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Edited by Kathleen M. Araújo

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Insights from Colombia, Cuba, and Mexico

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1. Introduction

Although climate change is frequently framed as a global issue, low-carbon transitions can often materialize through the implementation of renewable energy targets at the national level. In this context, reports such as the Global Renewables Outlook: Energy Transformation 2050 (IRENA, 2020a) adopt a regional perspective to assess energy transitions, bridging global aspirations and regional actions. Such regional assessment of energy transitions highlights the strong differences in terms of the deployment of renewable or low-carbon energy technologies across the world, always dependent on available energy resources, as well as economic, institutional, environmental, and political contexts. The IRENA Outlook (ibid.) suggests that Latin American countries are doing remarkably well for low-carbon transitions, presenting the highest share of renewable energy worldwide in terms of the regional total primary energy supply (30%) and in power generation (65%). However, focusing on the country level would present a different panorama, with a diverse mosaic of energy transitions.

To assess the full implications of low-carbon transitions beyond technical solutions or impacts, it is necessary to recognize energy systems as socio-technical systems where social, institutional, economic, political, and environmental processes play a significant role (Sovacool et al., 2020; Adil and Ko, 2016; Jenkins et al., 2016, 2018; Araújo, 2017). Such socio-technical recognition of energy systems then raises additional challenges, as it is not sufficient to only produce low-carbon energy but which also covers the increasing energy needs of a globally growing population, and that is reliably distributed from generation to consumption points. Such balance between clean, sufficient, and accessible or reliable energy is manifested in important instruments like the United Nations Sustainable Development Goal 7, which aims to "Ensure access to affordable, reliable, sustainable and modern energy for all" (UN, 2021).

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It is within this recognition of energy systems as socio-technical systems that the concepts of energy resilience and energy vulnerability gain relevance. Energy resilience has traditionally been understood as a multidimensional concept (Gatto and Drago, 2020), useful for assessing the ability of an energy system to prevent, absorb, recover, or adapt to disturbances or shocks of different forms (economic, social, environmental, technical, etc.) (Ahmadi et al., 2021; Araújo and Shropshire, 2021). On a related front, energy vulnerability can also be defined as a multidimensional concept, useful this time to assess the risk or potential of an energy system or a household to fall into a state where resulting energy services are inadequate or insufficient due to adverse effects or structural/systemic conditions of marginalization and inequality (Bouzarovski et al., 2015). These two concepts of energy resilience and vulnerability overlap and are key to understanding how low-carbon transitions may enhance our energy systems in terms of making them cleaner and also making them more reliable and robust, ensuring that the general population is able to access the energy services that form the backbone of daily activities in any country.

The rest of the chapter is divided into three sections. Section 2 provides an overview of the concepts of energy vulnerability and energy resilience and why they are important for understanding Latin American energy transitions. Section 3 explores illustrative micro-cases from Colombia, Cuba, and Mexico, analyzing how each one relates differently to energy vulnerability and energy resilience. Finally, Section 4 closes with some final thoughts and priorities for future research.

2. Energy Transitions in Latin America

Considering energy resources, Latin America has considerable amounts of water, biomass, solar, and wind energy distributed across the region, enabling a currently high penetration of renewable energy resources in the power sector, at roughly 65% (IRENA, 2020a). The region also has the potential to eventually reach 100% in the subcontinent (Noura Guimarães, 2020). However, examining trends at the country level reveals significant differences across the region. For example, Colombia produces around 73.2% of the electricity from renewable energy sources such as hydropower, solar, and wind, surpassing the regional average (XM, 2021). Meanwhile, countries like Mexico currently only derive around 21% of electricity from low-carbon sources (SENER, 2021), which is more similar to regions like East Asia or Southeast Asia (IRENA, 2020a), while Cuba has an average share of renewable power similar to countries in the Middle East and North Africa at around 4% (ibid.).

Many countries in Latin America have a high dependency on specific resources and technologies for the generation of electricity. According to Noura Guimarães (2020), one group of Latin American countries relies mainly on low-carbon technologies, such as hydropower, as is evident in Brazil (62.5%), Colombia (79.8%), Costa Rica (74.4%), Panama (61%), Paraguay (99.7%), Uruguay (63.2%), and Venezuela (64%). By contrast, a second group of Latin American nations relies on fossil fuel endowments for electricity generation, as may be seen in Argentina (66%), Bolivia (79.3%), Chile (63.7%), Cuba (96%), Dominican Republic (88%), and Mexico (79%) (ibid.). This diversity of natural resource use translates to differentiated challenges for an energy transition, such as social conflicts around wind power in Mexico (Mejia-Montero et al., 2020), or the integration of the indigenous population's preferences into the production of renewable energy in Chile (Merino et al., 2020). Within this context, stark differences may be expected when considering the work needed to achieve a decarbonized energy sector and successful energy transition. Moreover, successful energy transitions should be understood from the perspective of households and countries and cannot be completed without affordable access and reliable energy services.

