacturers by giving them time to adapt, but today it prescribes mandatory energy consumption labels and minimum standards for 11 types of appliances as well as overseeing voluntary labels for 19 other appliances. The Perform, Achieve and Trade (PAT) programme has operated since 2010 to incentivise energy efficiency improvements in energy-intensive sectors via improvement targets and tradeable certificates, and was similarly designed to ensure buy-in from industry stakeholders. For example, extensive data collection and consultation with industry representatives and technical experts were needed to set targets that were neither too stringent nor too lax.

With UJALA, India chose to support technologies like LEDs through market pull measures, but did not only seek the lowest-cost imports: provisions were included to ensure development of a domestic supply chain. The country's familiarity with public sector-led policy implementation created an opportunity to address both market creation and technological development goals through a large-scale public procurement model. Specifically, UJALA promoted domestic manufacturing by mandating a certain share of domestic value-addition for the procured LEDs, and by procuring LEDs from domestic small-scale manufacturers. By 2018 it had contributed to the creation of around 25 medium-sized and large, and around 400 small-scale manufacturers of electronic drivers, heat sinks and bulb encasements and final assemblers of LEDs.

In 2021 market pull measures to promote the manufacturing of LEDs and air conditioners were further bolstered with manufacturing incentives in the form of Production-Linked Incentives (PLI), which, as of September 2024, had provided incentives for domestic manufacturing of these products to 66 applicants with committed investments of USD 830 million. The PLI was reopened for applications in July 2024. Over time, market pull measures have fostered an energy innovation ecosystem around energy efficiency technologies – one that can produce, adapt and tailor the technology to the local context – with only modest use of resource push measures.

Implementation and monitoring of energy efficiency policies has had to be adapted to local capacities

India's experience with implementing its chosen energy efficiency programmes and measures shows the importance of adaptation to the local context and innovation system. Despite technology innovation not being a priority outcome of the measures, the need to improve the understanding and testing of technologies for effective administration did lead to an improvement in the overall energy efficiency technology ecosystem in India.

As an example of how the adaptation of policies to local contexts can delay or hinder policy outcomes, India has had to adjust and update its measures for energy efficiency in buildings several times since the National Mission on Sustainable Habitat was announced as one of the eight missions in the 2008 National Action Plan on Climate Change. “Green buildings” are a key policy intervention area of this mission and building codes with energy conservation standards have been pursued accordingly. However, the actual implementation of building codes and standards continues to face challenges with compliance and enforcement due to the fragmented and informal nature of India’s construction sector, as well as the limited resources of regulatory authorities. This is despite successive updates to prescriptive standards for energy efficiency in residential and commercial buildings including:

- The Model Building Bye Laws (2016).
- The revised National Building Code (2016).
- The updated Energy Conservation Building Code (2017).
- The Eco-Niwas Samhita (2018).

One learning from the implementation experience has been the importance of sub-national co-operation and engagement, including raising the level of regulatory enforcement. State governments now play a supporting role by channelling funding as well as translating the standards into state-level guidelines for their construction sectors.

The most successful programmes have been PAT, S&L and UJALA. Of the estimated 50.81 mtoe (2.1 TJ) saved in FY2022/23 – an increase from 2.46 mtoe (0.1 TJ) saved in FY2012/13 – 51% has been attributed to the PAT programme, and 44% to the S&L and UJALA programmes.[5]

Energy efficiency education, skills and awareness have had to be built from a relatively low level in India since the early 2000s. In the early stages of the S&L programme, India had limited capacity for the design, manufacture and testing of energy-efficient appliances, and limited awareness among end users regarding the performance of energy-efficient appliances. Therefore, MEPS and energy performance labels had to be complemented with the creation of institutions, capacity and networks within the energy efficiency ecosystem.[6] These institutional capabilities are often already present in more mature industrial and innovation ecosystems when embarking on a new policy direction. To illustrate this issue, the S&L programme was delayed after its 2006 launch because there were no accredited test laboratories. BEE and CLASP worked closely with several international and local bodies (including national labs such as the Central Power

[5] The 2023 savings are equivalent to 8% of India’s total energy consumption.

[6] This ecosystem includes policymaking agencies, standard setting agencies, research labs, testing labs, manufacturers, energy auditors, energy service companies and other actors.

Research Institute and academic institutions like IIT Delhi and IIT Bombay) to support the development of new labs to meet the demand, and to develop accreditation procedures and standards for these labs. This enabled manufacturers to supplement their existing capabilities for in-house testing by collaborating with labs and strengthening their capabilities for more advanced testing procedures (for example, balanced ambient calorimeter labs for testing air conditioners). It also allowed BEE to conduct check testing of labelled products in accredited third-party laboratories, thus enabling monitoring and enforcement of the programme. A consequence of this capacity building has been the generation of technical expertise on energy efficiency technologies in Indian government and academic institutions, which provides a platform for future innovation.

Experiences with implementing energy efficiency policies in India have helped inform subsequent policy designs for energy efficiency and other areas. The design, measurement and verification elements of the PAT tradeable certificates programme have informed India's forthcoming Carbon Credit Trading Scheme. EESL has adapted and replicated the LED programme for other energy-efficient technologies such as brushless fans, air conditioners and electric buses. Among the learnings from these programmes has been the importance of continuous assessment and enforcement, as well as flexibility and responsiveness to evolving technological and market contexts. For the PAT programme, BEE created "accredited energy auditors" that could be engaged by Designated Consumers to carry out the necessary energy audits, establish a baseline for their energy intensity and periodically measure progress towards their targets. Once the auditors were trained and certified, the data they collected were critical for the effective issuance and trading of certificates, as well as for setting targets in subsequent phases of the programme. In addition, as the PAT programme covered highly heterogeneous sectors, it became necessary to adopt "performance buckets" to enable equal treatment of similar firms. For EESL, a key learning relates to the value of a payment security mechanism to mitigate the risk on non-recovery of capital, something that affected the finances of its street lighting programme for which the customers were municipalities. For EESL's recent electric bus programme for state transport utilities, such a security mechanism is included. [7]

Findings

India's experience with energy efficiency policymaking provides several insights for the development of policy on energy technology innovation. While the policy framework was not explicitly targeted towards technology innovation outcomes, it

[7] One part of the payment security mechanism is an escrow account that provides payment security for 3 months. If payments are not provided by state transport utilities beyond this period, the government of India can put tax-related payments to the state on hold.

nonetheless highlights aspects of policy design that are important in emerging market economies. In particular, the insights highlight the need for such support to be relevant and tailored to the local context. The insights can be summarised as follows:

- Policymaking and implementation are effective when well aligned with national visions for technology change and when technology areas are strategically identified. In India, energy efficiency fitted well with the national vision for ambitious climate mitigation at a time when household appliances, in particular, were a national concern for their contribution to rapidly rising energy demand, exacerbating financial strain on the national electricity system.
- In nascent policy areas, early successes are important for political buy-in as well as public support. In this context, the selection of appliances and lighting among the main policy targets enabled more visible and rapid results than, for example, building codes or industrial processes.
- In emerging market and developing economies there is sometimes a trade-off between promoting rapid deployment of a new technology and domestic economic development aspirations, including development of domestic industrial capabilities and employment opportunities. This is especially true for clean energy technologies for which the country has only weak R&D and manufacturing capabilities at the outset of the policy development process. For LEDs, India chose not to include very strict requirements for domestic manufacturing or R&D. Instead, it benefited from the low price of LEDs from other countries, which allowed the rapid scale-up of the programme at lowest cost and secured wide support from EESL's customers. However, it has been suggested that this impeded the development of local technological capabilities in this space, something that was indirectly supported by the need to develop effective testing facilities and manufacturing for certain LED components and assembly.
- When dealing with end users, feedback on technologies is typically slow and for energy efficiency technologies it is even slower. Given the wide range of users and the challenges of monitoring their use of the technologies, it can take time to understand if and how the technologies need to be adapted to local markets. Specifications for both LEDs and industrial efficiency equipment needed to be adjusted once the behaviour and criteria of local users was better understood. Additionally, the energy savings from the deployment of these technologies accumulate over time, which means that their performance is often only understood several years after the upfront investment. Unless the end user makes regular use of the installed equipment as expected, something that depends on well-designed business models by suppliers like EESL, performance may never be fully understood. Attention to financial and business elements of a new technology deployment programme, as well as the broader social and economic contexts, are therefore essential elements of well-designed clean energy innovation policies in addition to more traditional elements such as R&D projects and risk finance.

- Adaption of technologies for use in a new local context requires appropriate technological capabilities. These are generally not R&D skills, but are more closely related to the technical skills of procurement managers, installers, retailers and programme auditors.
- Consultation is essential, and by engaging a range of institutions in policy design it is possible to make use of existing skills and knowledge. In the case of the appliance programme, consultation helped bring the industry on board and ensure that there was a latent market for energy-efficient appliances. In India, BEE has played a critical role as a "systems integrator" and helped organise an energy efficiency innovation ecosystem by marshalling the relevant actors. It has facilitated the engagement of academic and other research institutions, financial entities such as banks or donor institutions, and other actors that might provide technical support or market knowledge. This type of role may be particularly important for developing countries where the ecosystems are fragmented or suffer from significant gaps.
- New institutions may be needed to take responsibility for certain activities, especially if they require policy creativity or could conflict with the primary objectives of existing ministries or state-owned enterprises. Both BEE and EESL were created to support India's energy efficiency policies. The establishment of EESL, in particular, was critical for its ability to aggregate LED demand and use new financial approaches. This finding is not necessarily specific to developing countries – the establishment of ARPA-E as a new government entity in 2009 significantly changed the momentum behind clean energy innovation in the United States and illustrates that even well-functioning innovation ecosystems can benefit from new institutions with the flexibility to find alternate approaches to arising challenges.

7. Energy and industrial transitions in Kazakhstan

Aliya Sembayeva (SDSN Kazakhstan, Nazarbayev University), Stella Tsani (Department of Economics, National and Kapodistrian University of Athens), Serik Orazagaliyev (SDSN Kazakhstan and Graduate School of Public Policy, Nazarbayev University) and Stefanos Xenarios (SDSN Kazakhstan and Graduate School of Public Policy, Nazarbayev University and CSIRO Environment, Australia)

Kazakhstan is a hydrocarbon-rich country with large mineral endowments and a unique geopolitical position in the Eurasia region. The country has made a solid commitment to accomplish the national targets in the Paris Agreement and reduce GHG emissions by 15% in 2030 compared to 1990 levels, with a conditional goal to reduce emissions by 25% and achieve carbon neutrality by 2060. The national sovereign fund (Samruk-Kazyna), which owns industrial and commercial firms accounting for about 40% of national GDP, has initiated several energy innovation initiatives to curb emissions and stimulate economic development in its portfolio, contributing to national carbon reduction efforts. This chapter highlights the unique position of Samruk-Kazyna in Kazakhstan to channel capital towards long-term socioeconomic and environmental objectives in a manner that may not be feasible for private investors in similar emerging market economies. Unlike private investors who face pressure to prioritise short-term returns, the long-term value of Samruk-Kazyna's portfolio is intricately tied to climate change and its enduring effects. This linkage presents an opportunity to integrate climate risk into the core of its corporate strategy while also providing an economic foundation for the nation.

Country context

Kazakhstan is the ninth-largest country in the world by land area, spanning 2.7 million square kilometres of steppe and mountainous landscape. It borders China, Kyrgyzstan, Russia, Turkmenistan and Uzbekistan. With a population of 20 million, it is the second most populous country in Central Asia after Uzbekistan. Along with the other Central Asian countries, Kazakhstan gained independence from the Soviet Union in 1991. Since independence, the country has reoriented towards becoming a market economy. Its GDP has grown steadily at 5% per year on average between 1995 and 2022, reaching a per-capita GDP of around USD 11 500.

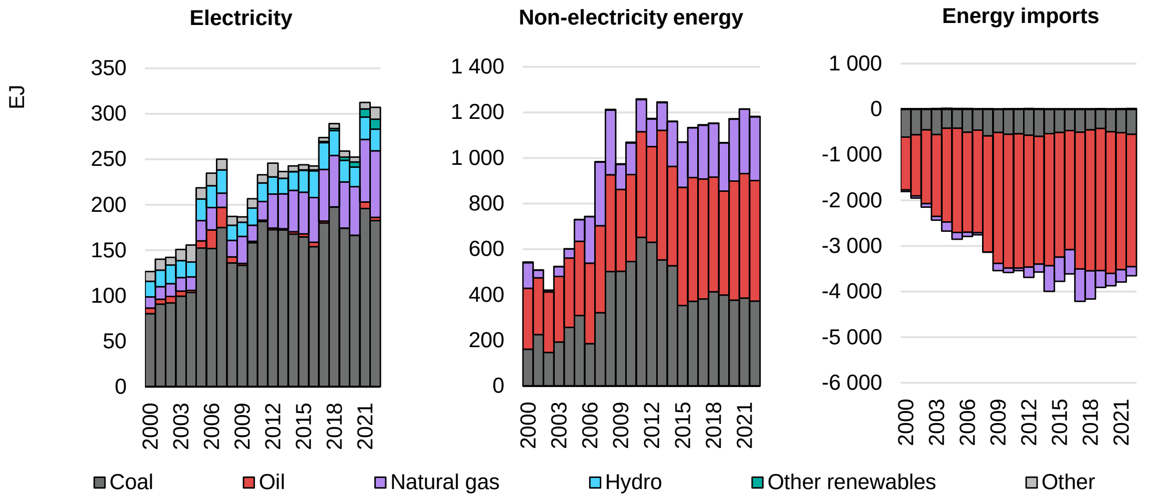
In 2012 the government adopted the Kazakhstan-2050 strategy, prioritising investment and the country's economic outlook. The strategy aims to make Kazakhstan one of the top 30 most developed countries by 2050. To date, growth has been led by extractive industries, including the oil, natural gas and mining sectors, which have enabled it to have a net trade surplus since 1998. Oil and natural gas revenues represent 17% of GDP and mining also represents 17%. However, the outlook for Kazakhstan's oil sector is clouded by uncertainty over whether the Caspian Pipeline Consortium, which carries about 80% of Kazakhstan's oil exports, will continue to be able to transport oil through Russia. Since 2021 inflation has exacerbated economic fragility, reducing export demand, real incomes and foreign direct investment (FDI), thereby weakening the national currency. In response, the government has taken measures to raise FDI and grow the contribution of agriculture, manufacturing and tourism to the economy. These measures include establishing Special Economic Zones (SEZs) across various regions, each equipped with the necessary infrastructure and a special legal regime. Participants in the SEZs benefit from a specific legal framework, entailing exemptions from tax obligations such as corporate profit tax, property tax, social tax, land tax and VAT on goods sold within the SEZ territory. In the global ease of doing business ranking, Kazakhstan ranked 25th out of 190 countries in 2022.

Despite consistent economic growth, there remains an income inequality gap – Kazakhstan's Gini index has been rising since achieving a low of 27 in 2015 and now stands at 29, still much lower than the level of 36 in 2001. Poverty rates have fallen from 35% in 2006 to 9% in 2017. The unemployment rate has also dropped, from 13% in 2000 to 5% in 2020.

Energy sector context

Kazakhstan is one of the world's biggest fossil fuel producers, extracting roughly 2% of global oil supplies, 1% of global natural gas supplies and 1% of global coal supplies each year. Domestic energy supplies are dominated by fossil fuels, which meet 98% of final energy needs (38% from coal, 36% from oil and 24% from natural gas). Electricity generation in Kazakhstan is 65% from coal, 26% from natural gas and 8% from hydropower. Other renewable electricity sources make up just 3% of the total. Electricity demand has risen broadly in line with economic growth (in purchasing power parity terms) over the decade to 2022, a change in pace compared with the period from 1995 to 2015 when GDP grew four times faster than electricity demand. Some of this growth has been attributed to the emergence of cryptocurrency mining as an economic activity in Kazakhstan, and there are extensive opportunities to improve energy efficiency. Kazakhstan is a net exporter of electricity, but to balance total power supply and demand it has net imports from Russia, which are expected to rise in the near term.

Figure 7.1 Kazakhstan's energy sources for electricity and other uses, and level of imports, 2000-2021



Notes: Electricity and non-electricity energy are shown on a final consumption basis. Imports are shown net of exports. "Other" refers to imported or exported electricity.
Source: IEA (2024), World Energy Balances.

The Ministry of Energy is the primary government department responsible for implementing energy policies and supervising and regulating Kazakhstan's energy production and distribution companies.

While electricity transmission and distribution are undertaken by Kazakhstan Electricity Grid Operating Company (KEGOC), a regulated state-owned entity, a competitive market exists for wholesale power supply and most generators are privately owned. Overall, four large companies produce 62% of electricity, with many plants continuing to operate beyond their original design life. The average age of coal-fired power plants in Kazakhstan is 55 years, and that of gas-fired power plants is 40 years, while hydroelectric power plants have an average age of 56 years. The age of the power and heat networks contributes to the high losses that can reach 35% of the energy input. Cost recovery for operating power plants and networks is made more challenging by subsidised consumer tariffs as part of the countries' social policy to ensure affordable energy for all segments of society.

The potential for renewable energy in Kazakhstan is high, but the current share of renewable energy in the total energy mix varies between 1 and 2%. A range of efforts have been made to increase the share of renewable energy and reduce the reliance on coal, starting in 2009 with the Law on Support for the Use of Renewable Energy. In line with these efforts, the Development Concept for the Electric Power Industry of the Republic of Kazakhstan for 2023-2029 outlines a set of target indicators, including the aim to achieve a 12.5% share of electricity from renewable sources by 2029. The Ministry of Energy has also formulated plans for holding auction trades from 2024 to 2027, with the intention to auction up to 6 720 MW of renewable energy projects by 2027.

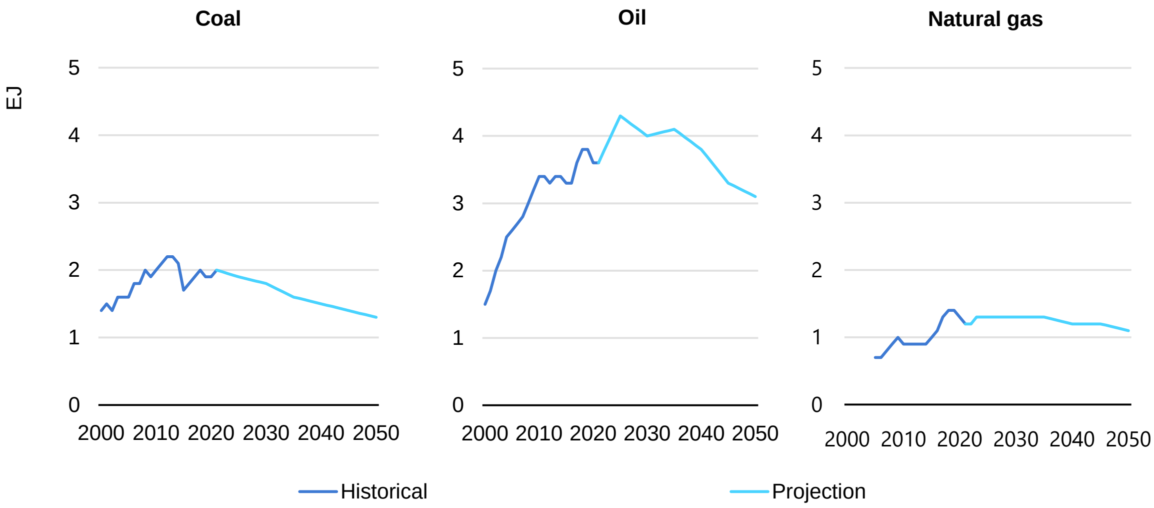
In 2012, as part of the Kazakhstan-2050 strategy, a target was articulated for 50% of total energy consumption to be from alternative and renewable energy sources by 2050. In 2013 a Concept of Transition to a Green Economy was published, and priorities for more efficient use of natural resources were outlined, including modernising energy infrastructure and increasing the use of renewable energy. This policy gave more responsibilities to the Ministry of Ecology and Natural Resources under its accountability for green economy matters, including regulations on emissions, pollution, waste management and environmental impact assessments. For renewable energy, KEGOC is responsible for designing, constructing and operating transmission infrastructure, and collaborates with the Ministry of Energy to identify potential sites for renewable energy projects.

In 2014 two further strategic plans raised ambitions for cleaner energy sources and further diversified ministerial responsibilities in this area. The State Programme of Industrial and Innovative Development for 2015-2019, under the supervision of the Ministry of Industry and Infrastructure Development, set an agenda to enhance energy security, improve environmental security, modernise energy-related infrastructure, adopt novel energy-efficient technologies and reduce energy intensity. The Fuel and Energy Sector until 2030 Concept, overseen by the Ministry of Energy, separately covered a similar agenda. In parallel, the Ministry of National Economy, the Ministry of Investment and Development, the National Bank of Kazakhstan and the Development Bank of Kazakhstan developed the Nurly Zhol programme for the period 2015-2019 to boost trade and encourage economic and trade corridors, including energy

Through a partnership with the United Nations Development Programme (UNDP), financial incentives have been introduced to support environmentally friendly projects in Kazakhstan, and provide technical assistance and capacity building. These mechanisms have been developed in co-operation with partners such as the Astana International Financial Centre Green Finance Centre – a Belt and Road Initiative institution chaired by the President of Kazakhstan – to promote a market for green bonds. To date, progress towards the renewable energy goals has been promising, with the supply of non-hydro renewables growing by 34% per year on average between 2014 and 2021. Chinese investment in Kazakh energy projects has shifted towards renewables from fossil fuels. The cost of solar energy in Kazakhstan was 55% lower in 2020 than in 2014, and the cost of wind energy fell by 14% over the same period. However, renewables only grew from 0.1% of final energy consumption to 0.7% between 2014 and 2020 and are hindered by the influence of hydrocarbon interests in the decision-making process and faltering capital availability due to lower exports and economic growth since 2019.

Spurred by the Russia-Ukraine war, which has highlighted the vulnerabilities of dependence on Russia for access to export markets for fuel, and by Kazakhstan's ratification of the Paris Agreement on climate change, the country's energy planning now focuses on reducing economic reliance on oil and domestic consumption of coal. Policy statements endorse solar, wind and hydropower initiatives and consider nuclear power in the energy mix. Under its climate commitments, Kazakhstan aims to cut all greenhouse gas emissions by 15% by 2030 compared to 1990 levels and reach carbon neutrality by 2060. The government's stated intention is to halve the share of coal in the electricity mix by 2050 (Figure 7.2).

Figure 7.2 Kazakhstan's annual coal and gas production since 2000, with projection to 2050 based on official government indicators



IEA and IITD. CC BY 4.0.

Source: SEI et al. (2023), The Production Gap: Phasing down or phasing up? Top fossil fuel producers plan even more extraction despite climate promises as modified by the IEA.

In general, Kazakhstan aims to align as much as possible with the environmental law of the European Union, where much of its exports are shipped. An example of this is the 2021 Environmental Code, which tightens the regulations for large industrial installations. The Environmental Code shares implementation responsibilities among the Ministry of Ecology and Natural Resources and regional and local government authorities.

Innovation context

Kazakhstan's economy is based mainly on exports of raw materials rather than innovative and high added-value products. The country's innovation and technological development are characterised by:

- A low share of high-tech product exports in the total volume of manufacturing industry exports, amounting to just 6.9% (2021).
- Expenditure on technological innovation amounting to 0.51% (2021).
- A relatively low proportion of registered enterprises in the manufacturing sector that report in surveys that they are engaged in some kind of innovation activity, at 12.9%. (2021).
- A low share of innovative products in GDP at 1.7%. (2021).

These indicators highlight the ongoing challenges in transitioning towards a more innovation-driven economy.

Overall, just 0.1% of GDP is allocated to R&D, in contrast to countries with development aspirations – for instance, average spending on R&D in the OECD countries stood at 2.7% of GDP for the year 2022. It is worth noting that the highest intensity of R&D activity is observed in Japan, Sweden, Austria and Germany, where the corresponding indicators have surpassed 3% of GDP. Kazakhstan also does not demonstrate a high rate of patents, probably due to low R&D expenditure.

The state is the primary investor in scientific research, accounting for 58% of R&D expenditure in Kazakhstan, compared to 33% coming from the private sector. In the past, this reliance on public funds has been enshrined in laws such as that On Commercialisation of Scientific and Technical Activity Results. It is notable that the balance of public and private R&D expenditure is not significantly different in other developed countries. In the case of Australia, for instance, a sparsely populated country with mineral-rich deposits like Kazakhstan, public R&D expenditure stands at 72% of the total and the private sector at 28%. However, Australia devotes the equivalent to 1.8% of its GDP to R&D, which is distinctly higher than Kazakhstan's allocation.

To further encourage private sector investment in R&D and increase collaboration between the public and private sectors, legislation was passed in 2017 that obliges companies in the extractive industries to allocate 1% of their total annual income to R&D. However, despite changes in 2020 to improve accountability and transparency, this obligation has yet to deliver its stated aims of fostering organisational change, technological efficiencies, and increased integration of digital solutions into processes.

The government published a resolution in 2018 entitled Concept of Industrial-Innovative Development of the Republic of Kazakhstan for 2021-2025, which contains targets for the value-added and productivity of the manufacturing sector by 2025. However, the document dropped the target stated in its predecessor of increasing R&D spending from 0.2% of GDP in 2013 to 2% in 2020, and also discontinued a target related to the share of innovative projects and initiatives among all contracts.

It is recognised that additional measures will be required to improve co-ordination among research actors in Kazakhstan and increase the rate of success in translating R&D into scaled-up production. In 2024 the Ministry of Science and Higher Education introduced a new law that seeks to address a range of barriers to a more innovative business culture in Kazakhstan, including the introduction of financial tools, improvements to social conditions for scientists and other non-financial measures. It remains to be seen whether this can help develop more knowledge-intensive firms, improve the availability of human capital for R&D and increase the sharing of information among experts, investors and innovators.

The case of Kazakhstan's sovereign wealth fund

Creation of Samruk-Kazyna as a central co-ordinator of economic reform

As a post-Soviet economy, Kazakhstan's institutions have a history of central planning and the close involvement of government in strategic and investment decisions, despite liberalisation measures in recent decades. Shifting to a more dynamic economy has proven challenging for Kazakhstan when such a large share of national wealth is concentrated in a small number of sectors and businesses related to resource extraction. Such concentration tends to create political dependencies in these industries, makes it harder for new entrants to grow market share and exposes the country to fluctuations in commodity prices and geopolitical uncertainty.

To address these challenges, the government devised two typically centralised responses. One was a fund managed by the central bank and accountable to the country's president to manage revenues from natural resources and protect the economy from commodity price cycles. The other was a state-owned holding company to maximise the long-term value and competitiveness of all state-owned enterprises in the global market.

The National Fund of the Republic of Kazakhstan (NFRK) was created by presidential decree in 2000 at a time when the high oil price environment created sufficient political support for the idea. It was initially funded by the returns of 11 hydrocarbon companies and three metal and mineral mining companies, later reduced to six hydrocarbon companies by removing the mining sector. The NFRK was first capitalised by selling the government's share in the TengizChevroil consortium, which operates one of the world's largest oil fields.

The Samruk-Kazyna Sovereign Welfare Fund holding company was created in 2008 from the merger of Samruk (an institution that had been tasked with preparing state-owned assets for privatisation) and Kazyna (a national fund focused on long-term investments). Initially, Samruk-Kazyna's portfolio included five companies that held monopolies in sectors including the railways, natural gas, electricity distribution, postal services and telecommunications. Since then, 17 more companies from the energy and transport sectors have been added, and Samruk-Kazyna's total assets account for about 40% of the country's GDP (Table 7.1).

Table 7.1. Selected Kazakh state-owned enterprises controlled by Samruk-Kazyna

Company	State ownership share	Business area
Kazakhstan Temir Zholy	100	National railway company
KazPost	100	National postal company
KEGOC	100	Kazakhstan electricity grid operating company, subject to natural monopoly regulation
QazaqGas	100	National gas company
Samruk-Energy	100	Largest electricity producer in Kazakhstan, which owns the world's largest coal mine and largest CHP plants
Samruk-Kazyna Ondeu	100	Chemical investment company
Tau-Ken Samruk	100	National mining company
KazMunaygas	90	Largest oil and gas company in Kazakhstan
KazAtomProm	75	The world's largest uranium extractor
KazakhTelecom	52	National telecom company
AirAstana	51	The national airline, the largest in Kazakhstan and Central Asia

Source: Samruk-Kazyna (2021), Portfolio companies.

Samruk-Kazyna has a mandate to develop its subsidiaries and direct investments in line with a long-term national strategy and maintain the national economy in the short term. The portfolio companies have a responsibility to generate revenue, maintain infrastructure and support employment in their sectors while remaining aligned with the overall government vision. As a sovereign wealth fund, it can participate in networks, including the International Forum of Sovereign Wealth Funds and the Extractive Industries Transparency Initiative.

Responses to a changing national vision for the energy sector

Kazakhstan's dual target to reduce economic reliance on oil exports via Russia and achieve carbon neutrality by 2060 has significantly changed the national energy policy vision. These government objectives emerged into a policy-making environment shaped by the co-ordinating presence of Samruk-Kazyna. In this regard, Samruk-Kazyna faces internal tensions. Its revenues, and those of NFRK, are heavily dependent on hydrocarbons – its firms are collectively responsible for around 13% of Kazakhstan's total CO_2 emissions (of which Samruk-Energy is responsible for 70%) – and yet it also possesses unique capacities to implement the necessary technological changes in the country. Given the range of different ministerial actors and responsibilities present in the area of energy sector modernisation, the unifying role of Samruk-Kazyna is a potential strength for co-ordinated decision-making.

To align with Kazakhstan's signing of the Paris Agreement, Samruk-Kazyna adopted a Low-Carbon Development Concept and began disclosing its companies' direct and indirect CO_2 emissions (Box 7.1). The companies in the funds' portfolio aim to achieve carbon neutrality by 2060, with a 10% reduction in carbon emissions expected by 2032. These measures affected firms representing 40% of Kazakhstan's GDP in one step.

