Innovation Systems for Sustainable Energy: The Case of Mexico

by

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ABSTRACT

Global decarbonization requires a large-scale shift to sustainable energy sources. Innovation will be a key enabler of this global energy transition. Although the energy transition and innovation literatures overwhelmingly focus on the Global North, energy innovation is arguably even more important for the Global South because it can enable them to grow their energy demand and power their development with sustainable resources. This dissertation examines three aspects of energy innovation, focusing on Mexico, to advance the understanding of innovation systems and identify policy levers for accelerating energy innovation in emerging economies.

The first project utilizes econometric models to assess patenting drivers for renewable energy (wind and solar) and enabling technologies (energy storage, high voltage direct current technologies, hydrogen technologies, and fuel cells) across 34 countries, including Mexico. The examination of enabling technologies is a particular contribution, since most research on energy innovation focuses on renewable generation technologies. This research finds that policies have differential effects on renewable technologies versus enabling technology, with innovation in enabling technologies lagging behind the deployment of renewable energy. Although renewable energy policies have some spillover effects on enabling technologies, this research suggests that targeted policy instruments for enabling technologies may be needed for global decarbonization.

The second and third projects apply the innovation systems framework to understand energy innovation in Mexico. The second project analyzes the sectoral innovation system (SIS) for wind and solar technologies, using expert interviews to evaluate SIS structure and functions systemically. It finds that this innovation system is

susceptible to changes in its structure, specifically institutional modifications, and encounters cultural and social aspects that reduce its performance. Further, it finds that non-government organizations and local governments are trying to support the SIS, but their efforts are hampered by low participation from the federal government.

The third project studies the technology innovation system (TIS) for green hydrogen, an emerging industrial opportunity for Latin America. It evaluates this TIS's functionality and identifies 22 initiatives to improve its performance by interviewing green hydrogen experts in Mexico. The most important initiatives for strengthening the green hydrogen TIS are information campaigns, policy and regulation (taxes, subsidies, standards, and industrial policies), pilot or demonstration projects, and professional training.

Overall, this dissertation contributes to the nexus of energy transition and innovation studies by advancing the understanding of energy innovation in an emerging economy.

DEDICATION

This dissertation is dedicated to my wife Martha for her unconditional love and support. To my parents Amelia and Alberto.

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CHAPTER 1

INTRODUCTION

Introduction: Innovation and Energy Transitions

Decarbonizing human activities and their transitions to sustainable energy sources require great innovation efforts. This dissertation examines the factors that drive clean energy innovation, focusing on three aspects of energy innovation, predominantly in the case of Mexico. It advances the understanding of innovation systems and identifies policies and additional factors for accelerating energy innovation in emerging economies. The aspects analyzed include an international analysis of policy drivers at the national level and two analyses of different scales of the innovation system in the Mexican context: one for the sectoral innovation system (SIS) for wind and solar technologies and the other for the technological innovation system (TIS) for green hydrogen.

Innovation indicates the process of harnessing the knowledge and turning it into reality (Lundvall, 2007). It describes a new, useful, and legitimate idea, invention, or technology, particularly for solving problems or achieving goals (Raffaelli & Glynn, 2015). Innovation is a non-linear process that results from the interaction of multiple actors within a system of financial and market institutions, government policies, and technical infrastructure. To understand this complex process, this dissertation uses the innovation system framework to evaluate the structural components, functional patterns, and mechanisms driving or hindering the development and deployment of clean energy technologies. The technologies analyzed are renewable energy generation technologies such as wind and solar; and enabling technologies like green hydrogen.

Low-carbon energy innovation is a crucial determinant of climate change mitigation, reducing emissions associated with production, transformation, transportation, and energy usage. Transitioning to sustainable energy sources involves a global endeavor that should include multiple countries, regions, technologies, and sectors. However, energy transition and innovation literature are overwhelmingly focused on the Global North, leaving behind the case of the Global South, which represents an even more important case. Global South countries keep increasing their energy demands, and powering their development with sustainable energy resources will be a significant determining factor of a satisfactory global energy transition.

The case of Mexico

Mexico is the 12th largest carbon dioxide emitter country in the world and the largest emitter in Latin America (IEA, 2018). It is an emerging economy that recently reformed its energy sector, creating a partially liberalized electricity sector with country-level clean energy goals (Jano-Ito & Crawford-Brown, 2016). Mexico has supported clean energy innovation through federal funding for science and technology research (CONACYT, 2017) and participation in Mission Innovation. This global initiative seeks to double investments in clean energy research and development with 24 other countries (Mission Innovation, 2021). The energy market reforms and innovation efforts provide an opportunity to understand how policy can contribute to energy innovation and energy transitions, particularly in major emerging economies.

The electricity sector in Mexico was operated as a monopoly by a government-owned vertically integrated utility, the Federal Electricity Commission (Comision Federal de Electricidad, CFE). However, after the Mexican Energy Reform in 2013, the sector was opened to competition in generation and supply activities. The country has defined nationwide clean energy goals, these goals are linked to clean energy generation in the electricity sector and are a policy instrument created by the Energy Transition Law (Ley de Transición Energética, 2015). The goals are as follows: 25% of the electricity from clean sources by 2018, 30% by 2021, 35% by 2024, 37.7% by 2030, and 50% by 2050. The achievement of these goals is measured with the Clean Energy Certificates. These certificates accredit producing a certain amount of electricity from clean energy sources; one certificate is the equivalent of 1 MWh produced from clean energy sources and is tradable in the wholesale electricity market.

Innovation policies in Mexico are coordinated by the National Council of Science and Technology (Consejo Nacional de Ciencia y Technologia, CONACYT), the government agency promoting scientific and technological activities, setting government policies for these matters, and granting scholarships for postgraduate studies (CONACYT, 2017). Through CONACYT, the Mexican Government is the leading actor in the national innovation system. It was created in 1970, and since then, it has implemented science and technology programs and initiatives. In the 1990s, it started to include innovation in its programs and initiatives (Wood, 2014).

Research on the Mexican innovation systems is limited. In Mexico, the concept of innovation systems has been applied at the national level (Cimoli, 2000; Dutrénit et al., 2010; Solleiro & Castañón, 2005), regional level (Garcia & Chavez, 2014), and in the agriculture sector (Hellin, 2012). However, to the best of my knowledge, only Aguiar-Hernandez & Breetz (2022a, 2022b) have applied this concept to studies related to energy in Mexico.

Enabling technologies and emerging economies

In this dissertation, I use the term enabling technologies to refer to those supporting the performance of renewable generation technologies and additional energy operations such as transmission, distribution, and consumption. Examples include energy storage, high voltage direct current technologies, hydrogen technologies, and fuel cells. Renewable-based electrification is a critical element in reducing the CO_2 emissions generated by the energy sector (IEA, 2020), making the integration of renewable energy (RE) sources into the grid one of the most critical activities in the transition from fossil-based to zero-carbon energy sources. Moreover, the declining cost in particular renewable generation technologies allows higher rates of renewable energy deployment, increasing the challenges associated with high levels of variable renewable energy in the grid (Sinsel for et al., 2020). On the other hand, enabling technologies function as drivers of inter-sectorial integration toward more intelligent energy systems, matching the electricity and transportation sectors or the electricity and heating sectors, for instance (Nastasi, 2019), and their adoption is essential for energy transitions and decarbonization efforts.

Emerging economies account for 34% of the world's nominal GDP (Duttagupta & Pazarbasioglu, 2021) and a large portion of the CO_2 emissions worldwide as they keep increasing the energy demand to power their development. On the other hand, these countries still face barriers to energy innovation and fully capture the benefits of their innovation (Samant et al., 2020). Therefore, strengthening emerging economies' innovation systems for enabling technologies represents an opportunity for their energy transitions and sustainable development. Moreover, most of these technologies are in the early stages of development that could be advanced by emerging economies or be part of collaboration efforts. Specifically, multiple reports present Latin America as one of the regions expected to have lower production costs for green hydrogen, increasing the chances of emerging economies being part of the global energy transition and developing a green economy.

Methods

The innovation systems framework is used in this dissertation to understand three energy innovation aspects in an emerging economy context. This framework considers the interactions between organizations, material artifacts, and institutions (M.P. Hekkert et al., 2007), implying that the innovation process is highly influenced by a network of actors that are developing and advocating for the technology and by an institutional infrastructure that legitimizes, regulates, and standardizes the new technology. The outcome of the system is the generation, diffusion, and utilization of technology (Carlsson & Stankiewicz, 1991). Institutions are a critical component of this research, containing policies, regulations, cultural values, and formal and informal settings.

The aspects of energy innovation analyzed in this dissertation are an international analysis of policy drivers for renewable energy generation and enabling technologies, the Mexican SIS for wind and solar technologies, and the TIS for green hydrogen in Mexico. The first aspect evaluates patenting drivers for renewable energy (wind and solar) and enabling technologies (energy storage, high voltage direct current technologies, hydrogen technologies, and fuel cells) across 34 countries, aiming to evaluate the factors inducing innovation at the national level. The second and third aspects focus on other scales of innovation systems specifically for the Mexican case, sectoral and technology-specific analyses. Each of these aspects of energy innovation is studied separately and presented in chapters 2, 3, and 4.

Data for this dissertation are collected from multiple sources. In chapter 2, a comprehensive panel dataset of patents was created, policies, and factors at the country level for 34 countries from 2005 to 2018. The primary data sources include the Organization for Economic Cooperation and Development (OECD), the International Energy Agency (IEA), the World Bank, Our World in Data, and the Energy Information Administration (EIA). Chapters 2 and 3 use similar data collection processes: scientific literature, policy documents, and expert semi-structured interviews. Chapter 2 focuses on interviews in which experts were asked to express their views on the functioning, inducement, and blocking mechanisms of the wind and solar SIS in Mexico and aspects of the structural components of these innovation systems. In Chapter 3, experts were asked to express their views on the functioning of the green hydrogen TIS and their perspectives on improving it. Interviews were carried out between October and December 2021 and lasted between 1 and 1.5 hours.

Structure of the dissertation

This dissertation is structured in different chapters covering each aspect of energy innovation analyzed. Each chapter reports a literature review, method, results, and conclusions sections. The final chapter concludes the dissertation by reviewing the main arguments and contributions and discussing key takeaways and further research.

Chapter two explores how renewable energy (RE) generation and enabling technologies respond to factors within the system and create insights into possible policies' design to enhance enabling technology innovation. Enabling technologies are crucial for decarbonizing the energy sector. They integrate more renewable energy into the system, function as drivers of inter-sectorial integration, and are an alternative to challenging sectors to decarbonize, like transportation, chemicals, iron and steel, and cement. Nevertheless, enabling technologies are not among the current leading energy and innovation policies, impacting their development and deployment. The findings show that the factors analyzed affect in a differentiated way the innovation for RE generation and enabling technologies, the former influencing the latter, and that design policy instruments for enabling technologies will positively impact sectors in their decarbonization efforts, not only the electricity sector. This study differs from other studies with similar econometric models of energy innovation, as they focused on renewable generation technologies, and this research is also analyzing enabling technologies.

Chapter three analyzes the SIS for wind and solar technologies in Mexico. The IMF classifies the following countries as emerging economies: Argentina, Brazil, Chile, China, Colombia, Egypt, Hungary, India, Indonesia, Iran, Malaysia, Mexico, the Philippines, Poland, Russia, Saudi Arabia, South Africa, Thailand, Turkey, and the United Arab Emirates; accounting for 34% of the world's nominal GDP in US dollars (Duttagupta & Pazarbasioglu, 2021) and representing a considerable portion of current and future CO_2 emissions worldwide (IEA, 2018). Although the importance of emerging economies, they have received much less attention for energy innovation and energy transition research. To address this gap, I use the Mexican case as an emerging economy that recently opened its electricity sector to competition and increased its innovation efforts. This study illustrates the importance of structural components in functioning SIS for renewable energy technologies, specifically the role of governments as actors in the system, and the importance of the institutional setup such as cultural values, policy, and regulation.

Chapter four examines how the green hydrogen TIS in Mexico could be strengthened. Green hydrogen is a clean fuel that could be used for transportation, heating, and power generation, reducing the emissions in these sectors and supporting their decarbonization. However, it faces multiple challenges, such as high production costs and a lack of hydrogen infrastructure and regulation (IRENA, 2020). Different regions will have different potential for cost reductions due to renewable resource potential, infrastructure and transport costs, labor costs, and other factors. Latin America is one of the promising regions for low-cost green hydrogen production, including Mexico. This chapter identifies 22 initiatives to enhance Mexico's TIS for green hydrogen. The most relevant initiatives include information campaigns for the entire society, development of regulation instruments (e.g., taxes, subsidies, standards, strategies, industrial policies, infrastructure), pilot or demonstration projects, improving academia's capacity through international cooperation, specialized professional training, and supporting renewable energy projects.

Chapter five concludes the dissertation by expanding on the findings mentioned in the other chapters. It provides broader insight into three bodies of literature: energy transitions, innovation systems, and policy mix. This research contributes to energy transitions literature by evaluating two understudied factors that would be determinants for the global energy transition and the decarbonization efforts worldwide: enabling technologies and emerging economies. Energy transitions represent an opportunity for countries like Mexico but simultaneously represent multiple challenges in the institutional infrastructure that sometimes go beyond the energy and innovation efforts. The contributions of this dissertation to the innovation systems knowledge include the application of the framework in the Mexican context for energy research. Another contribution is the study of the role governments have in the innovation system, not only as part of the institutional setting but as actors, working beyond fixing market failures and having a more dynamic role through public procurement and public-private partnerships. The mutualistic approach between private and public sectors would be vital in developing and deploying sustainable energy technologies. In terms of the policy mix concept, this research uses this concept to explain the findings partially. Given the importance of innovation for energy transitions, the complexity of energy systems, and the levels of technological change, the policy mix concept will become essential for policy formulation and implementation, and policy interactions.

CHAPTER 2

INNOVATION FOR RENEWABLE ENERGY AND ENABLING TECHNOLOGIES: AN INTERNATIONAL ANALYSIS OF POLICY DRIVERS

Abstract

Enabling technologies are critical for energy transitions, as they can support the integration of variable renewable energy in the grid and facilitate emissions reduction strategies in sectors that are difficult to decarbonize, such as transportation, chemicals, iron and steel, and cement. Furthermore, by using enabling technologies (e.g., energy storage, high voltage direct current technologies, hydrogen technologies, and fuel cells), a more inter-sectorial integration is possible, generating more intelligent energy systems and matching the operation of different sectors. Nevertheless, energy and innovation policies do not focus on enabling technologies, which might impact their development and deployment. This chapter explores the impact of different policies and factors on innovation performance for RE generation and enabling technologies, and creates insights into possible policies' design to enhance enabling technology innovation. I estimate econometric models to evaluate the effects of policies and other factors on patenting performance for RE generation and enabling technologies in 34 countries. The results show that policies have differential effects on renewable technologies versus enabling technologies, suggesting targeted policy instruments for enabling technologies. These findings further suggest that the policy mix concept provides a solution to cluster the policy instruments that involve multiple sectors, different levels, technologies, and actors while interacting in a complex system.

