3. Bioethanol and wind in Brazil

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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.

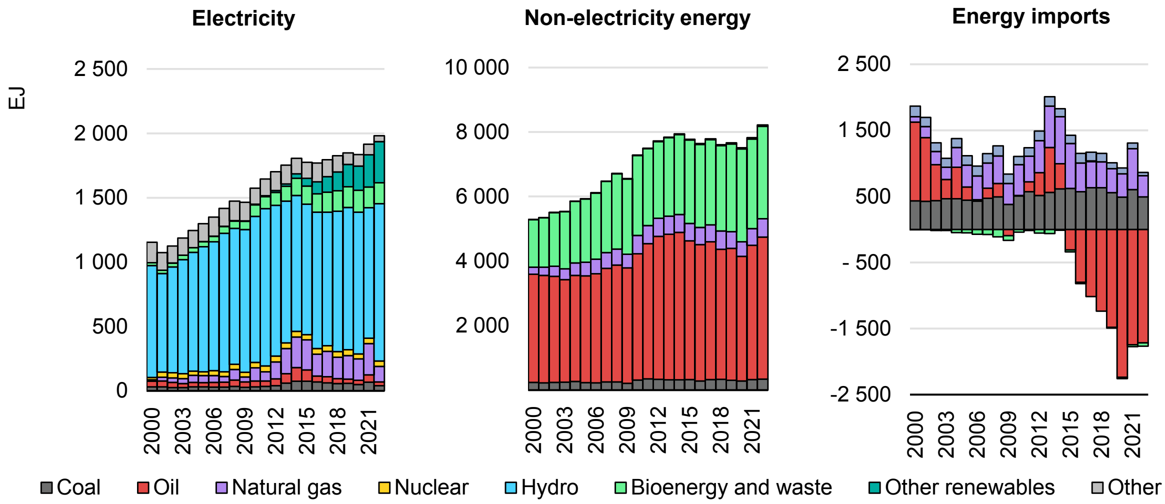
The period since the 2008 financial crisis, which significantly dented the economy, has been more focused on public investment and spending, exports, household consumption and social policies, including a minimum wage. However, the macroeconomic impacts of the global pandemic and its aftermath have counterbalanced 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



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.

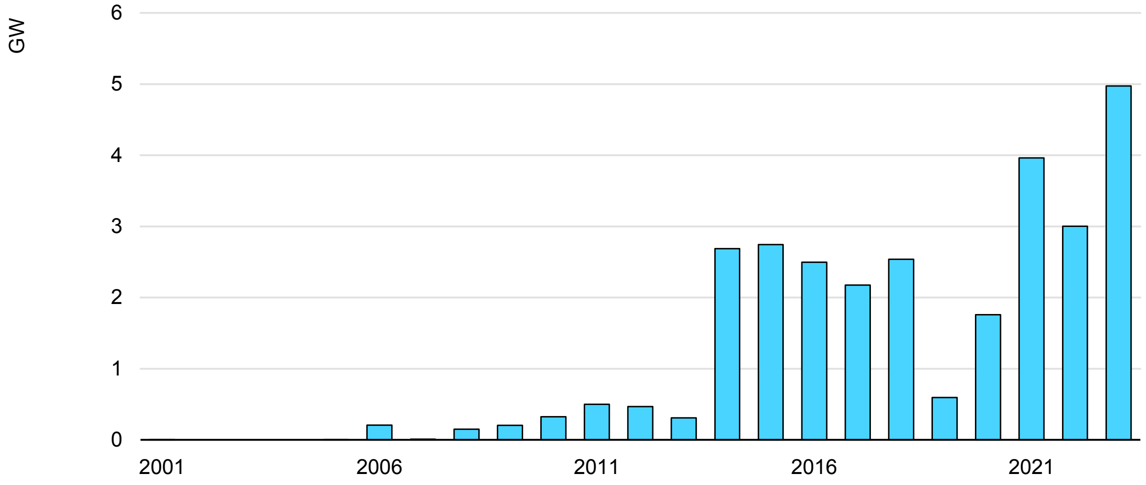
This type of support policy for renewables was at the forefront of government activity internationally. Germany's Renewable Energy Sources Act, with its feed-in tariff for utility-scale renewable energy, was passed in 2000. The United Kingdom's Renewables Obligation was introduced in 2002. China's Renewable 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