Box 7.1 Low-Carbon Development Concept of Samruk-Kazyna

Published in 2021, Samruk-Kazyna's Low-Carbon Development Concept for energy transitions explores two scenarios and compares them with a business-as-usual baseline. The two scenarios have different levels of emission reductions by 2032, on the way to the 2060 goal. The 50 activities identified in the document have an estimated implementation cost of USD 20-25 billion. For the R&D projects, the costs can be covered by the existing regulation requiring 1% of extractive industries' revenues to be spent on R&D.

Five of the six proposed R&D projects relate to hydrocarbon technologies:

- Coal enrichment and gasification (to be executed by Samruk-Energy).
- Analysis of the possibility of implementing carbon capture, utilisation and storage (CCUS) technologies (the potential for carbon storage tanks) (Samruk-Kazyna).
- Investigation of the possibility of using enhanced rock weathering technology to absorb carbon dioxide (Samruk-Kazyna).
- CCUS pilot project according to the assessment of the potential for CO_2 injection to increase oil recovery from developed oil reservoirs (KazMunayGas).

- Investigation of the possibility of implementing the project "Biofuels, including sustainable aviation fuel" (Air Astana).

The non-hydrocarbon-related project is a 5 MW and 20 MWh stationary electricity storage pilot.

The document also publishes the CO_2 emissions trends for Samruk-Kazyna and its companies. This aligns with the government's 2021 policy of tightening the existing national emissions trading system (ETS), taxing more of the emissions from processes, goods and services not covered by the ETS and improving monitoring and verification. It is noted that since its establishment in 2013 the ETS has faced some challenges in accounting for production growth and posing risks to the quota market. There are, however, plans to enhance the monitoring and assessment methods for greater effectiveness by also enlarging the number and type of emitters included in the ETS in the coming years. The investment considerations in the document align with the government's intention to create a "taxonomy" of allowable investments consistent with the 2060 goal.

A central pillar of Samruk-Kazyna's strategy for contributing to the government's goals is nuclear power. Kazakhstan has large uranium reserves and plans exist for a 2 800 MW nuclear power plant to be developed by Samruk-Kazyna's nuclear subsidiary, KazAtomProm, in collaboration with international partners such as China National Nuclear Corporation, Korea Hydro & Nuclear Power, ROSATOM and Electricité de France. This would be the country's first commercial nuclear plant since its only Soviet-era power station closed in 1999. Samruk-Kazyna has stated that it considers nuclear to be the lowest-cost means of meeting climate, energy security and social goals and it created a new project company – Kazakhstan Nuclear Power Plants Ltd – to co-ordinate development of multiple nuclear power plants. The affordability of energy for the Kazakh population, reflecting the widespread use of district heating derived from the country's coal power plants, is an especially important consideration in national energy policy.

In the area of renewable energy, Samruk-Kazyna subsidiaries own three wind power plants and plan to expand them further. The Ministry of Energy, together with Samruk-Kazyna and its subsidiary KazMunayGas, signed an agreement for a 1 GW wind farm with French energy company TotalEnergies in 2023. KazMunayGas has also signed an agreement with the Italian energy company ENI to explore joint renewable energy projects to help meet the firm's goal of 300 MW of renewable capacity by 2031. Another Samruk-Kazyna company, Kazakhtelecom, is assessing renewable and other low-emissions options for supplying power to data centres. Samruk-Kazyna's strategic planning indicates that it will also explore a geothermal energy pilot project.

Samruk-Kazyna has also begun considering technologies requiring more innovation and market reform before investment can proceed. Among these are smart grids, CCUS, and hydrogen for use in power generation and vehicles. Samruk-Kazyna companies already produce hydrogen from steam-reforming natural gas, and are now exploring methane pyrolysis as a technology that can replace steam reforming without associated CO_2 emissions. However, at present, methane pyrolysis remains in development, with one operational demonstration project in the United States and several pilot plants in development around the world to test a range of competing technological options. Samruk-Kazyna is also considering the use of CCUS to avoid emissions from steam reforming.

Samruk-Kazyna's Low-carbon Development Concept also foresees the continued development of fossil fuels in the period to 2032, something that is not consistent with climate goals. Kazakhstan's coal industry has around 40 000 employees, of which more than 12 000 belong to Samruk-Kazyna companies. Coal transport accounts for 16% of the total domestic freight turnover of the railway industry. Many towns in Kazakhstan are dependent on Samruk-Kazyna coal activities, and concerns about the cost of energy transitions are high following unrest that accompanied higher liquefied petroleum gas (LPG) prices in 2022. In line with the vision for the energy sector prior to the Low-Carbon Development Concept, Samruk-Energy is rehabilitating four coal plants as a means of reducing reliance on electricity imports and does not intend to reverse subsidised electricity tariffs. Also, the company is converting a coal-fired power plant to operate on natural gas and foresees a key role for natural gas-fired power to substitute coal.

Broad plans have been made to implement the Samruk-Energy Green Transformation, under which restructuring of conventional power plants will be conducted and investment will increase the share of renewable electricity supply capacity to 10% by 2025. In support of this initiative and the broader need to increase renewable power in the country, Kazakhstan established a competitive auction system in 2018 to allocate long-term offtake contracts to private sector renewable electricity projects. For the 14 projects totalling 440 MW that were awarded contracts in the 2022 auction, the prices were 50% lower than in prior auctions, something that has been attributed in part to improvements to regulatory framework, infrastructure, and international financial support from the United Nations Development Programme (UNDP) and European Bank for Reconstruction and Development (EBRD). At USD 0.033 per kWh, the awarded tariff is significantly lower than residential and commercial consumer prices, which are USD 0.045 per kWh and USD 0.049 per kWh. Still, this has not yet impacted the profitability of fossil fuel plants, and greater effort is needed to encourage Samruk-Energy and the companies in its portfolio to expand their renewable energy activities.

Policy choices to address energy innovation priorities

Clean energy technology development features among the objectives of Samruk-Kazyna's strategic plan and the government's Concept of Scientific Development 2022-2026. The strategic plan's scenarios emphasise the importance of technologies such as electric (and natural gas-fuelled) vehicles, electric trains and sustainable aviation fuels for reducing emissions more quickly.

To build the capacity for selecting, testing and improving these technologies, Samruk-Kazyna has taken a lead in co-ordinating projects through its companies. These projects have elements of funding (resource push), capacity building (knowledge management), partnerships with international entities (knowledge management) and involvement of potential customers at large firms (market pull).

Resource push

Under pressure to modernise and transform its subsidiaries in line with energy transitions, Samruk-Kazyna has significantly reformed its R&D spending strategy since 2021. The reforms include:

- A new structural unit to co-ordinate R&D and improve the sustainability and self-sufficiency of funding.
- Greater transparency of procurement processes used to fund R&D projects, including opening tenders to public bids rather than allocating contracts directly to Samruk-Kazyna companies such as KMG Engineering and the Institute of High Technologies.
- Audits of the funding processes and evaluation of the scientific excellence.
- A first internal corporate R&D planning document with technical and practical instructions on scientific projects, their classification, the decision-making process and other relevant guidelines.
- A new portfolio company focusing on R&D and commercialisation of intellectual property, starting with projects in the areas of CCUS, hydropower and underground coal gasification.

A spur for these reforms was a government decision in 2021 to strip companies in the extractive industries – including the Samruk-Kazyna companies KazAtomProm, KazMunayGas, Samruk-Energy and Qazaq Gas – of their responsibility to choose how to spend the 1% of their revenues that they been obliged since 2017 to spend on R&D. The lack of impactful results of this regulation led the government to allocate the 1% directly to the state budget for allocation to projects by the Ministry of Energy and the Ministry of Industry.

Socio-political support

Various measures have been taken to increase support for clean energy technologies in Kazakh society. At the highest level of government, President Tokayev has publicly recognised the challenges of climate change and air pollution and made commitments to carbon neutrality. In a meeting with foreign investors, he has emphasised the priority of improving the investment situation for non-extractive and environmentally friendly sectors. The Expo 2017 international exhibition in Astana had a central theme of "Future Energy" and hosted leaders in clean energy and sustainable development, along with various educational and awareness-raising activities.

Samruk-Kazyna energy innovation initiatives

Samruk-Kazyna's initiatives relating to clean energy R&D and innovation have so far focused on individual large-scale projects, most of which build on the existing expertise of its holding companies in hydrocarbon extraction and processing. They include:

- Underground coal gasification for hydrogen production. Samruk-Energy is funding and operating an R&D project to see if hydrogen can be competitively produced from coal that is hard to mine without extracting the coal from the subsurface. While it has not yet entered a construction phase, it is an ambitious step for Samruk-Energy as the technology has not yet operated at scale anywhere in the world with separation and storage of the resulting CO_2 generated by the gasification process.
- A vapour capture system to reduce methane flaring at a natural gas facility. KazMunayGas has launched a pilot project to measure methane and other combustible pollutants at its natural gas sites with a view to developing a system for capturing and selling or using them if possible.
- CCUS and CO_2 storage. KazMunayGas has partnered with Shell Kazakhstan to co-operate on CCUS R&D and a possible joint implementation project. This includes assessing two potential CO_2 storage reservoirs, which are estimated to be able to store over 40 million tonnes of CO_2, but are so far undeveloped. KazMunayGas has also initiated a project on technology to store CO_2 while increasing the output of mature oil fields. These efforts are complemented by grants made available by the Ministry of Science and Higher Education in 2023 for geological studies on CO_2 storage and scientific work on CO_2 absorbents for CCUS.
- Natural gas-fuelled vehicles. KazMunayGas and Kazakhtelecom have been replacing their fleet with vehicles that run on natural gas, including compressed natural gas. Kazakhtelecom plans to convert 30% of its fleet to natural gas by the end of 2024.

- Electric and natural gas trains. Kazakhstan Temir Zholy, the national railway company, plans to pilot battery-powered shunting locomotives and liquefied natural gas (LNG) powered locomotives. Several tens of battery-power locomotives are in testing or construction around the world, and a handful of LNG locomotives already operate in the United States and Europe.
- Sustainable aviation fuel. Air Astana is not yet engaging in R&D projects in this technology area, but it has begun studies to learn more about the options.
- Smart electricity grid technologies. KEGOC has initiated a smart grid project that will assess international experience with digital technologies for power grids, develop a roadmap for their adoption and educate government officials and other stakeholders.

Findings

It is too early to know whether Samruk-Kazyna's strategy of co-ordinating R&D and developing clean energy technologies that can contribute to future economic growth will bear fruit. However, the ambitious clean energy technology projects under development would probably not exist today if it were not for two key factors:

- The rapidly changing national vision for energy after the signing of the Paris Agreement and commitment to the 2060 carbon neutrality target.
- The ability of a centralised institution like Samruk-Kazyna to formulate a strategic response that aligns closely with this vision and co-ordinates corporate actions in an economy dominated by powerful state-owned enterprises, many of which have significant vested interests in fossil fuels.

By grouping the activities of its state-owned enterprises under a mandate to manage the revenues of its raw materials exports in a way that mitigates the risks of price volatility and short-term decision-making, Kazakhstan also created a platform for climate change action. This has the advantage of closely aligning the goals and management of the energy companies in Samruk-Kazyna with government priorities while reducing transaction and co-ordination costs. Samruk-Kazyna is uniquely placed in Kazakhstan to mobilise capital towards long-term socioeconomic and environmental goals in a way that is not possible for private investors in other similar emerging market economies that are under pressure to prioritise nearer-term returns. The long-term value of Samruk-Kazyna's portfolio is closely linked to climate change and its long-term impacts, making it easier to integrate climate risks into the heart of its corporate strategy. The presence of various companies in different sectors under the control of Samruk-Kazyna has enabled it to act as both developer and potential customer for clean energy R&D and projects, for example by engaging Air Astana and Kazakhtelecom in projects.

The outlook for clean energy in Kazakhstan and the success of Samruk-Kazyna's strategy are linked to the country's strong tradition of stepwise policy planning. Legislative documents and processes underpin a transparent planning process that takes long-term strategies such as Kazakhstan-2050 seriously. Long-term plans align well with short- and medium-term strategies such as the Strategic Development Plan to 2025, five-year programmes, sectoral approaches and subnational development plans. In February 2023 the country's first national low-carbon development strategy was issued to update previous strategy documents in line with the newer targets to reduce CO_2 emissions by 2030 and achieve carbon neutrality by 2060.

While Kazakhstan is a frontrunner in Central Asia for developing clean energy innovation policies and has the resources to attract significant foreign direct investment in areas like renewable energy, its experiences in the past decade also highlight some notable challenges and learnings. They indicate areas where Kazakh policy makers might focus their attention in future and how other countries wishing to follow a similar path might design policy measures to accommodate these lessons (Table 7.2).

Table 7.2. Risks and challenges faced in the implementation of Samruk-Kazyna's clean energy technology plans

Area of risk	Description	Types of possible action
Historic and continued reliance on income from hydrocarbons, metals and mineral exploitation. Carbon lock-in of the labour market and the economy	The technology expertise within Samruk-Kazyna's companies is strongly weighted toward resource extraction and fuels. This creates innovation opportunities in areas such as hydrogen and CCUS, but also a potential technology selection bias.	Map any gaps in human capital for R&D and work closely with universities to ensure they can be closed. Seek to ensure that low-emissions energy sources cannot be at a disadvantage due to tariff or regulatory design, compared with more emitting sources. Establish consultation processes to listen to different stakeholder views and engage them in the process of scenario design as a means of discussing alternative future paths. Communicate clearly how clean energy technology projects will benefit local communities and the economy, and ensure the future of major employers.
	The set of institutions that have evolved with the fossil fuel-intensive economic model do not produce sufficient domestic human capital for R&D and deployment of nuclear and renewable energy projects.	
	Non-hydro renewable energy sources face higher consumer tariffs than those for fossil fuel and hydropower generation, reducing the perceived market value of new renewable technologies.	

Area of risk	Description	Types of possible action
Historic and continued reliance on income from hydrocarbons, metals and mineral exploitation. Carbon lock-in of the labour market and the economy (continued)	The fossil fuel energy system, especially in relation to coal, is a major employer and Samruk-Kazyna has a duty towards communities that rely heavily on its fossil fuel activities, potentially slowing the pace at which it can transition to cleaner energy. On the other hand, this social awareness can ensure smoother technological change.	
	The politics of climate policymaking may focus intensely on how to protect existing industries rather than generate new economic value through innovation. This is observable in extensive current discussions about emissions trading and carbon border adjustments.	
Capital constraints	The structure of R&D spending and business ownership in Kazakhstan does not strongly incentivise private spending on energy R&D, yet experience in other countries indicates that innovation can be more effective when public funds catalyse more private innovation spending.	Consider tax incentives for private sector R&D spending and investment in innovative start-ups. Continue to make R&D funding publicly open to bidders based on transparent evaluation.
	Financial markets and markets for clean energy products are relatively immature in Kazakhstan, which has created some reliance on development banks and other international investors for renewable energy projects. This model has been effective for early-stage developments, but could limit the speed with which the country is able to deploy innovative technologies.	Shore up the regulatory frameworks and incentives to ensure that they can attract private sector investment in clean energy R&D and new-to-Kazakhstan technologies.
Institutional co-operation and exchange	There is room for improvement in co-ordinating the various initiatives and parties involved to reduce administrative costs and time required to meet targets.	The Ministry of Science, together with the Ministry of Energy and the Ministry of Infrastructure and Industrial Development, have developed policy tools, such as the Science Law and joint orders, to streamline R&D efforts that align with the low-carbon vision. This could be developed further
	A lack of close co-operation between actors could delay innovation activities or make them unnecessarily expensive. New institutions, such as the	

Area of risk	Description	Types of possible action
Institutional co-operation and exchange (continued)	Ministry of Ecology, Geology and Natural Resources, created in 2019, are less well integrated into existing power structures.	with efforts to create industry–academia partnerships and networks and international linkages to experts. All relevant ministries could have formal input into the R&D strategies of Samruk-Kazyna and the energy R&D spending of ministries to avoid duplication and set common technology expectations.
Monitoring and evaluation	Without the articulation of ex ante objectives and the ex post evaluation of outcomes it is difficult to maximise the effectiveness of energy innovation policies, which often target intangible advances. However, documents such as Samruk-Kazyna's strategic plan, and the government's Concept of Scientific Development 2022-2026 do not include provisions or accountability for monitoring and evaluation. There is no formal process for reviewing Samruk-Kazyna against its climate or long-term strategic goals, creating a risk that its performance might be judged only by short-term financial performance. This is a well-debated issue on the role of sovereign wealth funds in financing the energy transition.	Establish systems for setting policy objectives in line with ex ante impact assessments and assign responsibility for evaluation at various stages of implementation. Engage with international partners to understand the options for innovation policy evaluation. Increase the level of knowledge of and data available on new technologies from the public and private sectors (including internationally) to address information asymmetries and enable ex ante and ex post impact assessments to help guide Samruk-Kazyna's technology spending.
Centralisation of decision making	Samruk-Kazyna has significant potential as a co-ordinating entity aligned with the government's long-term priorities, but centralisation also carries risks of politicised and rigid investment decisions. A lack of distinction between governing and overseeing bodies can reduce transparency and accountability. When the entity setting the goals is also responsible for meeting them and they are not legally enshrined, long-term objectives can become subordinated to	Samruk-Kazyna could explore partnerships with private sector firms, innovation incubators, and national and international organisations, for example on pilot projects. Mechanisms that combine small investments by public and private actors into larger investment projects might help scale up innovative technologies and increase collaboration.

Area of risk	Description	Types of possible action
Centralisation of decision making (continued)	near-term pressures relating to prices or job security.	
	Innovation often stems from competitive forces and market opportunities, which can be hindered by highly centralised control and interdependency of the key companies in the markets.	
Infrastructure	The absence or poor quality of critical infrastructure can significantly hinder clean energy innovation, and the government typically needs to guide and facilitate investment in this area.	Any expectations for the development of coal gasification, CCUS, smart grids or hydrogen will need to match reasonable expectations for the availability of associated pipelines and networks.

Kazakhstan's approach to fostering clean energy innovation via Samruk-Kazyna can provide valuable insights for other emerging market and developing economies facing the challenges of energy transition and carbon lock-in. This is especially the case for resource-rich countries that face tensions between maintaining revenues from fossil fuels and grasping the opportunities presented by clean energy technologies in markets that disadvantage CO_2-emitting activities. The experience of Samruk-Kazyna indicates one approach to using revenues from depletable resources to invest in clean energy technologies that align with a strong government vision of a clean energy future. The case study demonstrates how policy can build upon existing strengths, existing socio-economic conditions and evolving institutional and economic trends. It also highlights challenges with such an approach (e.g. administrative costs, co-ordination issues and principal–agent problems) that are likely to need to be addressed before it yields success.

8. Off-grid solar PV and geothermal in Kenya

Vincent Ogaya (Kenya Climate Innovation Center)

This case study on Kenya focuses on the Kenya Off-grid Solar Access Project (KOSAP) and its impacts on innovation. KOSAP is an initiative by the World Bank and Kenya's Ministry of Energy aimed at enhancing energy access in underserved Kenyan counties with the goal of promoting solar technology use, largely through a distributed model. Notably, while KOSAP lacked a specific innovation objective, it has nonetheless succeeded in harnessing Kenya's fintech innovation community to create an internationally competitive cohort of private companies engaged in the financing and sale of solar PV home systems.

The case study also addresses the impact of geothermal energy development on Kenya's energy technology landscape. In particular, the creation of local expertise in geothermal project development and execution by state-owned enterprises has led to Kenya gaining technological capabilities that now offer potential export opportunities.

Country context

Kenya is the largest economy in East Africa by GDP and the seventh largest in Africa. Its population is also the seventh largest in Africa, at around 54 million. It is classified as a lower middle-income country. Kenya's economy has expanded robustly in the past two decades, at an annual average of 4.2%, much higher than the 1.7% average it recorded in the 1990s and higher than the sub-Saharan average. Since 2014 the country's growth rate has been slightly higher, at around 5%, and has been driven by the expansion of the service sector, in particular financial services, tourism and transport. This growth has helped reduce the poverty rate from 37% in 2005 to 27% in 2019.

Kenya launched its Vision 2030 programme in 2008 as a guiding document for the transformation of the nation into a globally competitive, industrialised, middle-income country with high quality life for everyone. Infrastructure development, including for energy, is emphasised strongly in Vision 2030. The programme involved extensive stakeholder dialogue among government bodies, private enterprises and civil society. It is broadly considered to capture a consensus ambition for the country's future.

However, progress in diversifying the economy and boosting growth has been hit in recent years by several crises, including the global pandemic, inflationary pressures, commodity price volatility, high debt costs, the worst drought in four decades, violent flooding and tightening global financing conditions, which put major pressure on the exchange rate and foreign exchange reserves. The drought in 2021 was declared a national emergency by the government and left an estimated 2.8 million people in need of urgent food assistance, with some requiring malnutrition treatment and smallholder farmers needing emergency finance. The 2019-2020 locust invasion was described as the worst in 70 years, leading to cereal supply disruption and shortages and a rise in food prices that pushed large amounts of the population into poverty. Kenya is particularly vulnerable to the pass-through effect of rising global energy prices on domestic food prices, as most of its staple foods are imported. Floods in early 2024 displaced over 300 000 people and damaged infrastructure.

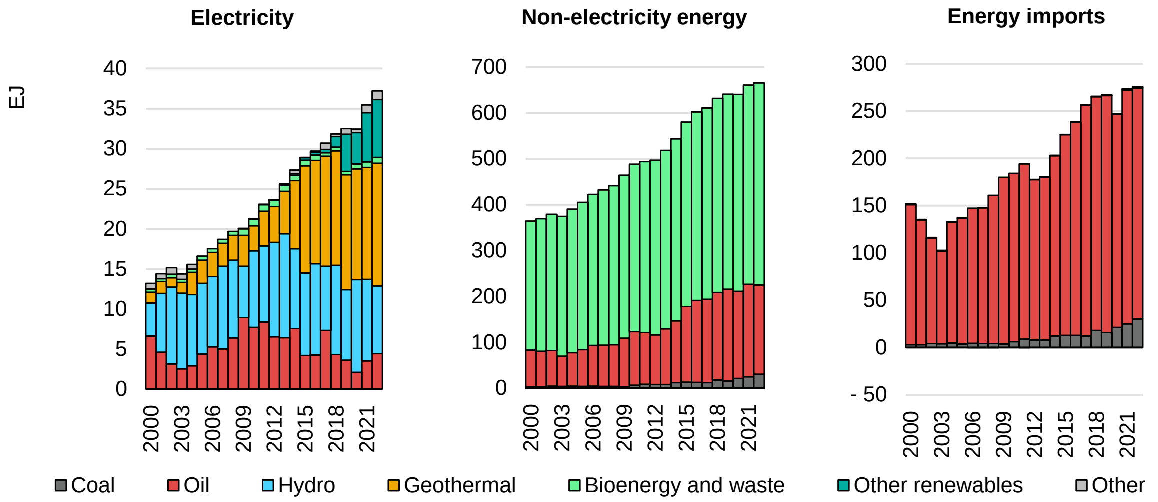
In the global context, Kenya's human development index score is relatively low, ranking 146 out of 189 countries. A significant portion of Kenya's economy is informal, and is estimated to be equivalent to as much as 25-30% of the country's official GDP. However, Kenya's internet connectivity rate is relatively high for the region, at 30% of the population in 2020.

Kenya is a presidential representative democratic republic, whereby the president is both head of state and head of government. Its governance structure has a high level of devolution to 47 county governments. A governor oversees the affairs of each county government, and this executive branch – along with the president – has a major role in setting government policy. However, legislation must be passed by the parliament or, at county level, by a county assembly.

Energy sector context

Kenya's energy consumption has grown by 86% since 2000, most of which has been supplied by bioenergy and oil. Bioenergy is largely reliant on traditional gathering of wood fuel, which is a time-consuming practice with serious health and equality impacts on the population. Electricity, while accounting for just 5% of total energy demand, has grown more steeply than other forms of energy and has undergone a remarkable shift from reliance on hydropower and oil to a situation where most electricity is now from geothermal and a rising share is from solar PV and wind. KenGen, the state-owned electricity generation company, indicates that demand for electricity has been steadily rising over recent years. Peak demand is projected to grow at an average of 3.1% annually in coming years. At the same time, the government has set a target of 100% renewable electricity by 2030, a goal that appears feasible based on current trends.

Figure 8.1 Energy sources for electricity and other uses, and level of imports, Kenya, 2000-2022



Notes: Electricity and non-electricity energy are shown on a final consumption basis. Imports are shown net of exports. "Other" refers to imported or exported electricity.
Source: IEA (2024), World Energy Balances.

The expansion of renewable electricity has helped Kenya deliver electricity access to almost three-quarters of its population and to 97.5% of those in urban areas. While this fell short of the goal of the 2015 Last Mile Connectivity Programme to achieve universal access by 2020, it represents an enormous improvement from a level of 14% in 2010. The programme helped the Kenya Power and Lighting Company (KPLC) – a public company with 51% government ownership – to install new transformers and extend the low-voltage network with a USD 900 million budget supported by the African Development Bank and European bilateral and multilateral development finance institutions, in addition to Kenyan government funds. Kenya now has one of the highest electricity access rates in sub-Saharan Africa, although, like many other African countries, the level of access has declined somewhat since 2020 as consumers have faced lower purchasing power due to incomes being hit by the global pandemic, drought and subsequent commodity price spikes. In addition, electricity suppliers are grappling with climbing debt burdens as they shoulder losses to keep bills affordable.

Kenya's centralised grid infrastructure and electricity supplies are not always reliable, partly due to the stretched finances of KPLC. Blackouts are common and this has a negative impact on the country's economic productivity as well as social outcomes. A rate of roughly one power outage per week was recorded in 2013 with a nearly six-hour average outage duration, and 83% of firms experience power shortages. In October 2021 Kenya announced a plan to create a super energy services company as a unit within KPLC. This company is intended to develop energy efficiency projects for the public and the private sectors.

Among the major investments in the power grid that are under consideration, the 8 000 km North–South Power Transmission Corridor linking Egypt with South Africa is perhaps the most ambitious. It could link Kenya to hydropower resources in Ethiopia and elsewhere while bolstering supply resilience through diversity. It would complement parallel efforts to build an international power market – the Eastern Africa Power Pool – which has been under development since 2005 to facilitate cross-border power trade among 11 participating nations. However, little has been accomplished since creation of the pool, as there are technical and political barriers to its operationalisation.

Geothermal sources have provided most of the additional supply of grid-connected electricity. Kenya has the world's seventh-largest geothermal potential and has made concerted efforts to exploit this natural resource. Geothermal electricity was first introduced to Kenya in 1981, but did not become a major component of the electricity mix until the opening in 2014 of the Olkaria IV power plant, which was co-financed by the World Bank and European Investment Bank. With nearly 900 MW now installed, Kenya's geothermal power output is the eighth largest in the world and further expansion is underway following a positive government evaluation of the costs and high load factors.

Alongside geothermal, there has been investment in solar PV and wind energy. Kenya hosts Africa's largest wind farm, which became operational with a capacity of 310 MW in 2019, after construction began in 2014. The country's installed utility-scale solar PV capacity also includes a 50 MW plant that is the largest in East and Central Africa. Off-grid deployment of solar PV has also had a significant impact, especially in rural Kenya. The country has been a pioneer in the development of pay-as-you-go (PAYG) business models for solar home systems and mini-grids, integrating digital communications and banking technologies ("mobile money") along with appliances designed to run directly from solar and battery systems. Ethiopia and Kenya together accounted for 30% of sales of global solar home systems and solar appliances in 2021. In addition, Kenya has around 40 MW of small hydropower plants.

In 2021 Kenya's net oil imports were equivalent to around 40 million barrels of oil, nearly twice as much as 20 years before. The cost of these imports was around USD 3 billion, a value that increased to around USD 5 billion in just one year when oil prices rose in 2022. Alongside energy efficiency and electrification of transport, recent offshore oil discoveries could provide a way of reducing the import bill. The region is attracting multinational companies, including Chinese oil companies, looking to invest in the Lokichar South Basin, discovered in 2012. After initial optimism, Lamu Basin was deemed unviable in 2022 due to a lack of accessible oil. Plans for an export pipeline are still in the design phase and poor infrastructure has previously hampered oil developments; the long-planned Uganda–Kenya Petroleum Products Pipeline is delayed until around 2030.

However, tackling climate change has become a higher priority topic in Kenya, which is among the top 40 most vulnerable countries to climate change. Among other impacts, the loss of Mount Kenya's glacier – which could happen as soon as 2030 – would lead to river shrinkage, affecting up to 85 000 people annually, reducing hydropower generation capacity and costing Kenya some USD 50 million every year. As part of its commitments under the Paris Agreement, Kenya has pledged to reduce greenhouse gas emissions by 32% by 2030 compared to a forward-looking business-as-usual scenario.

Innovation context

In recent years Kenya has nurtured a burgeoning start-up scene, with innovators securing funds to build companies in financial, agriculture, health, commerce and education technology areas. In most cases their products involve digital software and systems. Over the past 20 years Kenya has emerged as a pioneer in "mobile money" – banking services, including micro loans, via mobile phones. A bottom-up burst of innovation in this area has led to dramatic changes in the country's payments and banking, including giving parts of the population access to the financial system for the first time. In 2022 Kenya was ranked 88th in the world for innovation performance, and third in sub-Saharan Africa. Nairobi now sits alongside Cairo, Cape Town, Lagos and Johannesburg as one of Africa's top start-up ecosystems.

This outcome was not entirely government directed. Kenya has a relatively high rate of education and literacy compared to its neighbours, but one in five adults are still illiterate. Government funding and support for R&D has been sporadic and inconsistent over the years. Much innovation occurs in the informal economy, where there are pressures to find cheaper ways to provide services and rapid exchange of knowledge in the absence of intellectual property protections. It was only in 2013 that the Kenya National Innovation Agency (KENIA) was founded by the Science, Technology and Innovation Act. It has a mandate to stimulate socio-economic progress through innovation in line with Vision 2030. At around the same time, the Kenya Climate Innovation Center was established (Box 8.1).