Introduction

Renewable-based electrification is a crucial element to reduce the CO_2 emissions generated by the energy sector (IEA, 2020), which makes the integration of renewable energy (RE) sources into the grid one of the most critical activities in the transition from fossil-based to zero-carbon energy sources. However, the dramatic cost declines in certain renewable generation technologies allow higher rates of renewable energy deployment, increasing the challenges associated with high levels of variable renewable energy in the grid (Sinsel et al., 2020). Several technological solutions have been developed to handle these challenges, enabling the access of more renewable energy into the power system. Nevertheless, enabling technologies are not among the main energy and innovation policies considered, which might impact their development and deployment. Throughout this chapter, I refer to enabling technologies as those supporting the operation of renewable generation technologies; some examples include energy storage, high voltage direct current technologies, hydrogen technologies, and fuel cells.

While enabling technologies accompany renewable generation technologies as part of their deployment; in some cases, these technologies operate beyond power generation activities, supporting energy transmission, distribution, and consumption, and as a consequence, creating the need to reconceptualize different aspects of the energy sector (Kittner et al., 2017). An additional advantage of enabling technologies is their capacity to function as drivers of inter-sectorial integration towards more intelligent energy systems, matching the electricity and transportation sectors or the electricity and heating sectors, for instance (Nastasi, 2019). Because of the importance of decarbonizing the energy sector and integrating a more robust energy system, this chapter explores how different technologies respond to factors within the system and create insights into possible policies' design to enhance enabling technology innovation. In this chapter, I ask the following questions: How do various policies and factors impact the innovation performance for RE generation and enabling technologies? To what extent this impact is different across these two technologies?

Enabling technology innovation was induced, to some extent, by the deployment of renewable generation technologies. Theoretical and empirical studies have been focused on renewable generation technologies; this study aims to advance enabling technologies by analyzing the systemic factors that support them, particularly public policies. I use econometric models together with data on the total global patents to analyze the factors that drive the innovation of RE generation technologies and enabling technologies.

This chapter examines the impact of policy and other factors on innovations RE generation and enabling technologies, using a panel data set consisting of 34 countries in the period 2005-2018. Data were collected from multiple sources, including OECD, and World Bank. The study contributes to the literature by examining enabling technologies, as most research on energy innovation focuses on renewable generation technologies, and by evaluating the effects of systemic factors on the innovation activities of enabling technologies and suggesting policy recommendations to move specific policies from generation to enabling technologies, as the latter is becoming a key element in decarbonizing the energy sector.

A key finding is that enabling technologies and generation technologies experienced different impacts from factors such as policy and renewables capacity. In general, patenting rates for enabling technologies falls behind the generation technologies. To some extent it is not surprising that policies have different effects on these two technology types, since policies were largely aimed at renewables deployment and may have had more indirect effects on enabling technologies. Among the policies examined, Feed-in tariff (FIT) is the only policy that is statistically significant for both technologies, but with opposite effects: positive for generation technologies and negative for enabling technologies. As for renewables capacity, wind and solar generation capacity has a negative impact on generation technologies but a positive impact on enabling technologies.

Given these results and the importance of FIT in inducing innovation for RE generation technologies (Lindman & Söderholm, 2016), I evaluate the lagged effect of this policy on both dependent variables. These econometric models aim to control for different systematic characteristics among the countries that implemented these policies which enables me to control for unobserved characteristics that might be affecting the adoption of specific policies. The models show that FIT is a direct policy instrument for RE generation technologies. I find that this instrument will affect enabling technologies through the deployment of RE generation technologies. This result has important policy implications: similar instruments can directly stimulate the development and deployment of enabling technologies, positively impacting multiple sectors in their decarbonization efforts, not only the electricity sector.

Innovation in Clean Energy Technology

This analysis takes a systems perspective on clean energy innovation. In assessing the drivers of innovation, this systems perspective recognizes that technology innovation does not advance in isolation. Innovation is influenced by the entire system in which technologies are embedded, including market structures, public support for entrepreneurship, and direct government investments (Hekkert et al., 2007; IEA, 2019). The institutional infrastructure within the innovation system plays a significant role in innovative activities, as it legitimizes, standardizes, and regulates the technology within the system (Carlsson & Stankiewicz, 1991). Policy and regulation are important institutional factors that can induce innovation (Jaffe et al., 2003; Vollebergh, 2007). For example, policies may change factor prices, stimulating innovation to directly lower the prices of the factors that have become expensive (Jaffe et al., 2003; Popp, 2005), or they may incentivize innovation by directly mandating technological deployment. Due to these differential inducement mechanisms, different policies may be needed to achieve different types of innovation at each stage of technological maturity (Breetz et al., 2018). In addition to policy, systems-oriented research on energy innovation recognizes that there may be positive feedbacks from technological change. Specifically, renewables capacity could enable further innovation through learning-by-doing, capacity-building, and the development of further public constituencies and policy supports (Schmidt & Sewerin, 2017).

As for the targets of innovation, a systems perspective emphasizes that clean energy transitions require not only renewable generation technology, but also an array of technologies for energy storage and transmission to support the grid performance. Other studies with similar econometric models of energy innovation have focused on renewable generation technologies; this study differs from them as I aim to also analyze enabling technologies. This is under the premise that enabling technologies are designed, among others, to support additional renewable generation capacity (Mileva et al., 2013), therefore advancing the energy transition by decarbonizing the energy sector and, in some cases, interconnecting different energy sectors into a better energy system (Nastasi, 2019). In the following subsections, I describe what is included in this study as renewable generation technologies versus enabling technologies.

Renewable generation technologies

Renewable generation technologies have the potential to reduce emissions associated with the power sector, who is currently responsible of 40% of global GHG emissions. According to the International Energy Agency (2020a), renewable-based electrification is one of the four pillars of the energy sector's decarbonization.

Existing literature suggests that policy and regulation are key factors that promote renewable generation technology innovation; different policy designs and instruments have been evaluated; here are the most significant examples: renewable energy policies, including tax credit, energy mandates, investment incentives, feed-in-tariffs, tradable certificates (Bayer et al., 2013; Bourcet, 2020; Johnstone et al., 2010; Nesta et al., 2014; Popp, 2019; Sivaram & Norris, 2016); market regulation or deregulation, including decrease in regulation intensity (Bettencourt et al., 2013; Cambini et al., 2016; Jamasb & Pollitt, 2008); R&D funding (Bettencourt et al., 2013; Cambini et al., 2015; Johnstone et al., 2010); research subsidies (Acemoglu et al., 2014); and environmental regulations (Jaffe et al., 2004; Markard & Truffer, 2008; Vollebergh, 2007).

Theoretical and empirical research suggests that policy and regulation might be the primary drivers of renewable generation technology innovation (Bettencourt et al., 2013; Cambini et al., 2016; Jaffe et al., 2004; Jamasb & Pollitt, 2008; Johnstone et al., 2010; Markard & Truffer, 2008; Nesta et al., 2014; Popp, 2019; Sivaram & Norris, 2016; Vollebergh, 2007). The above is framed by the induced innovation hypothesis, which proposes that technological change relates to the direction of the change in relative prices that can be influenced by policy (Jaffe et al., 2003; Vollebergh, 2007). Exogenous factors also impact innovation activity; high oil prices consistently predict innovation in renewable generation technologies (Bayer et al., 2013).

While the policy and regulation mentioned above have been successful, the power system faces challenges in terms of quality, flow, stability, and balance when considering increasing the renewable energy penetration. Specific examples of these challenges include safety hazards, local and regional trips, curtailment, increased losses, stability violations, control and resonance issues, and mismatches between supply and demand (Sinsel et al., 2020).

Enabling technologies

As more renewable and clean energy sources are integrated into the grid, the electricity sector faces the challenge of integrating large amounts of variable renewable energy. This requires technologies for storage and transmission that provide flexibility and support system performance at both the distributed and centralized level (Sinsel et al., 2020). I refer to these technologies as enabling technologies since they enhance the utilization of renewable capacity.. Since most are in the early stages of the innovation process, R&D is the primary indicator of driving innovation among enabling technologies (Kittner et al., 2017; Mileva et al., 2013; Nastasi, 2019).

The most common examples of enabling technologies are energy storage (e.g., pumped hydro, batteries, and flywheels), high voltage direct current technologies, hydrogen technologies (e.g., reforming or gasification, gasification with carbon capture, pyrolysis, electrolysis), and fuel cells. Here I describe each of these types of enabling technologies, including how they support renewables deployment. *Energy storage* such as pumped hydro, batteries, and flywheels provide balancing services (Guinot et al., 2015), supporting the integration of solar PV and wind technologies while absorbing the excess of power generation when the demand is low and allowing energy to be used when generation is not available (Denholm & Margolis, 2007). Innovation and cost decline for energy storage are essential for deploying a low-carbon electricity supply system (de Sisternes et al., 2016), which requires R&D spending across energy research and synergies with deployment policies, creating a more balanced set of policies (Kittner et al., 2017).

Another technology supporting the adoption of renewable energy sources is *high voltage direct current technologies*, which moves large amounts of electricity over long distances. They reduce losses and heat and carry higher power density than conventional lines. This superconducting technology can support the accommodation process of renewable energy sources, matching supply with demand. R&D is needed to help this technology overcome the technically challenging and expensive conversion between alternating current (AC) and direct current (DC) (Crabtree et al., 2011).

Electromechanical *hydrogen production* can also balance the power system similar to energy storage, absorbing excess electricity and delivering when needed (Guinot et al., 2015), enhance the overall energy system flexibility, increase energy security, decrease environmental impacts (Alshehri et al., 2019; Wang et al., 2018). Hydrogen can be produced by different processes, being the most important reforming or gasification, reforming or gasification with carbon capture, pyrolysis, and electrolysis (Aguiar-Hernandez & Breetz, 2022a). The difference with energy storage is the variety of hydrogen applications, including industrial processes, electricity production, and transportation fuel (Wang et al., 2018). Hydrogen innovations and higher production volume will reduce investment costs, making this technology competitive against other enabling technologies (Buttler & Spliethoff, 2018), with the additional advantage that storing hydrogen is easier and cheaper than storing electricity (Wang et al., 2018). Besides R&D and deployment initiatives, Nastasi (2019) indicates further efforts in infrastructures, carbon taxation, and public willingness to adopt hydrogen as crucial elements of a hydrogen economy.

Data and Methods

This chapter analyzes the impact of different policies and factors on the innovation performance for RE generation and enabling technologies. This analysis uses a comprehensive panel dataset of patents, policies, and factors at the country level for 34 countries from 2005 to 2018. The sample was selected based on data availability. I include, among other factors, renewable energy policies, research and development (R&D) investments, and the share of wind and solar in electricity production. A database was built to empirically investigate how policy and additional factors affect clean energy technology innovations, including RE generation technologies, wind and solar generation technologies, and enabling technologies. The following sections explain the variables of interest and their sources.

Dependent variable

The main dependent variables of interest are the count of patents for RE generation technologies, and enabling technologies; the latter comprises energy storage, hydrogen technologies, high voltage direct current technologies, and fuel cells.

This chapter uses patent statistics as a proxy to measure innovation. Patents are commonly accepted in innovation research. Although they are not the only metric of innovative activities, they are quantitative, commensurable, empirical, and publicly available. They measure innovative output and indicate the level of inventive activities by providing a detailed record of information about the invention and the inventor, such as the inventor's name, sector, country, description of the invention, references to earlier patents, references to research articles, classification, among additional information (Haščič & Migotto, 2015; Huenteler et al., 2016; Popp, 2005, 2019). The number of patents is an important variable given that they allow to measure technological process (Lindman & Söderholm, 2016); evaluate public policies (Jamasb & Pollitt, 2015; Lindman & Söderholm, 2016); recognize previous knowledge that was utilized by the inventor (Popp, 2005); identify the flow of knowledge, from scientific articles to more applied research (Popp, 2017); understand technology evolution (Huenteler et al., 2016); and track the adoption of technology across countries (Popp, 2005). However, an indeterminate number of innovations are not part of the patenting process, therefore patents might not be entirely able to capture the innovation process. Other ways to measure the level of innovative activities include R&D expenditures, investments in intangible assets, scientific articles, cost reduction, efficiency improvement, knowledge creation and usage, multifactor productivity growth, among others (OECD, 2010).

The dependent variables are the number of patent applications in each technology category mentioned above, per country and year. Patent data are collected from the OECD statistics website. RE generation technologies gather wind and solar technologies, capturing patent applications for wind, solar thermal, solar photovoltaics (PV), and solar thermal-PV hybrids technologies, among other renewable generation technologies such as geothermal, marine hydro energy. RE generation and enabling technologies are grouped under climate change mitigation technologies related to energy generation, transmission, or distribution. This group of patents also includes other energy conversion or management systems reducing GHG emissions, which are not part of this study. used patent data to create two dependent variables: RE generation technologies, and enabling technologies; the latter comprises energy storage, hydrogen technologies, high voltage direct current technologies, and fuel cells.

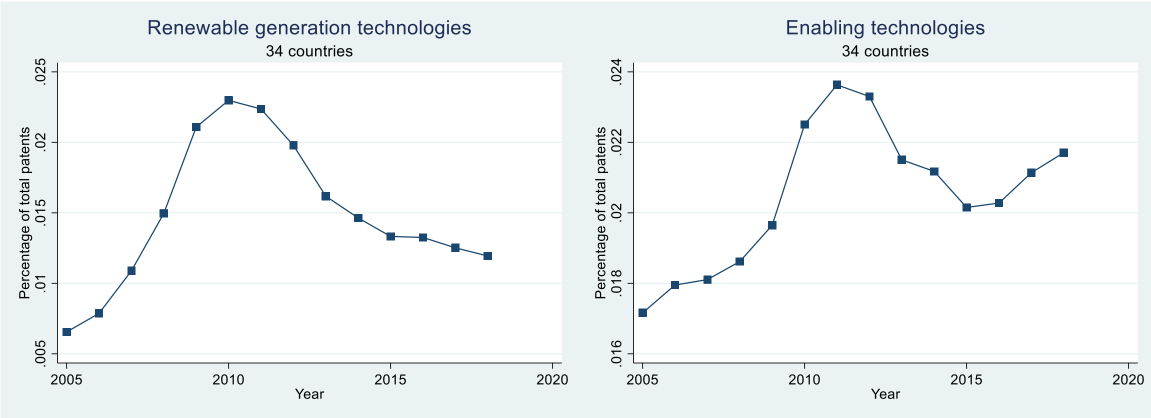


Figure 1. Evolution of Renewable Generation and Enabling Technologies.