2.1 A Quick Glance at Energy Vulnerability and Energy Resilience

The term *resilience*, from the Latin "resilire", refers to a series of physical movements, such as bouncing back and returning. A more modern use of the concept can be traced to France in 1430 where it was used as a legal term to describe the restoration of an original legal situation after the termination of a contract (Gößling-Reisemann et al., 2018). Over time, the concept of resilience has been used under various contexts, adopting different definitions, creating a fertile ground for interdisciplinary work (Thoren, 2014). Within this context, authors such as Holling (1996) reflected on the differences between the concept of resilience from an ecological and an engineering perspective. From an engineering perspective, important characteristics were conceptualized to measure systems resilience, such as its resistance to disturbances and the speed of a system to return to the equilibrium system. On the other hand, characteristics like efficiency, constancy, and predictability can be used to understand resilience as the stability of an ecological system near an equilibrium steady state, allowing us to identify strong resemblances between the engineering and ecological understandings of resilience.

Within this context, recent reviews of the term *resilience* as applied to energy systems (Ahmadi et al., 2021; Araújo and Shropshire, 2021) indicate there is currently no consensus on the terminology to define it. However, even without a shared definition of energy systems resilience, many authors agree that such definition is based on four essential characteristics: planning, absorbing, recovering, and adapting (Roege et al., 2014; Sharifi et al., 2016; Ahmadi et al., 2021).

It is starting from the area of energy research that this chapter seeks to adopt a multidimensional definition of energy resilience, which considers technical, social, institutional, environmental, and economic factors that can be framed and serve to operate within the context of power systems companies in Latin America. In this way, we define the concept of energy resilience as a concept useful for analyzing and evaluating the capacity of an energy system of different scales (from household to national) to anticipate, absorb, recover, or adapt to situations where energy services are insufficient or inadequate.

In a related note, the concept of energy vulnerability has its roots in the 1970s oil crisis, in which the rapid increase in pricing of this energy resource caused a stark increase in household energy bills, causing civil servants in the United Kingdom to coin the term "fuel poverty" (Isherwood and Hancock, 1979), which was later formalized by Brenda Boardman (1991) in her seminal work. This concept spread throughout Europe and other geographical areas, becoming known by the term energy poverty (Thomson et al., 2017), and later "energy vulnerability" (Bouzarovski and Petrova, 2015). To this day, some terminological confusion persists, with some arguing that fuel poverty and energy poverty are distinct concepts, with the latter concerning extreme access issues in low and middle-income countries and the former relating to energy affordability issues in Europe. However, we share the pragmatism of Bouzarovski and Petrova (2015) in seeing that "all forms of household-scale energy deprivation share the same consequence: a lack of adequate energy services in the home, with its associated discomfort and difficulty". Definitions of energy vulnerability often take the household as the unit of analysis, aiming to address social issues of accessibility to energy services and sensitivity to this phenomenon. In connection with this line of thought, Bouzarovski and Petrova (2015) define energy vulnerability as the propensity to experience an inadequate or insufficient amount of energy services. Authors such as Murias et al. (2020) highlight that one of the greatest challenges regarding the study of energy vulnerability from a household perspective is related to the lack of a precise definition of the concept and the persisting confusion that exists between energy and socioeconomic vulnerability. By comparison, some authors such as Gatto and Drago (2020) define energy vulnerability at a larger scale, seeing it as the state in which an energy system is unable to face or deal with adverse events and becomes at risk of falling into economic, social, environmental, and institutional traps. As can be seen in the literature, there is a great diversity of definitions for the concept of energy vulnerability. Gatto and Busato (2020) argue that the lack of a formal definition prevents an effective mainstreaming and measurement of energy vulnerability. However, despite the shortcomings, Murias et al. (2020) argue that a trend toward a commonplace for defining energy vulnerability from a household perspective can be observed in the literature, which coincides in three main points. First, energy vulnerability is considered as something potential or a risk, unlike the concept of energy poverty, which is characterised as an actual situation of need. Second, vulnerability is considered a dynamic phenomenon, dependent on aspects like place and time. Finally, the multidimensional nature of energy vulnerability is recognised as it is conditioned by various factors (social, economic, environmental, etc.). Therefore, energy vulnerability can be understood as a multidimensional concept useful for analysing or evaluating the propensity, risk, or likelihood of an energy system or a household to experience a state where energy services are inadequate or insufficient due to conditions of structural inequality or marginalisation over time or due to specific and punctual adverse events or disturbances.

It can be argued that the concepts of resilience and vulnerability share a strong connection across the different levels of the energy system, and in general it is possible to conceptualise them as different sides of the same coin that represents energy systems. While energy vulnerability represents the elements that define the propensity of an energy system or a home to fall into a deficient state, causing inadequate or insufficient energy services, energy resilience comprises all the existing elements in that same system to anticipate, absorb, recover, or adapt avoiding such a deficient state.

Due to the primary importance that energy services have for human development, the concepts of energy resilience and energy vulnerability are of great importance for the governance of the energy systems that provide them, especially within the context of climate change, where extreme natural events and energy transitions are becoming increasingly important (Murias et al., 2020). Within this context, the development of resilience represents one of the greatest challenges to improve the quality of life and well-being of people, especially in low- and middle-income countries (Gatto and Drago, 2020), like those in Latin America. Issues of energy vulnerability and resilience can also hold a special significance for vulnerable groups, such as rural populations, women, elderly people, or people with different health needs. Therefore, in the context of energy transitions, the concepts of energy vulnerability and resilience can be understood through frameworks, such as UNESCO's four dimensions of sustainable development: society, environment, culture, and economy (2021), in which a technical dimension could be added to represent the sociotechnical nature of energy systems (Jenkins et al., 2016; Sareen and Haarstad, 2018).