The government has also recognised the potential for its youth to contribute to technology development with appropriate training. In 2017, 55% of 18-35-year-olds were unemployed, with unemployment twice as likely in the 18-25-year age bracket than in the 26-35-year age bracket. There has been recent investment in technical and vocational education and training institutes to complement existing colleges and universities.

Box 8.1 The Kenya Climate Innovation Center

The Kenya Climate Innovation Center (KCIC) was established in 2012 as part of the World Bank's infoDev initiative. It was the first in a global network of Climate Innovation Centers whose design and establishment arose from the need to help developing countries overcome the challenges they face in acquiring, developing and deploying climate technologies in their local contexts. KCIC aims to foster a localised and durable approach to climate change-related innovation and has a mandate to accelerate the development, deployment and commercialisation of relevant technologies.

KCIC aims to support innovators to overcome barriers that are especially pronounced in developing countries, including inadequate skills, limited financial support and inhibitive policy frameworks, as well limited access to markets for climate technologies. Its services include business advice, technical assistance, financial support and policy advocacy to help create markets and support further innovation. As well as helping to tackle climate concerns, job creation is an objective of KCIC and a pressing need in Kenya.

Initially supported primarily by the World Bank, Denmark and the United Kingdom, KCIC has broadened its funding base as it has grown. In addition to working in Kenya, it has expanded to offer services elsewhere in East Africa. To do so, it now includes support from multilateral development partners like the European Union and foundations such as the IKEA Foundation and the Mott Foundation. By the end of 2022 KCIC had incubated over 3 000 businesses in areas such as renewable energy, agribusiness, forestry, waste and water management. This is estimated to have generated nearly 40 000 jobs and enable half a million tonnes of CO_2 emissions to be avoided. In recognition of its impact, KCIC was designated as the implementing agency of the "Promote Climate Technologies and Innovation" initiatives for 2018-2022 under Kenya's Vision 2030 agenda.

The case of off-grid solar PV in Kenya

Less than one-third of Kenyans live in urban areas and the rural population has long suffered from a much lower level of access to electricity. Efforts to connect rural communities to the power grid began in 1973 as an approach to stemming rural–urban migration by improving social amenities and employment opportunities. However, by 2004 just 91 000 people (0.3% of the target population) had benefited from new connections and the rural electrification programme was suffering operating losses. The 2004 Sessional Paper No. 4 on Energy set a goal of increasing rural electrification from 4% to 40% by 2020, and finding new funds to achieve it. The paper also marked the formal recognition of two important changes in the Kenyan energy landscape at that time:

- It noted that the previous three years had seen the annual installation of small solar PV home systems grow by 20 000 units per year, reaching 200 000 installed in total, and it made a direct link to the rural electrification challenge, saying that "the potential for photovoltaic solar home systems is virtually untapped. It is therefore expected that with the diversification of rural electrification strategies, the number of installed photovoltaic solar home systems will grow substantially".
- It expressed concern that past efforts in energy R&D had focused on policy analysis and demonstration activities, but limited attention had been given to technology-oriented research. It advocated a "a national energy research strategy, including defining specific roles of government, energy suppliers and private sector in R&D funding, increasing budgetary allocation for R&D, improving co-ordination and reporting mechanisms on energy research activities and results, and facilitation of local participation in international and regional research activities". As an example, the paper said that developers and consumers of wind energy needed to develop the technical capacity to procure and adapt wind technology for use in different conditions.

In 2007, when Vision 2030 forged consensus on the future among government institutions, the high-level strategic document highlighted renewable energy as a priority alongside electricity market reform, cross-border electricity interconnection and the exploitation of coal. It also said that the public resources for scientific research and workforce training would be increased.

However, between 2004 and 2015 there was scant progress towards realising the opportunities for off-grid solar PV and technology innovation identified in Sessional Paper No. 4. Strategic misalignments can be seen in socio-political support as outlined in two strategic documents in 2015. The Green Economy Strategy and Implementation Plan outlined actions to reach a 75% share of renewable energy in Kenya by 2025 and included reform of the feed-in-tariff subsidy policy to incentivise off-grid projects, which had been excluded up to that point. It also promoted the creation of "green-tech" start-ups through innovation and replication, and outlined the need for actions in the areas of knowledge management, monitoring and evaluation. In the same year, the Last Mile Connectivity Programme was launched to focus exclusively on extending the national grid to rural communities without any mandate for promoting renewable energy. This programme was managed by KPLC and the Rural Electrification Agency (REA) that had been established in 2006 to help rural communities connect to the grid.

The Kenya Off-Grid Solar Access Project accelerates solar PV uptake through international co-operation

A defining change in the outlook for solar PV in Kenya was the partnership between the Ministry of Energy and Petroleum and the World Bank in 2016 that led to the launch of the five-year Kenya Off-grid Solar Access Project (KOSAP) in 2018. The funding that the World Bank could bring, combined with the World Bank's mandate to support livelihoods and renewable energy, enabled a large-scale project that was on the margins of national energy policy, which was focused on market reform and grid expansion. KOSAP's goal is to use its USD 150 million budget to provide energy access to 14 underserved counties (representing 20% of the population and 72% of Kenya's land area) via solar technology, especially in areas further from the national grid.[1] These counties have population densities one-quarter of the national average, and poor road, water and social infrastructure.

The component objectives of KOSAP relate to different types of technologies, depending on the identified needs and least costly options for meeting them:

- Construction of 120 mini-grids in 12 counties for community facilities, enterprises and households, combining solar PV, battery storage and diesel gensets. The model for this component is public–private partnership whereby the project funding is used for the mini-grid network and private and public funds co-finance the generation facilities. Construction of the mini-grids is shared between KPLC and the Rural Electrification and Renewable Energy Corporation (REREC).[2] Accountable private service providers bid to manage the mini-grid construction and sign offtake and maintenance contracts of up to 10 years with KPLC, which collects the customer payments at the same tariff as for the national grid.
- The sale of 250 000 stand-alone solar home systems and 150 000 clean cooking solutions. For most households, these are the least-cost options. Project funds are used to provide grants and loans to private enterprises to help them expand their operations into the target communities.
- Installation in 387 community facilities of stand-alone solar PV systems and retrofitting of 380 existing community boreholes to be pumped by solar PV instead of diesel. The target facilities include health centres, secondary schools and administrative offices. Private sector contractors are selected competitively for each area and overseen by KPLC (in the case of new PV pumping systems) or REREC (in the case of borehole retrofits).

While the KOSAP implementation plan recognises the role that technology innovation had played in enabling the project's concept – international innovation in solar PV and Kenyan innovation in mobile payments – it contains no explicit

[1] While it is not discussed in this chapter, KOSAP also includes measures to support uptake of clean cooking technologies.
[2] The successor organisation to the REA. REREC is responsible for the rural electrification programme fund and master plan, including sourcing additional funds. It implements elements of the World Bank Kenya Electricity Modernization Project, which includes construction of mini-grids and sales of electricity to KPLC. It promotes renewable energy in Kenya.

references to objectives for technology innovation outcomes. It has, however, included training for solar technicians and entrepreneurs, as well as several aspects that make KOSAP a transformative project in Kenya.

One notable aspect is the involvement of all Kenya's key energy-related institutions. As manager of the World Bank partnership with accountability for the use of the funds, the Ministry of Energy and Petroleum co-ordinates to ensure alignment among different institutions and helps to ensure efficiency. The Energy and Petroleum Regulatory Authority is a regulatory authority for the energy sector in Kenya and has responsibility in KOSAP for technology standards and fair pricing of electricity from off-grid technologies via tariffs. The key bodies for grid modernisation and electrification – KPLC and REREC – are also involved as implementers to avoid development of a two-tier system by ensuring that the remote counties receive the same tariffs and service as elsewhere in Kenya.

Another key element of the project is the way that digital technologies are integrated into its core (Table 8.1). This makes direct use of Kenya's leadership in mobile communications technology for microfinance and PAYG payments, which was developed over the preceding decade and had already been applied with some success to off-grid solar in urban areas. Arguably, KOSAP was made possible by the existing local expertise in this area from the Kenyan "fintech" sector, which enabled the programme's funds to be directed via private PAYG providers that offered cutting-edge and affordable financing to the rural poor. This competitive environment created incentives for the companies to update their products and maintain lasting relationships with customers.

Table 8.1. Ways in which digital technologies are integrated into KOSAP

Digital service	Use in KOSAP
Communication	KOSAP's operators use text and interactive voice messaging to communicate with beneficiaries to gather feedback and disseminate important information.
e-learning	Used to educate communities about maintenance and the benefits of renewable energy, thereby fostering a sense of ownership and responsibility.
Geospatial data and mapping	Identifying areas in need of KOSAP services for efficient allocation of resources and to assist the customisation of interventions according to local needs.
Mobile money	Convenient and secure remote monthly payment systems, plus availability of micro loans that foster financial inclusion and are backed by World Bank guarantees. This has helped suppliers bundle other services, including hot water and clean cookstoves, with the solar electricity offering.
New apps	User-friendly applications were created for KOSAP to enhance user interaction with the systems and offer insights into energy consumption patterns.

Digital service	Use in KOSAP
Performance monitoring	The installed systems generate real-time data that are analysed by the project co-ordinators to adapt the means of implementation.
Smart metering	High-granularity energy consumption data facilitate reliable and transparent billing and hence trust between suppliers and customers. They can also be used to provide advice on efficient use of energy.

KOSAP has also had a strong component related to education from the outset. It was considered important to provide clear and thorough information about the technologies and services, their benefits and how to access them. One-to-one communication channels for regular feedback were put in place, including education campaigns, demonstrations and guidance on operation and maintenance. The acceptance of local opinion leaders was a primary target, given their importance in village contexts.

It is important to recognise that the KOSAP project has not been implemented in a vacuum, but interacts with other relevant policy measures. These include tax incentives for the purchase of renewable energy products and regulatory guidelines for off-grid systems that mirror the performance standards of the national grid. In the initial documents for KOSAP, the World Bank identified the need to ensure that regulatory standards are adaptable to facilitate the entry of improvements to technologies and services that might occur during the duration of the project.

KOSAP's successes bring solar PV from the periphery to the centre of energy policy

Implementation of KOSAP was delayed by the global pandemic in 2020-2021 and its end date was extended to 2025. By mid-2024 considerable progress had been made against the project target for stand-alone solar home systems (70% of the target sales achieved).[3] Progress with mini-grid installations, community facilities and solar water pumps has been slower. In the case of mini-grids, bids for all projects were processed by the end of 2023 and licences have been issued. Construction is anticipated to start in 2024, but is contingent on World Bank approval of submitted bidding documentation as well as land acquisition processes. Though the timeline will be tight, fulfilment of the targets by the new end date is still possible.

The positive experience of using stand-alone solar PV systems to provide electricity access in Kenya changed the expectations of the country's top energy planners. KOSAP was a key element in this because it explicitly paired the

[3] Progress update based on information received in July 2024 from the Ministry of Energy and Petroleum.

renewable energy and rural electrification policy goals with an approach to implementation that fostered lasting contractual relationships and inclusive access to capital. Influentially, initiatives to support uptake of solar home systems in Kenya led to their installation far exceeding new grid connections and on-grid solar capacity additions.

In 2018 and 2019 Kenya issued a National Energy Policy and then a new Energy Act, which was first major energy legislation since 2012 and consolidated various policy strands under one framework. As well as guiding the use of renewable energy via the national grid, the Act promotes small-scale and distributed renewable energy with a feed-in-tariff. Among the top objectives for this tariff are "encouraging local distributed generation thereby reducing demand on the network and technical losses associated with transmission and distribution of electricity over long distances [and] encouraging uptake of, and stimulate innovation in, renewable energy technology". It also established new electricity market design rules, including formalising the role of innovative, independent companies as electricity retailers subject to the same conditions as large, centralised utilities.

KOSAP influenced the development of policy and the enactment of the 2019 Energy Act in several ways. The emerging successes of the KOSAP project were referenced at public participation forums on the new policy and law, underlining the need to make energy affordable and accessible to all, a goal that was expressly stated in the Act. The role of the REA – now REREC – was expanded to incorporate renewable energy as well as rural electrification, forging a stronger link between them and a default expectation that rural areas, including schools and institutions, would be electrified via their abundant solar and wind resources. The Act also created a Rural Electrification Fund to support tariffs that respond to the needs of rural users without unnecessarily subsidising consumption, and it enabled market-based measures for the private sector scale-up of off-grid solar PV, both things that were pioneered in Kenya by KOSAP. Under the Act, responsibility for ensuring a conducive environment for private sector investment was elevated to the Cabinet Secretary.

Despite a lack of direct technology innovation policies, "market pull" drivers have yielded some innovation outcomes

Off-grid solar PV in Kenya scaled up significantly after 2015 and in particular with the KOSAP project, producing unanticipated innovation outcomes. This technology was not a good fit with the country's then main strategy to modernise its electricity grid, connect it to neighbouring countries and extend it to rural areas. While the centralised grid strategy had a strong and successful focus on renewables, the main priorities were large hydro, geothermal and, later, wind energy plants. Thus, the new market for solar PV, when it arose via funding from international finance, created opportunities for new technology approaches and the creation of entirely new businesses. The integration of micro finance and mobile payment solutions is a good example of new players in the private sector responding to the changes in the market.

Under KOSAP, Kenyan providers of equipment and services have been favoured by the small-scale nature of the installations, the value of local knowledge and the need to be registered within the Kenyan financial system. The project prioritised local content to support local businesses and help tailor the technologies and services to local needs. By providing funding – as grants and loans – and results-based finance, KOSAP addresses the lack of capital in the sector while also enabling start-ups and innovators to pilot, scale up and commercialise new technologies and business models, including for maintenance of installations. Participating firms have also been provided with access to collaboration with KPLC and universities to pilot new ideas in a less risky environment and learn from more established actors.

Some companies, such as M-KOPA, have now expanded their operations beyond Kenya. One of the smaller start-ups, Sunken Limited, was founded in 2018 and received funding from KCIC to manufacture solar home systems, water pumps, irrigation systems and clean cookstoves from local components. With a PAYG business model, it has now expanded from remote northwest Kenya to other parts of Kenya as well as regions of Uganda and South Sudan. Rafode Renewable Limited is a subsidiary of a Kenyan microfinance company and specialises in digital platforms for credit and payments that make its solar and clean cooking services affordable to low-income households. It has steadily expanded further into the remote North Rift area of Kenya.

This process of capacity building, innovation and manufacturing was dependent in large part on the national decision to impose no import duties on solar equipment. Access to the core and most technical components at lowest cost enabled Kenyan suppliers to integrate them into products and market them within KOSAP at affordable prices.

Another impact of the rise in rural electrification has been a change in the expectations for meeting national goals for access to clean cooking. To transition away from wood burning on open and inefficient stoves, LPG and efficient biomass cookstoves had long been the preferred options. The uptake of affordable solar PV has now enabled clean cooking goals to be set based on the electrification of cooking. This, in turn, is driving innovation in the replication of traditional cooking practices using technologies such as induction hobs. The Kenyan electric cooking campaign, Pika Na Power, uses television adverts, social media campaigns and live cooking classes to promote electric cooking. There are strategies in place to boost electric cooking in urban and rural areas by overcoming cultural barriers through cooking classes, recipes for local cuisine using electric cookware, time-saving techniques and dish-preparation contests.

An important lesson that emerges from the KOSAP experience relates to the challenges of enforcement of standards in a decentralised project with multiple suppliers and installations. In some cases, products did not perform as expected or were not in line with regulations. The core components of these products were mostly imported. This has led to a review of the processes by which the Energy and Petroleum Regulatory Authority regulates energy products as it incorporates new types of technology and fast-moving iterations in product design. This element requires a careful balance between strong standards and allowing new ideas to access the market quickly as they may have the potential to lower renewable energy prices and accelerate inclusive energy transitions.

The case of geothermal energy technology in Kenya

Since 2010 geothermal energy supplies have grown fivefold in Kenya and now account for over 40% of electricity generation. After initial failed test wells in the 1950s and then the first successful pilot in the early 1980s, Kenya was the first and only African country to invest in geothermal energy production until Ethiopia followed in 1998. Kenya continues to invest in the technology, allocating over USD 150 million of its 2022/2023 national budget for geothermal power development. Its geothermal resource in the Great Rift Valley is vast and relatively easy to tap due to the high temperature and pressure.

Geothermal development has been managed in Kenya by KenGen. It has done this with a high level of international co-operation. The equipment has been supplied by international engineering firms including Mitsubishi, Hyundai, Toyota Tsusho and KEC International. Finance for the sequential projects has been provided by the Japan International Cooperation Agency, European Investment Bank, International Development Association, French Development Agency and the World Bank.

Over the years, these collaborations have built significant technical capabilities in KenGen and in Kenya more generally. Project development skills are one example: it took a full year to build the pilot plant at Olkaria, but the next 14 wells were built in four years. When the 2006 Energy Act liberalised parts of Kenya's electricity system, a new state-owned company – the Geothermal Development Company (GDC) – was formed to develop geothermal fields and sell steam to

KenGen and private investors. GDC has a centre of excellence for Kenya's geothermal operations and trains operators to mitigate the risk of a skills gap opening in the sector.

The biggest cost and risk in the geothermal development process is the upfront drilling. This step accumulates costs if the drilling campaign takes a long time and also carries the risk of not finding a suitable resource – a so-called "dry well". To speed up the drilling campaigns and the ability to bring new fields online, GDC has increased the number of drilling rigs it operates from one before 2010 to seven in 2018, while KenGen has a further three. However, this is far from the availability of drilling rigs in places with extensive oil and natural gas exploration, such as parts of the United States. To manage the risks associated with dry wells, the World Bank developed a Global Geothermal Development Plan in 2013 and mobilised several hundred million dollars, including for insuring the costs of unsuccessful drilling. Validating commercial viability of a geothermal resource is an unavoidable step often requiring USD 15-25 million in drilling costs or around 15% of the capital expenditure upfront, with no guarantee of return. Commercial debt is often not available to finance this step.

In 2015 GDC began exploring the direct use of Kenya's geothermal steam, which represents a new frontier in technology innovation. Through a collaboration with the United States Development Agency (USAID), it operates five direct-use pilot projects for uses including greenhouses, fish farming, milk pasteurisation, grain drying and laundry. These uses can directly replace fossil fuels in these industries, while enabling geothermal projects to sell steam that is not suitable for power generation. The next step is to explore whether new industrial parks can be established near geothermal resources, seeding new sources of local economic growth. Direct uses have the potential to benefit women in Kenya, as several of the target applications are typically women-led businesses. Kenya has set a quota for employment and training of women in the sector. Geothermal energy can also create new business opportunities.

This expertise has allowed Kenya to lead the co-ordination of countries in the region in an alliance for geothermal development. The potential for export of expertise – as well as power – is significant. Ethiopia has three projects under construction, and the country plans to increase its geothermal power capacity to 10 GW by 2030. Plans to develop geothermal energy are also under consideration in Eritrea and Djibouti, where KenGen is directly engaged in project development.

Another clean energy technology opportunity that has been enabled by geothermal expertise in Kenya relates to material extraction. Titanium is used in geothermal power plants to withstand the harsh operating environment. While titanium production has historically been concentrated in a limited number of countries – with Australia, Canada and South Africa together accounting for 40%

of global production – Kenya entered the sector in 2014. Since then, it has produced between 5% and 7.5% of global output; it is now in the top four African producers and among the top seven global producers, with 250-350 000 tonnes of output per year. Demand for titanium is expected to rise significantly, especially for clean energy technologies such as geothermal. In IEA climate-driven scenarios, mineral demand for geothermal technologies grows more than seven times over the coming two decades.

More recently, several start-ups have been launched in Kenya in the technology areas of direct capture of CO_2 from the air and geological CO_2 storage. These innovators are building directly on expertise gathered from the expansion of the geothermal sector since 2010.

Findings

Rural electrification via solar PV, especially through KOSAP, has had a major impact on Kenyan energy policy since 2015. The involvement of international finance enabled a large-scale project to be designed around a technology that was not among the top national energy policy priorities but was important to the World Bank, which was keen to support a deployment model for off-gird solar that could be replicated across sub-Saharan Africa. KOSAP's success moved solar PV from the periphery to the centre of Kenyan policy in the 2019 Energy Act and afterwards. This demonstrates that international co-operation can have a catalytic effect on a new technology that might otherwise struggle to receive central government support if it is in tension with the preferences and expertise of incumbents. By working in a "protected niche" for policy experimentation, which in this case was in remote communities far from planned grid expansions, greater alignment with the national vision was achieved through demonstration of effective rural electrification and innovation. Involving key stakeholders from Kenyan energy policy, such as KPLC and REREC, in project execution and tariff collection helped build trust and a shared vision of the co-existence of national grid, mini-grid and stand-alone systems.

Building on the strengths of the Kenyan technology innovation system has been central to the effectiveness of KOSAP. Notably, this included integration of mobile payments, micro finance and app development, but it also leveraged the healthy start-up ecosystem that had built up around the fintech sector in the past decade. Through KOSAP's "market pull" policies and smart design, new private companies have been able to scale up and become nationally and internationally competitive in the energy sector despite the lack of a well-funded national energy R&D programme or innovation objectives for KOSAP. Many of these start-ups have been engaged in the financing and sale of solar PV home systems (Table 8.2).

Table 8.2. Selected energy-related Kenyan start-ups founded since 2010

Start-up	Year founded	Technology area
M-KOPA Solar	2011	Off-grid solar PV retail solutions and solar home systems
PayGo Energy	2014	Clean cooking retail solutions
Solar Panda	2016	Off-grid solar PV retail solutions and solar home systems
Spark Possibilities	2016	Solar home systems
Keep It Cool	2019	Solar PV systems for commercial services
Agrotech+	2019	Solar PV systems for commercial services
ecobodaa	2020	Electric motorbikes
Ecosafi	2020	Clean cookstoves using waste biomass
Stima Mobility	2020	Electric motorbikes and battery swapping technology
BasiGo	2021	Electric buses and financing solutions
Cella Mineral Storage	2021	Geological CO_2 storage
Octavia Carbon	2022	Direct air capture of CO_2

The experience of KOSAP highlights the need to invest in institutions and capacities to monitor and regulate quality in a fast-moving small-scale technology area like solar home systems. The types of hardware supported by KOSAP were unfamiliar to the existing regulatory regime for energy in Kenya and were largely produced overseas. The need to adapt standards and strengthen enforcement emerged from the project as lessons learned. However, the incentivisation of private companies to compete and innovate is a core design feature of KOSAP. There must therefore be a balance between this and the regulatory requirements for safety and product quality that are essential but could stifle innovation or the adoption of the latest overseas technologies if too strict.

International finance and technology were also fundamental to the exploitation of Kenya's excellent geothermal resources. However, in a technology area like geothermal, considerable local expertise in project development and execution is necessary. This played well to the strengths of state-owned enterprises that are large enough to take on strategic government priorities in risky areas. As a first mover in Africa, Kenya has accumulated considerable capabilities in geothermal as well as suitable drilling rigs. After several decades of development, Kenya's technological capabilities have now opened opportunities to diversify and generate technology-based economic returns. These include the provision of technical services to neighbouring countries, the development of techniques and business models for direct use of geothermal steam, and the expansion into CO_2 capture and storage in Kenya.

9. Solar PV distributed generation in Mexico

Diana Canales (Conahcyt), Rodrigo Palacios (Conahcyt, Iniciativa Climática de México), Regina Zamora (Universidad Nacional Autónoma de México)

Over the past decade, Mexico has implemented several policies to reduce greenhouse gas emissions from the energy sector while promoting sustainable environmental, social and economic development. During this period, Mexico's energy sector has seen a 50% increase in installed electricity generation capacity, driven largely by significant growth in wind and solar PV, which now account for around 20% of total installed capacity.

This case study examines how policies are encouraging innovation in the deployment of distributed generation from clean energy sources, particularly solar PV, and assesses the extent to which this has actually led to increased value added in the supply chain. Policies for distributed generation successfully drove a significant increase in installed distributed solar PV capacity in the last three years, which has spurred the growth of numerous small distribution companies across the country focused on installation and maintenance. This expansion of active solar PV companies throughout the country and demand for large solar PV power plants did not translate into significant investment in domestic manufacturing capacity. More recently, however, Mexico's world-renowned manufacturing expertise, combined with its close access to the large US market, where government measures seeks to reduce reliance on solar PV imports from China and Southeast Asia, has supported an increase in solar PV module manufacturing capacity in Mexico that can meet all domestic demand and produce products for export. Existing manufacturing capabilities and Mexico’s skilled workforce could provide a strong foundation for value creation in other clean energy technologies, particularly in the automotive sector. However, to realise these potential sources of future energy innovation and exports, there is an opportunity for better alignment between Mexico's R&D spending and the technology areas where it already possesses technical capabilities – such as mass-manufactured components and finished products – as well as more researchers in the country's clean energy innovation ecosystem.

Country context

Mexico is the 10th most populous country in the world, with an estimated 130 million habitants. It is the 13th largest in terms of territory and has the 14th largest GDP, whereas it has the 70th largest in GDP per capita. The country has a large income inequality and had a Gini index of 43.3 in 2022, giving it a rank of 30th most unequal globally. In 2021, labour poverty, the share of the population with insufficient income to access the basic food basket, was 38.5%.

Energy sector context

In 2022, Mexico's installed electricity capacity was almost 100 GW and the electricity generation of nearly 350 TWh. Efforts to improve electricity access in the country have increased it from 98.5% in 2015 to 99.2% in 2021; however, this still leaves around a million people without access, particularly in isolated areas with indigenous population. While this electricity access rate is above the 97.6% rate for Latin America, there are challenges for providing sufficient access, as 36.7% of homes live in energy poverty[1].

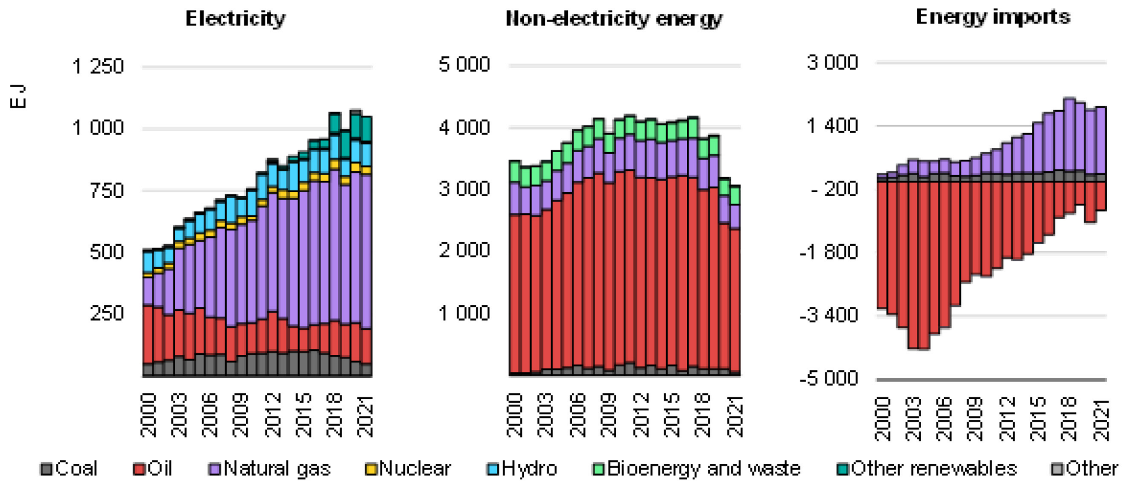
Fossil fuels currently account for 92% of Mexico's total energy supply, a share that has remained virtually unchanged over the past two decades. This is primarily driven by increased natural gas consumption for electricity generation. The country's declining domestic natural gas production, coupled with rising consumption, has resulted in a steady increase in natural gas imports, which now account for 50% of total consumption. Mexico's heavy reliance on fossil fuels and rising electricity demand have driven a significant increase in greenhouse gas (GHG) emissions. In 2022, Mexico ranked ninth globally in terms of absolute GHG emissions, with a total of 820 Mt CO_2-eq. The power sector is responsible for almost a quarter of total emissions, making it the second-largest source after transportation.

Despite Mexico's continued heavy reliance on fossil fuels, the country's electricity generation mix has undergone significant changes over the past decade (Figure 9.1). These changes have been largely driven by the enactment of the Electric Industry Law (LIE) in 2014 and the Energy Transition Law (LTE) in 2015. The LIE and LTE define which technologies can be classified as clean energy sources, establish clean energy deployment targets and a tradeable clean energy certificate system for meeting those targets. Since 2014, there has been a tenfold increase in the installed capacity of solar PV and wind, reaching nearly 20 GW today and accounting for 20% of the total installed capacity. Meanwhile, the installed capacity of natural gas generation grew by less than 15 GW over the same period. However, due to the higher capacity factors of natural gas plants compared to solar PV and wind, they made a more significant contribution to

[1] The energy poverty index used by the authors of this estimation reflects a multidimensional index of energy poverty in the household. This would imply the absence of at least one of the following services or goods that are considered essential to meet basic human needs: i) lighting, ii) entertainment, iii) water heating, iv) food preparation, v) food refrigeration, and vi) thermal comfort.

meeting the increase in electricity demand. This highlights the continued importance of fossil fuels in meeting new power needs despite the growth in renewable capacity.

Figure 9.1 Energy sources for electricity and other uses, and imports, Mexico, 2000-2021



Notes: Electricity and non-electricity energy are shown on a final consumption basis. Imports are shown net of exports. “Other” refers to imports or exports of electricity.
Source: IEA (2024), World Energy Balances.

As a signatory to the Paris Agreement, Mexico presented an updated NDC , in 2022 that included a commitment to achieve an unconditional 35% reduction in GHG emissions by 2030, compared to a baseline scenario. The previous NDC had set a much lower 22% unconditional reduction target. The earlier NDC also outlined specific GHG reduction targets by sector, with the electricity sector expected to play a leading role in the emissions reductions by cutting CO_2 by 31% by 2030 relative to a baseline scenario.