Figure 1 shows the evolution of patent applications for renewable generation and enabling technologies weighted by the total patent applications. The trend of renewable generation technology has started to decrease, reflecting less participation in the total of patent applications. On the other hand, enabling technologies have a positive trend with a reduction between 2012 and 2015. Data on clean energy and wind and solar generation technologies are not shown since they reflect similar trajectories as renewable generation technologies.

Independent variables

The main explanatory variables are renewable energy policies and additional factors at the country or national level. Three renewable energy policies are represented by categorical variables that provide information by country and year of adoption of the selected policy. I use the Policy Database available from the International Energy Agency (IEA) to construct these variables. The following variables are built using this approach: feed-in-tariffs, tax measures, and renewable energy targets. Bourcet (2020) identified renewable energy support policies as the primary mechanism for stimulating renewable energy sources in electricity production.

R&D investments are weighted by the Gross Domestic Product (GDP) and presented as a percentage; this empirical measure reflects an innovation input and is a standard indicator used to measure R&D investments across countries (Coccia, 2009). R&D expenditure as a percentage of GDP data is gathered from the OECD (2020). It is also known as R&D intensity and is one of several indicators used to measure progress toward accomplishing the UN Sustainable Development Goal (SDG) 9 on innovation (United Nations, 2021).

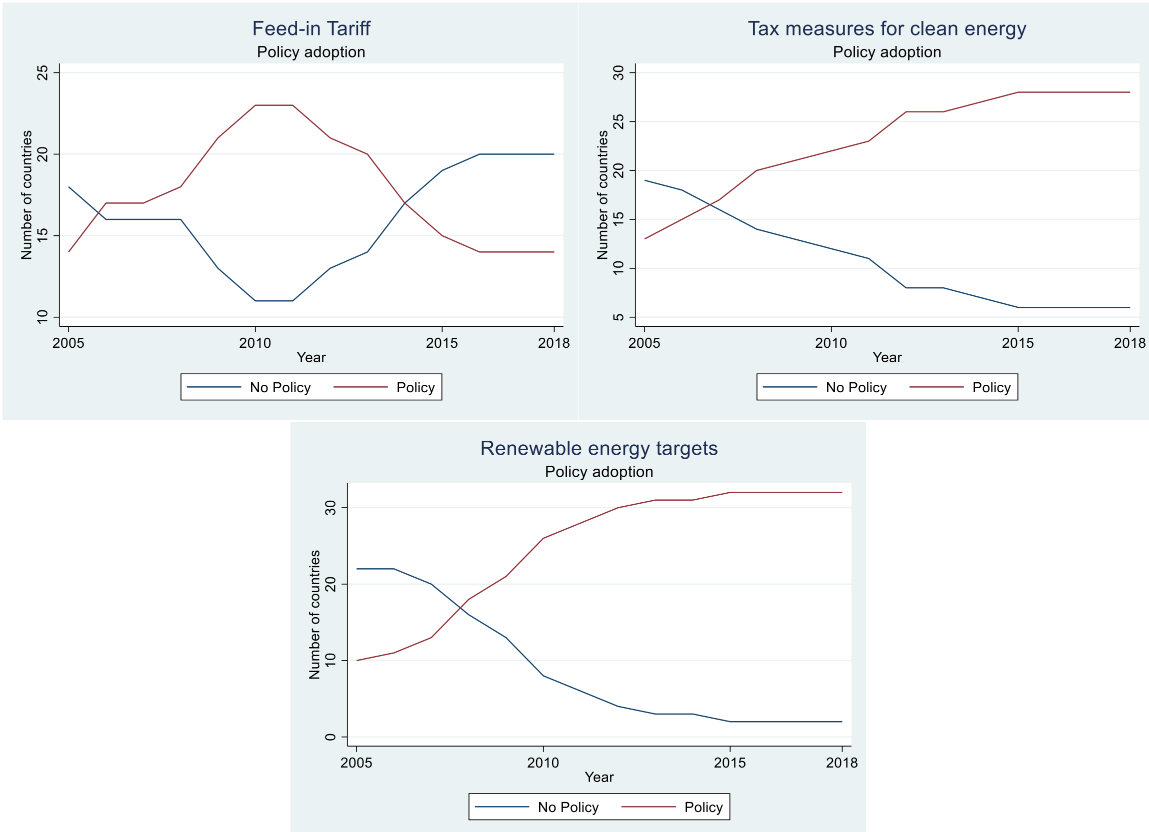


Figure 2. Adoption of Renewable Energy Policies.

Data on the share of wind and solar in electricity production expressed as a percentage is collected from Ritchie et al. (2020). This variable shows the level of adoption of these technologies, which reflects essential factors that stimulate renewable energy sources' deployment. Furthermore, according to Bayer et al. (2013), it positively impacts patenting activity for renewable energy technologies, assuming that a market for wind and solar technologies is in place, inducing renewable energy innovation.

Other independent variables and control variables

The empirical analysis includes some control variables. I use data on population, electricity production, crude oil spot prices, and solar PV module cost as control variables. These variables control other factors that affect the patenting performance of clean energy technologies. As shown in Figure 3, there has been a considerable decrease in the solar PV module cost, which might affect the number of patents, therefore controlling for these variables is important.

Table 1

Summary Statistics

Variable		
RE gen tech	Mean	840.625
	SD	(2110.348)
Enabling tech	Mean	1180.112
	SD	(3183.007)
FIT	Mean	0.525
	SD	(0.5)
Tax measures	Mean	0.682
	SD	(0.466)
Renewable energy targets	Mean	0.735
	SD	(0.442)
R&D / GDP	Mean	1.644
	SD	(0.988)
Share wind & solar	Mean	5.751
	SD	(7.787)

Note: N=472

Population data are obtained from The World Bank (2020). Electricity production data are expressed in TWh and are collected from Ritchie et al. (2020). Data on the crude oil spot prices consider the Europe Brent Crude in dollars per barrel Energy Information Administration (EIA, 2021). Solar PV module cost is data collected from the International Energy Agency and is expressed in USD (2015) per Watt (IEA, 2021). Crude oil spot prices and solar PV module cost change per year but not across countries, assuming similar oil and solar PV modules in each country. Innovation is influenced by economic incentives (Popp, 2005); empirical studies have found a positive correlation between higher oil prices and clean energy patents, some of which are summarized by Popp (2019). While the cost of solar PV modules could be explained by the patents part of this research, many technical challenges remain around the solar PV modules as they reduce cost over time, including efficiency, new materials and multijunction, integration, modeling, engineering, safety, and others (NREL, 2021).

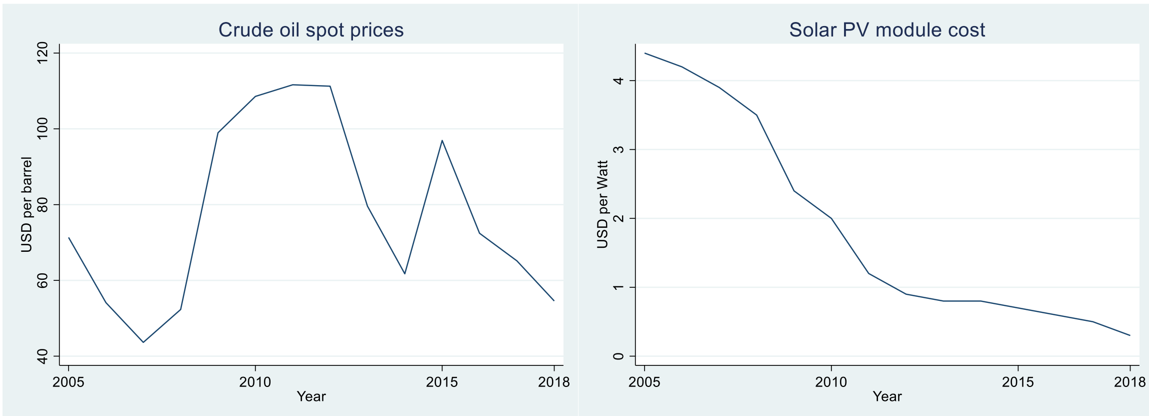


Figure 3. Crude Oil Spot Prices and Solar PV Module Cost.

Summary of regression variables

In this chapter, I hypothesize that the development of technologies enabling clean energy such as storage, hydrogen, high voltage direct current technologies, and fuel cells are impacted differently by policy and other factors compared to renewable generation technologies. Therefore, I calculate the following Poisson regression models to estimate the effects of the policies and factors mentioned above on the two dependent variables. As the dependent variables are count data, I applied Poisson regression models, one of the most commonly used count models, along with negative binomial (Cameron & Trivedi, 2013). I decided to utilize Poisson due to the limitation of negative binomial to remove the individual fixed effects in count panel data (Guimarães, 2008). In addition, I incorporated control variables, enhancing the internal validity and seeking to obtain unbiased causal effect estimates (Hünermund & Louw, 2020).

$$Y_{i,t} = \beta_0 + \beta_1 X_{i,t} + \beta_2 Endo_{i,t} + \beta_3 Exog_t + \mu_i + \varepsilon_{i,t} \quad (1)$$

where *t* = year, *i* = country and:

Y is the dependent variable; it represents each of the patent categories mentioned before.

X represents the independent variables:

Feed-in Tariff denotes a dummy variable for this policy in country *i* in year *t*

Tax measures represents a dummy variable for this policy in country *i* in year *t*

RE Target is a dummy variable for this policy in country *i* in year *t*

R&D / GDP denotes R&D expenditure as a percentage of GDP in country *i* in year *t*

Share Wind & Solar electricity production by wind & solar in country *i* in year *t*

Endo denotes endogenous control variables: population and electricity production expressed in TWh.

Exog represents exogenous control variables: crude oil spot prices and solar PV module cost.

μ represents the fixed effects at the country level

One of the main assumptions of this model is that countries that adopted these policies are similar to those that did not adopt these policies. If this assumption fails, there could be a selection issue where adopting countries are systematically different from the non-adopters. To test this, I performed an event study design to evaluate whether countries that adopted these policies were different from those that did not adopt these policies before the adoption of the policies. Figure 4 shows the coefficients of this specification with the confidence intervals. The graph displays that before enacting the policies, these countries were following parallel trends in the number of patents, which provides suggestive evidence that countries that adopted these policies are not systematically more likely to have higher numbers of patents than countries that did not adopt these policies. In the following models, I strengthen this model by adding other control variables that could be potentially endogenous to the number of patents.

Three models were estimated based on Eq. (1), explaining the effects of specific factors on the patenting performance of the two technologies described as dependent variables. Each of these three models is differentiated by its control variables, aiming to understand different internal and external factors. Thus, these models explain the difference across technologies and provide insights into the factors impacting the patenting performance for enabling technologies. Control variable coefficients are not shown, which according to Hünermund & Louw (2020), generally have no practical application.

Based on the results of the regression models detailed above, I decided to lag the independent variables that had more significant differences across dependent variables (see table 2). As a result, FIT and share wind & solar show coefficients with opposite signs when comparing renewable energy generation and enabling technologies. FIT has a positive effect on generation technologies and negative on enabling technologies; the opposite is shown for share wind & solar, as the effect is negative for generation technologies and positive for enabling technologies. As FIT positively affects RE generation innovation (Lindman & Söderholm, 2016), I aim to identify possible trends for the design of policies to increase the innovation for enabling technologies.

Equation 2 estimates the time lag for two independent variables, feed-in tariff and share wind & solar. This calculation follows Eq. 1 by using Poisson regression fixed effects.

$$\boldsymbol{Y_{i,t} = \beta_0 + \beta_1 X1_{i,t-q} + \mu_i + \varepsilon_{i,t}} \qquad \textbf{(2)}$$

where t = year, i = country and:

Y is the dependent variable.

X1 represents two independent variables:

Feed-in Tariff denotes a dummy variable for this policy in country i in year t

Share Wind & Solar electricity production by wind & solar in country i in year t

Empirical Results

Since the first three models are calculated using similar approaches and dependent variables (renewable energy generation and enable technologies), I present their results in table 2. The results suggest differentiated effects across technologies, specifically when feed-in tariff and share wind & solar are evaluated as independent variables. Table 2 describes the results based on Eq. (1). Table 2 shows differences across the two technologies used as dependent variables. These findings are significant and suggest that technologies enabling renewable generation technologies need a new policy design and additional factors aiming to spur innovation for those enabling technologies.

The explanatory variables reflecting renewable energy policies (feed-in tariff, tax measures, renewable energy target) are significant and consistent compared to RE generation technologies, except for FIT. In the case of FIT, their coefficients have opposite signs in each model, reflecting a positive effect for generation technologies and a negative for enabling technologies. R&D as a percentage of the GDP is significant throughout all technologies, with a larger coefficient for enabling technologies, showing the need for more R&D resources, as enabling technologies are in earlier stages compared to generation technologies. For renewable energy generation technologies, share wind & solar has a negative coefficient; for enabling technologies, this variable has a positive and statistically significant coefficient in these models. This might respond to the market opportunity for enabling technologies after greater renewable generation capacity.

Table 2

Effects of Different Factors on Dependent Variables

	Model 1		Model 2		Model 3	
	RE gen tech	Enabling tech	RE gen tech	Enabling tech	RE gen tech	Enabling tech
FIT	0.224***	-0.042***	0.092***	-0.238***	0.1***	-0.129***
	(0.005)	(0.004)	(0.006)	(0.004)	(0.005)	(0.004)
Tax measures	0.359***	0.155***	0.573***	0.499***	0.126***	0.008
	(0.006)	(0.005)	(0.006)	(0.005)	(0.007)	(0.006)
RE targets	-0.09***	-0.008**	0.23***	0.296***	-0.036***	0.035***
	(0.004)	(0.003)	(0.004)	(0.003)	(0.004)	(0.003)
R&D / GDP	0.315***	0.364***	0.61***	0.635***	0.238***	0.276***
	(0.007)	(0.006)	(0.009)	(0.007)	(0.009)	(0.007)
Share wind & solar	-0.027***	0.019***	-0.034***	0.02***	-0.039***	0.003***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Controls	Endogenous	Endogenous	Exogenous	Exogenous	Endogenous, Exogenous	Endogenous, Exogenous
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	472	472	472	472	472	472

*Notes: Standard errors are in parentheses. *** p<.01, ** p<.05, * p<.1*

Meanwhile, table 2 provides empirical evidence of a differentiated effect between generation technologies and enabling technologies. The results of more wind and solar capacity in the electricity system on the renewable generation patenting differ from those of Bayer et al. (2013). They concluded that more participation of renewable energy sources in electricity production positively impacts the participation of renewable energy sources in the patenting activity for renewable energy technologies. In this analysis, RE generation patent applications are negatively impacted by the share of wind and solar in the generation capacity; these dependent variables have similar coefficients, reflecting a reduction between 2.7% and 3.9% in the patenting activity, respectively when the share of wind and solar capacity is increased by 1%. On the contrary, patenting activities for enabling technologies grew between 0.3% and 2% as the share of wind and solar increased by 1%.