3. Illustrative Case Studies: The Diversity of Energy Transitions in Latin America

The following illustrative case studies provide the reader with a snapshot of how environmental or climate aspects (e.g., freezing temperatures, lack of rain due to climate events, and strong winds from hurricanes) constitute relevant vulnerabilities at the systems and household level for different Latin American countries. At the same time, such case studies provide a good entry point for discussing how these countries are building or could build more resilient power systems within their own processes of energy transition, to provide energy to their population that is not only clean but also reliable.

3.1 Colombia and the Influence of El Niño on a Vulnerable Hydropower

The Colombian case study highlights the importance of energy resilience and diversification of energy resources in the context of low-carbon transitions by illustrating how an initially "clean" power system highly reliant on hydropower can be vulnerable to environmental variables linked to climate change. Electric power generation in Colombia is mostly derived from renewable sources (73.2%), with only 26.8% of generation coming from nonrenewable energy (XM, 2021). As can be seen by Table 10.1, hydropower is a key element of installed capacity in Colombia, accounting for nearly 70% in 2018. Therefore, it is extremely important for the country to maintain permanent monitoring of water reservoirs since most hydropower plants are large capacity. However, coal (9.75%) and gas (9.61%) still remain very relevant players in non-variable electricity generation. By comparison, solar and wind power account for less than 1% of total power generation capacity (UPME, 2018).

In combination with the previously mentioned additions to the Colombian power generation matrix, it is expected that 11 solar projects accounting for 800 MW of solar photovoltaic will be added following a third energy auction held at the end of 2021 (Minergia, 2021). Such capacity is in addition to the 1,365 MW of combined wind and solar capacity awarded in the second auction in 2019, which are currently under construction or entering operation (ibid.). However, from 2019 to 2020, Colombia also increased the total percentage of power generation based on nonrenewable energy sources, going from 21% to 27%, in order to counteract seasonal low water inputs that represent a serious threat to the Colombian power system (XM, 2021).

The problem of climate change may be observed in Colombia with the El Niño southern oscillation (ENSO) phenomenon, which is the primary driver of the hydroclimate and has a strong influence on the power sector (Henao et al., 2020). This phenomenon occurs with greater intensity, frequency, and duration (ibid.). Since the beginning of the nineties, the episodes of the El Niño phenomenon, aggravated by climate change, have affected the economy and well-being of the Colombian population, reaching $564 million in damages from 1997 to 1998, with losses due to electricity supply issues representing around $308 million alone (CEPAL, 1999). This is due to the broad predominance of hydroelectricity in the country's energy matrix and the confidence of governments in hydroelectricity as a source of energy security that the country would enjoy in the near future (ibid.). Indeed, during the last third

Table 10.1 Installed Capacity for Electricity Generation by Technology in Colombia (MW) Across Years

Technology	*2015*	*2016*	*2017*	*2018*	*Increase (%)*
Hydro	10,945.80	11,532	11,682	12,258.40	12
Wind	18.4	18.4	18.4	18.4	0
Solar PV	0	0	9.8	9.8	-
Bioenergy	77.2	83.1	132.7	146.7	90
Coal	1,016	1,369	1,352	1,727	70
Oil	297	299	187	309	4
Gas	1,848	1,698	2,095	1,703.30	−7.8
Diesel	1,023	1,247	931	1,240	21.2
Jet A1	46	46	44	44	−4.3
Mix Gas–Jet A1	276	264	264	264	−4.3
Total	**15,547.40**	**16,556.50**	**16,715.90**	**17,720.60**	

Source: SIEL, 2018.

of the 20th century, the expansion strategy of Colombian energy policy was to replace the then precarious thermoelectric plants with hydropower plants (Ministerio de Minas y Energía, 2021). In doing so, investments also accelerated the build-out of the nascent National Interconnection System (SIN), with notable anticipation of the installation of the respective distribution networks and interconnection in the five most populated regions of the country (Ministerio de Minas y Energía, 2021; XM, 2021).

The predominance of hydroelectric generation in the power supply, in combination with the extreme drought of 1992–1993, positioned Colombia for a situation in which there was a decline in potential of the reservoirs without thermoelectric plant readiness to compensate for the power demand of the interconnected Andean and Caribbean areas (Planas-Martí et al., 2019). The programmed rationing of electricity for the Colombian population was not long in coming but stayed for over six months (Gobierno de Colombia, 2015). The recessive effects on the economy and the welfare of the Colombian population proved to be a hard lesson that prompted rapid institutional and regulatory changes in 1994 to diversify the energy mix. Such diversification was mainly based on incentives to increase the number and capacity of thermal plants to generate firm backup power in the event of reduced hydroelectric availability caused by the El Niño phenomenon (Colombia, 1994; Ministerio de Minas y Energía, 2021).