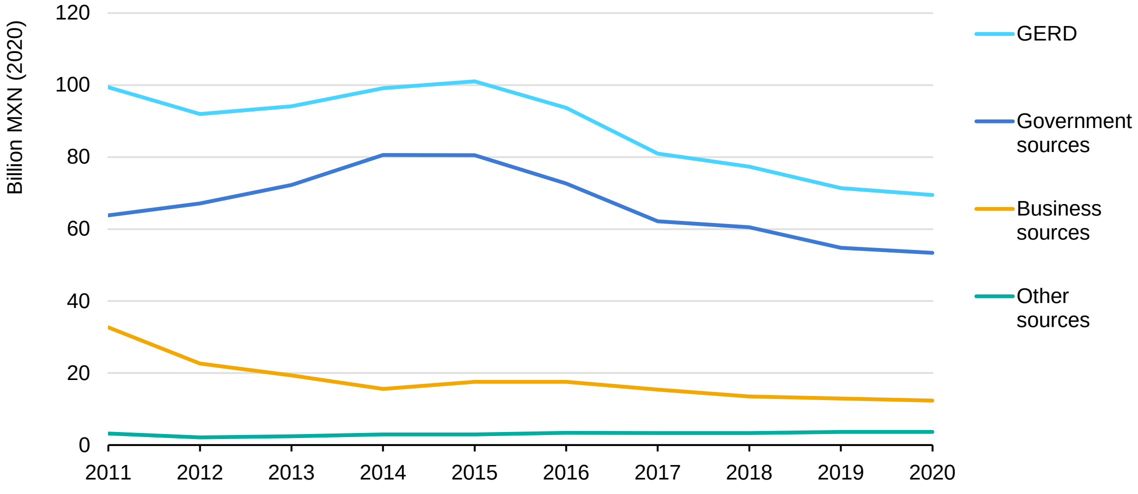
Innovation context

In the 2023 Global Innovation Index, Mexico ranked 58th in the world, a position that the World Intellectual Property Organization (WIPO), the author of the Global Innovation Index, considers to be consistent with its level of development. Among its peers, Mexico ranks 11th in the upper-middle-income category and 3rd in the Latin America and Caribbean region. The Global Innovation Index, recognises Mexico's strengths in areas such as R&D, trade, market scale and diversification, high-tech manufacturing and exports, unicorn valuations, production and export complexity, and creative goods and services. However, it also notes some weaknesses in the institutional environment and operational stability for businesses, a less favourable business environment and policy framework, and slow labour productivity growth, among others. On science and technology innovation, the Global Innovation Index identifies the top science and technology clusters worldwide, of which Mexico City is in the top 232. In Latin America, Brazil is the only country with clusters in the top 100. Mexico City is in the top 232. In Latin America, Brazil is the only country with clusters in the top 100.

According to UNESCO's database on number of researchers (in full-time equivalent), Mexico had 384 researchers per million inhabitants in 2021, well below the Latin America average of 625 and the world average of 1 283. In terms of scientific publications, as of 2017, Mexico participated in around 0.81% of articles according to information from Scopus.

The General Education Law and the Science and Technology Law both require the government to allocate the equivalent of 1% of GDP to scientific research and technological development. However, in 2020, gross domestic expenditure on R&D (GERD) is estimated at almost Mexican pesos (MXN) 70 billion (Figure 9.2). This equates to just 0.3% of GDP, well below the 1% target (Figure 9.3). The main contributors to GERD are the public and business sectors, with the public sector playing a disproportionately large role. Since 2012, private sector investment in GERD has declined significantly, largely due to the removal of the fiscal stimulus for scientific research and technological development, which was intended to encourage business participation. By 2020, the private sector's contribution to science and technology activities in Mexico had fallen to less than 24% of total spending.

Figure 9.2 Evolution of spending on scientific research and experimental development in Mexico, 2011-2020

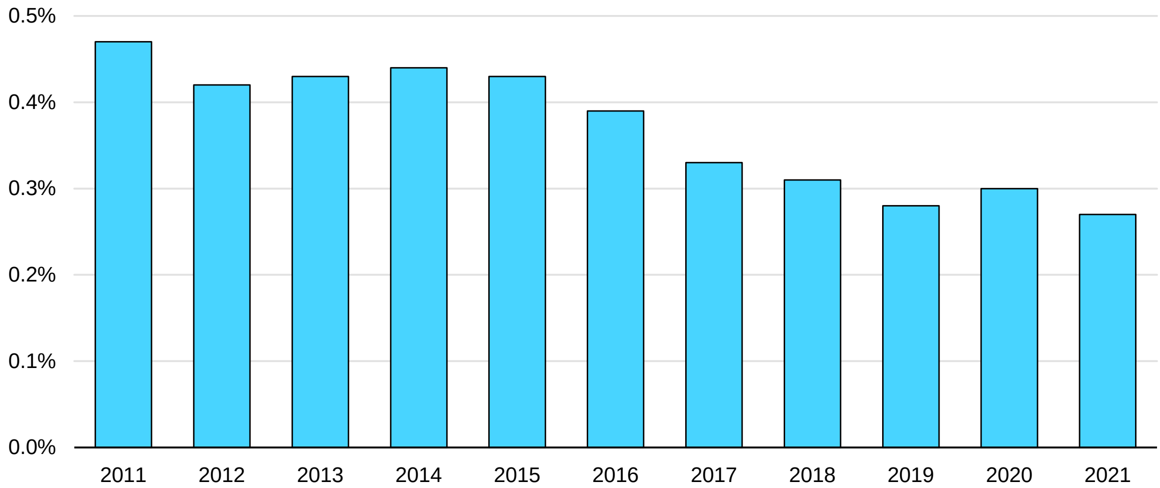


IEA and IITD. CC BY 4.0.

Note: GERD = gross domestic expenditure on R&D.
Source: Conacyt (2021), PROGRAMA Especial de Ciencia, Tecnología e Innovación 2021-2024. - Special Programme on Science, Technology and Innovation, 2021-2024.

There are 13 administrative branches with spending provisions in the federal expenditure budget that have allocations for GIDE. In 2020, the energy sector ranked third in terms of GIDE spending, accounting for 14% of the total, after allocations to the National Science Council and the education sector. Together, these three sectors accounted for over 86% of total government GIDE expenditure. Within the energy sector, the main recipients of public GIDE funds in 2020 were the Mexican Petroleum Institute (IMP), which accounted for 48% of the sector's expenditure; Petróleos Mexicanos (Pemex), with 31%; the National Institute of Nuclear Research (ININ), with 11%; and the National Institute of Electricity and Clean Energy (INEEL), with 10%.

Figure 9.3 Ratio of spending on scientific research and experimental development to gross domestic product in Mexico, 2011-2021



Source: World Bank (2024), Research and development expenditure (% of GDP) - Mexico.

In 2022, the Ministry of Finance and Public Credit (SHCP) proposed that for every MXN 100 of available public spending, MXN 16.8 would be allocated to education. Of this amount, MXN 2.9 would go to higher and postgraduate education, and only MXN 1 to science, technology and innovation. Although only 2% of the federal R&D budget was allocated to clean technologies, investment in science, technology and innovation increases by 4.2% from 2020 to 2021.

The case of solar PV distributed generation in Mexico

There are several policies and initiatives aimed at promoting distributed generation (DG) in Mexico as a means of meeting its clean energy goals and GHG mitigation targets, while improving electricity affordability. The first interconnection request for DG came in 2007, where the development of DG had been driven by interconnection schemes focused on self-sufficiency, through projects of up to 0.5 MW. The DG systems would exchange power with the grid, effectively storing it for use when demand was higher. Mexican regulations did not allow the sale of energy to the grid, so the scale of projects was limited to meeting their own energy needs. In 2014, the installed capacity of DG in the country was 64 MW.

DG first appears in energy legislation in the Law of the Electric Industry (LIE, by its acronym in Spanish) in 2014. There, it was defined as "the generation of electrical energy carried out by an Exempt Generator in a power plant interconnected to a distribution grid containing a high concentration of load centers". An Exempt Generator (EG) is one whose power plants have a capacity of less than 0.5 MW. They can be connected to the transmission or distribution networks to sell surpluses and purchase power, as long as the EG enters into an interconnection contract. Under the new regulatory regime, small generators can meet their energy needs and also sell energy to the grid. In addition to regulatory changes, response times for grid interconnection requests have been shortened.

As of Q2 2024, more than 450 000 interconnection contracts have been registered, resulting in an installed capacity of almost 4 GW, representing about 4% of the national installed capacity, with an estimated investment of more than USD 5.2 billion. Given Mexico's high levels of solar irradiation, approximately 99.4% of DG capacity is solar PV. While generators are free to choose their tariff regime, almost all opt for net metering, as opposed to other compensation mechanisms such as net billing or buy-all/sell-all models.[2]

Solar PV DG has the potential to significantly support Mexico's clean energy and emission reduction goals by enabling rapid deployment of renewable energy and offering potential savings on electricity bills. However, 99.5% of Mexico's approximately 41 million households currently receive some form of electricity subsidy. The only residential tariff that operates without subsidy is the High Domestic Consumption (DAC) tariff, which applies to users who on average consume above 500 kWh in each two-month period. Other residential tariffs are divided into seven geographical groups based on summer temperatures, with higher subsidies in regions with extreme temperatures to offset cooling costs. To illustrate the impact of these subsidies, the Mexican government estimated that it would spend MXN 575 billion (USD 25 billion) in 2022 on various mechanisms and subsidies to control inflation, of which MXN 73 billion would go to subsidise residential electricity consumption. In 2023, this amount allocated rose to almost MXN 77 billion.

[2] Net metering offsets the flow of electricity fed into and withdrawn from the grid during the billing period. Net billing assigns a value to the flow of electricity received and delivered to and from the grid, which may be different for purchases and sales. The buy-all/sell-all model assigns a sale value to the flow of electricity delivered to the grid.

Solar PV DG generally only provides economic savings compared to traditional grid-connected electricity for consumers under the DAC tariff. However, without the impact of subsidies, solar PV DG would be socio-economically feasible for most consumers. As the introduction of solar PV DG through innovative policy measures could reduce reliance on electricity subsidies and free up public funds for other critical needs in Mexico, several initiatives are exploring how to unlock this potential.

Deployment incentives

Regulatory mechanisms

Mexico has introduced several incentives to encourage the use of renewable energy, including distributed energy resources such as solar PV. One such incentive is the exemption of solar PV modules from import duties. However, in October 2015, the Tax Administration Service (SAT) reclassified solar PV modules into the 'electric generators' tariff category, resulting in a 15% tariff on module imports. In response, the PROSEC programme, introduced in 2018, allowed up to 3 660 solar PV modules per power company to be imported duty-free. In 2019, a court ruling reversed the reclassification, restoring the exemption of solar modules from import tariffs.

Mexico's Income Tax Law (Article 34, Fraction XII), enacted in 2013, further supports renewable energy by allowing a 100% tax deduction for investments in machinery and equipment used to generate renewable energy or efficient cogeneration systems. This benefit includes solar PV DG systems, thereby incentivising investment by allowing it to be deducted.

Another regulatory mechanism supporting the deployment of solar PV DG is that of Clean Energy Certificates (CELs), established under the Energy Transition Law (LTE) and regulated by the Electricity Industry Law (LIE). CELs are issued to Clean Energy Generating Units (CEGUs) that generate electricity from renewable sources. Each CEGU receives one certificate for every megawatt-hour (MWh) of clean energy produced, which can be sold to regulated entities, typically large electricity consumers, required by the LIE to purchase a certain number of CELs each year. By trading CELs, clean energy producers can access additional revenue, making solar PV DG projects more financially viable, particularly those in the medium-scale category.

Financial support programmes

Mexico has implemented several financial support schemes to promote the adoption of clean energy technologies, including solar PV DG systems. These include the Energy Transition and Sustainable Use of Energy Fund (FOTEASE), a public trust fund, and the Mexican Trust for Electricity Savings (FIDE), a private organisation that manages both public and private resources. Neither scheme is exclusively focused on solar PV DG.

FOTEASE

The Energy Transition and Sustainable Use of Energy Fund (FOTEASE) was created in 2009, based on the previous Law for the Use of Renewable Energy and the Financing of the Energy Transition (LAERFTE), known as the Energy Transition Law since 2015. FOTEASE had an initial budget of MXN 600 million. The objective of FOTEASE is to implement actions in line with the National Strategy for Energy Transition and Sustainable Use of Energy (ENTEASE) and to support the diversification of primary energy sources, promoting and incentivising investment in renewable energy and energy efficiency.

FOTEASE was built as a public trust fund, funded through the Federal Expenditure Budget. It has the purpose of "capturing and channelling public and private, national or international financial resources" to promote priority and strategic areas of national development, energy in this case. The FOTEASE has three main targeted focus areas: technological deployment of renewable energy or equipment to reduce the use of energy; provide a benefit to the society; and the development of human capital, generating knowledge and training for personnel in the installation, operation and maintenance of the equipment.

FOTEASE is designed to use competitive processes where possible to ensure that resources are allocated to projects that offer the greatest benefits for the amount invested. Likewise, it is supposed to ensure that the public contribution is the minimum necessary to make projects viable, considering other income and incentives that may be received. The allocation and distribution of the fund is intended to balance clean energy and energy efficiency project spending. Its financial instruments include grants, loans, loan guarantees and other forms of financial support.

In the latest report published by FOTEASE in 2023, there were 27 projects active at the end of 2022. Five projects were concluded in 2022. Several of the 32 projects were related to distributed energy resources, such as:

- Support for DG: Encourage the use of electricity generated from clean energy sources to meet the ENTEASE targets. Facilitated access to new distributed clean generation technologies by providing incentives for the purchase of PV systems and efficient combined heat and power. Developed a more competitive product market that allowed for lower prices for PV systems and efficient cogeneration. It had a budget of MXN 100 million (about USD 5 million).
- Massive Eco-credit Programme for Businesses: Supported micro, small and medium enterprises in accessing preferential credit to replace inefficient

equipment with new high-efficiency equipment, as well as promoting technologies that help reduce consumption from the grid, including solar PV DG.

- Installation of solar PV cells in primary schools: Installed PV systems in twenty primary schools to reduce their energy bills. Raised awareness of climate change mitigation, ecology and sustainability among students. The panels consisted of 21.5 kWh modules, reducing the schools' average demand on the electricity grid by at least 20%.
- Sustainable improvement of existing housing: Installation of technologies – such as solar PV systems, fast recovery gas heaters, solar water heaters, thermal insulation, efficient air conditioners, insulating windows and thermal films – in homes.

The "Bono Solar" (Solar Bond) programme, conceived and developed by Iniciativa Climática de México (a non-profit think-tank) and funded by FOTEASE, was designed to transform the existing electricity subsidy for low-income, low-electricity consumption households into a subsidy through a leasing mechanism to finance the installation of rooftop solar panels. Under this scheme, homeowners on subsidised electricity tariffs could make their roof available and lease solar panels from CFE, with monthly payments that could be around 15-20% lower than their current electricity bills. The homeowner received a rooftop solar PV installation with generation capacity 10% larger than their historical consumption, leaving CFE with a surplus of electricity. The aim of the programme was to help citizens become clean energy producers, selling surplus electricity to the grid at a lower cost than CFE's unsubsidised tariffs. This approach was intended to reduce household electricity bills and reduce Mexico's spending on electricity subsidies, freeing up public funds for other national priorities such as health and poverty reduction, while helping to reduce GHG emissions.

The programme set an ambitious target of reaching 4% of subsidised residential users, or about 1.4 million households, over a 15-year period. The first phase required an initial investment of MXN 985 million (USD 55 million) to cover the installation of 32 334 solar roofs. However, despite the potential economic and environmental benefits, the programme was ultimately cancelled due to several bureaucratic challenges. The programme has been recently revised and renamed "Hogares Solares" (Solar Homes) for implementation during the next presidential term from 2025.

The CSOLAR Fund, also designed by Iniciativa Climática de México and financed by the CSOLAR Guarantee Fund with MXN 96 million (USD 5 million) from FOTEASE, is designed to facilitate the financing of solar PV systems for small and medium-sized enterprises (SMEs) in Mexico. The programme focuses on the deployment of solar PV DG systems with capacities below 500 kW, targeting unsubsidised commercial and industrial users. Financing of up to MXN 15 million (USD 0.8 million) with a fixed annual interest rate of 13% (lower than typical market rates), which may be adjusted, is offered and has a maximum repayment term of seven years. Additionally, CSOLAR offers partial loan guarantees via Mexico's development bank, Nacional Financiera (NAFIN), in collaboration with local financial institutions that have solar PV portfolios. The programme uses Mexico's Reliable Supplier Initiative as a means of quality assurance and provides support to financial institutions for the creation of tailor-made solar PV financing solutions. Finance is complemented by educational campaigns to raise end-user awareness of the benefits of solar PV DG.

FIDE

Another notable player in the allocation and distribution of resources for clean energy technologies in Mexico is the Mexican Trust for Electricity Savings (FIDE), a private organisation with public-private participation created in 1990 by initiative of Mexico's state-owned "Comisión Federal de Electricidad" (CFE, Federal Electricity Commission). FIDE's mission is to develop and implement initiatives that promote the efficient use of electricity and the generation of renewable energy, thereby supporting both economic and social development. Through various support programmes, FIDE provides financial assistance for distributed solar PV generation projects, offering interest rates lower than those typically available in the market. For example, the "Eco-crédito Empresarial" programme offers SMEs a financing rate of 14.75% over five years for loans exceeding MXN 250 000. The "Paneles Solares para tu Casa" (Solar Panels for Your Home) programme provides a 25% grant from the Energy Secretariat and 75% financing at a preferential rate for five years, targeting low-income households in regions with extreme temperatures and high electricity bills.

In addition to financing, FIDE also offers the "Sello FIDE" (FIDE Seal), a voluntary certification that guarantees specific energy efficiency and safety standards. The FIDE label assures customers of a product's energy savings, maintenance requirements and expected lifespan. It is awarded to a variety of products, including lighting, appliances and solar PV systems, and has been widely adopted by prominent manufacturers. More than 600 companies have entered the Mexican distributed PV market, with most of their products certified under the FIDE label, whether produced by national or international companies. Solar PV modules bearing the FIDE Seal are also eligible for FIDE financing.

Although Mexico does not have a legal requirement for certification of solar PV DG module installers and maintenance services, several voluntary certifications have been developed. The National Council for Standardisation and Certification of Work Competencies (CONOCER), a sectoral body under the Ministry of Public Education, has issued several certifications aimed at professionalising the sector. These include Competence Standard EC0586.01 for the installation of PV systems in residential, commercial and industrial buildings, and Competence

Standard EC1181 for the supervision of such systems. For example, EC0586.01 outlines the main responsibilities of installers working with low-voltage (up to 2 000 V) non-battery backed PV systems in residential, commercial and industrial environments. Various institutions, including FIDE, offer training to prepare workers to apply for these certificates.

Bridging deployment needs and innovation aspirations

Mexico's solar PV DG sector is facing the challenge of supporting the rapid expansion of renewable energy while simultaneously driving technological innovation. The current policy landscape offers preferential support for market deployment through financial incentives, CELs and a favourable regulatory framework. However, this focus on expansion can overshadow the need for technological advancements that could improve system efficiency, lower costs, and enhance integration with the national grid, while creating jobs and broader economic welfare for society as a whole. Without a stronger focus on innovation, the sector may miss out on the opportunities that innovation could bring to the country. While Mexico has made impressive progress in deploying distributed solar PV systems, its capacity for technological innovation in this field appears to be underdeveloped. Despite various financial and policy support mechanisms to drive market growth, few schemes explicitly support technological innovation, something that could make Mexico more competitive in the global clean energy market.

R&D efforts have been modest, although the Mexican Energy Innovation Centres (CEMIEs) have worked in this area. The CEMIEs, created by the Conacyt-Sener-Energy Sustainability Fund, were designed to create innovation alliances to address scientific and technological challenges related to the sustainable use of energy. Among the various CEMIEs, which cover wind, geothermal, ocean and biomass energy, CEMIE-Sol focuses specifically on solar technologies. Like its counterparts, CEMIE-Sol was created to overcome the scientific and technological barriers within Mexico's energy sector. These centres aim to foster collaboration between academia and industry, promote R&D efforts and build human capital. While these initiatives may contribute to the long-term growth of the sector, their focus on capacity building has not yet led to significant technological advances, largely due to limited public and private funding and weak links between academia and the private sector.

In addition to the CEMIEs, Mexico has launched the "Investigadoras e Investigadores por México" (Researchers for Mexico) programme, led by the country's Science Council. This initiative places PhD scientists in public institutions and promotes collaboration between academia and the public sector. It evolved from the 2014 "Cátedras Conacyt" (Conacyt Chairs) programme that aimed to attract young doctoral graduates to research centres and universities. In 2023, it was updated with a mandate to place doctoral graduates in federal public administration institutions to improve the dissemination of scientific and technical knowledge, inform policy development, and encourage science-based public policy implementation. Unlike researchers in academic institutions, those placed in public administration are not required to publish scientific papers. Energy is one of the three priority areas of the programme.

Public funding mechanisms such as FOTEASE include goals to support technological innovation, but their main focus remains on broader clean energy deployment and capacity building. While these efforts can indirectly support innovation, they are not specifically designed to drive technological improvement. Instead, the focus is on the efficient deployment of clean energy systems, with less direct support for advancing new technologies. Programmes such as PROSENER have recognised the critical need to promote science, technology and engineering to develop supply chains for the manufacture of clean energy equipment. However, the level of direct added value in Mexico's solar PV supply chain remains relatively low. Although the country has some capacity to manufacture solar PV modules, it imports most of the high-value components, particularly PV cells. There is an opportunity for Mexico to improve its domestic manufacturing capacity and increase value added within the supply chain.

There is great potential for Mexico to improve its solar PV innovation through increased collaboration between the academia, public sector and the industry and the expansion of domestic manufacturing capacity, particularly in higher value-added segments. The growing use of smart grid technologies and energy storage solutions also presents an opportunity for Mexico to improve the efficiency and feasibility of integrating solar PV DG. As the country continues to build its clean energy manufacturing sector, it has the potential to develop its own solutions tailored to the local market. This hands-on approach, combined with more targeted investment in R&D and innovation in DG technologies, could enable Mexico to strengthen its position in the global clean energy supply chain and ultimately become a leader in solar PV technological innovation, particularly given its proximity to some large markets such as the United States.

Findings

Mexico's strong manufacturing sector, currently ranked 7th in the world for manufacturing output, provides a solid foundation for expansion into clean energy technologies. Mexico's expertise, skilled workforce and capabilities in sectors such as automotive manufacturing are highly transferable to clean energy technologies, including solar PV. A manufacturing base in a fast-moving technology area can be a source of learning-by-doing, incremental innovation in components and final products, and spin-off businesses. However, such outcomes are less likely in the absence of functioning innovation ecosystems.

Over the past decade, Mexico's policies and favourable regulation have driven the deployment of DG, particularly solar PV, from 62 MW in 2014 to nearly 4 GW by the first half of 2024. This represents around 4% of the country's total electricity generation capacity today. Mexico is internationally competitive as a major manufacture of mass-produced high-tech products, yet the rapid deployment of solar PV was achieved via imports and was not accompanied in the first decade by investments in domestic manufacturing to meet the rising solar PV demand. However, the consistent year-on-year growth spurred the emergence of numerous small distribution companies specialising in the installation and maintenance of solar PV systems. While policies were effective in incentivising deployment, they were not complemented by policies to enhance Mexico’s technical capabilities in the sector, for example through R&D and projects involving academia, public institutions and the private sector, including projects with a social perspective.

As trade tensions between the United States and China have increased and with the passing of the US Inflation Reduction Act in 2022, Mexico investment in solar PV manufacturing capacity has increased. By 2023, domestic solar PV module manufacturing capacity had surged to 2.5 GW per year, driven by Mexico's established manufacturing capabilities and strategic proximity to major markets such as the United States. This growing capacity positions Mexico as a potential key player in the global clean energy supply chain, creating opportunities for innovation through learning-by-doing, as the manufacturing base can support innovation under the right conditions. Near-term opportunities may be more closely related to components, manufacturing and assembly, which can evolve into more sophisticated innovations over time.

By capitalising on its comparative advantages in manufacturing and access to the North American export markets, Mexico has an opportunity to enhance the contribution of clean energy exports to its GDP and make a more substantial contribution to global clean energy technology markets. In 2021, its imports of solar PV cells and modules, at USD 1.3 billion, far exceeded its exports, at USD 140 million. By steadily strengthening its innovation ecosystems for products such as solar PV, electric vehicles and lithium-ion batteries, Mexico could capture a higher share of the value in these supply chains. This would be in line with the government's stated priority of strengthening the country's innovation capacity overall. Among other measures, this could be supported by aligning its R&D spending with international benchmarks and increasing the number of researchers. Currently, Mexico has half the number of researchers per million inhabitants than the Latin American average. By integrating energy technology innovation into its development strategy, Mexico could unite developmental goals, such as reducing energy poverty, with industrial and environmental policy objective. Furthermore, Mexico’s renowned capabilities in public policy evaluation, supported by long-standing and experienced institutions in conducting them, would be likely to give it an advantage for learning the lessons of addressing these overlapping objectives and honing its approach.

10. Renewable energy in Morocco

Soukaina Boudoudouh (L'Institut de Recherche en Énergie Solaire et Énergies Nouvelles)

Morocco's national energy strategy has evolved rapidly to meet the policy challenge of increasing energy demands, environmental commitments and reliance on energy imports. As an emerging economy with limited fossil fuel resources, Morocco has focused on developing sustainable and local energy sources and has set ambitious targets to spur investment in renewable electricity. This is exemplified by the successful development of the world's largest concentrating solar power (CSP) plant in 2016, as well as a range of efforts in energy efficiency. As Morocco has moved into new technology fields, including solar PV, hydrogen and batteries, it has been guided and supported by new institutions, including the Institute for Research in Solar Energy and New Energies (IRESEN), which focuses exclusively on R&D and innovation related to renewable energy.

IRESEN has ensured that the strategic goal of technology leadership has received sufficient attention in alignment with the national vision for renewable energy. It has come to play a central role in research and innovation in renewable energy in Morocco and also in international co-operation. It develops pilot projects and facilitates collaboration between academia and industry. This institutional innovation has been highly successful and demonstrates the value of fostering technical expertise within government and co-ordinating the actions of academic and private actors. However, this model has also raised challenges of financial continuity.

Country context

Morocco is the third-largest economy in North Africa by GDP and the third-largest in terms of population. It is classified as a lower middle-income country, and has per-capita national income 45% higher than the average of all lower middle-income countries and just 18% lower than the upper middle-income threshold. Its economy has expanded robustly in the past two decades at an annual average rate of 3.8% between 2000 and 2021, although the rate has been below that average for the period since 2010 at 2.8%.

Progress in diversifying the economy and boosting growth has been hit in recent years by several crises, including the global pandemic, inflationary pressures, commodity price volatility and the Al Haouz earthquake in 2023, as well as tightening global financing conditions. Nonetheless, Morocco has demonstrated a capacity to respond to shocks in recent years. It managed the humanitarian response to the earthquake and has a development plan to unlock the development potential of the most affected provinces.

More broadly, foreign direct investment has consistently flowed into Morocco in recent years and is increasingly directed towards the manufacturing sector. Various modern industrial niches well connected to global value chains have emerged and the country maintained access to international capital markets despite the ongoing tightening of global financial conditions. Exports of cars rose 27% in 2023 to USD 14 billion.

The European Union is Morocco's largest trading partner. In 2022, 56% of Morocco's exports went to the European Union and 45% of Morocco's imports came from the bloc. EU imports from Morocco amounted to EUR 22.9 billion, and were led by transport equipment (23.5%), machinery and appliances (21.2%) and textiles (14.3%). EU exports to Morocco amounted to EUR 33.3 billion. They were led by machinery and appliances (21.2%), followed by mineral products (15.5%) and transport equipment (11.1%).

In the global context, Morocco’s human development index score is relatively strong and has risen continually since 1990. It ranks 120 out of 189 countries on this measure, just one place below the “high human development” category. Morocco is a parliamentary constitutional monarchy, whereby the king has some powers to appoint the prime minister and guide policy, in addition to the elected government.

Energy sector context

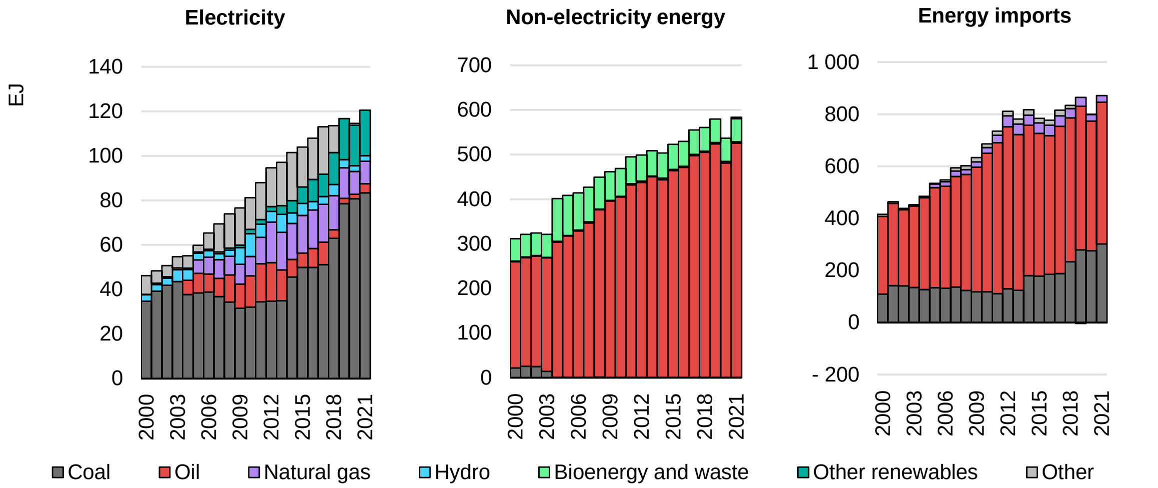
Morocco’s energy system is dominated by coal and oil, and it imports more energy each year than any other African country. In 2021, 89% of Morocco’s final energy needs were met by imported fossil fuels, mostly oil. This makes its economy particularly vulnerable to fluctuations in global oil and gas prices. The country’s energy demand has risen steadily over the past two decades, with electricity demand rising faster than GDP, at an annual average rate of 4%, and other energy uses rising at 2%, more slowly than GDP. As a result, Morocco’s CO_2 emissions from fuel combustion are on an upward trend, rising at an average of 3.5% per year since 2010 and reaching 67 million tonnes in 2021. These CO_2 emissions come almost exclusively from the burning of imported fuel, which is often used in inefficient conversion technologies – coal-fired power plants and internal combustion engines. This means that significantly more energy content is imported than is required to replace the same fossil fuels with domestic electricity sources, including for use in electric vehicles. This brings a double dividend of lowering import bills as well as emissions.