Table 3

Lagged Independent Variables, Feed-in Tariff, and Share Wind & Solar

	Model 4	
	RE gen tech	Enabling tech
FIT_t	0.224***	-0.127***
	(0.011)	(0.009)
FIT_{t-1}	0.109***	0.068***
	(0.013)	(0.01)
FIT_{t-2}	0.087***	0.048***
	(0.013)	(0.01)
FIT_{t-3}	-0.11***	-0.107***
	(0.011)	(0.01)
FIT_{t-4}	-0.167***	0.053***
	(0.008)	(0.007)
Observations	336	336

Notes: Standard errors are in parentheses.
**** p<.01, ** p<.05, * p<.1*

	Model 5	
	RE gen tech	Enabling tech
Share Wind & Solar $_t$	-0.024***	0.052***
	(0.003)	(0.003)
Share Wind & Solar $_{t-1}$	-0.01**	-0.034***
	(0.005)	(0.005)
Share Wind & Solar $_{t-2}$	-0.067***	-0.041***
	(0.005)	(0.005)
Share Wind & Solar $_{t-3}$	0.045***	0.022***
	(0.005)	(0.006)
Share Wind & Solar $_{t-4}$	-0.029***	0.004
	(0.004)	(0.005)
Observations	336	336

Notes: Standard errors are in parentheses.
**** p<.01, ** p<.05, * p<.1*

The models with exogenous control variables have larger coefficients on enabling technologies when compared to the models with endogenous control, which shows the importance of controlling for these variables in the main specification. The opposite is for RE generation technologies, as their larger coefficients result from endogenous. Lindman

& Söderholm (2016) stated that the renewable energy sector is endogenously defined and induced by targeted policies. The differentiation across technologies might respond to this criterion, as enabling technologies not only respond to the renewable energy sector but also to chemical, electronics, and infrastructure sectors.

Table 3 presents the regression results of Eq. 2. FIT and share wind & solar were the variables with more significant differences between the technologies analyzed. Their results were statistically significant and consistent among the models presented in Table 2. RE generation technologies are positively impacted by FIT and negative by share wind & solar. On the contrary, enabling technologies are negatively impacted by FIT and positively affected by share wind & solar. These two independent variables and their lags are evaluated in models 4 and 5, aiming to identify possible trends that allow me to propose a new design of policies or regulations to increase the innovation for enabling technologies. Models 4 and 5, like previous models, use Poisson regressions with endogenous and exogenous control variables and country fixed effects.

Model 4 shows the effects of FIT on RE generation and enabling technologies over five years. All the lags are significant and show different effects depending on the technology. In the case of RE generation technologies, the trend is consistent among the endogenous and exogenous models, reflecting a large and positive effect in the first years and reducing over time. On the other hand, enabling technologies are not as straightforward as RE generation technologies when measuring FIT effects over time. Considering the results in table 2, I could conclude that FIT, as a policy instrument that is not designed for a market for enabling technologies, falls behind between one and two years, having a positive effect after the RE generation technologies collected the benefit of this policy instrument.

Share wind & solar is a factor that has a negative effect on RE generation technologies. In contrast, enabling technologies using both control variables, endogenous and exogenous, show a trend with the first year of positive effect followed by two or three years of negative impact, depending on controls. The capacity of a country to produce wind and solar electricity is determined by several factors, including policy and regulation and the availability of renewable resources. If these factors are in place, a country might reflect its deployment efforts instead of development, reducing the innovation activities for this kind of technology. The nature of enabling technologies, improving flexibility in the power system, and enhancing the use of renewable sources of energy, provides a better explanation of the positive effect of share wind & solar on the patenting performance for enabling technologies; nevertheless, this effect is short.

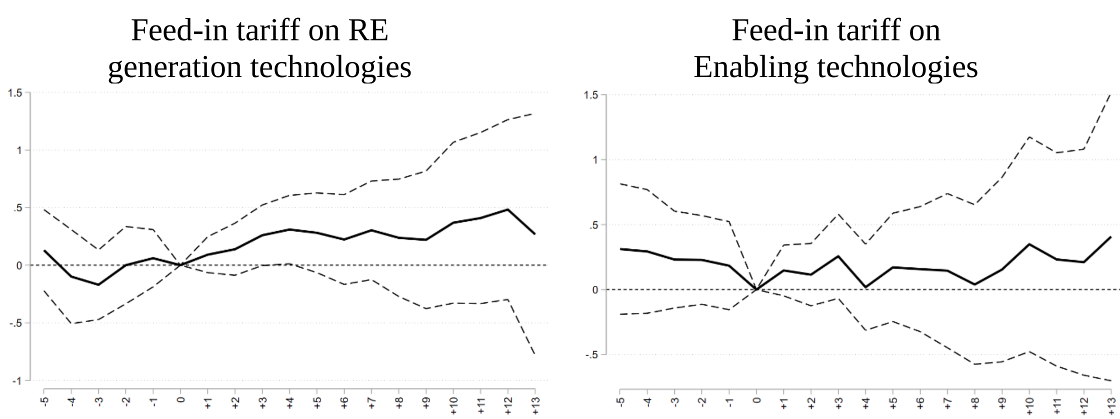


Figure 4. Trends in Effects of FIT on RE Generation and Enabling Technologies.

Figure 4 presents the results of the event study design mentioned above. It shows the difference in the number of patents between those countries that adopted feed-in tariff policies compared to those that did not adopt them after implementing these policies. As

Figure 4 explains, there are no significant differences between these two countries before implementing the policies, which means that a fixed-effects estimator can measure the impact of the policy, as shown in previous models.

Overall, I can identify differences across these two technologies and how some factors impact their innovation performance. Most of the current policies and additional factors were designed to develop and deploy RE generation technologies. Understanding their effects on enabling technologies could create insights for policy-making processes to stimulate the development and deployment of enabling technologies, given the importance these technologies are acquiring, as they are becoming an essential element in the energy transition. Although different studies have shown the effects of specific policies and regulations on the patenting performance of renewable energy capacity; the case of enabling technologies has not been deeply analyzed. Further research is required to adjust the policy and regulation required for these technologies to thrive. Kittner et al. (2017) explained that the co-evolution of innovation, investment, and deployment of different energy technologies, such as storage, is essential for clean energy transitions. Understanding the distinction between RE generation and enabling technologies and their levels of adoption based on the policy and other factors will be crucial for the design, implementation, and evaluation of clean energy and innovation policies. The policy mix made of demand-pull and technology-push policies would include RE generation technologies and those enabling technologies that generate grid flexibility and support the integration of variable renewable and clean energy sources. Although both technologies are considered climate change mitigation technologies related to energy generation, transmission, or distribution by the OECD, the policy mix should consider both as complements and on two scales, development and deployment.

Conclusions and Policy Implications

This chapter explores the impact of different factors and policies on the patenting performance for RE generation and enabling technologies. I identify the differentiated impact of renewable energy policies and other factors on the patenting activities for the technologies mentioned above, contributing with suggestions for possible factors or policies that stimulate the development and deployment of enabling technologies.

I find that wind and solar generation capacity induces innovation of enabling technologies. This might be explained by the challenges the energy system faces due to intermittency and other challenges as more renewable generation capacity is added to the grid. This aligns with the induced innovation hypothesis, which says that innovation is influenced by a change in the prices of the factors, promoting innovation to directly economize using the factors that have become expensive (Popp, 2005). In this case, enabling technologies such as energy storage, hydrogen, and high voltage direct current technologies could support the introduction of more generation capacity of renewable energy sources, reducing the barriers and costs of deployment and operation. Further, the models show that FIT has a spillover effect on enabling technologies through its initial boost of RE generation technologies, such that the effects of FIT on enabling technologies fall behind for some years. I also find that other renewable energy policies, such as tax measures and RE targets, have similar effects on both dependent variables in the models.

In this chapter, I identify the important role that R&D has on innovation performance for RE generation and enabling technologies, being more relevant for the latter. The results are consistent with Lindman & Söderholm (2016), reflecting the value of R&D investments in the innovation systems for renewable energy technologies. R&D investments will play a significant role in developing enabling technologies and would be an essential component of its policy mix. Technology-push policies as a complement of demand-pull policies, such as the renewable energy policies analyzed in this study, would increase the impact of the innovation system. The interaction of demand-pull and technology-push has been proved to drive and shape the speed of technological change (Costantini et al., 2015; Mowery & Rosenberg, 1979; Nuñez-Jimenez et al., 2019). The empirical results can be interpreted as an explanatory approach into the demand-pull and technology-push policies for enabling technologies, using the current RE generation technology system.

The findings have important policy implications for the clean energy sector and energy transitions. One implication is that targeted policy instruments for the development and deployment of enabling technologies may be needed to support decarbonization efforts worldwide, especially for supporting renewable electrification, heat, and transportation sectors. These policy instruments could be clustered as a policy mix for enabling technologies, due to multiple sectors involved, different levels and actors interacting, and the complexity of the systems where they participate (Flanagan et al., 2011). In addition, the transversal attribute of enabling technologies allow them to provide solutions for multiple sectors, but at the same time different policies and regulations might be needed. For example, hydrogen production needs the participation of industrial, electrical and gas regulation (Aguiar-Hernandez & Breetz, 2022a). Grouping the policy efforts of enabling technologies implies an additional level of complexity that can be handled by the policy mix approach.

The advantage of the remarkable costs declines for RE generation technologies would not be transferred to consumer without the participation of enabling technologies, creating more intelligent energy systems, and interconnecting multiple sectors for their decarbonization. The impact of enabling technologies is beyond the electricity sector and their participation in energy transition strategies will increase in the following years. Another implication is that enabling technologies, such as hydrogen, represents an opportunity for emerging economies, countries in Latin America are expected to contribute to the hydrogen economy by low-cost green hydrogen production, due to the abundant solar and wind resources with low prices in comparison with other regions like Asia, Europe, and North America (IRENA, 2019).

Further research is required to better understand the role of enabling technologies in the energy transition, as well as the policy mix for their development and deployment. Overall, the empirical result from the research suggests an opportunity for policy entrepreneurship, design and implementation from both, energy and innovation policies, balancing technology-push and demand-pull policies. This recommends an improved policy process and a broader impact of the innovation system.

Limitations of this chapter

This research has limitations in terms of its Data and Methods, specifically, the data used as part of the analysis. Although multiple research projects use patent data to measure innovation, as mentioned before, this is not the only way to measure it. In addition, patent data have multiple scales and detailed record information that could be utilized as a part of the analysis. This chapter uses patent applications instead of the patent granted data, limiting the analysis by considering a portion of patent applications that might not be granted by the government office in charge of this matter.

Another limitation is data availability; most of the countries part of this study are advanced economies with some emerging economies (according to the list of emerging economies shown in Chapter 3). Therefore, developing economies are not part of this study, reflecting the constraints based on data availability.

Lastly, the recognition of heterogeneity across countries and that rules of operation of Patent Offices differ between countries bring the possibility to further research in this regard.

CHAPTER 3

INNOVATION FOR WIND AND SOLAR TECHNOLOGIES IN EMERGING ECONOMIES: THE CASE OF MEXICO

Abstract

Emerging economies represent a considerable portion of the global CO_2 emissions, as energy demand keeps increasing as part of their development, despite many of these countries' efforts to adopt renewable energy technologies. This chapter analyzes the SIS for wind and solar in Mexico to identify inducement and blocking mechanisms using the innovation systems framework. The Mexican case represents an emerging economy that recently reformed its energy sector, creating a partially liberalized electricity sector with country-level clean energy goals and that has supported clean energy innovation efforts. The analysis was conducted based on scientific literature, policy documents, and 16 expert interviews. It finds that structural components are essential for the performance of the SIS in the Mexican context. Other crucial factors are the role of governments as actors in the system and the importance of the institutional setup, such as cultural values, policy, and regulation.

Introduction

The electricity sector in emerging market and middle-income economies[1] (hereafter emerging economies) represents a considerable portion of current and future CO_2 emissions worldwide. Many of these economies are adopting renewable energy technologies to reduce their emissions from electricity production while meeting their growing demand for electricity. Although the electricity sector's emissions intensity in emerging economies is still high compared to developed countries (IEA, 2020b), they have been increasing their efforts in renewable energy. This includes making gains not only in adoption, but also in energy technology innovation, which can help these countries with economic growth in addition to decarbonization (IEA, 2020a). At the same time, emerging economies still face barriers to energy innovation, requiring special attention in policy and regulation to overcome these market and system failures (Samant et al., 2020).

Since developed economies have traditionally been the innovation leaders, they are overwhelmingly the focus of innovation and energy transitions research. However, energy innovation in emerging economies has received much less attention. To address this gap and contribute to the energy innovation literature, this study analyzes the sectoral innovation system (SIS) for renewable energy in the case of Mexico. The SIS approach recognizes that clean energy technologies are influenced by policy and regulation and are impacted and shaped by the entire system where the technologies are embedded (Hekkert

[1] Given the absence of an official definition of an emerging market economy, I use the classification presented by the IMF. This approach identifies the following countries as emerging economies: Argentina, Brazil, Chile, China, Colombia, Egypt, Hungary, India, Indonesia, Iran, Malaysia, Mexico, the Philippines, Poland, Russia, Saudi Arabia, South Africa, Thailand, Turkey, and the United Arab Emirates; accounting for 34% of the world’s nominal GDP in US dollars and 46% in purchasing-power-parity terms.

et al., 2007). Mexico has made several policy changes that could enhance innovation in renewable energy, making it a useful case for understanding energy innovation in emerging markets. It recently opened its electricity sector to competition and increased its innovation efforts, including the commitment with other 24 countries to double public investment in clean energy R&D, among other innovation activities through the global initiative Mission Innovation (Mission Innovation, 2021). More broadly, wind and solar technologies have demonstrated a great way to diversify the Mexican energy sector (Gallardo et al., 2020) and an excellent opportunity to tackle climate change, create jobs and meet the growing electricity demand. These efforts show that there is momentum behind renewable energy in Mexico. But enhancing and capturing the benefits of innovation in clean energy technologies will likely require further targeted interventions. The purpose of this study is to identify the structure and functionality of the SIS for wind and solar technologies. assess the mechanisms that induce and block the performance of this SIS, and identify recommendations for supporting the innovation system.