Within this context, the El Niño phenomenon between 1994 and 2014 tested the resilience acquired by the construction and commissioning of suitable thermoelectric plants to serve as backup during critical junctures in hydropower generation. In fact, the 1997–1998 El Niño was as intense as that of 1992–1993, but its economic impact was more mild to moderate (CEPAL, 1999). Moreover, the phenomenon did not affect the energy sector either, which at that juncture was more flexible and resilient, allowing it to adapt to the climatic phenomenon thanks to advances in interconnection and the support of non-variable or non-intermittent thermal power. Therefore, in these occasions, the dramatic reduction in reservoir levels did not translate into forced energy rationing.

The economic incentive that drove private investment in thermal and hydropower generation based on the complementary strategy between hydropower and thermal plants was known as the Reliability Charge, implemented in 2006 (Botero Duque et al., 2016). This mechanism represents an additional income to generators, financed in part by the collection of tariffs from consumers. It is distributed, through an auction process, in proportion to the offer of firm power and must always be available, especially at critical junctures when El Niño causes severe droughts, for which impacts are intensified by global warming.

This novel mechanism operates as a short-term incentive for the water system, and long-term as support for the financial sustainability of generators, and control of energy price volatility (Juvinao, 2021). The antecedents of the Reliability Charge go back to Laws 142 and 143 in 1994 that led to the expansion of the power system, and the interconnection based on incentives for private investment and the organization of a regulated energy market. These laws respectively established the provision of home public services and the power system, with a market regulated by a commission that is independent of public powers and the private sector.

The litmus test to the Colombian system's resilience after expansion and strengthening came roughly two decades following 1992–1993, during El Niño phenomenon in 2015–2016. However, despite expansion of the system's infrastructure and capacity, a succession of shortcomings cast doubt on the effectiveness of short-term management to such an extent that the specter of electricity rationing from the early '90s once again haunted the country's interconnected region (Mateus Valencia, 2016).

Due to this, generating companies and Public Ministry entities have shown concern since mid-2014 for the delay in readjusting the scarcity price, a key mechanism/incentive used to stimulate the supply of backup power. Delays by the regulatory commission resulted in losses from supporting generation technologies (Ahumada, 2017), and there were concerns about projected fluctuations in reservoir levels being out of date by the time the climatic phenomenon was confirmed (ibid.). Such predictions were finally updated in 2016 at the height of the climate crisis experienced by the Colombian power system, which according to Mateus Valencia (2016) would only need to lose an additional 130 MW to trigger the imposition of generalized energy rationing across the country.

A voluntary plan to subsidize energy savings and penalize excessive consumption took three months to apply, resulting in achieved savings remaining below the target of 5% per month, established to avoid stressing the power system (Mateus Valencia, 2016). Additionally, during these two years of drought, natural gas supply to thermal generation stations also presented some problems, being unable to keep up with the crisis. Under this context, Colombia had no alternative but to replace electricity generation based on hydropower or natural gas with higher-priced liquid fuels (Mateus Valencia, 2016; Morcillo et al., 2020).

At the peak of the drought experienced in 2016, water contributions to the reservoirs dropped to an average of 31% – lower than that of 1992 (Mateus Valencia, 2016). During this year, Colombia's power system generated 52% of its electricity by thermal power and 48% by hydropower plants (ibid.). However, despite many shutdowns of hydroelectric and thermal power plants due to technical and logistical difficulties, Colombia's power system was able to avoid blackouts and scheduled rationing by operating at full capacity across the remaining power plants. Overcoming the crisis caused by El Niño, amid so many signs of failures in the financial and technical management of the interconnected system, provides two insights: (1) the interconnected system demonstrated sufficient resilience amid all the technical, climatic, administrative, and logistical adverse events; (2) without ignoring the seriousness of the technical and administrative failures determining power losses in the midst of the drought, the delay in readjusting the scarcity price stands out as the most serious deficiency suffered by the Colombian power system since it is a key parameter for a reliable backup thermal generation. Therefore, it is imperative that the allocation of economic benefits from regulatory mechanisms are able to outweigh the potential challenges of climatic phenomena to guarantee a resilient Colombian power system.

3.2 Cuba and the Development of Resilient Wind Power

The Cuban case study exemplifies the vulnerabilities faced by a power system that heavily relies on costly foreign fossil fuel for electricity production. This case study also illustrates the quest of Cuba to build a more resilient and clean energy matrix based on a recent increase in the installation of wind power and its adaptation process to the Cuban environmental and sociopolitical landscape. As Table 10.2 illustrates, electric power in Cuba is produced with a generation capacity of over 6,500 MW. The main component of the National Electric Power System (SEN) is thermal generation, which produces approximately 60% of the country's electricity (ONEI, 2021). Nevertheless, Cuba also has about 2,700 MW in both diesel and other fuel engines distributed throughout the country (ibid.), providing electricity access to the general population, and stability to the Cuban grid. Currently, only around 4.5% of the total generation is produced from renewable energy sources. At the moment, the consumption of fossil fuels at the national level is close to five million tons, of which about half is imported fuel, representing a considerable expense for the country (ibid.). Within this context, Table 10.2 illustrates Cuba's dependence on electricity from fossil fuel sources. It also shows how Cuban power production has been diversifying since 2016 with the entry of wind and solar photovoltaic generation.