The Ministry of Energy Transition and Sustainable Development (MTEDD) is responsible for Morocco's energy policy. It is accountable for security of supply, energy market rules and authorising and supervising projects. It has a mandate to promote energy efficiency and renewable energy. MTEDD oversees the Office National de l'Électricité et de l'Eau Potable (ONEE), which is a legally and financially autonomous public entity with monopoly ownership of the electricity transmission system. It generates around one-third of the country's electricity and is involved in the purchase and sale of all electricity sold via the national grid. In 2008 a law was passed to create an Energy Development Fund.

Morocco has made significant strides in providing universal access to electricity, to the extent that it is no longer a major policy focus for the country. This milestone was achieved in 2017, marking a critical success in the nation's energy policy. This achievement distinguishes Morocco from several other countries on the African continent and highlights its commitment to improving living standards and fostering economic development through reliable energy access. The completion rate of the Global Rural Electrification Programme had reached 99.85% by the end of 2022.

In 2009 Morocco made the strategic decision to maximise the use of its domestic renewable resources to increase energy security and limit CO_2 emissions. The 2009 National Energy Strategy committed the country to increasing the share of renewables to 42% of electricity capacity by 2020 and improving energy efficiency by 12% by 2020 and 15% by 2030. This is in the context of the united goals of sustainable development, energy security and independence from fossil fuel imports. The renewables target was further broken down into 2 GW of solar, 2 GW of wind and 2 GW of hydropower. At the time, Morocco's installed solar and wind capacity was around 0.2 GW in total, while hydropower was at 1.8 GW. This strategic shift has led to significant changes in Morocco's electricity mix, with renewables reaching 19% of total generation in 2021 (Figure 10.1). Solar and wind electricity have almost entirely displaced the use of oil in electricity generation, which reached a high point in 2012 and declined to just 3% in 2021, and imports of electricity. However, solar and wind have not yet compensated for lower hydro output in recent years, or the lower imports of natural gas in the recent higher-price environment – these changes have so far been covered by more coal-fired power generation.

Figure 10.1 Energy sources for electricity and other uses, and imports, Morocco, 2000-2021



Notes: Electricity and non-electricity energy are shown on a final consumption basis. Imports are shown net of exports. “Other” refers to imports or exports of electricity.
Source: IEA (2024), World Energy Balances.

The 2009 National Energy Strategy has been complemented by successive legal instruments to enable investment towards its achievement:

- Law 13-09 (2009) mandated the national grid operator with facilitating the feed-in of renewable electricity and its export to other countries.
- Act 02.09.410 founded the Société d'Investissements Énergétiques (SIE) to manage the Energy Investment Funds and facilitate the diversification of energy resources and the promotion of renewable energy and energy efficiency.[1] SIE’s budget is capitalised by MTEDD and the Hassan II Funds, which were created in 2000 to support social and economic development.
- Law 54-14 (2014) allows owners of capacity above 300 MW to sell electricity that they do not self-consume to ONEE.
- Law 48-15 (2015) established a National Authority for the Regulation of the Electricity Sector (ANRE). It also more than doubled the 2030 solar and wind capacity targets, to 4.6 GW for solar and 4.2 GW for wind.
- Law 39-16 (2016) established the National Agency for Energy Efficiency (AMEE) under the auspices of MTEDD, to be responsible for implementing energy efficiency policy, including regulations, incentives and awareness campaigns.

Energy price reforms are ongoing to reduce the fiscal burden of consumer energy subsidies. Since 2000 the government has covered the difference between fixed energy tariffs and the cost-recovery rates. While the subsidy was one of the lowest

[1] In 2023 the name of SIE was changed to Société d’Ingénierie Énergétique and given a narrow focus on investment in energy efficiency as a “Super ESCO” (energy services company).

in North Africa and the Middle East, it still exerted pressure on the national budget and reforms began in 2014 to partially index prices to fuel costs.

Morocco's 2021 update of its NDC, submitted as a signatory to the Paris Agreement, raised the renewables target to 52% of total installed electricity capacity by 2030. This is in the context of an unconditional target to reduce greenhouse gas emissions to 18.3% below business as usual by 2030 and a target of 45.5% below business as usual by 2030 conditional on receiving international assistance. Its conditional measures include reducing the emissions intensity of the cement industry through carbon capture and storage equivalent to 2.5% of the total reduction, or 20% of the emissions from the economically important phosphate sector. Morocco is estimated to hold approximately 75% the world's phosphate reserves.

Active areas of energy policy development in Morocco today include:

- Continuing to expand electricity capacity to meet growing demand.
- Strengthening energy links with Europe and sub-Saharan Africa, including through electric interconnection projects and strategic partnerships.
- The possibility of constructing a liquefied natural gas terminal for diversifying natural gas imports.
- Managing water stress and land degradation, which are being exacerbated by high vulnerability to climate change, as well as energy sector resilience to climate change.
- Managing urban air pollution.

Innovation context

Morocco has a well-developed research system relative to many of its peers in North Africa and among emerging economies. It is currently ranked 70 out of 132 countries in the Global Innovation Index and eighth among 37 lower middle-income countries. Within the last decade it has risen more than 20 places on this scale, partly due to an above-average ability to convert limited inputs into impactful outputs. One reason is its network of universities with science and engineering research departments that have dependable government funding. The Ministry of National Education, Vocational Training, Higher Education and Scientific Research is responsible for policy related to fundamental and applied research in universities and research centres. It works closely with other ministries, including MTEDD, to promote innovation and is subject to the financial control of the Ministry of Economy and Finance. The National Centre for Scientific and Technical Research coordinates the research programmes of universities and scientific institutions, and is also responsible for establishing and maintaining connections and collaborative programmes with research institutions in foreign countries.

The country has pursued a strategy of innovation through applied R&D since 2000, with an objective to reduce Morocco's dependence on imported technology, move up value chains to capture more of the added value and create a dynamic environment for industrialisation. To this end, the Hassan-II Academy of Science and Technology, a learned society under the responsibility of the prime minister, has been given responsibility for setting the general orientation for scientific and technological development, funding scientific and technical research programmes, and integrating scientific and technical research into national and international collaborative activities. A Permanent Inter-Ministerial Committee on Scientific Research and Technological Development is chaired by the prime minister and co-ordinates technology innovation activities across government, with the contribution of MTEDD on energy topics.

The importance of two new technology-related institutions in Morocco: MASEN and IRESEN

The 2009 National Energy Strategy sought to position the country as a leader in renewable technologies within Africa, in addition to setting energy security and environmental ambitions. This clear technology-related goal distinguishes Morocco's renewable energy policies from those of most of its peers in lower middle-income countries. By developing its expertise and capacity in this sector, the country aimed to seize the opportunity to export know-how and strengthen its economic and political ties with other nations. In addition, by positioning itself in this way, the government viewed its renewable energy strategy as a means of strengthening its attractiveness to foreign investors. The electricity sector in particular needed sizeable investment to modernise and keep pace with economic growth.

The intrinsic link between the 2009 strategy, the reduction of uncontrollable and high fuel import bills, and the nation's economic future created a strong alignment with the national vision. Compared with other countries, Morocco did not have a politically powerful incumbent fossil fuel production industry that was threatened by the turn towards renewables and this helped build consensus. In the Moroccan context, the public support of the king for this strategy was critical for generating momentum behind the targets. However, given that the costs of solar and wind technologies were at the time high compared to fossil fuels, there remained some scepticism among the public and within government departments about the risks of higher-than-expected economic costs.

One of the first acts in the implementation of the 2009 strategy was the creation of two new institutions to co-ordinate and undertake projects in the renewable energy area. It is notable that Morocco decided to use two new bodies entirely dedicated to low-emissions energy development rather than giving responsibility for renewables to existing entities. The two new institutions were:

- The Moroccan Agency for Sustainable Energy (MASEN), which has responsibility for the deployment and operation of commercial-scale technologies.
- The Institute for Research in Solar Energy and New Energies (IRESEN), which has responsibility for technology analysis and R&D.

To bring solar electricity online on a large scale and with maximum compatibility with the existing electricity grid, MASEN was given responsibility for developing a CSP project and, one year after its creation, signed a power purchase agreement with a private sector project developer from Saudi Arabia, which also provided USD 126 million in debt and equity. The final investment decision for the initial 160 MW plant was taken quickly in 2013, with USD 800 million of financing secured at preferential rates from international partners.[2] It also secured USD 20 million in equity from the International Finance Corporation. The finished power station was connected to the grid in 2016, having cost Moroccan Dirham (MAD) 7 billion (USD 855 million), just 60% of the amount appraised by the World Bank in advance.

It has since been expanded twice with further support from international development finance. The aggregate CSP capacity is now 510 MW, making it the largest such plant in the world. In a 2014 assessment, the World Bank noted that its finance was justified in the global interest because the project could potentially contribute to halving CSP costs worldwide in the following years and because Morocco had a preference for power generation that could be dispatched in the evening as well as during the day.

Technology-related input to energy policy from IRESEN is highly valued by the government

The mission of IRESEN at its founding was to fill a gap in applied research and technological development in renewable energy in Morocco, including undertaking pilot projects and building prototypes to test and validate technologies before large-scale investment. It was a direct response to the needs identified in the 2009 strategy to develop internal skills and try to ensure lowest-cost technology choices. This function was important in the context of a lower middle-income country with high energy price sensitivity due to significant proportions of low-income households and manufacturing in the economy. Politically, an institution with a

[2] Financing partners included the World Bank. European Investment Bank, l'Agence Française de Développement, African Development Bank, Kreditanstalt für Wiederaufbau, the German Federal Ministry of the Environment, Nature Conservation, Building and Nuclear Safety, and the European Commission.

mandate to develop domestic capabilities and monitor the cost of renewables was useful to gain consensus around the overall 2009 strategy.

IRESEN is under the aegis of MTEDD and, while solar electricity was the initial priority, it has a mandate to explore technology topics relevant to all renewable energy sources and enabling technologies. It is also responsible for collaboration between national research institutes and engagement in relevant international forums. It has several means of supporting R&D and technology innovation. Its model is a hybrid between the operations of a funding agency and that of a research institute. It has a particular focus on collaboration between researchers, institutions and the private sector, with the objective of strengthening the overall energy innovation ecosystem in Morocco.

As regards knowledge management at IRESEN, it manages a network of research and innovation platforms across Morocco, equipped with state-of-the-art laboratories to foster collaboration between academia and industry on technologies well-suited to the national and continental context.

It has several resource push initiatives, which include the following:

- Operating a funding agency that organises competitive calls to finance R&D projects of around USD 0.1-0.5 million at research institutions or between universities and companies, while incorporating socio-economic factors whenever feasible (Table 10.1). Calls have included: INNOTHERM (2012, 2013 and 2014) for enhancing the efficiency and installation of CSP; INNOPV and INNOWIND (2013 and 2014) for developing designs that could fit well with Morocco's existing electricity infrastructure; INNOBIOMASS (2014) to explore more sustainable processes for bioenergy conversion; and INNOPROJECTS (2015) for high-potential early-stage technologies, including energy storage and other topics.
- Operating a funding agency that organises competitive calls for collaborative projects that take promising technologies to the stage of product development. Calls have included: GREEN INNO-PROJECT (2018) for collaborations between an academic partner and industrial entity on projects at or above technology readiness level 3; and GREEN INNOBOOST 2.0 (2018) for collaborations between a start-up, an academic partner and industrial entity on projects at or above technology readiness level 6. GREEN INNOBOOST 2.0 is notable for the creativity of funding design to target capital-constrained innovators who could choose to receive the funding either as a non-dilutive grant or an equity investment from IRESEN, in addition to access to a 1.5-year programme of business services, public procurement support, connections with Moroccan experts and access to research infrastructure including the Green Energy Park. The funding can be used for a variety of purposes: to acquire equipment, test and certify the prototype, pay staff or buy consultancy.
- Training future engineers and project managers, and funding doctorates and post-doctoral research.

- Establishing dedicated infrastructure for technology testing, including the Green Energy Park and Smart Buildings Park. The Green Energy Park, a joint venture between IRESEN and the Université Mohamed VI Polytechnique created in 2017, includes dedicated facilities for piloting solar PV and smart grid technologies and a laboratory environment that encourages interaction between researchers, project developers and the private sector.

IRESEN also undertakes actions to build socio-political support. For example, it inaugurated the Solar Decathlon Africa exhibition and competition with Mohammed VI Polytechnic University, MTEDD and the Department of Energy. It was held first in 2019 and raised public and policy maker awareness of the benefits of renewable energy and sustainable construction, leading to pilot projects, the creation of specialised research laboratories and strengthened academic collaborations. The IRESEN research infrastructure of the Smart and Green Building Park arose from this initiative. Projects inspired by Solar Decathlon Africa include work on energy management systems, next-generation PV panels, phase-change materials and energy storage. Solar Decathlon Africa boosted international co-operation, especially within Africa.

Table 10.1. Selected R&D projects funded by IRESEN to date

Project	Description and outcome
BioF2S	Development of solar hydrothermal carbonisation for converting waste from olive oil production to solid biofuels. The project proved the concept.
Ecomataf	Development of a process to produce construction blocks from local bio-based or recycled materials to achieve good thermal properties.
EV plan	Development of tools for city planners promoting EVs to identify areas with high EV acceptance and size charging facilities in line with demand and grid infrastructure. It also explores grid-friendly charging models.
Li-Sol	Development of a residential energy storage system that integrates with solar PV and has intelligent energy management algorithms connected to cloud services for customers. The result of the project has been spun-off as a start-up selling a package including a solar PV system, charge controllers, batteries and a control interface that can also enable backup power from the grid. The aim is to produce 100 units per year initially and maintain a rate of local equipment content of over 85%.
MCS Bitume	Development of an industrial-scale pilot facility to keep 40 tonnes of bitumen at 150°C using solar concentrators, and a feasibility study to scale up to 3 000 tonnes. The project proved that using solar could reduce fuel costs.
TahalaGrid	Development of a micro-grid demonstration encompassing eight public buildings for solar PV, solar hot water and load management integration.

IRESEN has provided a platform from which to explore opportunities for hydrogen energy

Morocco has high ambitions for hydrogen energy. It has multiple co-operation agreements with international partners to explore opportunities related to the country's extensive renewable resources and its proximity to export markets in Europe. When IRESEN was established, hydrogen was not a priority topic. However, IRESEN's flexibility and initiative in identifying new prospects was key to Morocco's readiness to engage internationally as the topic gathered high-level political interest in Europe from 2019 onwards.

IRESEN's first formal work on hydrogen was in 2018. Its interest in the topic was stimulated by its co-operation with Morocco's large industrial companies, of which the state-owned OCP Group is the biggest employer in the country. OCP Group is active in phosphate extraction and fertiliser production, which requires it to import large quantities of ammonia each year because Morocco does not have sufficient access to the natural gas typically used to produce the hydrogen needed to make ammonia. As OCP Group and IRESEN explored the opportunities for the company to use renewable energy, the electrolysis of water to produce hydrogen in Morocco surfaced as a potential research topic. In 2018 IRESEN and Fraunhofer IMWS – its German research partner – directed their co-operation towards hydrogen with a technical feasibility study of piloting ammonia production using renewable electricity and brought it to the attention of MTEDD. The study assessed Morocco's potential for hydrogen production from renewable electricity and its export.

In 2019 a National Hydrogen Commission was established, chaired by the minister of energy and including IRESEN alongside the Ministry of Economy and Finance, Ministry of Industry, Trade, Investment and Digital Economy, ONEE, MASEN, the National Office of Hydrocarbons and Mines, OCP Group and the National Higher School of Mines. IRESEN was charged with developing a Green Hydrogen Roadmap, which was published in 2021. With the technical capabilities and national co-ordination already established by IRESEN, the development of the roadmap did not require support from international bodies, unlike the case for hydrogen roadmaps in some other emerging market countries, and it drew on Moroccan perspectives only. The roadmap outlines Morocco's technical potential for hydrogen production from renewables and a strategic pathway to installing enough capacity by 2050 to satisfy domestic demand and establish Morocco as a prominent export hub to Europe. The roadmap also outlined stepwise R&D and pilot projects that would be needed for different applications of hydrogen, starting with ammonia production.

The roadmap identified Morocco's need to attract investment through public–private partnerships and international co-operation. In 2021 IRESEN and the OCP

Group established GREENH2A as a platform to spearhead R&D in hydrogen and related technologies to foster innovation.

From IRESEN's initial exploration into hydrogen, it took just four years to achieve full alignment with the national vision of the future. In November 2022 King Mohammed VI announced a significant investment programme by the OCP Group, including USD 13 billion to enhance the country's renewable energy capabilities towards production of hydrogen and ammonia. This initiative is part of Morocco's broader efforts to end reliance on imported ammonia, which became much more expensive in the aftermath of Russia's invasion of Ukraine in 2022. The programme aims to support local industries by requiring 70% of the components, materials and services to produce hydrogen and ammonia to be sourced from within Morocco, creating 25 000 direct and indirect jobs and involving 600 Moroccan companies. In 2023 King Mohammed VI announced a further initiative called The Morocco Offer to speed up the deployment of hydrogen technologies and create incentives for investment. Reaching these high-level announcements was undoubtedly facilitated by the foundation that the government had built from 2011 with the creation of IRESEN, which had the flexibility to pursue and explore arising topics related to renewable energy.

IRESEN continues to pursue this area and has recently launched a project call with French research institute SATT Paris-Saclay. The call is dedicated to fostering innovation in hydrogen from renewable electricity between 2024 and 2027 by jointly supporting two to three consortia of three research partners from both countries. It will draw upon SATT's specific expertise in bringing the fruits of research to market.

Battery-related R&D could lead to investment in the EV supply chain and use of local resources

Battery R&D for high-performance lithium-ion designs was among the first projects funded by IRESEN in 2012. The projects undertaken have tested the use of Moroccan mineral resources (especially phosphates, of which it has the world's biggest resources), creating laboratory prototypes, scaling up production to semi-pilot levels, and comparing the performance of these batteries with commercial counterparts in solar PV systems.

As with hydrogen, electric mobility was not a priority topic when IRESEN was created in 2011. However, as the EV market has expanded globally, there has been dramatic market growth for lithium iron phosphate (LFP) batteries, the type that was researched by IRESEN and which could rely on domestic phosphate as a raw material. These batteries may not have the same energy density as other designs, but they have long lifespans and less reliance on mineral inputs from countries about which there are supply chain or sustainability concerns. IRESEN's early work in the area of LFP batteries showed that Moroccan designs had promising properties. This led to the OCP Group launching several initiatives, including R&D to further enhance efficiency and durability, as well as partnerships with international companies and research institutions. The outlook for the EV market has strengthened – it is now projected that global sales will pass USD 1 trillion per year by the early 2030s, with batteries representing the largest single cost component. Consequently, IRESEN started pilot projects to explore the feasibility of LFP battery production in Morocco, which could support a transition to EVs for the existing producers of internal combustion engine vehicles and components in the country. Renault, Stellantis, Sumitomo, Varroc Lighting Systems and Valeo operate in Morocco, and Hyundai may join them. Chinese electric carmaker BYD has been considering opening a factory in Morocco since 2017. In 2023 LG Chem, a Korean chemical company, and Hauyou Group, a Chinese industrial company, announced an agreement to make LFP batteries in Morocco, including conversion of imported raw lithium. This is in part because, since 2022, Morocco's free trade agreement with the United States makes Moroccan-produced batteries eligible for US sales subsidies when exported to the United States. In 2024 Chinese firm Gotion, backed by Volkswagen, confirmed investment in another battery factory in Morocco, which could potentially use cobalt mined in Morocco, and another Chinese firm BTR New Material announced plans for a LFP battery component factory in Morocco.

The OCP Group plays a crucial role in Morocco's industrial development and has recently shown interest in the production of LFP batteries due to the increasing demand for sustainable energy solutions. This interest is driven by the abundance of raw materials, particularly Morocco's significant phosphate reserves, a key component of LFP batteries. The OCP Group has launched several initiatives to enter this market, including investment in R&D to enhance the efficiency and durability of LFP batteries, and strategic partnerships with international companies and research institutions to leverage their expertise. Pilot projects are also underway to test the feasibility of LFP battery production in Morocco.

IRESEN was closely involved in producing the roadmap for electric mobility in Morocco, which outlines a plan for a charging network, charging standards, incentives for vehicle uptake and international co-operation to learn from experiences overseas. Alongside market pull policies, the roadmap highlights the importance of funding R&D for technology innovation. It also proposes socio-political support policies such as public awareness campaigns about the benefits of EVs. In 2023 the World Bank published Unlocking Electric Mobility Potential in the Middle East and North Africa (MENA), with a focus on Morocco and input from IRESEN. The report broadly supports the roadmap recommendations and could lead to further World Bank finance to tackle challenges including technical standards, electricity sales regulation, charging station profitability and a technical platform for integrating the various stakeholders' data needs.

While much of the work on LFP has shifted to OCP Group-led projects (via Innovx, an OCP Group subsidiary established for the purpose), IRESEN's R&D in the area has focused strategically on charging technologies. This is in part because the market in Morocco is not yet big enough to attract any of the major international EV charging providers. The R&D has resulted in the creation of a start-up, iSmart, to commercialise a charging station fully designed and developed by IRESEN at the Green Energy Park. It includes technical advances in charging infrastructure. iSmart started its first production line in 2021 and now has two production lines to meet growing demand. The startup plays an important role in IRESEN’s Green Miles project, which aims to identify optimal locations for these stations to maximize their utility and accessibility. Sale of iSmart’s business could help IRESEN reinvest in new projects in new technology areas.

IRESEN has become a strategic foundation for clean energy knowledge and international co-operation

IRESEN initially received a budget for ten years of operation and this was extended for an additional 6 years in 2021. This reflects the value it has created for Morocco’s policymaking and its success in raising complementary funds. Between 2012 and 2019 most of IRESEN's resources came from foreign donors (57%), comprising 60% bilateral funding and 40% other foreign co-operation agreements. The remaining 43% is from the national budget. The public grant was mostly used towards the project calls, while the money from external fundraising went mostly to establishing the research infrastructure.

IRESEN’s notable contributions to solar, hydrogen and electric mobility in Morocco are all considered to be of national strategic importance for local businesses and foreign direct investment. Its projects have led to 34 patent applications since 2017, and since IRESEN’s foundation in 2012, Morocco has built a much stronger clean energy technology ecosystem and has proven it can react to changes in the international technological landscape. One of the success factors has been the co-ordination of networks of excellence through dialogue with universities and industrialists to identify needs and challenges.

In the last few years, IRESEN has initiated international projects with governments in Africa. The first of these is in Côte d’Ivoire. The Green Energy Park – Morocco Côte d’Ivoire is a platform for testing solar energy technologies under semi-tropical climatic conditions at INP-HB in Yamoussoukro, Côte d’Ivoire. It will build on the Green Energy Park platform in Morocco and focus on the agricultural sector. As well as calls for projects to be undertaken at GEP-MCI, it will fund students from INP-HB and train industry professionals in the field of solar energy.

However, with the possibility that its public grant will not be fully renewed, and the culmination of many R&D projects without commercial products, IRESEN is exploring a new orientation to ensure its financial viability. It is developing a 2030 vision to become Africa's leading centre for applied R&D and innovation in renewable energy by 2030. This vision foresees IRESEN organising itself around a set of core themes aligned with national priorities and IRESEN's capabilities. Continued government funding is likely to be essential until 2030 to realise the vision, especially for the operational costs of infrastructure, but also to ensure partial financial autonomy and reduce reliance on the state. Several options are under consideration:

- Entering the business of selling services to private entities or international bodies. New commercially oriented activities could include certifying renewable components according to European and other standards (for example for solar PV technologies, batteries and electrolysers), feasibility studies, detailed engineering, site monitoring and inspection, and training. Given that the public sector is still present in most investments in renewable energy technologies in Morocco, these activities could also help to build essential private sector competences, help manage excessive financing costs and foster public support. IRESEN already has many contacts within industry that may wish to use such services.
- Generating revenue from supporting and investing in start-ups that emerge from the IRESEN ecosystem, including the Green Energy Park. The incubation and strategic support elements of GREEN INNOBOOST 2.0 could be expanded and equity could be offered, either with or without direct management involvement.
- Expanding the level of support for technologies at higher technology readiness levels, i.e. those that need specific resources to move from the laboratory to the market. Calls for projects would continue, but with extra emphasis on the part of the original mandate aimed at developing innovative products, services and processes that can create jobs in Morocco in solar PV wind, bioenergy, energy storage, hydropower, smart grids, sustainable mobility and energy efficiency. In some cases, this could involve continued support to ideas already explored at an early stage in the first decade of IRESEN.
- Licensing or selling intellectual property. To date, IRESEN has overseen projects that fully own patents and projects where a consortium shares the rights. It may be possible to raise money in future through a more strategic intellectual property strategy.
- Continuing to diversify funding sources via international co-operation, applying to overseas project calls and sharing some costs of R&D centres with the host regions than benefit from them.

Findings

The experience of IRESEN reveals several insights that are relevant to the encouragement of clean energy technology innovation in other emerging market and developing economies.

Firstly, local know-how is highly valuable when evaluating or procuring a new energy technology. As was discovered in Morocco for CSP, solar PV and EVs, products and projects often need adaptation to local conditions to be smoothly integrated with local infrastructure and the local context. IRESEN was able to play the role of "informed consumer" and develop complementary technologies to accelerate uptake, such as home electricity storage systems and EV chargers.[3] It is difficult for a government to support the achievement of an ambitious renewable energy target without informed opinions and expertise among decision-makers and in the domestic scientific community. While international partners can be very helpful, they may not always agree with each other or may not appreciate local nuances. Furthermore, international consultants can be very expensive.

While it may seem a bold move and requires a budget commitment, the creation of a dedicated institution for clean energy innovation can bring significant value. IRESEN was established at arm's length from MTEDD with a long-term mission to pursue technology in the interest of Morocco's national vision for economic development. IRESEN regularly evaluates the outcomes of its projects to inform policy makers and relevant institutions, enabling them to improve and see the benefits of investing in R&D.

A dedicated institution can become a focal point for a new network of researchers, companies and experts who have common interests and can work together. This tends to lead to expansion of this network, especially when backed by a government agency like IRESEN and an ambitious target for energy transitions that lends weight and credibility to the projects. The result in the case of IRESEN has been the creation of a strong national innovation ecosystem in the space of a decade. It can also act creatively in its design of interventions in a way that a government ministry might not be able to – IRESEN has developed smart new approaches to equity investment, international co-operation and research infrastructure.

Having a strong foundation in clean energy technologies has been shown to afford Morocco the opportunity to quickly enter new areas, such as solar, hydrogen and electric mobility. However, the impressive developments in these areas were conditional on IRESEN's flexible mandate and good alignment with national resources, including the strategic orientation of a major state-owned company (OCP Group) and domestic resources (solar radiation and phosphate). In cases where these capabilities align, it can be possible to rapidly develop new co-operative R&D projects and infrastructure with the industrial sector. In

[3] There is significant value in being an informed buyer of technology. The next 800 MW expansion of Morocco's CSP power plant, which was due to start operating in 2024, has yet to enter construction after MTEDD and ONEE rejected the proposed technology of the supplier. With a USD 2 billion price tag, it is worth getting the technology choice right in advance.

Morocco, this was helped by the support that renewable energy investors have given to local content and the creation of jobs and local industries.[4]

The case of IRESEN in Morocco demonstrates that many of the theories of technology innovation policy that have been developed around advanced economies apply equally as well in a lower middle-income country. Clean energy technology development in Morocco has responded to a combination of resource push, market pull, knowledge management and socio-political support policies. However, in a resource-constrained context, it is shown to be particularly important to ensure alignment with dominant national visions, foster international partnerships and focus on technologies that do not need to be developed from scratch, but where value can be added by adapting them in line with a clear national strategic benefit. In the case of IRESEN, this had particular impact when new information shifted an incumbent company towards more radical innovation and away from incremental development of known processes where they had only marginal international advantage. The OCP Group's pivot to hydrogen from renewable electricity and the potential tie-ups between Moroccan automakers and a new battery supply chain encapsulate this dynamic.

[4] At the same time, good practice on individual projects and strong technological capabilities are insufficient on their own. In Morocco, further work is needed to ensure that smaller-scale renewable projects receive the same opportunities as utility-scale projects, including enabling new entrants in the market and more community ownership. There remain opportunities to improve co-ordination between the various stakeholders, political groups and ministries to reach a common vision of how best to implement the renewable energy targets.

11. Solar PV and rural electrification in Nigeria

Olufolahan Osunmuyiwa (Chalmers University of Technology) and Vivian Ogechi Nwadiaru (University of Massachusetts Amherst)

As Africa's largest economy and most populous nation, Nigeria plays a key role in the continent’s transition to clean energy and has had a national net zero emissions target since 2021. However, despite abundant renewable resources, the country relies on fossil fuels and faces significant energy access and energy security challenges. Nigeria's efforts to diversify its energy mix with clean energy technologies since 2005 have largely focused on rural electrification via solar PV. It has made notable progress in this area with small-scale and off-grid projects. While technology innovation has been stated as a goal, it has been driven more by local and foreign private actors and less by government programmes. Public research funding remains weak. Under challenging currency exchange rate conditions, import tariffs on solar PV have so far mostly raised the cost of installations rather than spurring local development. The Rural Electrification Agency has emerged as a key institution for pioneering technology demonstrations and has partnered with international funders to accelerate the pace of uptake. It has also created opportunities for synergies with fast-growing innovation ecosystems in the financial and agricultural sectors. The rural electrification strategy and plan (RESIP) has been one of the main policies in this area; it was designed to expand electricity access in Nigeria and grow the renewable energy sector. As of 2023, the government is working to attract investment in solar manufacturing from foreign technology companies and has proposed R&D spending requirements for local firms, but whether this leads to domestic innovation will depend on strengthening the local innovation ecosystem.