In this chapter, I systemically analyzed the structural components and functional patterns of Mexico's SIS for wind and solar technologies. The analysis was conducted based on scientific literature, policy documents, and 16 expert interviews; these interviews aimed to generate insights on the functioning, inducement, and blocking mechanisms of the wind and solar SIS in Mexico and aspects of the structural components of this innovation system. The structural components include actors, networks, and institutions; the latter contains policies, regulations, cultural values, and formal and informal settings. For the functional analysis, I adopted the innovation systems approach (Bergek et al., 2008; Hekkert et al., 2007), which evaluate a number of critical processes called functions that have been proven helpful in identifying and understanding inducement and blocking mechanisms across different systemic approaches, such as national innovation systems (NIS), sectoral innovation systems (SIS) and technological innovation systems (TIS) (Jacobsson & Bergek, 2011).

The findings show the need for institutional stability in the Mexican SIS for wind and solar technologies. This sector is currently vulnerable to institutional changes that directly or indirectly impact the performance of the SIS. The changes made by the 2018 – 2024 federal administration in Mexico, presided by Andres Manuel Lopez Obrador (popularly known by his initials, AMLO), are impacting the development of utility-scale wind and solar projects and R&D and innovation funding. This structural component was identified by the interviewees as a blocking mechanism, reducing the performance of the SIS. As an alternative, certain activities that are not reached or affected by the institutional changes made by the federal government are recognized as inducement mechanisms. Some of these activities include the role of national and international non-government organizations (NGOs) in various activities that support the development and deployment of wind and solar technologies; the role of local governments, that under their attributions, are undertaking non-regulatory activities to stimulate market formation for wind and solar technologies and creating strategies to support the knowledge creation and diffusion. An additional blocking mechanism detected by the interviewees is the disconnection between academia and the private sector. This disconnection is not only perceived as working together to solve the industry's needs and collaboration in R&D activities; but researchers encounter a cultural conflict when they aim for patenting, being entrepreneurial with the technology they developed, or collaborating with companies, reflecting the lack of social acceptance when these two sectors are operating together.

This chapter assesses the SIS for wind and solar technologies in Mexico, intending to identify inducement and blocking mechanisms to improve the performance of the innovation system, contributing to the literature by analyzing the SIS for wind and solar technologies in the context of an emerging economy.

Theoretical Framework

This chapter utilizes the innovation system approach to evaluate the development of wind and solar technologies in Mexico, identifying their drivers and barriers. This systemic approach considers all institutions and structures that affect both rate and direction of technological change (Hekkert et al., 2007). With different system boundaries, different system approaches have emerged, including NIS, SIS, technological innovation systems (TIS), and regional innovation systems (RIS) (Jacobsson & Bergek, 2011). The framework of innovation systems aims to identify processes that could be identify as inducement and blocking mechanisms in the system, and can then be used as a focusing device for policy maker for moving the innovation system towards the expected outcome (Bergek et al., 2008).

In this chapter, the analysis is focused on the structure and functioning of the SIS for wind and solar technologies in Mexico. The structure evaluation examines the SIS elements, including actors and institutions (Carlsson & Stankiewicz, 1991); functions describe the activities in the system resulting in the development and diffusion of technologies (Hekkert et al., 2007). Even though the SIS approach shares multiple aspects with the rest of innovation systems, it provides a framework that uses a multidimensional, integrated, and dynamic view of sectors to analyze innovation. In addition, it examines other agents other than firms, placing great emphasis on knowledge, focusing on non-market and market interactions, and paying much attention to institutions (Malerba, 2004).

Table 4

Description of Seven System Functions of Innovation Systems

Number	Function name	Description
1	Entrepreneurial activities	The role of the entrepreneur is essential for the well-functioning of an innovation system. Their role is to turn the potential of new knowledge, networks, and markets into concrete actions to generate and take advantage of new business opportunities.
2	Knowledge development	Knowledge is a fundamental resource that is linked to the process of learning. The creation of knowledge is a crucial part of innovation systems, and this function covers learning by searching and learning by doing.
3	Knowledge diffusion through networks	Knowledge diffusion through networks. The exchange of relevant knowledge between actors in the system is essential to promote learning processes.
4	Guidance of the search	It refers to those activities within the innovation system that can positively affect the visibility and clarity of specific needs among technology users, reflecting technological expectations and societal discussion.
5	Market formation	New technologies need protected spaces in the early phases of development, this can be a small niche market but later a larger market is required to facilitate cost reductions and other incentives.
6	Resource mobilization	Financial, human, and physical resources are required as a basic input for all activities within innovation systems. Without these resources, other processes are obstructed.
7	Creation of legitimacy	New technologies receive opposition as they become part of the incumbent regime, and advocacy coalitions are can function as a catalyst. A certain level of legitimacy is required for actors to commit to the new technology and invest.

Note: Adapted from Bergek et al. (2008); Hekkert, Suurs, Negro, Kuhlmann, et al. (2007).

The structural components of SIS are the network of actors operating under a specific institutional context. Actors do not share the same goal, and they do not have to work together; examples of actors are firms, universities and research centers, non-governmental organizations (NGOs), industry organizations, and energy clusters. Institutions can have different forms, being the most important the culture, norms, laws, regulations, standards, and routines.

Nevertheless, there are critical processes known as functions, which are considered essential for the operation of innovation systems. These functions are commonly given high importance in innovation systems analysis (Bergek et al., 2008; Hekkert, Suurs, Negro, Kuhlmann, et al., 2007). Table 4 shows a list and descriptions of the functions of innovation systems.

Innovation systems literature used to be more focused on the importance of structural components, cumulative learning processes, and spatial and technological characteristics, but the functional approach of innovation systems has become a prominent procedure (Rogge & Hoffmann, 2010). It has been used successfully to explain innovation systems dynamics, producing explanations for technological innovation systems' success or failure in different countries (Negro et al., 2007). In studies for clean energy and technologies supporting transitions to low-carbon energy systems, the functions of innovation systems have been applied to different technologies and sectors such as wind (Jacobsson & Karltorp, 2013; Reichardt et al., 2016; Wieczorek et al., 2013), solar (Esmailzadeh et al., 2020; Huang et al., 2016; Kebede & Mitsufuji, 2017), lithium-ion battery (Stephan et al., 2017), biomass (Hellsmark et al., 2016; Negro et al., 2008), biofuels (Suurs & Hekkert, 2009), carbon capture and storage technologies (van Alphen et al., 2010), and power generation technologies (Rogge & Hoffmann, 2010). Most of the studies mentioned before were performed in Europe and Asia. In Mexico, the concept of innovation systems have been applied at the national level (Cimoli, 2000; Dutrénit et al., 2010; Solleiro & Castañón, 2005), regional level (Garcia & Chavez, 2014), and in the agriculture sector (Hellin, 2012). There is no research available that applies this concept to studies related to energy in Mexico.

This chapter defines the sectoral system for wind and solar technologies, reflecting the technologies part of the system. According to Malerba (2004), sectoral systems differ in terms of technologies, and more than one technology may be relevant. Wind and solar technologies are the most important sources of clean energy in the electricity grid (Gallardo et al., 2020). Both are linked by the same institutions that regulate and operate them and share actors and networks; according to Gallardo et al., (2020) these generation technologies presented a great energetic complementary in the Mexican context . Several firms use both technologies to generate electricity in the Mexican context; these firms can be labeled as multi-technology corporations and the sectoral system. Wind and solar are intermittent generation technologies with zero marginal operating cost, creating challenges for wholesale electricity markets (Joskow, 2019), similar to the market that started after the Mexican Energy Reform (Alpizar–Castro & Rodríguez–Monroy, 2016).

This study complements the innovation systems literature by empirically analyzing the SIS for wind and solar sectoral technologies in Mexico. Particularly how a developing country that recently reduced its restrictions to competition in the electricity sector can strengthen its SIS for the most important renewable energy sources in its territory.

Research Methods

This analysis focuses on the Mexican wind and solar sectors. I analyze how the SIS for wind and solar technologies operate using different sources of information: scientific literature, policy documents, and 16 expert interviews (see Appendix A; due to confidentiality reasons, not all names and companies can be published). Innovation systems are complex and different sources of information are required to analyze them. The focus on the SIS allows me to exclude from the analysis specific materials or characteristics that are part of the wind and solar technologies, conceptualizing them as a “black box” transforming sunlight or wind into electricity regardless of their internal processes.

The interviews mentioned above were semi-structured interviews of 1 – 1.5 hours. Experts were asked to express their views on the functioning, inducement, and blocking mechanisms of the wind and solar SIS in Mexico and aspects of the structural components of these innovation systems. Even though these technologies are not similar in their components, they have followed similar trajectories in their development and deployment in the Mexican context, making them the most important clean energy source of energy for electricity production in Mexico and the main technologies for energy transition in the country. Four categories of experts have been identified: government; companies; non-governmental organizations; and universities and research centers. Four experts per category were interviewed, and all responses regarding the functionality of the SIS analyzed were analyzed critically to guarantee that nothing was neglected or looked after.

The interviews were conducted in Spanish and recoded by Zoom, using only audio; then, the audios were transcribed, coded, evaluated, and the analysis translated into English. The interviews were carried out between October and December 2021. We used the functions of innovation systems mentioned in Section 2 to structure semi-structured interview questionaries and analyze the interviews, aiming to identify how well each system function is fulfilled and which function reflects the most significant barriers. After this deductive process, I divided the information into two elements: inducement and blocking mechanisms. The former are system instruments being particularly important for understanding the possibilities of wide deployment of a technology (Sawulski et al., 2019), the latter are system failures that not positively stimulate the innovation system performance (Wieczorek & Hekkert, 2012). Different articles have used inducement and blocking mechanisms to analyze the functioning of innovation systems (Jacobsson & Karltorp, 2013; Palm, 2015; Sawulski et al., 2019; Wieczorek et al., 2013).

Structure of the Innovation Systems

This part outlines the structure of the SIS for wind and solar technologies in Mexico. The structural analysis supports the assessment of the SIS, including the connections between the actors. In the next section, I complement by evaluating the functions of the SIS.

Actors and Networks

Companies. The Electricity Industry Law (Ley de la Industria Eléctrica, 2014) allows private companies to participate in the electricity sector in generation and supply (only large end-users) activities and import and export activities. In addition, the Mexican Energy Reform established the Wholesale Electricity Market (WEM) to allow competition in the sector. It creates the space to trade electricity, ancillary services, electrical power, or any other product that guarantee resources to meet the demand, transmission rights, and clean energy certificates. Before the reform, private participation was limited, letting private firms participate under specific generation projects like self-supply, cogeneration, independent power production, and imports and exports (Alpizar–Castro & Rodríguez–Monroy, 2016).

Distributed generation started in 1992 under the self-supply mode, being natural gas-driven cogeneration and solar the most important technologies (Jano-Ito & Crawford-Brown, 2016). The Electricity Industry Law (Ley de la Industria Eléctrica, 2014) defines distributed generation as the electricity produced by an end-user, not requiring a permit to generate electricity and is interconnected to the distribution grid, using a power plant with a capacity less than 0.5 MW. End-users can decide the type of contract between them and the distribution company; net metering, net billing, and "buy-all, sell-all" options.

Large national and international companies are part of the WEM, generating and supplying electricity to the market, large users, and other suppliers. Most of the renewable energy generated in the WEM is produced by wind and solar technologies, being foreign private companies the main actors in adopting these technologies at the utility-scale and part of the WEM; this happens typically through technology transfer, bringing technology from other countries. Some of these companies are developing new products and technologies investing in R&D activities in Mexico and other countries. Given the high barriers to entry in the utility-scale electricity production, small companies are focused on commercializing solar PV systems for distributed generation. This kind of generation is flexible in terms of the type of contract. It generates savings in electricity bills, especially for those users paying high tariffs, such as small businesses, high consumption households, and some industrial clients. Small companies and startups are disconnected from larger companies. Most of the time, this disconnection creates a lack of information about the needs for entrepreneurial experimentation the industry requires.

Universities and Research Centers. According to the National Association of Universities and Institutions of Higher Education (ANUIES, 2019), Mexico has 207 universities and research centers, including public and private universities and CONACYT's research centers. Research centers part of the Secretary of Energy (SENER), such as the National Institute of Electricity Clean Energies (Instituto Nacional de Electricidad y Energias Limpias, INEEL) and Mexican Petroleum Institute (Instituto Mexicano del Petroleo , IMP), are not included.

Universities and research centers are perceived as leading advocates for entrepreneurial experimentation activities for wind and solar technologies in Mexico. Most universities in Mexico have business incubators, which are the ideal universities areas where entrepreneurial experimentation could be performed. However, interviewees mentioned that these business incubators underperform, and more could be done to spur wind and solar innovation across the entire country. Although universities and research centers are doing research, the absence of strong links with the industry has created difficulties bringing inventions into the market.

Non-governmental Organizations (NGOs). Many NGOs are impacting, directly and indirectly, the Mexican energy sector and, consequently, the sectoral innovation for wind and solar technologies. These organizations take different forms and have various objectives. The most common example are energy clusters, energy hubs, academic associations, business associations, international cooperation, international development organization, gender equality in the energy sector, climate action, and environmental organizations.

Besides academia, the private sector, and government, several interviewees emphasized the role of NGOs in supporting innovation activities for wind and solar technologies. An example of this process is the Mexican Association of Solar Energy (Asociación Mexicana de Energía Solar, ASOLMEX), an active promoter of innovation in the solar sector; this association put together more than 100 companies in the entire supply chain of solar energy, including energy storage. International NGOs are another essential piece in the sector. They promote sustainable development, development, and deployment of renewable energy, encourage better governance, strengthen civil society, perform studies and projects, and support local NGOs' creation.

Several NGOs have started to work together, reflecting the maturity of the system and the opportunities these interconnections bring to the innovation activities and the market.

Local Governments. Local governments operate as actors in this system, creating innovative business models to compete in the WEM as generators and suppliers. The case of the State of Tamaulipas is a significant one; this State government initiated a renewable energy company in a joint venture with a global wind turbines manufacturer, aiming to generate electricity for government agencies via self-supply, and sell electricity in the WEM. Tamaulipas also started an alliance with universities in the State to train wind energy technicians. Furthermore, in collaboration with the State of Tamaulipas, the German International Cooperation Agency (GIZ) developed a study to measure the potential production and use of green hydrogen in the State. The results show a theoretical potential of 57,500 kilotons annually with 800 GW of electrolysis PEM (HINICIO, 2021).

Institutions

The institutional setup described below affects Mexico's SIS for wind and solar technologies. Directly or indirectly, these laws, regulations, standards, norms, and cultural values impact the system's performance.

The Electricity Sector Regulation. From 1940 to 2013, Mexico's electricity sector was operated as a monopoly by a government-owned vertically integrated utility, the Federal Electricity Commission (Comision Federal de Electricidad, CFE). However, after the Mexican Energy Reform in 2013, the sector was opened to competition in generation and supply activities. The suppliers are three, basic service supplier, qualified service supplier, and last resource supplier. Private companies can operate as the previous two, and CFE manages the three supply kinds. Transmission and distribution are strategic areas, and the State maintains the ownership. CFE is in charge of the national transmission grid and the general distribution grid (Jano-Ito & Crawford-Brown, 2016). Figure 1 presents the Mexico’s electricity sector, including the regulatory framework, the WEM and its participants, and the national electricity system.