Table 10.2 Electricity Generation Capacity Installed in Cuba from 2016 to 2020 in MW

					Public Service Power Plants				
Year	*Total*	*Thermoelectric*	*Combined-Cycle Gas Turbines (CCGT)*	*Diesel*	*Isolated Diesel*	*Other Fossil (a)*	*Hydro*	*Wind and Solar PV*	*Other Thermal (b)*
2016	6,453.6	2,525	580	117.8	32.3	2,592.0	65.9	46.6	494.0
2017	6,475.9	2,528	580	113.0	75.2	2,497.6	65.9	85.1	531.0
2018	6,661.0	2,498	580	114.1	95.8	2,617.2	64.0	139.0	553.0
2019	6,507.8	2,498	580	114.1	106.1	2,527.5	64.0	159.2	458.9
2020	6,660.5	2,498	580	111.2	105.2	2,515.0	64.6	221.5	565.0

Note:
(a) Includes different scales of electricity generation using fossil fuels.
(b) Includes self-supply schemes from the Energy and Mines Ministry and from sugarcane producers (AZCUBA).
Source: ONEI, 2021.

Despite wind power's novel application in the Cuban power system, it reflects the strongest annual growth in terms of installed capacity, among renewables and other energy technologies. Such growth is driven both by large investments and by the large size of the turbines being built or tested today in Cuba.

It is estimated that the development of eight new wind projects in the east and central region of Cuba would prevent the island from emitting around 184,000 tons of carbon dioxide and other greenhouse gases per year (Reyes Tamayo and Rodríguez Córdova, 2018). The Engineering and Projects Company for Electricity (INEL), from the Cuban government, estimated the potential wind resources in the Greater Antilles could reach 1,200 MW and is thus a promising environmental solution for Cuban energy transition (ibid.). Nevertheless, the elongated and narrow shape of the island makes it vulnerable throughout its geography to extreme meteorological events such as hurricanes and tropical storms, these two natural elements being the main external agents causing damage to wind technologies (Medrano Hernández et al., 2019).

Future investment in wind power is planned for the north coast of the island, in the easternmost region (Ministerio de Minas y Energía, 2021a). However, its coastal position presents a double risk to investment costs in the presence of extreme winds and saline spray of seawater, which present problematic conditions in terms of the structure, electronics, and control of the turbines. Facing such technical and operating vulnerabilities, the Cuban Wind Program has considered strict compliance with policies defined through the investment process of wind farms in Cuba (MEP, 2021). These policies aim to guarantee a resilient wind energy sector by adopting a multidimensional approach, including the assimilation of this energy technology at the social level, as well as the inclusion and stabilization of wind energy in the national energy matrix. The most relevant characteristics taken into account to ensure a resilient development of wind power in Cuba are listed here:

- National ownership of wind power data and training of Cuban personnel: Studies of wind potential resources at the national level must be in collaboration with national companies and endorsed by international institutions (Reyes Tamayo and Rodríguez Córdova, 2018).

This decision allowed the wind resource database to be owned by the country and not by foreign companies, providing also an organic process of training and preparation for Cuban personnel throughout the measurement of wind resource and evaluation campaign (Ministerio de Minas y Energía, 2021a).

- Wind power matching the expected energy consumption in the country: Investments in the wind power sector must be in line with the energy demand policies coming from different sectors and with the future development plans at the national and local level (Martín Barroso et al., 2021).
- Linking national companies, institutes, and universities: Knowledge and know-how must be part of the investment made so the development of this energy source remains a transcendent public good for the country over time (Moreno Figueredo, 2012).
- Selection of appropriate technologies according to geographic location: The use of completely folding turbines in areas where the passage of hurricanes is frequent, or the selection of specific wind turbines for certain wind class sites reflects relevant examples to illustrate this point (Torres-Durán and Moreno-Figueredo, 2018).
- Social appropriation of technologies: Realizing that any wind power project proposal modifies how social groups interact with their vital spaces leads to the need for such projects to positively impact the cultural, economic, organizational, and consumer spheres. In this way, wind farms can be awarded new meanings, uses, and purposes, allowing different groups to control their own narrative of social transformation within the context of a technological boom and energy transition (Reyes Tamayo and Rodríguez Córdova, 2018).
- Development of own technologies: The Cuban wind power program requires the development of its own technologies based on the scientific and technical capacity available in the country. Within this context, national electro-mechanical workshops, specialized in the construction of large technological equipment, start with the development of medium and small machines that provide the basis for greater efforts. Such workshops also provide technical assistance and spare parts for technologies already installed by imports.

(Ibid.)

All these factors have allowed the Cuban Wind Program to mitigate some of the existing vulnerabilities of a nascent wind power industry using a multidimensional approach that includes technical, social, environmental, and economic approaches. Total independence is discernible in technological decision-making, access to technologies, availability of data for analysis, development of new investments, and preparation of highly qualified personnel in the different areas related to wind power generation. Such an approach has fostered the resilience of the entire Cuban Wind Program, both from a technological point of view, as well as its linkage with the social and economic programs planned by the country.

