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.

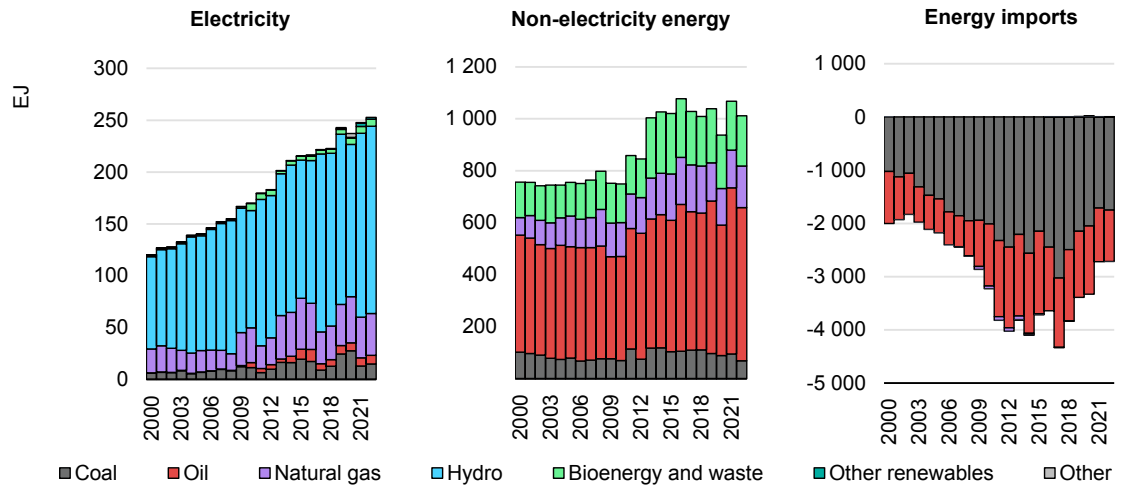
Energy sector context

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

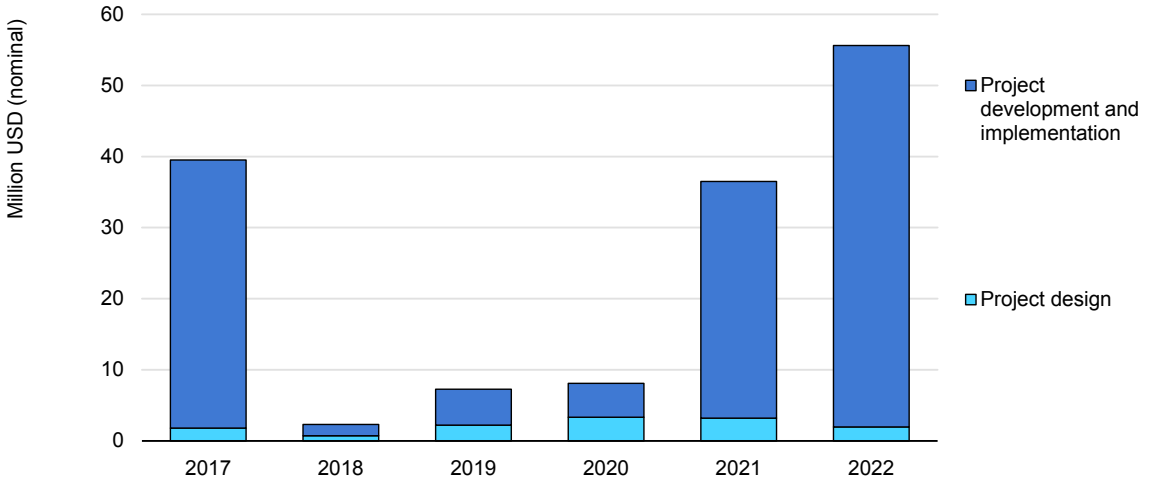
Since 2014, the main policy measures adopted by the government have been chosen to incentivise investment by the private sector rather than direct investment in publicly owned renewables projects. In this regard, policy choice was constrained by the institutional history of energy governance, which included 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.