AMLO’s Administration (2018 – 2024) has argued that the competition generated by the reform harms CFE, creating instability across the electricity sector (Hernández Ibarzábal & Bonilla, 2020). Aside from the open position the government has against private companies, these can be explained by the merit order in the WEM, as private companies own most of the wind, solar and new combined cycle power plants, while the Federal Government aims to reach self-sufficiency with fuel oil, coal and gas (Rousseau, 2021). The Federal government has proposed changes in the electricity sector to reverse it to its previous version, being CFE a monopoly with some exemption in generation activities (Barrera, 2021). Although this proposal is still under discussion, the level of uncertainty in the electricity sector is high. Multiple projects were canceled, and private companies used legal resources to prevent their power plants from being out of business. Private companies and investors in renewables no longer have confidence in the political, economic, and regulatory framework (Rousseau, 2021). Various NGOs, companies, and experts, national and international, have expressed their concern about the impact this change will have on the Mexican economy, the electricity sector, and electricity prices for end-users (Barrera, 2021; Delgado & Martínez, 2022; Semple & Lopez, 2021).

Clean Energy Policies. The Electricity Industry Law (Ley de la Industria Eléctrica, 2014) defines clean energy as the sources of energy and electricity generation processes in which emissions or wastes do not go beyond the thresholds established by complementary regulation. Wind and solar radiation are part of the list of clean energy sources under this Law. This consideration, and current technology prices, made wind and solar the primary sources of clean energy in the country (Gallardo et al., 2020). Furthermore, clean energy generation is linked to Mexico's Clean Energy Goals. These goals are a policy instrument created in the Energy Transition Law (Ley de Transición Energética, 2015), adopted nationwide to generate from clean energy sources. The goals are as follows: 25% of the electricity from clean sources by 2018, 30% by 2021, 35% by 2024, 37.7% by 2030, and 50% by 2050. The achievement of these goals is measured with the Clean Energy Certificates. These certificates accredit producing a certain amount of electricity from clean energy sources; one CEC is the equivalent of 1 MWh produced from clean energy sources and is tradable in the WEM.

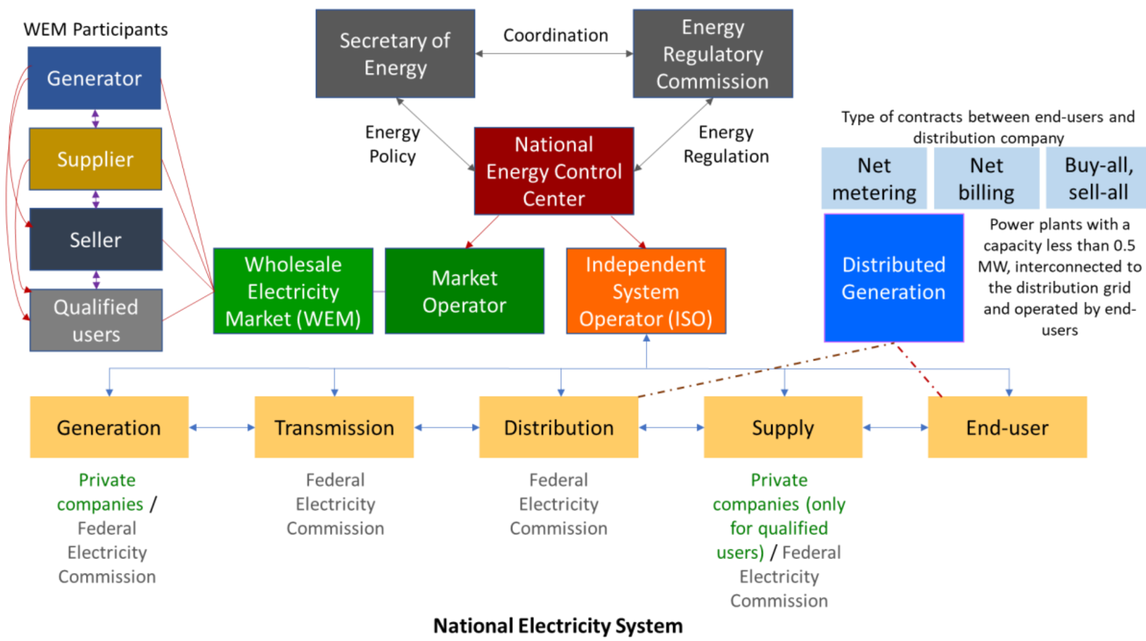
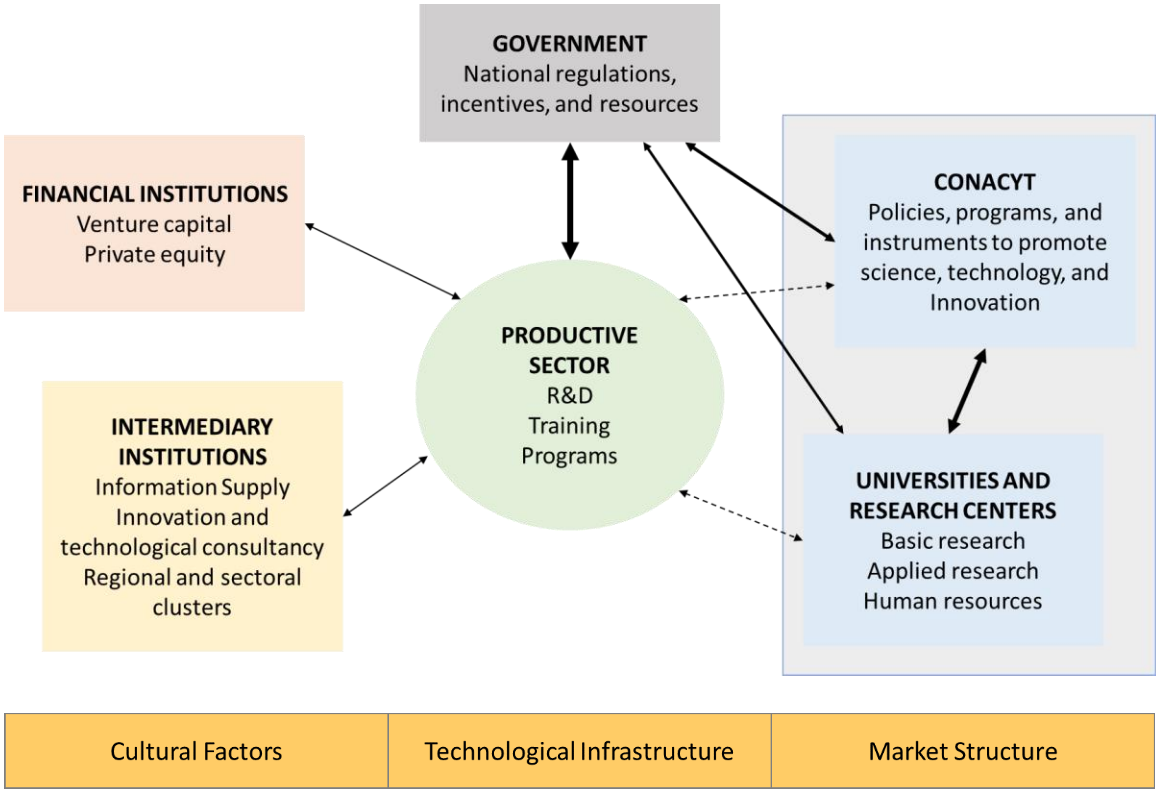


Figure 5. Structure of the Electricity Sector in Mexico. Adapted from the Electricity Industry Law (Ley de la Industria Eléctrica, 2014).

Innovation Policies. The National Council of Science and Technology (Consejo Nacional de Ciencia y Technologia, CONACYT) is the government agency promoting scientific and technological activities, setting government policies for these matters, and granting scholarships to postgraduate studies (CONACYT, 2017). Through CONACYT, the Mexican Government is the leading actor of the national innovation system. It was created in 1970, and since then, it has implemented science and technology programs and initiatives; in the 1990s, it started to include innovation in its programs and initiatives (Wood, 2014).

Supervised by SENER and CONACYT, the Mexican Centers of Innovation in Energy (Centros Mexicanos de Innovación en Energía, CEMIEs) are groups of public and private research center, universities, companies, and government entities that have the objective of working together on developing technologies, products, and services, taking advantage of Mexico's great renewable energy sources. CEMIEs are virtual centers that use the infrastructure of their participants; five CEMIEs were created, one for each primary energy source: bioenergy, wind, geothermal, ocean, and solar (SENER, 2015). This initiative was accompanied by creating technology roadmaps for the leading renewable energy sources, involving companies, government, universities, and NGOs. These projects were created by the last Federal Administration, which enacted the Mexican Energy Reform, aiming to boost clean energy innovation, and link academia and industry (SENER, 2015). According to the interviewees, CEMIEs were a great success creating knowledge but not generating innovations, reflecting an academic sector that did not evolve towards innovation. This aligns with a cultural value mentioned by the interviewees, a researcher doing entrepreneurial activities with their research. It is not well seen in the academic sector, being socially unacceptable patenting or working with private companies for doing businesses with the inventions generated.

The 2018 – 2024 Federal Administration has reduced the total budget for science, technology, and innovation. The Science and Technology Law establishes that this budget should be at least 1% of Mexico's gross domestic product (GDP); according to The World Bank (2020), the research and development expenditure as a percentage of the GDP in 2018 was 0.3%. In addition, this Administration has eliminated all the science, technology, and innovation escrows (including energy and sustainable energy), which were developed to keep continuity of science and technology projects besides the limitations of the Federal budget (Flores, 2021). The funds saved by these escrows' cancelation were used to acquire the Deer Park Refinery in Texas (El Financiero, 2021).



Note. The thickness of lines denotes relevance in interactions and collaborations. Dashed lines mean irregular and weak linkages. Shaded area embraces the actors whose linkages are stronger and relevant for the National Innovation System in Mexico. Productive sector includes firms, producers, and communities.

Figure 6. The Mexican System of Innovation: Actors and Networks. Adapted from Dutrénit et al. (2008) and Cimoli, (2000).

Analysis of the Innovation Systems Functioning

In this section, the seven functions expressed in the Theoretical Framework section (Table 4) are applied to evaluate the functionalities of the SIS for wind and solar technologies in Mexico. In addition, drivers and barriers are identified.

Entrepreneurial Experimentation

Wind and solar projects for electricity production were part of the Mexican electricity sector before the Energy Reform. However, this participation was limited due to the configuration of the industry, in which a government-owned vertically integrated utility planned and operated the electricity system in the entire country, leaving limited space for entrepreneurial experimentation, which was focused more on the solar self-supply and distributed generation. The Mexican Energy Reform opened the electricity sector to competition for generation and supply activities, bringing new ideas and creativity for wind and solar, which are the renewable energy technologies adopted mainly by the new configuration of the sector. Several interviewees expressed how innovation in the industry advanced after the Energy Reform, which was accompanied by additional policy instruments such as Energy Technology Roadmaps, CEMIEs, research grants, scholarships, long-term auctions, and the participation of local government in collaboration with private companies for wind and solar technology development and adoption. Unfortunately, the current Federal Administration has reduced or eliminated most of these policy instruments. According to the interviewees, this reductionist approach is not investing in clean energy or innovation, affecting the entire SIS.

The SIS for wind and solar technologies has adapted to the lack of support from its principal benefactor, the Federal Government. Research centers and universities are considered the main affected actors in the system due to their dependency on federal grants to advance energy innovations. On the other hand, energy startups were reduced, leaving no incentives for entrepreneurship among young people and different segments of the population. Only big companies keep investing in R&D and performing entrepreneurial activities. An additional condition in the SIS is that the needs of the industry are not covered. Most of the interviewees agreed that academia and firms are disconnected in terms of innovation; they lack a bridge to move ideas, projects, and inventions among them, and business incubators do not have the results the sector is expecting.

While Federal policies are moving in the opposite direction of renewable energy and innovation, distributed generation is perceived as an opportunity besides current rules, and where entrepreneurial activities are growing, adapting technology for specific local needs. This type of generation in Mexico does not require permits; a contract with the distribution company and complying with interconnection standards is enough to produce electricity in-situ, using power plants less than 0.5 MW of capacity. In 2021, distributed generation had 270,506 contracts, representing 2,031.25 MW of generation capacity. Solar is the leading source for distributed generation in Mexico, with 99.2% of total capacity under this type of generation, according to the Energy Regulatory Commission(Comisión Reguladora de Energía, 2021). The regulation allows end-users to decide the kind of contract to use: net metering, net billing, and "buy-all, sell-all".

Collaboration among different actors has been improved over the last years; private companies, local governments, non-governmental organizations, and academia are getting together into energy clusters. These clusters are usually at the State level, aiming to improve businesses performance and propose public policies that promote economic and social development.

The opportunities to innovate in the wind and solar technologies in Mexico are tremendous, with several conditions that could make Mexico grow these technologies, support the country's energy transition, and develop other technologies that rely on renewable sources like green hydrogen. The interviewees mentioned how Mexico is behind other countries, including Latin-American countries, lacking in promoting entrepreneurial activities for green hydrogen technologies and creating policies and regulations around this energy carrier. Energy innovation policies should evolve to improve how technologies are developed, reducing the perception that technology is adopted and supported only when it is mature or somehow tested somewhere else.

Knowledge Development

Universities and research centers are perceived as the leading actor in knowledge development in Mexico's SIS for wind and solar technologies. Still, the knowledge produced by these actors is mainly disconnected from the industry. This disconnection forces wind and solar companies to create their knowledge, designed to solve specific problems, that at the same time, do not leave the firm's environment, traveling across firms but not beyond this context. The perception is that public, private, and academic sectors work in silos. Although the academic sector produces most of the knowledge, there is a difference between private and public academic institutions. Private universities are more open to working with private companies and adapted faster to the Mexican Energy Reform's structural changes. On the contrary, public universities were slower adapting to the new conditions of the electricity sector; this aligned with Cimoli (2000), who indicated that private universities in Mexico were created to address the demands of the industry, utilizing research resources primarily for diagnosis and consultancy activities, contrary to public universities that use these resources towards basic science.

The Mexican Energy Reform changed the knowledge creation in the electricity sector. Before the reform, private companies were under the supervision of CFE. The openness of the electricity sector in generation and retail activities brought a different environment in terms of knowledge creation. For example, the competition among generators in the wholesale electricity market or the participation in long-term auctions incentivized companies to improve their processes. However, the Mexican market for wind and solar technologies is still in the process of awareness, after being for many years close to private participation and depending on a government-owned utility that imported most of the technology used.