However, the wind program has not been free of technical, organizational, and human mistakes, and setbacks, the most notable of which are related to the investor process, given limited experience in the installation and execution of wind projects. According to Reyes Tamayo and Rodríguez Córdova (2018), the nonexistence of a program from the Cuban government specialized in wind energy in combination with the struggles of wind farm power operators has translated into difficulties for the effective integration of wind power in the national electrical system.

Even if these past experiences allow us to identify where there is still room for improving the energy resilience of Cuban wind power, the experience so far has shown the success of Cuban wind power development at the national and local level (MEP, 2021). Within this context, investment in the Cuban wind power sector has also generated wider benefits for the population, such as the creation of new jobs in areas removed from urban centers and the renovation of highways (Reyes Tamayo and Rodríguez Córdova, 2018), which was essential for connecting remote areas where the wind parks are located. Such measures aim for the appropriation of technology by residents and the contribution of wind power to the local development, becoming a heritage asset of the communities and not only a company operating in its territory.

3.3 Mexico and Rolling Blackouts due to Low Temperatures and Texan Natural Gas Dependence

The Mexican case study portrays the technical and geopolitical vulnerabilities faced by the Mexican power system, which is heavily reliant on natural gas imported from the neighboring United States, by analyzing the domino effect that the Texan power outages in February 2021 had at the other side of the border. At the same time the case study portrays how the aforementioned energy vulnerabilities at the system level between Texas and Mexico cascade down to the household level impacting millions of Mexican families. As can be seen in Table 10.3, the highest installed capacity of power generation in Mexico is represented by combined-cycle gas turbines, with 39.2% of the national total installed capacity.

Table 10.3 Installed Capacity by Technology in MW

Technology	2017	2018	2019	2020	2021	MAGR (2017–2021)*
Hydro	12,612	12,612	12,612	12,612	12,614	0.0%
Geothermal	899	899	899	951	976	2.1%
Wind	3,898	4,866	6,050	6,504	7,691	18.5%
Solar PV	171	1,878	3,646	5,149	7,026	153.2%
Bioenergy	374	375	375	378	408	2.2%
Nuclear	1,608	1,608	1,608	1,608	1,608	0.0%
Efficient cogeneration	1,322	1,709	1,710	2,305	2,309	15.0%
Clean total percentage	**30.7%**	**32.8%**	**34.3%**	**35.5%**	**36.5%**	
CCGT	25,340	27,393	30,402	31,948	35,060	8.5%
Conventional thermoelectric	12,665	12,315	11,831	11,809	11,809	−1.7%
Turbogas	2,960	2,960	2,960	3,545	3,781	6.3%
Internal combustion	739	880	891	850	734	−0.2%
Coal	5,463	5,463	5,463	5,463	5,463	0.0%
Conventional percentage	**69.3%**	**67.2%**	**65.7%**	**64.5%**	**63.5%**	
Total installed capacity	**68,051**	**72,958**	**78,447**	**83,122**	**89,479**	**7.1%**

Note: *MAGR = mean annual grow rate. The change in the value of measurement over the period between 2017 and 2020.
Source: CENACE, 2021.

Hydroelectric energy represents the highest share of renewables at 14.1% and all the clean renewable technologies contribute 32.1% of the total in the country (CENACE, 2021). However, it should be noted that there has been sustained growth in solar photovoltaic power, which has grown annually at an average rate of 153%, rising from 171 MW of capacity in 2017 to 7,026 MW in 2021 (ibid.).

A large share of gas used in the combined-cycle gas turbines originates from the US, which as the following section outlines, left Mexico exposed to winter blackouts in 2021, and highlighted the need for power systems that are not only cleaner but also more resilient and less vulnerable.

In February 2021, an uncharacteristically harsh winter weather in Texas (recording temperatures of −14°C) resulted in the loss of electricity for about ten million people in the state during peak demand and, in the following days, for the less fortunate (Busby et al., 2021). According to preliminary reports from the Electrical Reliability Council of Texas (ERCOT), climate-related problems, fuel limitations, and equipment failures led to the loss of 51 GW of electricity generation capacity, causing blackouts in the state (ERCOT, 2021). Climate-related problems were one of the most obvious causes of the blackouts related to the inability of the Texan system to react to the low temperatures. These causes are related but not limited to the freezing of gas pipes and water used in nuclear power, accumulation of ice on the blades of wind turbines, snow or ice covering solar panels, and the flooding of equipment due to melting of ice and/or snow (ibid.). From an energy resilience point of view, the aforementioned causes are related to environmental variables such as the management of natural resources necessary for power generation (such as water), effects due to extreme weather and the effects of climate change, and the lack of institutional capacities to face extreme weather events. Other reports, such as that of the University of Texas at Austin (2021), indicate that there is a great diversity of causes of a multidimensional nature, such as the lack of regulations related to winterization, a spike in energy demand, generation units experiencing outage, and so on (King et al., 2021). Finally, from the perspective of energy vulnerability in households, King et al. emphasize the effect of electricity price escalation in the market, which impacted energy affordability for households with variable price contracts.