Country context

Nigeria is Africa’s second-largest economy and its most populous country. With a population of around 220 million people, it is the world’s seventh most populous country. It is classified as a lower middle-income country. Nigeria’s GDP has grown at an average of around 1% over the past five years, below its average of 5% since 2000, resulting in a level of GDP per capita that is above the average for sub-Saharan African countries and similar to that of Pakistan. However, in 2015 India and Nigeria had comparable levels of GDP per capita, with Pakistan’s 15% lower, but India’s is now 40% higher than Nigeria’s. As of 2023, 42.5% of Nigerians live below the poverty line, although the government has set a goal of lifting

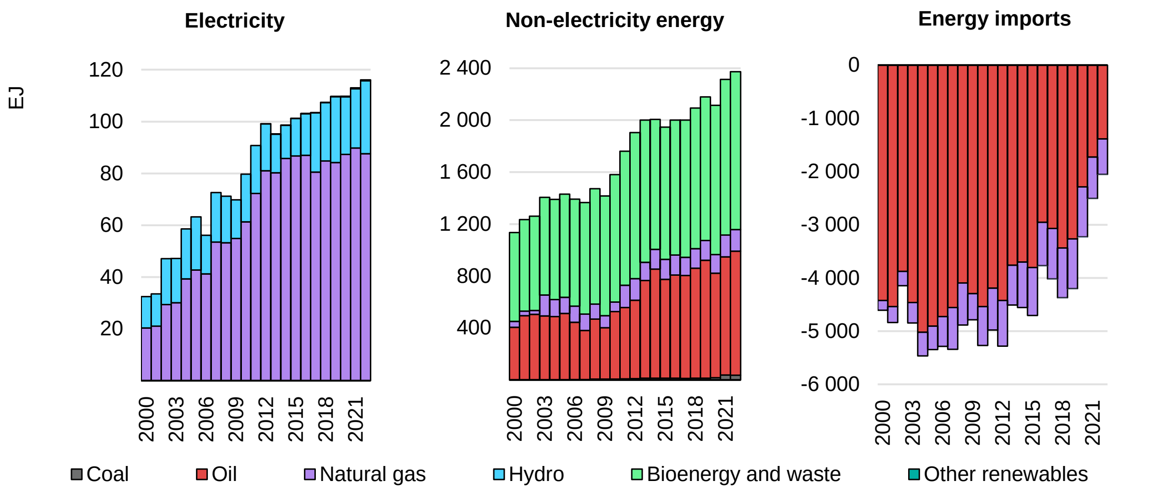
100 million Nigerians out of poverty by 2030, which would reduce the poverty rate almost to zero under expected population growth trends.

Economically, services are the largest sector in Nigeria at almost 60% of GDP in 2023, with agriculture adding a further 22% and the oil and gas sector adding 5%. The remaining balance is contributed by other industrial sectors. However, despite the relatively small contribution to overall GDP, the oil and gas sector dominates the energy landscape in Nigeria. It represents 65% of foreign exchange earnings and over recent decades has accounted for over 90% of export value, a level that is considerably higher than most other oil-exporting countries.

Energy sector context

Nigeria is an oil- and gas-producing country. In Africa its crude oil reserves are second only to Libya, and so too was its crude oil production in 2023. Its natural gas reserves are the largest in Africa. However, despite its sizeable crude oil and natural gas exports (Figure 11.1), Nigeria is a net importer of refined petroleum products due to low refinery capacity. This situation presents challenges for the economy, with imports of refined petroleum products reaching USD 7.75 billion in 2020, representing 14.5% of total imports. To reduce the price of imported fuel for citizens, the Nigerian government spent USD 4.5 billion on fuel subsidies in 2021, an amount equivalent to 35% of its oil and gas revenues and 2% of its GDP. Unplanned production interruptions and other disruptions have prevented Nigeria from exporting as much oil as intended in recent years. However, it is considered to be a leader in Africa for its efforts to reduce emissions and flaring of methane from its oil and gas sector and these could be economically valuable – it is estimated that Nigeria's high natural gas flaring rates lead to natural gas worth around USD 1 billion not being captured for sale each year.

Figure 11.1 Energy sources for electricity and other uses, and level of imports, Nigeria, 2000-2022

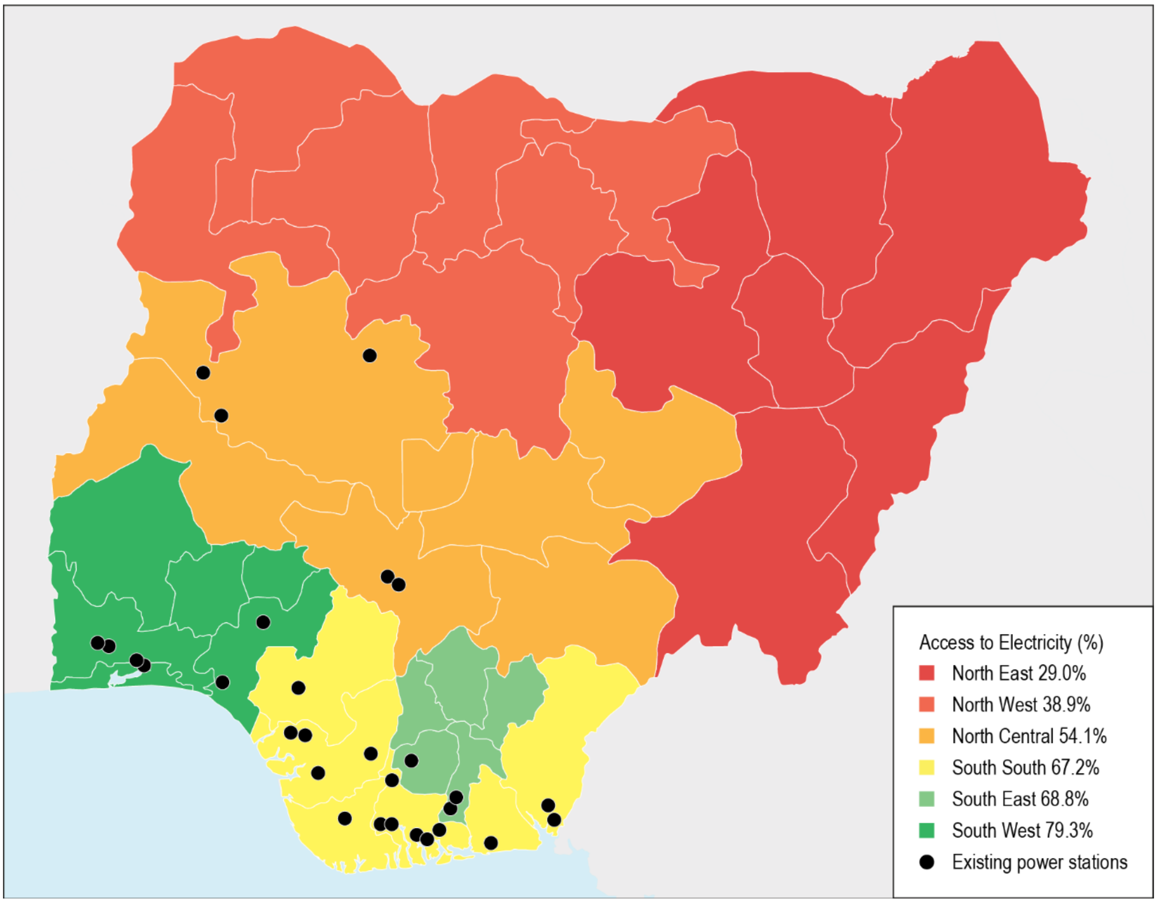


Notes: Electricity and non-electricity energy are shown on a final consumption basis. Imports are shown net of exports.
Source: IEA (2024), World Energy Balances.

Natural gas meets around 75% of electricity demand, with almost all of the rest supplied by hydropower. However, 40% of the population lack access to grid electricity and only 30% of the urban population has reliable access to Tier 5 electricity, which allows the operation of energy-intensive appliances such as air conditioners. Of those connected to grid electricity, 22% rely on additional non-grid sources such as generators, solar home systems and rechargeable batteries. There is a large gap between the total installed capacity of the 23 grid-connected plants on the electricity system (12 760 MW) and the available capacity of 7 788 MW.[1] The transmission network has a theoretical capacity of 8 500 MW, but has never conveyed more than 5 459 MW. Technical losses in the transmission network over the past five years on average have been between 8% and 13%. Many thermal power plants also struggle to procure sufficient fuel to meet demand. In 2014 survey data suggested that Nigerians may have been experiencing 4 000 hours of blackouts or more annually, equivalent to nearly 50% of the year. After China and India, there are more people living without access to clean cooking in Nigeria than in any other country. An estimated 83% of Nigerians lacked access to clean cooking in 2021, although this should decline as the government implements its clean cooking policy (Figure 11.2).

[1] The gap between installed and operational capacity can be traced to inefficiencies in the transmission and distribution infrastructure as well as loss of generation due to fuel availability.

Figure 11.2 Access to electricity and distribution of power stations across the regions and states of Nigeria



Source: Based on USAID (2022), Power Africa Annual Report 2022.

These inefficiencies have consequences for the economy. Most manufacturing facilities and other enterprises rely on backup diesel generators, which are costly and contribute to local air pollution. It has been estimated that challenges related to electricity provision cost the economy around 2% of GDP annually.

Electricity consumers in Nigeria pay much lower rates than the cost of electricity provision, and several reforms have been initiated to make power prices more cost-reflective. In 2019 the customer tariff was 30% of the average cost of supply. The Nigerian Bulk Electricity Trading Company (NBET), a state-owned enterprise, is the sole buyer of electricity from generation companies and the sole seller of electricity to all distribution companies. The fiscal gap between the cost of electricity supply and the amounts recovered via tariffs is covered by payments from NBET to distribution companies. It has been estimated that only 8% of total fiscal expenditure to reduce electricity prices for consumers benefits the poorest 40% of households, while less than 2% benefits the poorest 20%. Since 2020 the Nigerian Electricity Regulatory Commission has initiated reforms to make electricity tariffs cost-reflective and make the sector financially viable. The new tariff model splits consumers into five bands, depending on the quality and duration of supply that they have access to. The lowest band is guaranteed at least four hours of supply. However, this system has faced opposition from labour unions and civil society groups concerned about the increases in the cost of living, given that electricity is still considered an expensive good for most low-income households.

The use of renewable energy has expanded in recent years but remains low. Hydropower output is growing steadily but its contribution to total electricity generation fell from 37% in 2000 to 24% in 2022. Solar PV has not yet grown above 0.3%, with the first grid-connected solar projects only approved in 2016. The Nigerian government has set a target of generating 30% of its electricity from renewable sources by 2030 and has launched several initiatives to promote renewable energy development. Much of the effort to spur solar PV deployment has not been for grid-connected projects, but has instead focused on off-grid and rural electrification where solar is in many cases the most appropriate and cheapest option for providing electricity access.

International companies have dominated Nigeria's oil and gas sector for decades. Shell, ExxonMobil and Chevron have all engaged in joint ventures with the state-owned Nigerian National Petroleum Corporation (NNPC). These companies have provided crucial technical expertise and capital, controlling a significant portion of the country's oil exploration since the 1950s. In contrast, international companies have not been present in Nigeria's electricity sector, in which control by a single state-owned monopoly was only recently changed by the privatisation of power generation and distribution companies.

Slight changes to the balance between international and domestic firms are underway in both the oil and electricity sectors. International oil companies are divesting from onshore and shallow water projects to concentrate on offshore production, partly due to environmental concerns. In the power sector, the government has engaged Siemens to help upgrade the power grid, and the introduction of solar PV has enabled international companies to invest and participate in the market. Some of these companies are international oil companies seeking to diversify, including Shell and TotalEnergies, which have both invested in companies to operate or sell solar PV systems in Nigeria.

Over the past two decades, Nigeria has implemented several clean energy and climate policies and laws to close its energy access and clean cooking gaps, bolster its energy security and transform itself into a green economy. The sequential issuing of key policy documents has helped communicate a national vision with higher levels of clean energy ambition. The 2003 National Energy Policy was followed by the 2005 Renewable Energy Master Plan, the 2006 Renewable Energy Action Programme and the 2007 Nigerian Biofuel Policy and incentives to initiate a domestic biofuel sector. In 2015 Nigeria launched the National Renewable Energy and Energy Efficiency Policy (NREEEP) and in 2016 it introduced the Rural Electrification Strategy and Implementation Plan (RESIP). Among these planning documents, RESIP was notable for shifting investment in the Nigerian renewables sector to being more centrally directed and less dependent on sub-national programmes, such as Lagos' Solar LED street lights project and Jigawa State's promotion of wind energy. State-led initiatives had been hampered by a lack of resources and co-ordination. In 2021 the Climate Change Act was passed and facilitated Nigeria's Energy Transition Plan in 2022, which contains the goal of reducing emissions to net zero by 2060.

Innovation context

In recent years Nigeria's innovation-related activities have increased, with participation from both public and private actors. The number of technology-focused start-ups and supportive government agencies has risen and Nigeria now ranks alongside Kenya, Egypt and South Africa as one of Africa's innovative economies. In 2023, 124 Nigerian technology start-ups received venture funding, compared with 62 in Kenya, 60 in South Africa and 46 in Egypt. These start-ups raised a combined UD 400 million. Overall, Nigeria was ranked only at 109 in the world for innovation performance in 2022, which was 11th in sub-Saharan Africa, below other lower middle-income countries in the region. One reason is Nigeria's relatively low public and private R&D expenditure as a share of GDP, which was 0.28% in 2019, lower than the sub-Saharan African and North African averages of 0.34% and 0.67%.

Most government funding for R&D and innovation in Nigeria is managed by the National Agency for Science and Engineering Infrastructure (NASENI), the National Office for Technology Acquisition and Promotion (NOTAP) and the Lagos State Employment Trust Fund (LSETF). On average, annual government expenditure on R&D was around USD 62 million between 2010 and 2019. Spending on education is higher and is set to account for 7.9% of the USD 34 billion 2024 national budget. With over 60% of the population under 30, a well-educated young workforce is a potential strength for innovation.

Energy innovation is less prominent in Nigeria than other technology areas. Two federally supported institutions are housed within universities: the National Centre for Energy Research and Development at the University of Nigeria was founded in 1982, and the Sokoto Energy Research Centre at Usmanu Danfodiyo University was launched in 2002 with support from the United Nations Educational, Scientific and Cultural Organisation (UNESCO). Compared with Kenya, Nigeria's efforts are more focused on financial and agricultural technologies. In 2023, two solar PV start-ups raised more capital in Kenya than all of Nigeria's start-ups in all sectors. However, some of the entrepreneurial activity in Nigeria's financial and digital sectors has spilled over into clean energy. Together, Nigerian start-ups working on clean energy raised USD 2.3 million between 2020 and the first quarter of 2024. Mobile Power is an example of a Nigerian start-up active in this area. Digital technologies have also spilled over into the area of clean energy and "cold chains" for refrigerating produce. The start-ups ColdHubs and Fresh Direct Nigeria use solar-powered refrigeration to provide cold storage to farmers and small businesses, enabling them to preserve their produce and extend its shelf life. In these cases, access to reliable telecommunications infrastructure and predictable regulation was a more important prerequisite than access to physical energy infrastructure, such as power grids.

The case of innovation-oriented projects in the context of rural electrification

This case study considers how Nigeria's policies to promote solar PV in the country have gradually increased their coverage of R&D and other types of technology innovation support. The early plans and support measures did not give much attention to the innovation aspect, but by the time of the Climate Change Act in 2021 the idea of generating future economic prosperity through technology leadership and manufacturing had become a key policy objective. The story of policy development and the various initiatives launched to implement the policy targets highlights the importance of international co-operation, institutional empowerment and identifying market niches outside the established energy system in the Nigerian context. The results have been mixed, with a flourishing entrepreneurial culture that has developed to tackle energy challenges, but one that is hampered in part by a fragmented institutional setting and a disjointed project environment.

In Nigeria it took nearly a decade for the national vision for clean energy to translate into domestic clean energy innovation. Prior policy choices were strongly influenced by the need to address near-term objectives, such as tariff reform, privatisation and energy efficiency. However, by engaging in mini-grid projects for rural electrification and electric mobility programmes, it was possible to experiment and generate experiences that underpinned the inclusion of energy innovation goals in the Climate Change Act of 2021. The momentum had built up over the period since 2007, and the establishment of the Rural Electrification Agency contributed to the start of the construction of a USD 0.2 billion solar cell production plant in 2023 as a spin-off from NASENI.

First steps in solar energy innovation policy as part of Nigeria's renewable energy goals

The first key policy document to promote renewable energy in Nigeria (excluding large hydropower) was the 2003 National Energy Policy (NEP).[2] Its predecessor, the 2001 National Electric Power Implementation Policy, was drawn up by a federal committee tasked with addressing the unreliability of the distribution and transmission grids. While that policy focused primarily on grid-related issues, the NEP made the case for a rapid expansion of solar PV as a means of sustainably expanding the power sector to meet demand. However, it stopped short of including any specific support measures or targets.

In 2005 a further planning document was published to help implement the NEP. The Renewable Energy Master Plan (REMP) was partly funded by the United Nations Development Programme and set a goal for 10% of Nigeria's electricity supply to be from non-hydro renewable resources by 2025. At the time, all solar PV modules in Nigeria were imported from overseas, yet the REMP outlined a proposal for R&D spending in different renewable energy technology areas that would see Nigerian nairas (NGN) 187 million (USD 1.4 million) spent by the government in 2005-2007, NGN 350 million in 2008-2015 (USD 2.7 million) and NGN 690 million (USD 5.3 million) in 2016-2025.

The rationale for including R&D was stated as follows:

"If Nigeria is to optimally benefit from the application of RET [renewable energy technologies] it must have a credible R&D infrastructure for adapting and modifying imported RET to local conditions, set a stage for innovation and local manufacturing of RET, derive applicable business models and appropriate policies. R&D is also needed to address the social and cultural dimensions of deploying RET to secure their contribution to sustainable and participatory development."

The REMP proposed two new energy research centres, as well as co-operation with academia and attention to the commercialisation of any resulting innovation.

For solar PV, the R&D and training priorities included:

- Establish strong links between the two renewable energy research centres and PV research centres in Europe, America, India, China, Brazil, etc.
- Train engineers, technicians and other workers locally.
- R&D to ensure locally researched cells and modules have compatible efficiencies.

[2] Prior to this, the government had established the National Centre for Energy Research and Development (NCERD) at the University of Nigeria and the Sokoto Energy Research Centre (SERC) at the Usmanu Danfodiyo University in the early 1980s to research renewable energy technologies.

- Arrange exchange visits between Nigerian centres and overseas centres to determine state-of-the-art equipment for acquisition.
- Acquire research equipment.
- Source funding to install mini-module production plants.
- Initiate research on local raw materials to support the PV products industry.
- Collaborate on R&D between renewable energy research centres and engineering and physical science facilities at Nigerian universities.
- Organise training workshops, seminars and conferences at state, zonal and national levels for skills development.

In addition, the REMP suggested R&D priorities for geothermal energy, hydrogen energy, ocean energy, small hydropower and solar thermal energy. To help co-ordinate the research in new technology areas, a New Energy Research and Development Programme was proposed to prepare these energy sources to "play important roles in meeting the energy challenges of Nigeria in a post-fossil economy". In addition, a demonstration project for testing hybrid solar PV and wind and a national wind energy technology centre for training and maintenance were proposed, at a combined cost of NGN 800 million (USD 6.1 million).

While the inclusion of technology innovation goals and proposals represented a significant step forward, the REMP lacked legal status and more efforts were directed towards other NEP priorities than renewables-related R&D and training. By 2007 the electricity reforms led by the Ministry of Power were centred on the liberalisation and tariff reform agendas for the centralised grid. Implementation of the REMP struggled for funding and attention, the target of 0.8% of electricity from non-hydro renewables by 2007 was missed and the New Energy Research and Development Programme was never established. As the REMP had highlighted, a key barrier to the R&D programme was a lack of funds, something that the REMP proposed to address via international partnerships.

In parallel, a new area of energy policymaking for rural electrification emerged strongly. Nigeria's Rural Electrification Agency (REA) was established in 2007 to co-ordinate funds and projects. The REA is a quasi-autonomous entity within the Ministry of Power that has a mandate to pursue Nigeria's rural electrification agenda via grid extensions or off-grid resources.

From 2007 the REA worked towards the approval of the 2009 Rural Electrification Policy target to make reliable electricity available to 75% of the population (rural and urban) by 2020. The policy also enshrined the goal of 10% of electricity to be from non-hydro renewable sources by 2025. The combination of these two elements helped to institutionalise solar PV as an important means of meeting a widely supported social policy goal, and was instrumental to the progress that followed. To an extent, it benefited from some independence from issues concerning investment in the centralised grid.

As regards technology innovation, a new entity was established in 2011 within the science and engineering agency NASENI with the mandate to set up a solar PV manufacturing facility that would initially use imported raw materials and then transition to using only domestically sourced raw materials. In 2013 it was registered as a company called NASENI Solar Energy Limited (NSEL). However, while the government-funded 7.5 MW production plant was rapidly constructed, and subsequently expanded to 21 MW, it served mostly as a developmental facility. For comparison, the world's commercial solar PV cell factories were already much larger in 2011, with several above 1.5 GW of output per year, 200 times larger than the NASENI plant.

Overall, during this initial period of renewable energy policy development, energy technology innovation policy was boosted by Nigeria's formal systems for policy planning. The existence of the Energy Commission of Nigeria as a body responsible for planning, and the regular revisiting of planning documents for the short and medium term, were key elements in the articulation of a role for renewable energy in Nigeria, and the need for associated R&D. The familiarity with target-setting and planning documents helps explain the government's choices with respect to solar PV during this period. However, the lack of institutional capacity to manage longer-term policy priorities prevented plans from being implemented that did not align with the near-term visions for the centralised power grid and retail market. This situation began to change with the establishment of the REA, which could take a longer-term view of the role of solar PV and also take responsibility for its delivery.

A focus on technologies for rural electrification under the 2016 Rural Electrification Strategy and Plan

The next major institutional step towards the development of a sustainable solar PV sector in Nigeria was the 2015 NREEEP,[3] which was closely followed by the 2016 RESIP. The NREEEP had a list of incentives intended to support producers, manufacturers and importers of solar PV goods and services. It stipulated that manufacturers of solar PV equipment were entitled to interest-free capital relief of 50% on initial investments. Despite the stipulated support for manufacturing, only the biofuels section of the NREEEP had clear language on and a target for R&D spending, stating that an R&D fund would be established "to encourage synergy between the private and public sectors in R&D in which all biofuel companies shall contribute 0.25% of their revenue for research in feedstock production, local technology development and improved farming practices".

[3] The NREEEP was complemented by a National Renewable Energy Action Plan (NREAP) and a National Energy Efficiency Action Plan (NEEAP).

The NREEEP also provided a menu of authorised policy instruments that could be used to give preference to renewable energy in Nigeria, including:

- Voluntary or mandatory renewable portfolio standards.
- Auctions or bidding rounds for independent power producers.
- Disclosure requirements to increase consumer information.
- Capital grants and tax exemptions.
- Production tax credits for electricity generation.
- Feed-in tariffs or net metering for small-scale generators.
- A public benefits fund to allocate a percentage of tariff revenue to support on- and off-grid projects.

However, while the NREEEP established the basis for government agencies to create a market for renewable energy technologies, it was the RESIP that pushed forward the deployment most strongly. By promoting a least-cost approach to the electrification of rural communities, along with a Rural Electrification Fund to stimulate uptake, solar PV was immediately prioritised.[4] The RESIP established an interim target to add 1 million connections and 800 MW of mini-grid capacity (of which 80% to be solar PV) in rural communities by 2020. In addition, the RESIP contained measures for improving R&D in the sector and reducing the fiscal barriers to private sector participation. For instance, one of the core policy themes of the RESIP was capacity building for the execution of projects by local Nigerian companies by improving their understanding of and qualification for developing and running renewable energy projects and encouraging these actors to play a more active role in the renewables value chain (materials, manufacture, construction and operation of the assets). Among several instruments for supporting the deployment of solar PV in different types of communities, the Energizing Education Programme, launched in 2019, has a significant component related to technical training in the solar PV area, including a dedicated programme for women.

The R&D and localisation goal of the RESIP has been supported through performance-based grants, a minimum subsidy tender, an output based fund and a market scale-up challenge fund for qualified renewables projects. The REA proposed a Research and Innovation Hub in 2021 to provide grants for R&D and innovation by start-ups (Figure 11.3). While the student support element is the only one established to date, the innovation hub idea signalled a change in ambition for the REA in this area. Notably, it considered not only supply-side technologies for off-grid renewables, but also energy-efficient appliances and solar-powered end-use applications such as irrigation and electric mobility.

[4] This was complemented by a Nigerian Sovereign Green Bond, the first certified green bond in Africa, issued for USD 250 million in 2017 to provide foreign exchange support to solar PV importers.

Figure 11.3 The structure of the Research and Innovation Hub proposed by the REA in 2021

R&D

- University challenge
- Research open call
- Student support

Concept and technology adoption and demonstration

- Biomass gasification
- E-mobility solar-powered tricycles and motorcycles
- Hydro
- Solar-powered irrigation
- Standalone cold storage refrigeration

Start-up innovation grant

Source: REA (2021) Unveiling the REF research and innovation hub.

The RESIP had a catalytic effect on the levels of activity around solar PV in Nigeria. Because it focused on a socially important topic that could be accomplished via multiple, parallel, independent projects, it could attract considerable financial support from international donors. Between 2016 and 2020 a wide range of initiatives were launched with international partners, many of which included an innovation dimension (Table 11.1).

Table 11.1 Selected rural electrification projects in Nigeria with international partners

Partners	Project	Year started	Financial contribution (USD million)	Technology innovation contribution
African Development Bank and Shell	Nigeria Energy Access Fund	2019	15	Equity/quasi-equity investments in small- to medium-scale sustainable energy projects that have measurable climate-positive and energy access impact.

Partners	Project	Year started	Financial contribution (USD million)	Technology innovation contribution
African Development Bank/ World Bank	Nigeria Electrification Project	2019	550	Technical and financial support to enhance project delivery and management to strengthen the off-grid ecosystem. So far the project has delivered 120 mini-grids and 1.4 million solar home system connections.
Germany and the European Union	Nigerian Energy Support Programme I, II and III (including Interconnected Mini-grid Acceleration Scheme)	2016*	61	Technical assistance to mini-grid developers and tenders for registered mini-grid developers in Nigeria to install mini-grid capacity.
Rockefeller Foundation, The Global Energy Alliance for People and Planet, and Shell	All On Hub	2020	(Has invested USD 0.24 million in 24 start-ups in addition to providing prizes and grants)	Support to nascent ventures in the Nigerian energy sector, including grants, workspace, incubation, technical assistance and business advice.
United Kingdom	Solar Nigeria Programme	2014	100	Works with 40 private sector actors within the solar value chain (manufacturers, installers, and financers). Offers market scale-up grants.

Partners	Project	Year started	Financial contribution (USD million)	Technology innovation contribution
United States (US African Development Foundation) and Shell	Expand the solar panel assembly capacity of Auxano Solar Nigeria Ltd.	2020	1.5	Auxano has now trained 800 people in solar assembly, distribution and aftersales services.
World Bank	Technical assistance	2018	27	Technical assistance to public and private sector stakeholders, including the REA and Ministry of Power to build a sustainable framework for scaling up rural electrification.
World Bank	Market Scale-Up Challenge Fund	2019	15	Lump sum grants in support of strong business plans that have other co-funding sources for remaining 70-80% of scale-up funding needs.
World Bank and African Development Bank	Energizing Education Programme	2017	310	Installation of mini-grids at universities and creation of renewable energy training centres for students' innovation. Includes training for female students during the construction phase.

Partners	Project	Year started	Financial contribution (USD million)	Technology innovation contribution
World Bank and Climate-KIC	Nigeria Climate Innovation Centre	2018	Not known	An independent company that aims to accelerate energy access in Nigeria by supporting early-stage enterprise development and increasing the investable pipeline of local off-grid solar companies.

* Phase I of NESP ran from 2013 to 2018.

The variety of programmes launched with international partners in Nigeria has helped to build domestic expertise in the public and private sectors. Exposure to a range of partners has provided exposure to a diversity of technologies, processes and experiences. Importantly, most of the projects and initiatives share a consistent focus: the use of solar PV and mini-grids to create entirely new markets for electricity in rural areas. In a context where a single model solution does not yet exist globally, the importance of technology to overcome arising challenges, as well as the general absence of incumbent solar firms, ensured a focus on technology innovation and capacity building in most programmes.

Another public instrument used to incentivise corporate spending on R&D is the national local content policy in the power sector, which promotes the utilisation of local human and material resources across the electricity system's value chain. The Nigerian Content Development and Enforcement Bill 2020 has emerged as a product of the local content policy and aims to create 250 000 energy sector jobs and localise solar manufacturing. The markets for mini-grids and solar home systems have a combined potential annual revenue of USD 6 billion. To support investors in identifying potential market, the REA under the NEP has identified 10 000 sites for mini-grid development.

Alongside the various initiatives related to rural electrification, the Nigerian government also created market incentives to implement the NREEEP and assist the scale-up of the solar PV market in Nigeria. A feed-in-tariff was put in place for grid-connected renewables in 2016 and it was signalled that distribution companies would be set renewables procurement targets and penalised for not meeting them.[5] In addition, in 2016 the Nigerian Electricity Regulatory Commission published rules for mini-grid operators that made them eligible for predictable multi-year tariffs and compensation if the grid is later extended to the same territory. To assist market creation, the World Bank and the REA Nigerian Electrification Project provided USD 60 million as grants to private companies of different sizes to bridge the cost gap between solar PV mini-grid systems and other non-renewable electricity sources.