NGOs are playing a pivotal role in supporting knowledge creation activities. Local, nationwide, and international NGOs work in Mexico to keep the energy sector and its energy transition. Among international NGOs, German and English cooperation agencies are the most active, supporting renewable energy projects, research, studies, policy recommendations, and the creation of Mexican NGOs designed to work in the energy sector, such as REDMEREE and the Hydrogen Association. US Agency for International Development (USAID) used to be a central actor in the energy sector in Mexico, but since Trump Administration, its work has decreased considerably. Another supporter actor in the system is the local government, creating innovative strategies to work with private and academic sectors to promote and use the renewable sources available in the region. The State of Tamaulipas is a success story. A global wind turbines manufacturer teamed up with the government and a university to create studies, implement generation projects, and train wind energy technicians. At the same time, local companies were beneficiated from the deployment of wind energy projects in the region.

Knowledge Diffusion

As I mentioned before, the collaboration among actors of the SIS for wind and solar technologies in Mexico is not optimal. This gap is also perceived in the diffusion of knowledge but having more options for knowledge flow across the system. Events, like conferences and talks, are identified as one of the principal tools to disseminate knowledge. These events share information on technology, projects, research, and other valuable information. With some exceptions, most of these events are attended by a specific sub-sector, or type of actors, or a mix of both. For example, a solar event focused on research and excluding firms and the government. Several interviewees suggested that conferences should be adapted to use a common language across the sector, from firms, researchers, and government. "Conferences or any other event in where academia and the private sector interact would be beneficial for the sectors they represent". Conferences support the collaboration across the clean energy sector in Mexico.

COVID-19 pandemic changed how to attend these events, opening the audience and making it more plural. Conferences were usually in Mexico City and had an additional cost for those not living in the area. Having several events online is helping to reach more people and share more specialized knowledge. Cooperation across the sector would be vital to move knowledge, as the private sector is skeptical about using knowledge from universities and research centers, and academia is not putting ideas, research projects, and solutions into consideration of the rest of the industry.

Energy clusters, energy hubs, local governments, and NGOs are seen as intermediate institutions assisting in connecting demand and supply in terms of knowledge, from academia towards the industry and government, and vice versa. Because of the position of the current Federal administration towards renewable sources of energy and its participation in the energy mix, intermediate institutions are working together to support their associates and being a common and more robust actor to discuss with the Federal Government possible scenarios for renewable energy generation and innovation. Policies to improve cooperation in the sector are perceived as potential mechanisms to improve knowledge diffusion, moving not only among the system's actors but aiming the entire society.

Guidance of the Search

Mexico lacks a clear vision for developing the wind and solar sector. Aside from some policy instruments such as clean energy goals, and international agreements like the Paris Agreements and Mission Innovation, there is no commitment nor strategy to achieve internal and external goals in terms of clean energy. Several interviewees recognized that the current Federal Administration creates confusion and uncertainty in the energy sector, losing credibility as an actor in the energy transition. For example, CONACYT and SENER have areas that, in previous Federal Administrations, were identified as leading actors in developing clean energy technologies and supporting the energy transition. Instead, these areas have been degraded, losing personnel, attributions, and budget. This degradation is an effect of the current Federal Administration's position towards clean sources of energy and innovation.

Although past Federal Administrations were more involved and supported the energy transition, structural and cultural problems are present in Mexican society, slowing down the development of the clean energy sector. The Mexican system struggles with planning and seeing beyond presidential terms; this includes the energy sector that lacks support, development, and deployment of clean energy technologies and focuses on fossil fuels.

Private companies, primarily big and international corporations, accompanied by international cooperation and NGOs, are setting clean energy goals, not only for their operations but the entire supply chain, forcing Mexican companies to adopt renewable energy technologies and other CO_2 reduction strategies. On the other hand, local governments act as a counterbalance in guiding a more sustainable agenda that includes wind and solar technologies. Some examples of their activities are the creation of Energy agencies aiming to implement renewable energy and energy efficiency projects; enacting local climate change laws; investing in energy innovation and R&D; creating public-private partnerships; and striving to comply with the Paris Agreement and 2030 Agenda for Sustainable Development.

Mexico has vast wind and solar resources (IRENA, 2015) and can adopt and adapt technology. According to a researcher interviewed, Mexico can use 100% renewable energy by 2050. She and her research team have developed scenarios where this is reachable. However, this would require an energy transition model and energy and innovation policies and regulations to provide direction and guidance.

Market Formation

Energy policy and regulation are controlled at the Federal level in Mexico (Jano-Ito & Crawford-Brown, 2016). In addition to this, all commercial activities and sale taxes are also regulated at this level (Dalsgaard, 2000). State governments are out of the regulatory actions, but several States are doing non-regulatory activities to stimulate market formation for wind and solar technologies. These activities include market and non-market incentives, private-public partnerships, and the promotion of the advantages each region or state offers. For example, the State of Queretaro enacted a Law that forces each new industrial facility to have a clean energy or sustainability component; the State of Tamaulipas included the development and deployment of green hydrogen in a State

Law and transition programs; and the State of Guanajuato is building a PV solar plant with green hydrogen production in partnership with a private company (Aguiar-Hernandez & Breetz, 2022a).

The interviewees agreed that the market for wind and solar technologies is big enough to support innovation. With multiple factors in favor, such as extensive renewable energy resources, trained personnel, standards and certifications, specialized companies, non-governmental organizations, business organizations, and a considerable industry sector and a growing population demanding electricity; Mexico has the potential to maintain an innovative and R&D oriented clean energy sector with a robust market. However, so far, the country has been an importer of wind and solar technologies, lacks the capacity for radical innovations, and does not have an innovation strategy in which technology is protected and developed as other countries have done.

Companies are creating a market for renewable energy technologies. Section 5.4 discussed how specific companies have CO_2 reduction goals in their operations and the entire supply chain, doing their businesses in Mexico as clean as possible. Mexico, as part of the global supply chain of several products such as vehicles, machinery including computers, optical and medical apparatus, oil, furnitures, vegetables, gems and precious metals, beverages and spirits (Workman, 2021); is going to increase its wind and solar capacity by the market created by companies or industry groups, that are strengthening their environmental practices. More than a dozen companies are currently assembling solar panels in Mexico, implying that the solar market has been adequate for them to produce in the country. The clean distributed generation will keep having the components for its deployment. As I mentioned in previous sections, distributed generation has a great opportunity of growing under current circumstances, and most of these generation systems use solar PV technologies.

Resource Mobilization

For decades, CONACYT has been the federal government agency in charge of grants and other programs supporting R&D and innovation. Mexico's clean energy innovation sector is highly dependent on grants and programs CONACYT offers to universities and firms. As discussed before, the current policy for clean energy and innovation at the federal level reduced the support for these two activities, declining the availability of financial resources considerably. In addition, CONACYT's intellectual property policies have changed; the agency will keep the intellectual property result of the resources provided instead of being owned by researchers, firms, or universities. The new intellectual property policies would impact the number of solicitations for the already reduced financial resources. Alternately, private financial resources are not flowing because of the levels of uncertainty in the clean energy and innovation sectors. The interviewees perceive those private financial resources as standby, waiting for the conditions to change.

The SIS is perceived as capable of generating the market's human resources. Multiple higher education institutions have developed programs for training and formation of human resources for the energy sector. This includes technical training, bachelor's, master's, and doctoral degrees. Although CONACYT's reductions, some scholarships for graduate studies in foreign universities are still available, these scholarships are not specific for energy, and applicants need to compete with the rest of the disciplines. Some interviewees stated that more solar PV technicians are required, and some companies have struggled with the lack of trained personnel.

Research infrastructure is limited, and some cases underused. A better understanding of the research capacities would make more efficient use of the research infrastructure; the expectation is to reduce the resources to operate this infrastructure if financial resources keep decreasing. Some interviewees also discussed the status of the electricity infrastructure, specifically transmission and distribution infrastructure, that is essential for the deployment of wind and solar technologies. Transmission and distribution are not open to private participation. CFE keeps controlling and operating them; under investments in these areas are perceived, reducing the chances for wind and solar technologies to be adopted by the Mexican market.

Creation of Legitimacy

Overall, wind and solar technologies' legitimacy has been evolving and now is perceived as high. Among the main contributors for legitimacy creation are the adoption of wind and solar technologies by big companies, the social component in the communities where utility-scale projects are built, cost reduction in solar PV systems, information availability, prices of fossil fuels, and local programs supporting solar PV installations and solar thermal solutions.

Utility-scale wind and solar projects have been perceived as predators in specific regions and communities, predominantly indigenous areas. While communities with great wind resources opposed more projects in their areas, new approaches, and regulation changes were conducted, including a social component and information sessions benefiting the communities. As a result, the Mexican Energy Reform included evaluating social impact, a study for all new electricity projects that need to be conducted before issuing permits and authorizations. The Electricity Industry Law (Ley de la Industria Eléctrica, 2014) states that this study should consist of identification, characterization, prediction, and valuation of the social impacts caused by the project's operation, as well as mitigation measures. The most common mitigation projects of the social effects are reflected in pavement projects, water infrastructure, school renovations, street lighting, and urban infrastructure.

To some extent, these measures have contributed to improving the relationships between developers and communities. Otherwise, the uncertainties created by the position of the Federal government towards clean energy projects have been identified, by interviewees, as opposition to the legitimacy of wind and solar technologies. This opposition misinforms society about renewable energy's economic, social, and environmental benefits. Moreover, it reduces the chances of a more symbiotic relationship between private companies and the federal government by placing private energy companies as corrupt and unjust.

Social society organizations, such as energy clusters, have supported the legitimation of wind and solar technologies in Mexico. Usually, these organizations are local and structured by academia, government, NGOs, and companies, sharing information and benefits of renewable and clean energy sources. High legitimacy has also been induced by user experience. At the same time, technology improves its performance and reduces costs, the level of adoption increases. Several interviewees reflected on the role of universities and government agencies in setting a good example for the market, as these organizations adopt wind and solar technologies, more awareness among the public.

Inducement and Blocking Mechanisms

Inducement Mechanisms

The analysis presented in previous sections guided me to find two major inducement mechanisms within the sectoral system for wind and solar technologies. First, NGOs and local government support could function as an impulse to develop wind and solar technologies. The functional analysis shows that NGOs and some local governments complement other actors in the system, providing financial resources and being connectors between demand and supply of knowledge. Local governments are primarily promoters of developing and deployment activities of wind and solar technologies. In some cases, they act as more active agents, partnering with private companies to produce clean energy and comply with international agreements. Secondly, solar PV distributed generation is the main instrument for the energy transition in Mexico. Structural and functional analyses show the conditions for this generation to grow and become a source of innovation in the Mexican context. Some factors make distributed generation an essential piece in the Mexican energy transition, for example, the configuration of the electricity system, the efforts in standards and certifications, the research infrastructure, the levels of solar radiation across the country, and the fact that the current Federal Administration is not opposing to this activity.

Blocking Mechanisms

The analysis shows that the SIS is mainly hindered by the opposition of Lopez Obrador’s Administration to renewable sources of energy and innovation activities. This opposition increases the uncertainty across wind and solar technologies. The interviewees reflected on the impacts of this opposition and its effects on the functionality of the SIS;

they concluded that a negative impact practically in the entire structure and dynamics and slowing down the development and adoption of wind and solar technologies. This negative impact is not only in the clean energy policy but also in the innovation policies, changing the intellectual property rules for CONACYT's grants and reducing the financial resources available.

An older blocking mechanism was shown in the functional analysis, the disconnection between academia and the private sector. Historically, this relationship has been weak in Mexico. Multiple factors contributed to its improvement, being the most important the North American Free Trade Agreement (NAFTA), due to more private sector participation in financing and functioning of the technological systems (Cimoli, 2000). Currently, the gap between universities and the private sector in the SIS for wind and solar technologies has been reduced, as other initiatives positively impacted this relationship, the prominent example of CEMIEs. Despite these improvements, the perception about this weakness in the system is still present, and further intervention would be required to consolidate this relationship. The system's structure shows a cultural setting that hinders the SIS and its expected outcomes. Researchers confront the cultural conflict when they look for patenting or being entrepreneurial with the technology they developed. It is socially unacceptable and considered greedy or taking advantage of the institutions they represent, reducing the willingness of researchers to explore patentable technologies or collaborations with companies for jointly developing new products or processes.

Conclusions

In this chapter I examined the SIS for wind and solar technologies in Mexico. I applied the innovation systems approach to define the SIS structure and assess the crucial processes influencing the performance of the system. The application of this approach allowed me to specify the mechanisms that block and induce the development of wind and solar technologies in Mexico.

This study contributes to the innovation systems literature by analyzing the SIS for wind and solar technologies in the context of an emerging economy. None of the previous articles using the innovation systems approach were conducted for renewable energy technologies specifically in emerging markets. This study provides a better perspective of the mechanisms affecting the development and deployment of wind and solar technologies in Mexico. This allows me to identify some specific challenges by a developing country that recently opened its electricity sector to competition, with some efforts investing in R&D and innovation, and distance from the global technological frontier for wind and solar technologies. In this regard, I conclude that institutional and market reforms are not enough to advance the establishment of clean energy markets and its expected deployment outcomes, stressing the importance of combining policies and regulations to maximize the effectiveness of market formation.

The analysis reflects the importance of several institutional and cultural factors hindering and blocking the development of wind and solar technologies in Mexico. The sensitivity of the energy and innovation sectors to policy and regulation is especially high (Jaffe et al., 2003; Popp, 2005), and despite several other conditions that favor these technologies, the effects of political decisions impact the overall performance of this SIS. Some of the conditions mentioned above are the openness to the competition of generation and supply activities in the electricity sector, constant investment in R&D for energy technologies, and having nationwide clean energy goals. This led me to emphasize the role of institutions in the structural analysis and "guidance of the search," "market formation," and "legitimacy creation" in the functional analysis. In addition to this institutional sensitivity, a cultural issue has been recognized by the interviewees that hinders most of the processes in the SIS analyzed; this is the lack of connection between the research and private sector, affecting essential procedures to move knowledge and inventions from universities and research center to the electricity industry, reducing the possibilities to create technological solutions in the country. Broadly, I conclude that institutional and social innovations can significantly improve the SIS's structure and functionality for wind and solar technologies in Mexico.