The events leading to failures in the Texan power system had a domino effect in Mexico, with almost five million clients of the state electricity company Comisión Federal de Electricidad (CFE) experiencing blackouts in states bordering Texas due to a "generation deficit" (BBC, 2021a). These first disruptions in turn led to rotating load outages in 12 other states across the country (BBC, 2021b). On the Mexican side, the problems of vulnerability and resilience were closely related to dependency on the United States for the supply of natural gas and specifically due to the lack of supply from the pipelines that import the fuel from Texas.

According to information reported by the CFE (2021), the price of natural gas increased 5,000%, going from $3 per unit of volume to more than $200, reaching $600 in some parts of the United States. This strong reaction to the lack of natural gas made evident a double dependence that puts the Mexican power system in a strong state of vulnerability: the heavy reliance on imported natural gas as a primary source of electricity generation and the reliance on the United States as the main supplier.

When looking at these problems from the point of view of energy resilience, it is possible to name a number of variables that influenced this domino effect that heavily affected the Mexican system. From a technical point of view, this phenomenon is a wake-up call to increase the resilience of the Mexican power system by diversifying the energy supply, making it possible to balance the reliance on natural gas in the power generation at the national level, as well as a call to improve the reliability of the energy infrastructure by increasing the capacity of the natural gas reserves when a similar event happens in the future. From an environmental point of view, the crisis caused by dependence on gas pipelines, specifically in Texas, demonstrated that the geographic distribution of energy infrastructure must be considered to support a power system that is resilient to extreme weather events. At the same time, this incident highlights the need to build or strengthen institutional capacities to deal with natural disasters or extreme weather events. It is necessary to find strategies that allow Mexico to reduce its dependence on imported natural gas, specifically from Texas, or, failing that, to generate agreements that assure Mexico greater energy security, reducing the risk of events such as those of February 2021.

Analyzing this case study from an energy vulnerability perspective using an economic and market dimension, variables such as uncertainty in energy prices and energy affordability are represented very differently at the system or domestic level in Mexico. This is mainly because electricity prices are controlled by state agencies to be kept at a fixed price for domestic users, despite the sudden rise in natural gas prices for electricity generators. In the context of energy resilience, one of the most important dimensions to note is organizational due to the strong energy dependence of the Mexican electricity system on natural gas from the United States. In this sense, thinking about vulnerability from an institutional and regulatory point of view can lead one to surmise the need to develop and implement public policies and regulatory frameworks that analyze the weaknesses of the energy system and the necessary measures to reduce vulnerability (Gnansounou, 2008), as well as the promotion of programs for energy efficiency or energy saving (Michalec et al., 2019).

An analysis from an energy vulnerability perspective runs parallel to the lack of resilience of the Mexican power system but places emphasis on how different populations in Mexico may be prone to facing a lack of energy services in different ways when departing from initial circumstances of energy poverty (Cedano et al., 2021). The ways in which Mexican households experienced and coped with the power outages of February 2021 depended on a range of variables linked to the social dimension of vulnerability. In the first instance, the physical conditions of domestic properties influence the efficiency, risk and other characteristics of the home and play a great role in the way in which people experience or cope with energy vulnerability (Llera-Sastresa et al., 2017; Thomson et al., 2017; Willand et al., 2021). Likewise, energy vulnerability largely depends on the demographic characteristics of the people in the household, such as health conditions (Murias et al., 2020), stability of wages (Middlemiss et al., 2015), and gender (Robinson, 2019).

3.4 Case Studies Synthesis and Discussion

An initial look at energy transition processes in Latin America as a block provides a picture of fairly advanced attainment of low-carbon power systems, with 65% renewable energy share in power generation (IRENA, 2020a), yet national realities of energy transition processes are quite diverse. Within this context, this chapter analyzed the struggle experienced by countries like Cuba or Mexico, to overcome a power system that relies heavily on fossil fuels for the generation of electricity for domestic consumers and businesses. For these countries, the transition to low-carbon electricity generation and the diversification of their energy matrices also represents a path to reduce energy vulnerability. Even though both countries rely on fossil fuels for power generation, the environmental, economic, institutional, and geopolitical contexts in which they are both embedded represent a very different set of challenges toward a low-carbon and reliable power system.

The Mexican case study provides a multidimensional analysis of the general failure of the electrical system in February 2021, evidencing the geopolitical, environmental, and technical vulnerabilities on both sides of the US-Mexico border, stressing an exacerbated dependence on natural gas (Araújo and Shropshire, 2021; Busby et al., 2021). Within the Mexican context, the failure of the power systems in that cold month of February 2021 highlights the geopolitical dimension of energy vulnerability through the devastating effects that high dependence on natural gas from Texas produced. Aside from being a reminder of the need to promote the diversification of power generation to endow power systems with resilience, the Mexican case study highlights the need to develop means of collaboration between neighboring countries to overcome such energy vulnerability dilemmas and their effects on the household and systems levels.