Examining the background to this policy approach, it is evident that the REA was constrained by the lack of domestic public finance and limited political capital compared to institutions tasked with other major economic policy reforms. In parallel, its access to international support was elevated by the close alignment of the RESIP with development and sustainability goals. The global agenda around rural electrification via renewable energy had gathered momentum by the time of the signing of the Paris Agreement and UN Sustainable Development Goals, both in 2015. However, one potential downside of an approach reliant on multiple programmes with different partners – rather than a co-ordinated policy package steered by the government – can be a fragmentation of efforts or lack of co-ordination among donors and planning bodies. In the case of Nigeria, one element that helped avoid fragmentation of efforts and inter-institutional competition was the central presence of the REA as a national planning and co-ordination body.

Current status: Prioritisation within the 2021 Climate Change Act, local and foreign direct investment in manufacturing

In 2024 solar PV and clean energy technology innovation occupy more central positions in Nigerian policymaking. Their impact on total energy supply and economic indicators remains modest, but they are seen as integral parts of the future economy. One example of how the successful experiences with rural electrification projects have shaped government thinking is the support package assembled by the Central Bank of Nigeria in mid-2020 in response to the financial impacts of the Covid-19 pandemic: it included concessional loans for companies engaged in "manufacturing of solar components", "assembly of solar components", "maintenance of solar home systems and mini grid equipment", "solar component R&D" and "any other off-grid solar value chain activity". The rationale given was an economic one: "pay-as-you-go (PAYG) off-grid technologies… will create a USD 2 billion annual market opportunity [and, together with] the roll-out of 5 million new solar-based connections in communities that are not grid connected… this program is expected to generate an additional NGN 7 billion [USD 18 million] increase in tax revenues per annum and

[5] Renewable portfolio standards for renewables from independent power producers connected to the distribution grid were enacted in early 2024 and set separately for each distribution company at around 5% of contracted capacity for the following year.

USD 10 million in annual import substitution." Also in 2020, the Bank of Industry made USD 15 million available to provide low-cost debt to solar-related projects.

A year after this central bank intervention, Nigeria's national vision for clean energy was propelled into a new phase by the international consensus around the target of achieving net zero CO_2 emissions. Like many other countries in 2021, Nigeria pledged to achieve net zero emissions and set a date of 2060. To accompany and implement this pledge it published a Climate Change Policy, an Energy Transition Plan and a Climate Change Act. In these documents, energy technology innovation is given much greater prominence than in previous long-term energy plans. Among the ten policy goals of the Climate Change Policy, the third is to promote "scientific research, technology and innovations to address the challenges of climate change" to "pursue an alternative and sustainable path to industrialisation that takes advantage of innovations, technologies and business models for improved energy efficiency in the industrial sector". The document further commits to "support financial services entities with appropriate policies to play an adequate role of providing the financial and de-risking products needed to fund innovations necessary for climate actions". The Energy Transition Plan estimates that, if successfully implemented, the 2060 goal will result in the creation of up to 340 000 jobs by 2030 and up to 840 000 jobs by 2060, and will require innovation for cost reductions, local technology adaptation and skills development.

However, barriers to clean energy innovation remain in Nigeria beyond the limitations to government funds. The cost of capital for innovative companies in the energy sector is very high, with few alternatives to bank loans at 27-30% interest rates, a level that makes early-stage risk-taking impossible for hardware developers. While some dedicated sources of capital exist to support companies to implement the RESIP goals – such as the Bank of Industry Solar Energy Fund, the central bank's Solar Connection Intervention Facility and equity and debt financing from All On – they are limited in scale and scope. Innovators often rely on grants from overseas governments or equity from overseas sources. A downside of this is that some start-ups locate their headquarters abroad to be closer to sources of finance and foreign partners that can help them access these funds. For example, Lumos Global, a developer of solar finance solutions that has raised over USD 100 million including from All On, is now headquartered in Amsterdam. Koolboks, a start-up inventor of an efficient off-grid refrigerator for Africa, is headquartered in France.

Domestic start-ups can be valuable champions of renewable energy policy development because, as they grow, they bring a credible private sector voice to the political process. Auxano Solar and Lumos Global have played this role in Nigeria. Other related start-ups founded in recent years include Rensource, which uses digital technologies to optimise solar PV installations, Greenage Technologies, a maker of home solar products including inverters, Salpha Energy, a developer of integrated solar kits for off-grid use, and Powerstove Energy, a manufacturer of cleaner cooking equipment.

The ability of innovative companies in the solar manufacturing arena to scale up quickly is hampered by several additional factors. Nigeria imports the vast majority of the solar PV equipment it installs and its value has been estimated at over USD 518 million between 2018 and 2021, with panels being nearly 50% of this. Auxano, Blue Camel and other assemblers meet less than 20% of demand. This is despite several measures in place to support local manufacturing. In 2017 the government granted solar panel manufacturing Pioneer Status, which exempts the sector from corporate income tax for three to five years. There are also tariffs that disfavour imports. In 2019 the Nigerian Customs Service reclassified solar panels from a class that has no associated duty (85414000), to one for direct current generators (85013300), which carries a 5% duty. A 5% value-added tax on imported solar panels with diodes was also introduced, along with a 20% import tariff on batteries. Additionally, in 2020 the government proposed a Nigerian Content Development and Enforcement Bill.[6] However, rather than stimulate domestic manufacturing, this could make solar installations less profitable, reducing the uptake of renewable energy in Nigeria. One supportive factor is that the central bank provides foreign exchange to importers of solar products at the official government rate, which is advantageous.

Two promising developments in 2023 may improve the outlook further. In early 2023 China Great Wall Industry Corporation co-invested with the government's science and engineering agency to construct a solar PV cell factory for NASENI costing USD 0.2 billion. All but 15% of the cost will be covered by finance from the Bank of China. Additional investments with Chinese entities in a transformer production plant and high-voltage testing facility are planned. This total investment builds on over a decade of work since the establishment of NSEL by NASENI, during which time it has patented several technologies, including a mini solar generator and a 1.5 kVA "plug 'n' play" solar home system. NASENI has deployed 780 solar-powered streetlights and 850 kW of generation capacity. It has run an educational programme for schools and trained 150 people in technical capacity for solar PV design, installation and entrepreneurship. In addition to solar PV it has also manufactured small hydro turbines. The investment from China has the potential to transform the experience from a very small operation into a competitive player in Africa's solar market. The other notable development was the announcement in late 2023 of the Distributed Access through Renewable Energy Scale-up (DARES) programme, which could lift the solar PV market in Nigeria to

[6] The bill is not yet enacted, but would extend local content requirements to sectors other than oil and gas, requiring at least 40% of public works to be contracted to Nigerian companies, and create surcharges of 2-3% on all contracts in seven sectors, including the power sector. An additional part of the proposal is to require Nigerian companies in these sectors to domicile 5% of their net profits with the Central Bank of Nigeria for R&D, of which half would be allocated by the government to Nigerian universities and research institutions, and half would be spent by the company and be tax deductible.

a new level. It represents over USD 1.1 billion of combined funds from the World Bank, Japan International Cooperation Agency, Global Energy Alliance for People and Planet, International Finance Corporation and SE4ALL

Findings

After two decades of policymaking for renewable electricity, Nigeria could be well placed to take advantage of the economic opportunities offered by innovation in the rapidly growing solar PV market. Its innovation ecosystem has developed markedly in adjacent sectors such as finance and communications, and a series of programmes on rural electrification with international partners have helped this to expand into the clean energy domain. Nigeria's workforce is young and underemployed, and several private and public universities have strengthened and expanded their curricula in the area of renewable energy technologies. Recently, investment in the solar PV supply chain and in Nigerian energy start-ups has ticked up. Understanding how Nigeria reached this point and the strengths of its policy pathway provides valuable lessons that can inform further progress and also other countries or sectors facing similar challenges.

The case study shows the importance of goal setting and planning to pursue multiple policy objectives simultaneously. The existence in Nigeria of a formal planning body in the form of the Energy Commission of Nigeria was important for establishing common expectations. However, the plans for renewable energy, including R&D, were unable to be implemented as initially envisaged until there was strong alignment with the national policy vision. In the case of solar PV in Nigeria, the catalytic factor was alignment with a global vision, first for rural electrification and then for net zero emissions, which the financial donor community could support. This international finance was critical for overcoming a shortage of public funds for a policy objective that was not the central concern of the Ministry of Power in the 2005 to 2015 period.

A further insight from the case study relates to the co-ordination value of having a nodal government agency responsible for delivering a challenging and innovation-related policy goal. The REA provided continuity and expertise during a period of rapid policy design related to the RESIP and NREEEP, as well as during the design and execution of multiple programmes with international partners. The REA has helped maintain a level of institutional co-ordination, but has not entirely offset a more general fragmentation of institutional capacity. While the Ministry of Power controls the formal policy-making process related to electricity, adjacent projects and initiatives have been launched outside its formal channels. For example, the agriculture and environment ministries have been involved in new bioenergy programmes, and international donors have sometimes proposed their preferred projects with different stakeholders. Among these stakeholders are state and local governments, which play a key role in implementation, including for technology innovation via universities, but are not always well integrated into the policy design phase. There is therefore scope to foster more linkages between institutions to verify that planning targets are achievable and to ensure that policy instruments are designed to complement and reinforce each other.

For countries without extensive financial resources for long-term R&D, it is important to build on existing skills and identify promising technology niches that have synergies. In Nigeria this has been the case with knowledge spillovers from the innovation community around financial technology ("fintech"). Pay-as-you-go (PAYG) systems for solar PV and energy storage are popular in Nigeria as their microfinancing model accommodates the wage structure of most low-income earners, particularly those in the informal sector. This enables households and businesses to access solar power solutions more easily and it draws directly on local entrepreneurship in adjacent finance and digital sectors. Governments can enhance innovation outcomes by supporting these enabling conditions in adjacent parts of the economy, as well as links between sectors.

However, it has been more difficult to foster businesses for the large-scale manufacture of renewable energy components and equipment. The efforts of NASENI did not build on an existing high-tech manufacturing base. Despite the imposition of import tariffs and support from the national agency tasked with bridging science, technology and manufacturing, NSEL struggled to scale up between 2013 and 2023. As in many other EMDEs, significant headwinds face projects for building new and advanced technology manufacturing from scratch without international partners if there is a lack of transferrable knowledge and skills from similar sectors. In Nigeria, the inward investment by a Chinese firm in 2023 to partner with NASENI has potentially kick-started a solar PV production sector, but the extent to which NASENI's past research and personnel will be leveraged to create additional value for the joint venture is unclear. The government has an opportunity to ensure that local staff receive high-quality technical training and to support the conditions for entrepreneurship and additional investments in complementary and innovative activities alongside the new factory.

12. Renewable energy and just energy transitions in South Africa

Britta Rennkamp (University of Cape Town) and Loveline Muluh (University of Cape Town)

Clean energy innovation is a highly contested policy area in South Africa, Africa's largest economy. Many livelihoods, industries and political ideologies continue to rely on fossil fuels and extractive industries as a critical driver of economic performance. The country has an unusually carbon- and energy-intensive economy compared to other countries in the region. South Africa faces intersecting challenges of poverty, inequality, unemployment, electricity supply and climate impacts, particularly in the form of fires, floods and droughts. As a result, clean energy transition policies and regulations in South Africa are closely interconnected with climate policy and sustainable development agendas.

This chapter analyses current clean energy innovation policy within the evolution of South Africa's national energy innovation system. We briefly review the status and evolution of the political economy of energy innovation policy and then analyse two case studies of recent energy innovation policy: the Renewable Energy Independent Power Projects Procurement Programme (REIPPPP) and the Just Energy Transition Programme (JET-P).

The REIPPPP case study can be seen as a cautionary tale of mixed success in diffusing renewable energy in a highly contentious political environment. Over the past 12 years, REIPPPP has explicitly sought to address social inequalities through special provisions in the procurement process. The JET-P is a more recent dynamic to support clean energy transitions through an innovative climate finance partnership with South Africa, first launched at COP26 in Glasgow in 2021.

Both case studies show the difficulties in using well-intended climate action to transform structural inequalities beyond market mechanisms. The South African experiences also demonstrate how rapidly decarbonisation can progress through private investment as well as the limitations to market mechanisms. Progressing "just energy transitions" requires a strong state for the provision of public goods, including the creation of social safety networks for labour in fossil fuel industries, and the development of skills, alternative industries and alternative ownership models for renewable energy to enable access to the benefits of technological change. Actively implementing South Africa's many plans in a way that reduces inequality and deprivation among its people remains a constant challenge, undermined by the nagging resistance of corruption and powerful pro-fossil fuel lobbies.

Country context

South Africa is a nation of 62 million people, the sixth most populous country in Africa, with the largest GDP and the highest GDP per capita on the continent. Classified as an upper middle-income country, South Africa is the only African member of the G20 group of major economies. It is the most industrialised economy on the continent, concentrating income opportunities in its eight metropolitan municipalities. The country continues to urbanise, and it is projected that roughly three-quarters of its population will live in cities by 2035, up from 57% in 2000 and around 67% in 2020.

South Africa's current socio-economic structures continue to retain the legacies of resistance throughout centuries of colonial rule, extractive industrial development and the apartheid regime between 1948 and 1994. Mining continues to be a significant economic sector in South Africa, trading over 50 commodities.[1] The mining sector has shaped South Africa's society as well as its economy, with segregating hiring practices and low wages for local and immigrant miners from rural communities.[2] The displacement of male African workers from their communities continues to shape the social fabric of the present day. Half of South Africa's households counted as female-headed in the last census.[3]

These historical structures explain the results of Gini co-efficient measures that rank South Africa as the most unequal economy in the world. In 2021 the top 10% of earners received 65% of total income and controlled 86% of personal wealth. The benefits of economic growth and manufacturing have not been equally shared between ethnic groups and measures of inequality have not noticeably improved over the past 15 years. Progress on expanding access to healthcare, housing, electricity, piped water, sanitation and waste removal stagnated in the early 2000s and has even declined in some parts of the country in recent years. The global pandemic exacerbated existing vulnerabilities in 2020, during which the government enacted some of the world's strictest lockdowns. The economy shrank by 6% in 2020. Between 2016 and 2021 average annual GDP growth was 0.2%, compared with 2% between 2006 and 2016. In 2024 the economy is growing as a result of higher domestic demand.[4] The unemployment rate remains high, at 32% of the working population. Youth employment stands at 44%, resulting from a combination of the lack of opportunities in the labour market and weaknesses in the education system. Limited availability of apprenticeships and vocational courses, as well as difficulties in paying fees, resulted in a gross

[1] The main mining commodities are platinum, chromium, palladium, manganese, ferrochromium, zircon, vanadium, gold, diamonds, cobalt, nickel, coal and iron ore.
[2] Management positions were staffed predominantly by men of European descent.
[3] The authors acknowledge the controversies around household headship in South Africa and more generally, but have no space to debate the matter in detail. Further reading on the topic is available from Statistics South Africa .
[4] Water and electricity consumption are growing after the heavy rain in the winter storms and ease of loadshedding. Mining exports had carried the economy through the pandemic and its years of recovery.

enrolment rate in tertiary education of 27% of all youth, compared with an average of 10% in sub-Saharan Africa as a region. The prospects are challenging, given the state of basic education: 81% of ten-year-olds have reading difficulties and perform below international benchmarks, especially in rural areas.

The nation has faced several cycles of political instability since its first democratic election in 1994. The African National Congress could not win enough votes in the national election in 2024 to form a government alone. The seventh national assembly consists of a coalition in a so-called Government of National Unity (GNU) for the first time in the history of the young democracy.

Energy sector context

South Africa's energy sector continues to rely on its domestic coal resources, which provide over 70% of its primary energy. Oil and gas are imported predominantly from Nigeria, Saudi Arabia and Mozambique, respectively. In final energy terms, coal provides almost half of South Africa's demand, split roughly equally between coal-fired electricity and other uses, including conversion to liquid fuels. In 2022 the industrial and commercial sectors were responsible for 45% of total final energy demand (Figure 12.1). The transport sector was responsible for 27%, the residential sector for 13% and agricultural activities only 3%.[5]

The reliance on coal in the electricity sector has reduced significantly over the past two years, despite years of delays in implementing renewable energy policies in response to the shortages in electricity supply. The share of renewable energy in electricity generation almost doubled from 6.2 GW in 2023 to 12 GW in 2024 because more rooftop solar PV was added. The country currently has total installed capacity of 49 GW, of which 34.5 GW were available for consumption in 2024, almost 10 GW more than a year earlier at the height of the power supply crisis.[6]

South Africa's electricity governance has historically been centralised. Historically, Eskom has been a vertically integrated state-owned company, responsible for operating 15 coal-fired plants, Africa's only commercial nuclear power plant, and a few small hydroelectric and renewable energy plants. However, it is currently undergoing a process of "unbundling" to separate its transmission function as National Transmission Company South Africa, an independent entity. Eskom is a well-regarded employer in the Southern African Development Community region, providing 40 000 jobs in South Africa alone. Eskom's coal and large power plant focused business model struggles to keep pace with the changing costs of new

[5] Depending on the source, 4% to 9% of final energy demand is unspecified.
[6] These figures refer to maximum dispatchable capacity including imports and emergency generation resources and the available dispatchable generation, as well as renewable energy capacity and estimates of solar rooftop installations according to Eskom's weekly systems status report (in week 01/2023 and week 25/2024).

coal and nuclear power stations and the decline in renewable energy prices. The reasons for Eskom's debt crises are multifaceted, combining symptoms of a crisis in general governance, underinvestment and eroding infrastructure, market factors, human resources and institutional inertia to mention a few.

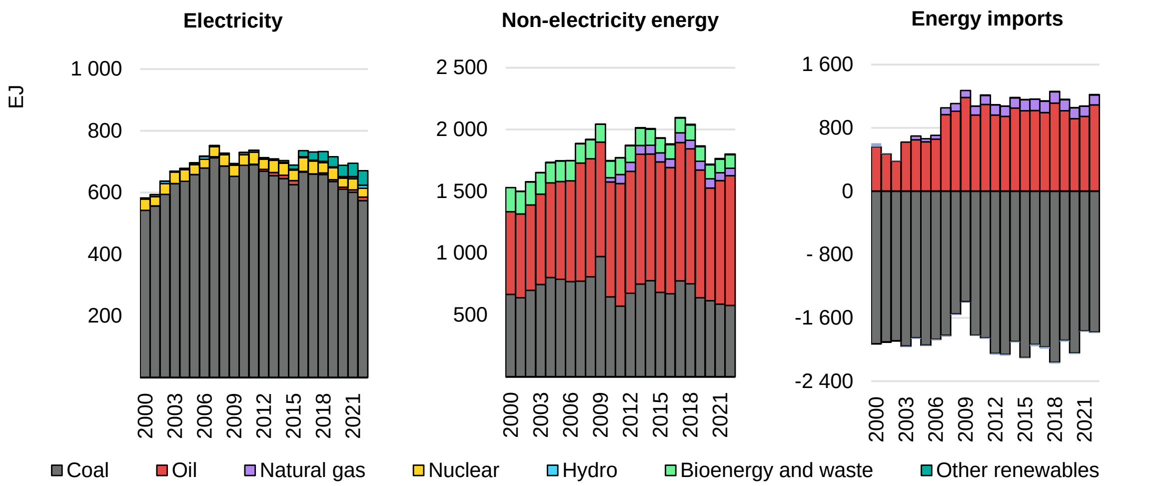
These factors also intersect with the municipal electricity industry, which distributes electricity to residential customers. In some cases, 75% of municipal revenues come from residential electricity sales, creating an incentive to use and sell more electricity rather than encourage energy efficiency or embedded generation. This model ran at a loss for Eskom from 2016, as some municipalities were unable to pay Eskom for the electricity they sold to their customers or to maintain the local infrastructure.

Despite public demand for increased generation capacity since electricity shortages began in 2007, the government's neglect of the urgency combined with the weakening governance at Eskom undermined its ability to efficiently allocate capital to new infrastructure and maintenance.[7] The electricity sector crisis had developed over a long time, as South Africa sold electricity at one of the lowest electricity tariffs worldwide, based on expectations of cheap and abundant coal. While the low price of electricity sustained the energy-intensive mining and mineral sectors, it has discouraged private investment in new generation capacity. In 2019 the Department of Public Enterprises declared Eskom to be technically insolvent unless it was supported via public bailouts. Rotational load shedding – a South African term for rolling power cuts to manage the gap between generation capacity and demand – became a common inconvenience of life in South Africa. Estimates of the costs to the economy range from South African rand (ZAR) 35 billion (USD 2.2 billion) to ZAR 58 million (USD 3.2 million) per day during the 12 years between 2007 and 2019. The lower of these estimates is approximately equivalent to South Africa's drop in GDP during the 2008 financial crisis.

The loadshedding crisis negatively impacted many livelihoods and caused frustration across the country. Political support for the ANC-led government declined significantly during the peak of the crisis in winter 2022. The government responded with an Energy Action Plan to End Loadshedding ahead of the national elections, which accelerated deployment of renewable electricity for residential and business use without the involvement of Eskom. The plan enabled an Energy Regulation Act, signed in 2024, that split Eskom's generation, distribution and transmission functions with the intention of addressing the municipal distribution conundrum and to enable more direct access for independent power producers.

[7] Over the past decade, a sequence of hearings and inquiries, including the Zondo Commission, have revealed details of corruption and state capture at Eskom. Mismanagement and misallocation of funds for maintenance worsened power plant efficiency and electricity supply shortages.

Figure 12.1 Energy sources for electricity and other uses, and level of imports, South Africa, 2000-2022



Notes: Electricity and non-electricity energy are shown on a final consumption basis. Imports are shown net of exports.
Source: IEA (2024), World Energy Balances.

These recent regulatory changes create uncertainty for the role of the targets expressed in the electricity sector plan. The participatory planning process for the Integrated Resource Plan (IRP) sets out a desired composition of power capacity up until 2030.[8] Beyond 2030, the 2019 IRP envisages the decommissioning of 24 GW of coal plants, which faces challenges due to the central role of coal in the South African economy. There is no equivalent of the IRP in non-electricity parts of the energy system. Plans for the oil and gas sectors are less formally co-ordinated and communicated in terms of the planning for major decisions, such as the closure of the oil refineries and development of national gas infrastructure.

Energy policy in South Africa is closely intertwined with climate policy. The energy sector accounts for 78% of the country's emissions and puts the country well above the world average emissions intensity.[9] The government actively engages in international climate negotiations with a focus on the mitigation component in its climate policy. The delegation to the UN has consistently been well staffed by trained government officials and technical experts, a legacy of President Mandela's prioritisation of multilateralism. In 2011 South Africa hosted the annual UNFCCC Conference of the Parties, which drew an international spotlight to the country's emissions and climate action. The event created a window of opportunity

[8] 33 GW of coal (a net reduction due to decommissioning), 4.6 GW of hydropower, 17.7 GW of wind, 8.2 GW of solar PV, 6.3 GW of natural gas and diesel, 1.8 GW of nuclear (no change) and 0.6 GW of concentrating solar thermal.
[9] South Africa's per capita CO_2 emissions are 60& higher than the world average and 20% higher than those of the European Union. Per unit of GDP, South Africa's CO_2 emissions are three times the world average and 6.6 times the EU average.

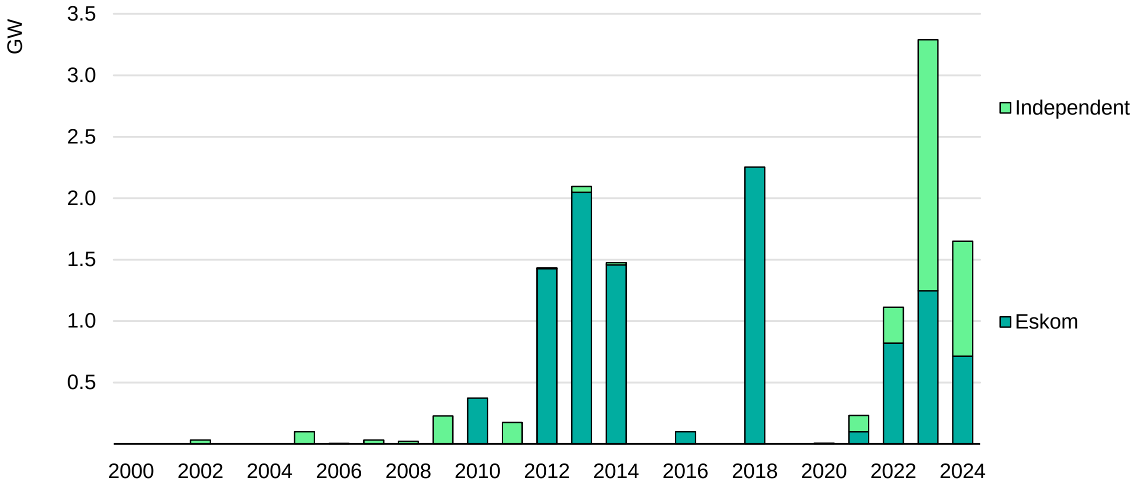
to approve three central climate policies, comprising the renewable energy programme for independent power producers (IPPs), a carbon tax and a National Climate Change Response White Paper.

As a signatory to the Paris Agreement, the South African government communicated in its NDC that it anticipates annual GHG emissions being in the range of 398-510 Mt CO_2-eq between 2021 and 2025. Between 2026 and 2030 South Africa's annual GHG emissions are anticipated to be in a range of 350-420 Mt CO_2-eq. The Greenhouse Gas Inventory reports emissions of 435 MtCO_2-eq for 2022, which implies that the NDC target ranges were already achieved in 2022.

The reductions result from a combination of factors, including the impact of the pandemic on the economy and its recovery period, stagnant electricity demand, reduced energy availability, loadshedding and limited additional renewable energy capacity. Progress in developing additional renewable energy capacity was delayed between 2016 and 2019 during the peak of state capture, which explains the gap in new IPP capacity between 2019 and 2022. It is essential to continue reforming the electricity sector as electricity consumption will eventually increase. Additional renewable energy capacity needs to be installed to meet the 2026-2030 emission reduction targets.

The regulatory changes in the electricity sector in response to the electricity supply crisis have encouraged the installation of large-scale renewable energy projects outside the renewable energy programme, with high uptake by industry. The uptake of private IPP projects shows that the market is responding to government policy (Figure 12.2). It also demonstrates that the additional climate finance generated in support of an equitable energy transition does not need to be used for further private sector incentives or to pay Eskom to close its coal-fired power stations. It needs to support training, skills development and innovation for new industries that create decent income opportunities and social protection in and beyond the energy sector.

Figure 12.2 Renewable electricity capacity additions, by power purchase agreement offtaker, 2000-2024



Note: By year of financial close.
Source: IPP database, Power Futures Lab, Graduate School of Business, University of Cape Town.

Innovation context

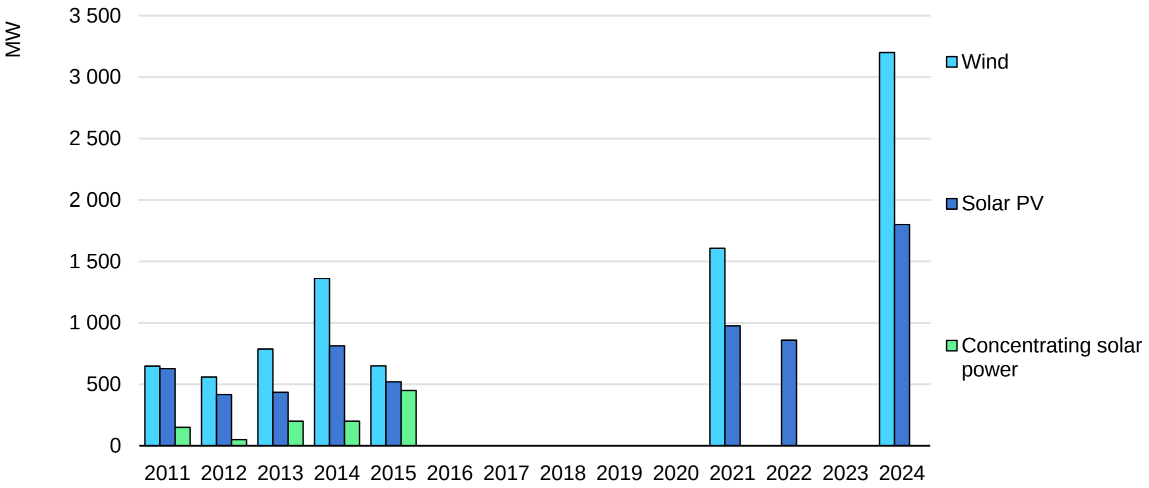
The South African government acknowledges the critical role of science, technology and innovation its White Paper on Science, Technology and Innovation (2019) and its Decadal Plan (2022-2032), which support achieving the overarching National Development Plan. A mix of science, technology and innovation policy aims to strengthen a national system of innovation across government departments and sectors to support equitable economic development. The Department of Science and Innovation and the Department of Trade, Industry and Competitiveness developed strategies for the localisation of support for job creation, industrial development and eco-innovation, including renewable energy innovation, with limited impact. Aspirations to create 400 000 new jobs by "greening" the economy are articulated in the White Paper for Science and Innovation, but require integrated approaches to economic development with the active implementation through the Department of Mineral Resources and Energy (DMRE), the Department of Public Enterprises and the Presidency.

South Africa's economy has pockets of innovation excellence, but it lacks the capital, strategic policy support and scale to produce many transformative technologies or innovation-intensive, competitive exports. The country was ranked 61st in the world for innovation performance in 2022, the highest-ranking country in mainland Africa. The latest survey of innovation in South African firms, which covered 57 000 firms for the period 2019-2021, found that two-thirds of South African firms were engaged in innovation activities, with 83% of these using or offering a product or process innovation during the reporting period, mostly based on improvements or adaptations to sustain the firm's existing products. Among sectors, the information technology industry had the highest level of innovation activity. Around 30% of the enterprises engaged in innovation activity were active in environmental technologies. However, less than a fifth of the companies surveyed carried out in-house R&D during the period, and most reported a decrease in their innovation efforts due to pandemic-related barriers to collaboration.