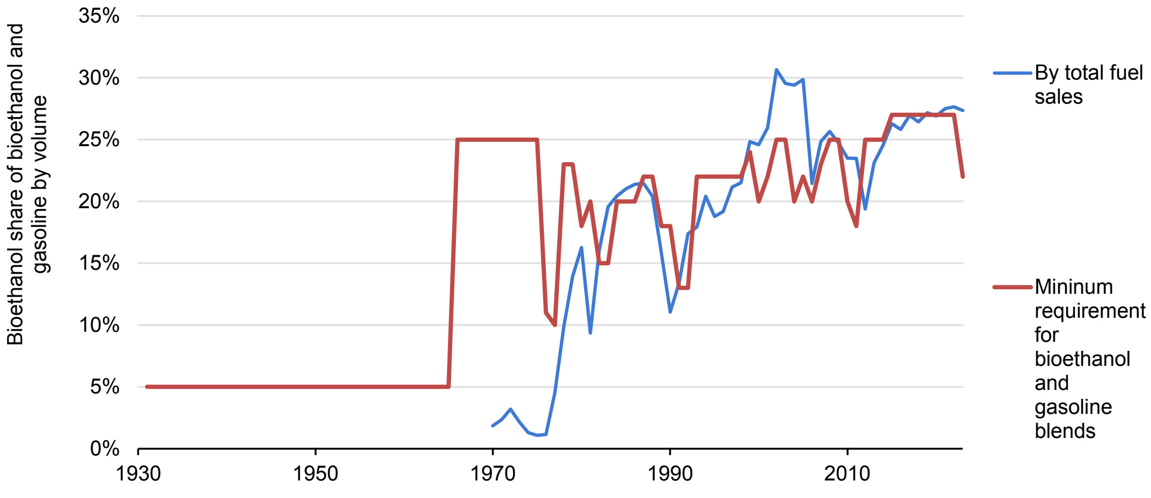
From its earliest days, support for bioethanol in Brazil had its foundations in a strong linkage between the national vision for a world-leading sugar industry and the broad consensus in favour of greater industrial independence. Sugarcane was the first major industrial sector in Brazil in the 16th century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

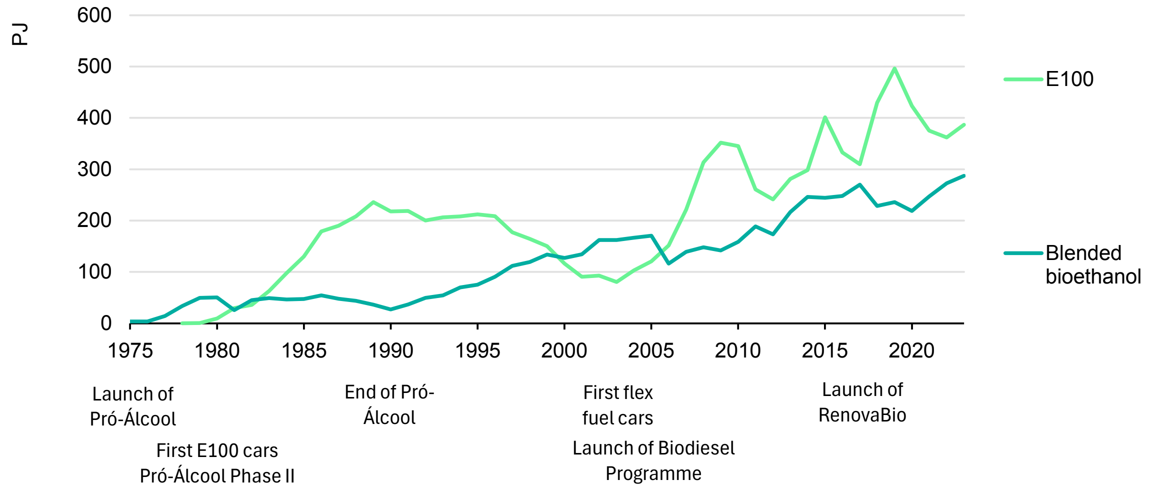


Sources: Mendes Souza, G. et al. (eds.) (2015), Bioenergy & Sustainability: bridging the gaps (p. 235); National Agency for Petroleum, Natural Gas and Biofuels (2018), ANP Resolution No. 758 of 23/11/2018, 27 November 2018; Puerto Rica, J. A. (2007), Programa de Biocombustíveis no Brasil e na Colômbia: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

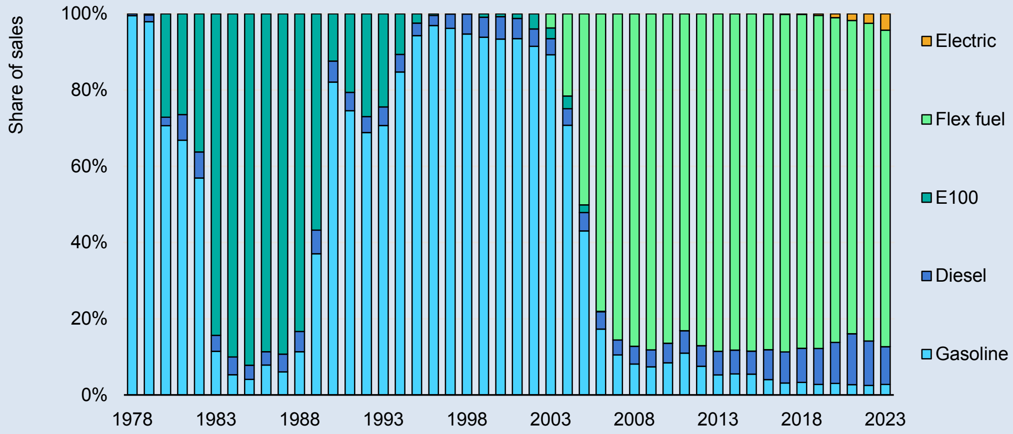
The first E100 vehicle hit the market in 1979, a version of the Fiat 147, which was produced in the state of Minas Gerais from 1976 until 1987. The augmented compression ratio worked well and the car outperformed expectations, becoming a big seller.

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.