However, there are some positive signs emerging in Mexico related to the recent acceleration in the amount of renewable capacity within the energy matrix (especially in terms of wind and solar power). By comparison, while Cuba experiences similar challenges to those faced by Mexico in terms of an energy matrix heavily reliant on fossil fuels, the island faces specific economic, environmental, and social challenges that play an important role in the relative energy vulnerability of its power system as a member of the Small Island Developing States (SIDS) (Genave et al., 2020). Nevertheless, the case study of Cuba's wind power illustrates some of the measures to improve the resilience of Cuban wind power, such as national ownership of data, training of Cuban personnel, and selection of appropriate technologies according to geographic location. Overall, the case study highlights the need for specific economic, geopolitical, and institutional considerations for Cuba and other SIDS that allow for the successful inclusion of renewable energy technologies within an energy matrix that is currently vulnerable to a heavy dependence on expensive foreign oil imports (ONEI, 2021).

Contrasting with the experiences of Mexico and Cuba to strive for greater low-carbon power generation, Colombia experiences a particular conundrum when dealing with issues of resilience and vulnerability, having a mostly clean or decarbonized electricity generation matrix based on a large share of hydropower generation. The case of Colombian hydropower and the influence of El Niño provides an opportunity to reflect on how issues of energy vulnerability can hamper processes of energy transition and decarbonization in countries with an already deep penetration of low-carbon or renewable energy generation technologies. The case of Colombia also demonstrates how a country can appeal to multidimensional solutions, including the development of financial mechanisms in combination with firm generation technologies to successfully mitigate the risks posed by extreme weather events to the power system.

Based on the analysis that was carried out using the different multidimensional variables of energy resilience and vulnerability for the three case studies in Colombia, Cuba, and Mexico, we call for further interdisciplinary research to deepen our understanding of these concepts. A more nuanced understanding of energy resilience and vulnerability could facilitate the development of power systems capable of dealing with the great diversity of technical, economic, social, institutional, environmental, and geopolitical challenges that the future holds. In particular, research is needed to explore the connections of energy vulnerability at the systems and the household level and to develop conceptualizations of these terms that better encapsulate the diversity of contexts where they are experienced.

Table 10.4 provides a summary of the most relevant features related to energy vulnerability and resilience present in the case studies from Colombia, Cuba, and Mexico, analyzed according to environmental, technical, economic, social, and institutional dimensions.

Table 10.4 Summary of Relevant Features Related to Energy Vulnerability and Energy Resilience Across the Three Case Studies

	Colombia	*Cuba*	*Mexico*
Environmental	Vulnerability to changes in precipitation due to El Niño southern oscillation (ENSO)	Vulnerability of wind power to tropical storms and strong winds	Vulnerability to extremely low temperatures
Technical	Vulnerability to lack of water reserves for hydropower to function properly Resilience through polluting and expensive, but non-variable thermal power	Vulnerability to salinity and extreme winds Resilience through the selection of technologies like wind turbines with folding blades	Vulnerable to failing infrastructure due to low temperatures and to the dependence on natural gas from the United States
Economic	Vulnerability toward increased fuel costs of thermal power Resilience through Reliability Charge mechanisms	Vulnerable to limited experience in the installation and execution of wind projects Resilience through nationally owned data and training of Cuban personnel	Vulnerability to a sharp increase in natural gas prices
Social	Vulnerability to forced energy rationing Resilience through a voluntary plan to subsidize energy savings	Resilience through social appropriation and assimilation of wind power	Vulnerability to rolling blackouts Resilience through a vast interconnected electricity network and subsidized domestic tariffs
Institutional	Vulnerability related to delayed institutional decision making to discourage increases in energy consumption	Vulnerabilities due to a lack of specialized national programs on wind power Resilience through national ownership of energy operation	Vulnerability to geopolitical dependence on energy resources from the United States

4. Conclusions and Priorities for Future Research

The concepts of energy resilience and energy vulnerability so far lack definitions upon which the academic community unanimously agrees. Nevertheless, within this chapter, the authors provide a working definition for the concept of energy resilience as a multidimensional concept useful for analyzing and evaluating the capacity of a power system, at different scales (from household to national), to anticipate, absorb, recover, or adapt to situations where energy services are insufficient or inadequate. On a related front, energy vulnerability can be understood as a multidimensional concept useful for analyzing or evaluating the propensity, risk, or likelihood of a system or a household, to experience a state where energy services are inadequate or insufficient due to conditions of structural inequality or marginalization over time or due to specific and punctual adverse events or disturbances.

The findings delineated across this chapter highlight the need to generate research dedicated to reviewing the conceptualization of energy resilience and energy vulnerability, pulling from the different strings of literature to develop comprehensive definitions of both concepts. Such comprehensive research looking to deepen our conceptual understanding of energy resilience and energy vulnerability would also allow us to better identify the similarities and differences between both concepts in a much more nuanced way. Therefore, this chapter makes a call for a comprehensive review of the various existing definitions that circulate in the academic literature. The authors of this chapter believe that such a contribution would facilitate the embedding of the energy resilience and vulnerability concepts in policy- and decision-making, influencing the development of more comprehensive and more integrated policies and regulatory frameworks.

Finally, this chapter also identifies the need to promote a pan–Latin American energy vulnerability and resilience network, where members of the public and private sectors, universities, and civil society can collaborate in an inclusive way and become better informed in order to generate effective and efficient solutions to address the major issues that pertain to energy resilience and vulnerability.

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