The case of the Renewable Energy Independent Power Producer Procurement Programme

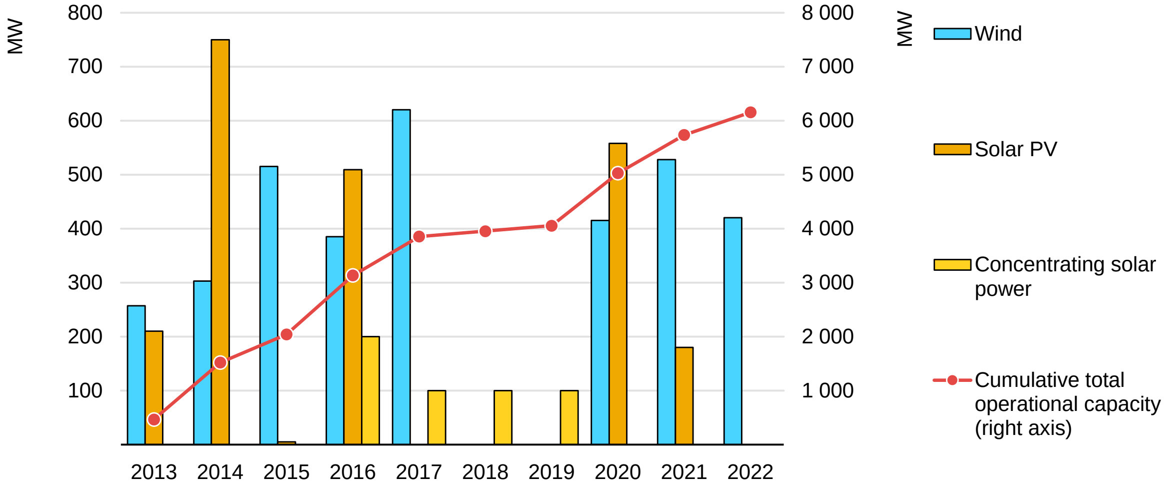
South Africa's Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) is an innovative renewable energy policy in many ways. It was launched in 2011, spurred on by the political focus on climate change at the time of the country's hosting of the UNFCCC Conference of the Parties. The REIPPPP is an auction programme in which private bidders compete to win fixed-tariff offtake contracts for the construction of specified amounts of grid-connected renewable energy generation. Winning bidders receive guarantees that Eskom will transmit and distribute the privately generated electricity for 20 years. Since 2011, seven rounds of bidding have been held and contracts have been awarded for increasing amounts of renewable energy, mainly wind, solar PV and concentrating solar power (Figure 12.3). The total capacity available to be awarded for each technology is specified in advance, and included biomass energy and small hydro in the first windows, and battery storage in the most recent. The total installed capacity supported by REIPPPP has now exceeded 6 GW (Figure 12.4).

Figure 12.3 Capacity allocated per bidding window by technology, South Africa, 2011-2024



Note: Based on the year of the announced awardees of bidding windows 1 (2011), 2 (2012), 3 (2013), 3.5/4 (2014), Expedited (2015), 5 (2021), 6 (2022) and 7 (2024).
Source: IPP Projects (2024), IPP Office Reports, Quarterly Reports.

Figure 12.4 REIPPPP annual capacity additions by technology and total operational capacity, 2013-2022

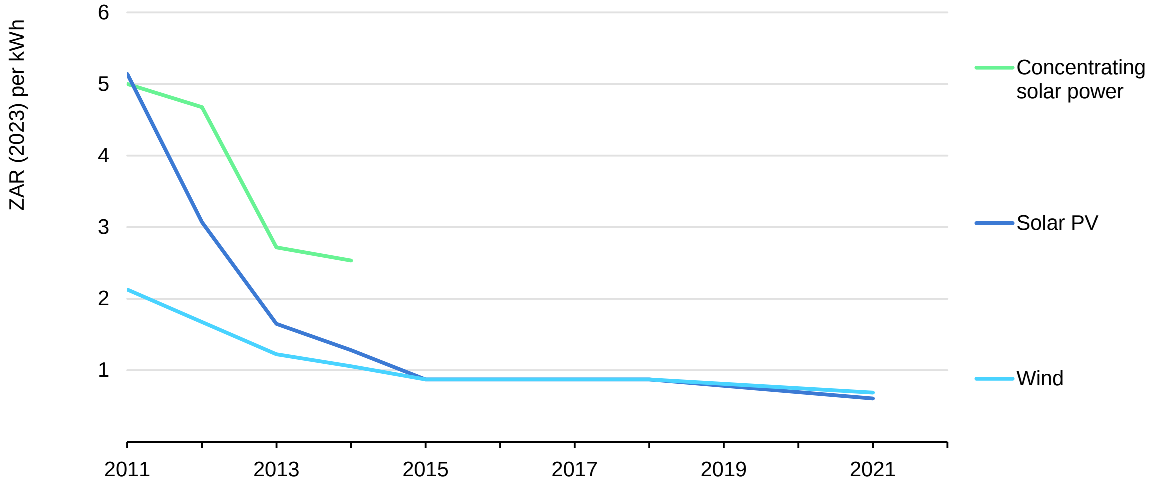


Source: IPP Projects (2024), IPP Office Reports, Quarterly Reports.

The competitive nature of the auctions, which attracted over 300 submissions to the first four bidding windows, led to rapid declines in contracted prices (Figure 12.5). These dropped below Eskom's average cost of supply. This development, as well as the REIPPPP's facilitation of the first IPPs in the South African power market, created competition for Eskom, who was building two new coal-fired plants at the time.[10] Eskom had a preference for a feed-in-tariff, which the National Energy Regulator (NERSA) had been developing before the REIPPPP superseded it, and also campaigned for renewables to be matched by an equal amount of fossil fuel-fired capacity. Between 2015 and 2018 Eskom continued to refuse to sign the offtake agreements and found allies in the government of the day. This opposition led to a three-year gap between bidding windows, which resumed under President Ramaphosa's administration in 2018.

[10] While coal-based technology has long been the core of Eskom's expertise, these two new plants suffered from delays due to technical and design faults, strikes and sabotage that reflected poorly on the company and its century-old monopoly on power generation and distribution.

Figure 12.5 Resulting tariffs from REIPPPP bidding rounds



Notes: Based on the year of the announced awardees of bidding windows 1 (2011), 2 (2012), 3 (2013), 3.5/4 (2014), Expedited (2015), 5 (2021). Bidding windows 6 and 7 not included. Other sources show slight differences with respect to concentrating solar power prices.
Source: IPP Projects (2024), IPP Office Reports, Quarterly Reports.

The REIPPPP had close alignment with the national vision for socio-economic development

The REIPPPP was well aligned with the national vision for energy supply articulated in the 2003 Energy White Paper and Renewable Energy White Paper, which contained both renewable energy and innovation objectives. The White Paper advocated "promoting the development and implementation of appropriate standards and guidelines and codes of practice for the appropriate use of renewable energy technologies [and] appropriate research and development and local manufacturing to strengthen renewable energy technology and optimise its implementation". However, the innovation objectives were not significantly pursued between 2002 and the Integrated Resource Plan of 2011, which established the renewable energy targets for which the REIPPPP was designed as the implementation instrument. Also in 2011 the National Climate Change Response White Paper introduced the concept of a "just transition" to create a new vision against which policy choices would be made. In this white paper, just transitions for South Africa have a clear innovation component (Box 12.1).

Box 12.1 Innovation-related elements in the South African concept of a just transition in its National Climate Change Response White Paper (2011)

South Africa's first formal climate policy, the National Climate Change Response White Paper, referenced clean energy innovation as an emerging idea of a just transition in 2011.

Relevant excerpts include:

"South Africa can become a significant global player in the green economy. More specifically, South Africa should aim to be a leading supplier of climate change knowledge, technologies and services."

"The decision at a national level to adopt innovations depends on the benefits users expect from the innovations as well as on the expected costs to research and master them. In addition, a country needs the technological capability to imitate, adapt and absorb foreign technologies into local productive activities. This capability influences the relative costs and benefits of adopting new technologies."

"For South Africa to enhance its international competitiveness in climate change response science and technology, it needs sound science, a robust technology base and sound human capital in this arena."

"Technology transfer continues to be very prominent in the multilateral environmental agreements in general, and in climate change-related agreements in particular. A national capacity to optimally engage climate change-related technology for South Africa, both as a recipient as well as donor to other developing countries, will be developed."

The Renewable Energy Flagship Programme "will be informed by enhanced domestic manufacturing potential and the implementation of energy efficiency and renewable energy plans by local government. Furthermore, the Department of Energy's solar water heating programme will be expanded through, amongst others, the promotion of the domestic supply of products for solar heating with support from the [Department of Trade and Industry] to build local manufacturing capacity."

"Reporting on climate responsibilities and adaptation measures will consequently be integrated into the Programme of Action and the Ministerial delivery agreements, as well as the quarterly reporting requirements of government at all levels. Key outcomes include… Decent employment through inclusive growth… A skilled and capable workforce to support an inclusive growth path… Vibrant, fair and sustainable rural communities and food security for all… Sustainable human settlements and an improved quality of household life… Responsive, accountable, effective and efficient local government system… Environmental assets and natural resources that are well protected and continually enhanced… Creating a Better South Africa and Contributing to a Better (and Safer) Africa and a better World"

The REIPPPP included incentives for local production and employment, but no provisions for R&D. The so-called socio-economic development criteria were implemented at the same time as the Preferential Procurement Policy Framework Act came into force, which required any public tender to use non-price elements for at least 10% of the decision criteria. To be consistent and credible in this dual context, socio-economic development (SED) criteria were introduced for the REIPPPP. SED accounted for 30% of the total project selection criteria (the rest being based on price) and initially consisted of the following components:[11]

- Rules for preferential procurement from black and female-owned local businesses.
- Local content requirements for a share of jobs to be staffed by South African nationals, rising from 12% to 20% over time.
- Requirements for transfer of 1-1.5% of the project value to the local communities in the proximity of 50 km of any renewable energy plant, a practice adopted from South Africa's mining policies.

The REIPPPP therefore goes beyond the basic requirements for non-price components and emphasised socio-economic development more strongly than other public tenders had before, especially broad-based black economic empowerment, which remains a key component of the REIPPPP. In addition, REIPPPP uses economic development criteria thresholds to determine whether bidders can pass on to subsequent rounds of evaluation. For bidding windows five and six, this required exceptional permission from the National Treasury to use such a measure. This, and the use of SED, show how South Africa was moving towards the concept of "just energy transitions" before the term had been widely promoted. The use of auctions and socio-economic selection criteria also made South Africa a frontrunner in policy design when many other countries were using fixed feed-in tariff approaches to support renewables deployment.

Choosing the REIPPPP approach precipitated several complementary policy choices

While the REIPPPP has been the dominant instrument to create a market for renewable energy technologies in South Africa, its effectiveness has required further market pull measures, including legislative reforms. These additional measures show how the decision to reward private investment in renewable energy, while minimising the cost to the government of the offtake contracts, led to a broader set of reforms that encouraged competition and innovation.

[11] As the evaluation criteria were adjusted for each bidding window, the weight of SED changed over time and was just 10% in bidding window seven.

Sections 12B and 12U of the Income Tax Act were amended to support investment in renewable energy, including:

- Accelerated depreciation for all wind energy and biomass projects, plus solar PV and concentrating solar power projects above 1 MW and hydropower projects up to 50 MW.
- One-year 100% depreciation for solar PV projects below 1 MW, instead of three-year accelerated depreciation.
- Accelerated depreciation for other infrastructure expenditure linked to the construction and generation of renewable power plants.

In addition, the CO_2 emissions avoided by renewable energy projects were made eligible under the carbon offset programme, which allows taxpayers to use offsets to reduce their carbon tax liability. This incentive was very successful in attracting interest and rapidly exhausted the availability of all credits in the South African carbon market.

The drop in the costs of renewable energy that were revealed by the bidding windows created a strong argument in favour of allowing municipalities to procure their own distributed electricity and reduce their incentive to demand more power from the grid. In 2020 DMRE amended the Electricity Regulation Act of 2006 to enable municipalities to procure electricity directly from IPPs. So far, only a few municipalities – including the City of Cape Town and Stellenbosch – have been in a financial position to take advantage of this provision.[12]

The IRP did not originally foresee power generation projects below 100 MW, except for small projects below 1 MW that were exempt from generation licences. All IPP projects above 1 MW were required to obtain a generation licence from NERSA and permission from DMRE. This administrative process was cumbersome and prevented renewable power projects from helping to alleviate Eskom's supply constraints. In 2021 the President increased the licensing threshold to 100 MW and amended the Electricity Regulation Act so that renewable electricity projects below this threshold need only register with NERSA. As small and medium-sized enterprises had found it difficult to compete with larger bidders due to the costly paperwork involved, a small project auction was launched in 2013 to accommodate these smaller companies and it has attracted 20 renewable energy projects between 1 MW and 5 MW. In 2022, when international energy prices rose steeply, the government lifted the licensing threshold altogether.

[12] The recent changes under the Electricity Regulation Act in 2024 enable future municipal procurement through a new National Transmission Company South Africa, which climate finance could easily support.

Implementation and evaluation of the REIPPPP

The performance of the REIPPPP has not yet been formally evaluated against its objectives of socio-economic development, job creation and enterprise development. However, there is evidence of how difficult it is to create new competitive businesses from scratch using only market pull policy measures without enabling pre-conditions to support local content and community preference rules. One design feature of the programme that possibly limited the "just transition" elements of the REIPPPP was the imposition of penalties for late implementation of projects, which firms had to trade off against penalties for non-compliance with local content requirements, which tended to make projects slower to arrange. Despite the government's concerns about ratepayer funds subsidising foreign technology suppliers, the REIPPPP did not include provisions to assist project developers with local content compliance. There was no support for vocational training and technical skills development to empower local workers to secure jobs in the new activities or help attract foreign investment. The REIPPPP catered for local project developers in collaboration with mature, international original equipment manufacturers that could demonstrate experience and absorb the substantial bidding costs. It is estimated that the costs of developing each project proposal for the first few bidding windows was almost USD 2 million, an issue that recent rounds have attempted to address, for example by streamlining applications from compliant developers from previous rounds.

Eventually, the local content requirements created manufacturing jobs in two wind turbine tower production factories and several assembly plants for solar PV panels.[13] These requirements stimulated the development of scientific, engineering and technical skills in the South African wind energy industry, despite conflicting policy barriers constraining their growth.

The wind tower manufacturing factories closed when the REIPPPP experienced delays between bidding windows. Some companies found creative workarounds, such as building wind turbine towers in situ at remote installation sites rather than using a local factory. The solar PV plants involved only low-tech assembly of imported components. These imports were cheaper and readily available due to global overcapacity and integrated production in China and elsewhere. South African production, by contrast was a new economic activity for which there was a shortage of trained personnel. The selection criteria in the REIPPP did not support innovation in South African manufacturing by companies with limited prior experience. To some extent, South Africa experienced disadvantages from trying

[13] Fyvie, Richard (2017), Local Content Requirements in the South African Wind Industry, University of Cape Town: Doctoral Thesis.

to attract international clean energy technology investment at the same time as Brazil's policy push in the same arena, but on a larger scale.

The structure of the community development criteria was an innovation itself, unique to the South African renewable energy programme and new to all actors involved. The first 64 projects generated approximately USD 600 million available to local communities for the duration of the power purchase agreement of 20 years. Local communities, businesses and government officials were equally unfamiliar and needed to work out how to set up the new SED system. Hence, the funds were only available after the installation of the plant and could not be used upfront in support of the project's installation. Most of the funds have been used to form community trusts and benefit projects that the communities can determine themselves.

The case of South Africa's Just Energy Transition Partnership

The JET-P is an innovative form of finance for equitable and climate-resilient development and emissions reduction.[14] The South African government developed the idea to attract climate finance in a collaborative effort with an international group of governments and funding agencies from Denmark, the European Union, France, Germany, the Netherlands, the United Kingdom and the United States.

The partners agreed on a five-year investment plan (JET-IP) was agreed in 2022. The Cabinet of South Africa – the executive branch of the government's most senior body – approved a JET Implementation Plan a year later. The partnership outlines actions for several highly emitting sectors, including the accelerated decommissioning of a 56-year-old coal-fired coal plant and repurposing the site to supply renewable electricity coupled with battery storage and employing the current workers. Two ambitious technology-specific elements of the investment plant are those for electric vehicles and hydrogen.

Alignment with the national vision and international diplomacy

The narrative of the JET-P caters for both national interests and international agendas. The government adopted a Just Transition Framework as a basis to align the country's development and climate change objectives, including achieving net zero emission by 2050.

[14] Since the announcement of South Africa's JET-P in 2021, Indonesia has launched a similar process and ten more are said to be under discussion in other countries.

The JET-P was originally presented to the Presidential Climate Commission as a programme to relieve Eskom's debt. The national interest in reforming Eskom and its financial sustainability stood at its core. The continuous downgrading of its credit ratings also impacted on the investment climate in the wider economy. Eskom had established its own Just Energy Transition Unit at the time to move this process forward internally. The plan attracted critique within and outside the government when it was presented by Eskom's former CEO André de Ruyter to the national planning commission ahead of COP26 in Glasgow.

The focus on Eskom expanded over the course of the negotiations between the South African government, its advisory group and the group of international partners to include the hydrogen and transport sectors, aligning with national programmes to develop these industries.

The South African government pronounced its ambition to support the development and expansion of local EV manufacturing capacity in its recent White Paper on EVs. The strategy aligns with the provisions in the JET-IP to incentivise investment in domestic industries for the manufacture of vehicles, charging components and infrastructure.

Alignment with international commitments

The Paris Declaration on Aid Effectiveness has had the aim of institutionalising the co-ordination of funding efforts between the industrialised countries since 2005. The principles of the Paris Declaration (ownership, alignment, harmonisation, results and mutual accountability) are reflected in the governance of the JET-P and its JET Implementation Plan in different ways. Ownership could be witnessed in the initial motivation to decarbonise Eskom's electricity supply infrastructure when the proposal was first put together in the context of the updating South Africa's NDC. The South African Climate Advisory Council, known as the Presidential Climate Commission, co-ordinated the processes and manoeuvred the NDC towards a more ambitious emissions reduction target, despite contention between political actors. The partnership is recent and was formed during preparation for COP26 in Glasgow in 2021.

The JET-P's results in terms of physical technological change remain to be seen. In terms of institutional innovation, however, the partnership has increased the alignment between climate finance and development efforts, focused around mutually agreed areas of socio-technical change. A detailed implementation and investment plan under the JET-P has an important function in the absence of an implementation plan for the NDC and can help to benchmark the progress in investment towards technological change that underpins the decarbonisation process in energy, fuel production and transport. The JET-P exemplifies the important role of cross-governmental co-ordination in directing incentives to private investment. Critiques express concerns about the inclusiveness of the most vulnerable members of society in the benefits of the JET-P, as well as the risk of corruption in the public sector.

Clean energy innovation in hydrogen and EVs in the JET-P

Hydrogen is a second priority sector for the JET-IP, after electricity. The production of hydrogen in South Africa currently accounts for around 2% of the world's total and is an emissions problem. Current hydrogen production is linked to South Africa's chemical sector, which is one of the largest among EMDEs and largely dependent on coal as a raw material and energy source. SASOL, a private chemical company that was previously state owned, is the largest single company in this sector and one of the country's largest emitters of CO_2. It is a global leader in the development of technology to convert coal to liquid fuels and chemicals, a technology that was originally selected and licensed by the apartheid government in 1955 in pursuit of energy independence based on the country's extensive coal reservices. Since then, SASOL has improved the core technology, which requires the production of hydrogen as an intermediate step, and has executed projects to make other types of synthetic fuels (including from bioenergy), hydrogen from electrolysed water and hydrogen fuel cells.

JET-P's funding of 11 hydrogen production projects, including the production of ammonia from hydrogen as a means of exporting it in a more convenient form, aligned South Africa's technical expertise and the policy interests of its funders in 2022. Particularly, the German government has a strong interest in diversifying its dependence on fossil fuels and energy security independently from Russian gas. There is a strong historical foundation in research collaboration in synthetic fuels between German and South African research organisations and universities, including hydrogen fuel cells, hydrogen-based cooking fuel and aviation fuels. In 2021 a feasibility study identified three potential hubs and nine potential pilot projects for hydrogen production from renewable electricity, for applications ranging from mining trucks, freight trains and heavy-duty trucks, to data centre backup power. SASOL has also launched a feasibility study into a large facility for making hydrogen from a dedicated new renewable power plant and converting it to ammonia for export markets, which are considered the only realistic markets that could cover the costs of hydrogen production by this method in the near term. Trade-offs between revenue from exports for the private sector need to be carefully weighed against the benefit of renewable energy for electricity use and security of supply for wider societal benefit in line with just transition objectives.

EV manufacturing is the third priority sector articulated in the investment plan, also with an export dimension. A total of USD 6 billion is earmarked to support industrial development and innovation. The choice of EVs reflects existing capabilities: nine international car manufacturers already produce vehicles in South Africa, of which around 60% are exported.[15] Existing supply chain infrastructure could support a transition towards EVs from internal combustion engines. There are other favourable economic factors, including high import taxes on cars that make imported EVs very expensive, high gasoline prices that could make sales of domestic EVs attractive in South Africa, and good solar resources that could be paired with manufacturing to give South African EVs very low life cycle emissions intensities. However, previous attempts in this area have encountered challenges. In the early 2000s the Department of Science and Technology used its Innovation Fund to invest USD 5 million in equity in a private company to produce a new South African car designed by Jaguar. Insufficient private investment made the business unviable and only a small of fleet of four "Joule" cars was built between 2008 and 2012.

Implementation of innovation priorities in the JET-P

The JET-P has raised expectations in South Africa for the development of new energy industries and international expectations for how multilateral co-operation can support emissions reductions and economic growth in EMDEs. Since 2021 international funding pledges for the JET-P increased from ZAR 170 billion to ZAR 240 billion and the inclusion of the New Development Bank of Brazil, Russia, India, China and South Africa (BRICS), located in China, is an encouraging sign of collaboration at a time of heightened geopolitical tensions. However, in terms of the design of the JET-P funding, the reliance on debt and guarantees rather than grants has been criticised in South Africa for its potential costs to the domestic economy in the longer term. Nonetheless, in terms of innovation, by selecting priorities that build on existing strengths in chemicals and automotive manufacturing, it attempts to address the country's concerns about the future of local jobs in fossil fuel-related sectors during a transition to clean energy.

As of mid-2024, it is too early to judge the overall contribution of the JET-P to technological innovation and just transitions in South Africa. Despite being a pioneer in its engagement with this model of financing, the institutional co-ordination between multiple countries and their development banks takes time. At the same time, a large number of projects have already been committed relatively quickly. The mixed pace of progress and ways of distribution of funds in implementing the plan are sources of concern among the South African public and funders, and for the model more generally.[16] One emerging issue to be navigated is the tension between the closure of coal plants, which is scheduled as part of the

[15] International carmakers in South Africa include Mercedes, BMW, Toyota, Ford, Mahindra, Nissan and Isuzu. South Africa has a competitive, low-cost workforce and is a strategic entry point to the African market, as well as a good location for imports of parts and vehicle exports to all other continents.

[16] Critics of the JET-P have expressed concerns about the rapid pace of the allocation of the grant funds, counterbalanced by the slow progress in phasing out coal.

JET-P, and the construction of renewable energy infrastructure to power clean energy technology and fuel production for export. The lack of improvement in the outlook for the availability of electricity and social security for local communities has begun to create political tensions about who will benefit from the JET-P.

Findings

The analysis of clean energy innovation policy reveals mixed success in advancing 'just energy transitions' in South Africa. The public policy processes to develop clean energy in South Africa reflect the slow progress of the country's energy transition, caused by the ongoing struggle between coal and renewables in the energy sector.

The narrative of a just transition to a sustainable and universally accessible energy future aligns with the country's policies over the past decades as well as its ambition as a global citizen to achieve the Sustainable Development Goals. These aspirations continue to be undermined by historical institutions designed to protect the fossil fuel industry, hidden incentives for fossil fuels and strong political interests.

The role of technology development in a just transition was articulated in the National Development Plan, the REIPPPP and National Climate Change Response White Paper, and this guiding vision has since supported the inclusion of local content and technology objectives in the REIPPPP and JET-P. These two initiatives are both innovative approaches to policy and funding challenges in an emerging economy. South Africa's experience is therefore highly valuable for learning about the viability of linking energy transitions with local community prosperity in this way.

The responses to the electricity supply crisis have fast-tracked regulation that had been resisted for decades, including the unbundling process of Eskom, lifting the limits for private sector involvement and closing the gap in overdue new capacity installation. The global economics of the cost of new energy installations did not support the preference for installing new coal and new nuclear, which the lobbyists from both industries negotiated into the electricity plans. The temporary spike in the uptake of renewable energy through private installation at household, business and utility-scale levels requires continuity to achieve the much-needed security of supply so that the ageing coal fleet can retire smoothly.

The electricity crisis has caused frustration and loss of quality of life for many South Africans, with the result that political support for the governing ANC party has declined. The responses to the crisis triggered action and reform, but there is a risk of slipping back into reactive rather than proactive management of energy transitions once the inconvenience of loadshedding has been resolved for parts of the population.

Overall, the country has made progress in the deployment of renewable energy technologies, but the innovation components of the REIPPPP were superseded with the opening of the market. The rapid installation of renewable energy through imports from China and other parts of the world has helped to resolve the load-shedding crisis, but possibly at the expense of developing local industries and much-needed manufacturing jobs. The window of opportunity for supporting domestic innovation in renewable energy technology as set out at the outset of the REIPPP is closing.

The more difficult parts of closing coal mines and power plants, and building and financing new transmission infrastructure, are already being contested and resisted – the harder parts of providing public goods beyond the market in the just energy transition have yet to be resolved and will require continued commitment to “justice” in the transition.

Annex

Abbreviations and acronyms

AC	Alternating current
ANC	African National Congress
ANEEL	Agência Nacional de Energia Elétrica
BEE	Bureau of Energy Efficiency
BNDES	Banco Nacional de Desenvolvimento Econômico e Social
BRICS	Brazil, Russia, India, China and South Africa
CAREM	Central Argentina de Elementos Modulares
CCUS	Carbon capture, utilisation and storage
CEGU	Clean Energy Generating Units
CEM	Clean Energy Ministerial
CFE	Comisión Federal de Electricidad
CFL	Compact fluorescent lamps
CHP	Combined heat and power
CO_2	Carbon dioxide
CONICET	Consejo Nacional de Investigaciones Científicas y Técnicas
CSP	Concentrating solar power
DAC	Direct air capture of CO_2
DC	Direct current
DG	Distributed generation
DMRE	Department of Mineral Resources and Energy
EBRD	European Bank for Reconstruction and Development
EESL	Energy Efficiency Services Limited
EG	Exempt Generator
EGTT	Expert Group on Technology Transfer
EMDE	Emerging market and developing economies
ESCO	Energy service companies
ETS	Emissions trading system
EV	Electric vehicle
FCTeI	Fondo de Ciencia, Tecnología e Innovación
FDI	Foreign direct investment
FOTEASE	Fondo para la Transición Energética y el Aprovechamiento
GDP	Gross domestic product

GEF	Global Environment Facility
GHG	Greenhouse gas
GST	General service tax
IEA	International Energy Agency
IITD	Indian Institute of Technology, Delhi
IPEEC	International Partnership for Energy Efficiency Cooperation
IRESEN	Institute for Research in Solar Energy and New Energies
IPP	Independent power producers
IRP	Integrated Resource Plan
ISEER	Indian Seasonal Energy Efficiency Ratio
JET-P	Just Energy Transition Partnership
KCIC	Kenya Climate Innovation Center
KOSAP	Kenya Off-grid Solar Access Project
KPLC	Kenya Power and Lighting Company
LED	Light-emitting diode
LFP	Lithium iron phosphate
LMIC	Low- and middle-income countries
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MENA	Middle East and North Africa
MEPS	Minimum energy performance standard
MOF	Ministry of Finance
MOST	Ministry of Science and Technology
NASENI	National Agency for Science and Engineering Infrastructure
NDC	Nationally determined contribution
NDRC	National Development and Reform Commission
NEA	National Energy Administration
NEP	National Energy Policy
NFRK	National Fund of the Republic of Kazakhstan
NREEEP	National Renewable Energy and Energy Efficiency Policy
NSEL	NASENI Solar Energy Limited
OECD	Organisation for Economic Co-operation and Development
OPAD	Office of Poverty Alleviation and Development
PAT	Perform, Achieve and Trade
PAYG	Pay-as-you-go
PHWR	Pressurised heavy water reactors
PLI	Production-Linked Incentives

PPA	Power purchase agreement
PPP	Purchasing power parity
PROINFA	Programa de Incentivo às Fontes Alternativas de Energia Elétrica
PV	Photovoltaic
PWR	Pressurised water reactor
R&D	Research and development
RD&D	Research, development and demonstration
REA	Rural Electrification Agency
REEEP	Renewable Energy and Energy Efficiency Partnership
REIPPPP	Renewable Energy Independent Power Projects Procurement Programme
REMP	Renewable Energy Master Plan
REREC	Rural Electrification and Renewable Energy Corporation
RESIP	Rural electrification strategy and plan
RET	Renewable energy technologies
S&L	Standards and labelling
SAF	Sustainable aviation fuel
SED	Socio-economic development
SEZ	Special Economic Zones
SGCC	State Grid Corporation of China
SME	Small and medium-sized enterprises
SMR	Small modular reactors
TNA	Technology Needs Assessments
UHV	Ultra-high voltage
UJALA	Unnat Jyoti by Affordable LEDs for All
UNDP	United Nations Development Programme
UNESCO	United Nations Educational, Scientific and Cultural Organisation
UNFCCC	United Nations Framework Convention on Climate Change
WIPO	World Intellectual Property Organization

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