This research shows that the main inducement mechanisms avoid the scope of the institutional position and are supporting the development and adoption of wind and solar technologies from a non-institutional perspective. These inducement mechanisms, supportive activities of NGOs and local governments and the role of distributed generation, function as the main drivers of the energy transition under current circumstances and using wind and solar technologies, which are the mostly adopted renewable energy sources in the country. On the other hand, the federal administration led by Lopez Obrador and its position in favor of the use of fossil fuels for electricity production is identified by the experts interviewed as a barrier for the development and deployment of wind and solar technologies at utility-scale, reducing the willingness to advance R&D and innovation activities for these technologies. This is aligned with Hernández Ibarzábal & Bonilla, (2020), who stated that AMLO’s administration needs to prioritize electricity, clean and renewable energy, and technological innovation over extractivism. Although NGOs and local governments are advancing innovation activities in the SIS, their efforts will be hampered without the participation of the federal government. A more symbiotic or mutualistic approach is required to move forward public-private partnerships for clean energy innovations and energy transition, similar to the ideas proposed by Mariana Mazzucato (2014).

An emerging economy like Mexico has the potential to become relevant players in developing technologies for energy transitions, such as wind and solar. As mentioned by some interviewees, developing the capacity to transition from technology adoption to innovation is a long process. It begins with importing technology as a first step and partnering with universities in the country to adapt and develop new inventions that eventually could become innovations. Mexico has many of the actors and institutions needed to develop energy technology, including universities and research centers, private companies, government agencies, NGOS, and resources, policy, and regulation to create a market for renewable energy technologies and, in a less proportion, generate technological advances in the sector. Although this is in place, institutional and functional deficiencies need to be addressed to enhance the SIS functions and overcome the blocking mechanisms mentioned in the previous section. The liberalization of the electricity sector was an important reform that incentivized private companies to invest in R&D activities. Nevertheless, certain institutional and cultural conditions that have been present in the electricity sector for decades continue to impact the performance of the innovation system; for example, the protectionism in the electricity and oil sectors and the country's historical dependence on fossil fuels make it challenging to incorporate private, renewable energy companies into the sector.

Energy transitions are long-term challenges that involve several factors moving at the same time. Technology, policy, regulation, markets, companies, and end-users are involved in the transition to using low-carbon energy sources (Smil, 2016). To address this complexity, a systemic approach is required to generate value from the entire structure of the innovation system. This study shows the case of an emerging economy with robust private, academic, and non-governmental sectors with low government participation, resulting in a limited functioning of the SIS for wind and solar technologies. Emerging economies must consider combinations of policies and regulations, recognizing that market reforms are not enough to develop and deploy clean energy sources and that institutional innovation would provide an advantage in their energy transitions and decarbonization efforts. Due to the amount of energy emerging economies require for their development and their R&D capabilities, these countries represent a crucial component in the global energy transition. Further research is needed to accelerate energy innovation in emerging economies.

Limitations of this chapter

One of the main limitations in Chapter 3 is related to the generalizability of the results. Although saturation was reached, and the participation of the sectors (government, companies, non-governmental organizations, and universities and research centers) was balanced, the study is limited in its methodology by leaving behind specific characteristics at the local level. This research focuses on the sectoral level using features of the national innovation system.

CHAPTER 4

ADOPTING GREEN HYDROGEN IN MEXICO: A TECHNOLOGICAL INNOVATION SYSTEM STUDY

Abstract

Green hydrogen is considered a central technological pillar for the decarbonization of the energy sector. It increases flexibility in electricity systems and offers alternatives to challenging sectors to decarbonize, like transportation, chemicals, iron and steel, and cement. However, green hydrogen faces multiple challenges, such as high production costs and a lack of hydrogen infrastructure and regulation. To understand how innovation could be accelerated, this chapter empirically examines the green hydrogen TIS in Mexico. Latin America is projected to be a significant contributor to lowering the production cost of green hydrogen, being the Mexican case an important contribution to developing green hydrogen technologies in the region. Semi-structured interviews were conducted with hydrogen experts in Mexico, aiming to know their views on the functioning of the green hydrogen TIS and their perspectives on improving it. This research identifies 22 initiatives to enhance Mexico's TIS for green hydrogen. The most relevant initiatives include information campaigns for the entire society, development of regulation instruments (e.g., taxes, subsidies, standards, strategies, industrial policies, infrastructure), pilot or demonstration projects, improving academia's capacity through international cooperation, specialized professional training, and supporting renewable energy projects. The study recommends creating both technology and markets at country and regional levels and participation in the global supply chain.

Introduction

Hydrogen gas (H_2) is an energy carrier that can be used throughout the energy sector. It is primarily used for crude oil refining and ammonia and methanol synthesis, and in the future it could be used as a fuel for transportation, heating, and power generation. Currently, 95% of hydrogen production comes from natural gas and coal, and electrolysis generates the other 5% as a by-product of chlorine production (IRENA, 2019). A more sustainable option is "green hydrogen," produced via water electrolysis powered by renewable electricity. Green hydrogen has been described as one of the four technological pillars for energy sector decarbonization, along with carbon capture and storage (CCS), renewable-based electrification, and bioenergy (IEA, 2020a). However, it faces multiple challenges such as high production costs and a lack of hydrogen infrastructure and regulation for promoting a green hydrogen industry (IRENA, 2020).

Reducing the production costs of green hydrogen will be critical for enabling its widespread use for decarbonization. According to the Hydrogen Council (2021), green hydrogen costs could fall up to 60% in the next decade by improvements in equipment capital costs, efficiency, energy costs, and other advances in the value chain. Different regions will have different potential for cost reductions, due to renewable resource potential, infrastructure and transport costs, labor costs, and other factors. Latin America is one of the promising regions for low-cost green hydrogen production. By 2050, Latin America is projected to be a significant contributor to lowering the production costs of green hydrogen, as the region would have an average of 2 - 2.5 USD/kg. Mexico and other countries in the region could reach hydrogen costs as low as 1.2 USD/kg

(HINICIO, 2021a). In contrast, countries like Russia, Korea, or Japan have projected production costs above 4 USD/kg.

Achieving these costs reduction is possible, but it will require concerted efforts and investment. To understand how innovation could be accelerated, this chapter empirically examines the green hydrogen technology innovation system (TIS) in Mexico. The TIS approach is a subset of innovation systems research (Bergek et al., 2008; Heckert et al., 2007), focusing on the development, application, and diffusion of specific technologies (Hekkert, Suurs, Negro, & Kuhlmann, 2007). Analyzing the functional patterns of the green hydrogen TIS enables me to understand its current state and identify policies that could accelerate technological development (Hekkert & Negro, 2009). This analysis contributes to two bodies of literature: first, it contributes empirical, policy-relevant knowledge on the development of green hydrogen technologies by identifying and proposing initiatives to improve innovation; second, it contributes to the innovation systems literature by applying the seven functions of IS in the context of an emerging economy, as most innovation systems studies are conducted in the context of developed countries.

Data for understanding the structure and function of the TIS is drawn from scientific literature, reports, and 12 expert interviews. Interviews focused on understanding the current state of each of the innovation systems functions and identifying initiatives to improve their functionality. Based on this analysis, I identified 22 initiatives to enhance the TIS. These initiatives were classified by the purpose of the policy instrument (demand-pull versus technology-push) and the organizations leading or executing the initiatives (government and non-government organizations). Some of the initiatives target multiple functions of TIS, suggesting broader impacts in strengthening TIS performance.

The initiatives cited across different innovation systems functions are the following: information campaigns for the entire society, development of regulation instruments (e.g., taxes, subsidies, standards, strategies, industrial policies, infrastructure) and pilot or demonstration projects, improving academia's capacity through international cooperation, specialized professional training, and supporting renewable energy projects. In regards to the last of these initiatives, it is important to acknowledge that renewable energy projects have recently become more challenging in Mexico, due to restrictions under President Andres Manuel Lopez Obrador (popularly known by his initials, AMLO), so in the current political context green hydrogen may need to be produced off the grid. Overall, most of these initiatives are clustered in two functions, "guidance of the search" and "resource mobilization," denoting the priority level for some activities under the current context of the green hydrogen TIS, as this sector is under construction and its technologies in early stages. "Market formation" is the innovation systems function with fewer initiatives, indicating that most of the activities in the green hydrogen TIS in Mexico remain in R&D and pre-commercial activities.

In short, this chapter evaluates the green hydrogen TIS in Mexico, aiming to identify initiatives to strengthen its functioning. This research complements the existing literature by assessing the TIS of early-stage technologies with great potential for decarbonization in an emerging economy that is expected to have a significant role in developing and deploying these technologies.

Literature Review

To provide context for this study, I review two branches of relevant literature. First, I provide background on green hydrogen, focusing on its development in emerging market economies. Second, I discuss the conceptual framework of technological innovation systems that I apply in this study.

Background on Green Hydrogen

Pathways for Hydrogen Production. Hydrogen is the smallest and most abundant element in the universe. However, because it is so reactive, it is rarely found in a pure state on the Earth. Hydrogen gas (H_2) must therefore be obtained by separating it from compounds such as hydrocarbons or water. It can be produced through multiple conversion pathways, using a variety of different material and energy sources, with varying cost and sustainability implications (Table 5). Grey hydrogen is produced with fossil fuels and involves CO_2 emissions. Blue hydrogen is also made with fossil fuels but includes carbon capture and storage (CCS), reducing carbon emissions. Turquoise hydrogen is still in the pilot stage; it uses natural gas through pyrolysis, producing solid carbon black, which is easier to store than gaseous CO_2. Finally, green hydrogen is generated using water electrolysis fueled by renewable electricity (IRENA, 2020).

H_2 is an energy carrier with a high energy density per unit of mass. It can be combusted to provide heat for a variety of industrial purposes, or it can provide electricity using fuel cells. This enables hydrogen to serve applications in multiple energy sectors, including industry, electricity, and transportation. It will not necessarily reduce greenhouse gas emissions if the primary energy source for hydrogen is coal or natural gas. Nevertheless, low-carbon sources of hydrogen can play a crucial role in the global energy transition. It offers alternatives to challenging sectors to decarbonize, like transportation, chemicals, iron and steel, and cement. In addition, green hydrogen increases flexibility in electricity systems; can be produced by different energy sources, including variable renewable energy; and provides solutions to store energy from renewable sources (IRENA, 2019).

Table 5

Hydrogen Colors and Processes

Hydrogen color	**Grey**	**Blue**	**Turquoise**	**Green**
Process	Reforming or gasification	Reforming or gasification with carbon capture	Pyrolysis	Electrolysis
Energy source	Fossil fuels	Fossil fuels	Renewable or carbon-neutral energy	Renewable energy
Raw material	Methane or coal and water	Methane or coal and water	Methane or biomethane	Water
Estimated emissions from the production process (CO_{2-eq}/kg)	Reforming: 9-11 Gasification: 18-20	0.18-6.1	0	0
Production volumes (2020)	100 - 600 tons H_2/day	100 - 600 tons H_2/day	Laboratory scale	0.1 - 2 tons H_2/day
Average production cost (2018)	1.2 – 2.2 USD/kg	1.5 – 2.9 USD/kg	NA	3.0 – 7.5 USD/kg

Note: Adapted from HINICIO (2021a); IEA (2019); IRENA (2020, 2022)

However, several challenges need to be overcome to have more widespread use of green hydrogen in the energy sector. According to the International Renewable Energy Agency (2020), green hydrogen faces several challenges that include high costs of production, low participation in the industry with high potentials such as transport, buildings, and power generation, lack of hydrogen infrastructure, including upgraded pipelines and efficient shipping solutions, and regulation that promote a green hydrogen industry. Its combustion is not widely adopted because it is not available in abundance and is more expensive than fossil fuels (HINICIO, 2021a).

Green Hydrogen in Latin America. Current production and usage of hydrogen in Latin America is limited to a small number of countries, as a feedstock for refineries and chemical industry. To transition its use as an energy carrier, many countries are moving forward with strategies and pilot projects, aiming to understand demand and production patterns, and collaborations in terms of infrastructure and development (IEA, 2020c). A key element in determining further cost reductions for green hydrogen is renewable energy costs, specifically wind and solar (IRENA, 2019), representing the main advantage of Latin America for low-cost green hydrogen production, as this region has abundant solar and wind resources with low prices in comparison other regions such as Asia, North America and Europe. Some Latin American countries such as Chile, Argentina, Brazil, Colombia, and Mexico are great candidates for competitive production of green hydrogen, representing an opportunity for the region to export H_2 at competitive costs (IEA, 2020c).

Several Mexican geography and policy features are advantageous for both the production and consumption of green hydrogen. Mexico is part of the countries with low-cost and abundant wind and solar resources that plan to be a main exporter of green hydrogen to adopters like Japan, South Korea, and the European Union. At the same time, Mexico has certain conditions that make it an attractive market for green hydrogen technologies. The following are characteristics shared by countries with excellent market conditions for these technologies:

- Decarbonization efforts
- Energy independence
- Supply diversification
- Grid flexibility while introducing renewables
- Development of a green economy
- Development of new value chains in the energy sector

In addition, Mexico has a well-developed infrastructure that could support green hydrogen developments, including international seaports, robust power and gas transmission networks, and solar and wind power plants (HINICIO, 2021a). Furthermore, the Electricity Industry Law (Ley de la Industria Eléctrica, 2014) classifies hydrogen as a clean energy source, enabling electricity produced by hydrogen combustion or fuel cells to generate Clean Energy Certificates, which can be traded in the Wholesale Electricity Market. The adoption of green hydrogen in the electricity sector will positively impact the National Climate Change Strategy and the General Law of Climate Change (Rodríguez-Martínez et al., 2018). The combination of a liberalized electricity market, clean energy goals, a market for clean energy certificates (Jano-Ito & Crawford-Brown, 2016), low electricity prices from renewable energy plants (wind and solar), an industry sector willing to participate in the green hydrogen industry, and an at least one international company planning to invest in green hydrogen infrastructure in the country (I. Hurtado, personal communication, Nov 25, 2020) create an opportunity for the development and adoption of green hydrogen technologies in Mexico.

However, challenges to green hydrogen in Mexico include the current energy policy of the country and its opposing ecosystem to renewable energy investments, the lack of regulation towards emission reduction and meeting climate commitments (HINICIO, 2021a), the absence of roadmaps and other guidance instruments for the development of hydrogen in Mexico, barriers for access to energy infrastructure (HINICIO, 2021b), and the non-existence regulation for storage and final applications for H_2 technologies (Ávalos Rodríguez et al., 2019).

Technological Innovation System

Technology innovation, including for early-stage technologies like green hydrogen, requires the interaction between organizations, material artifacts, and institutions (Hekkert, Suurs, Negro, & Kuhlmann, 2007). The innovation process is highly influenced by a network of actors developing and advocating the technology and institutional infrastructure that legitimizes, regulates, and standardizes the new technology, resulting in the generation, diffusion, and utilization of technology (Carlsson & Stankiewicz, 1991). Innovation scholars describe this network of actors, institutions, and infrastructures as an innovation system. A well-functioning innovation system accelerates technological development, while a poorly performing system hinders innovation (Hekkert & Negro, 2009).

The functions of innovation systems are key processes supporting the development, application, and diffusion of new technological knowledge (Hekkert, Suurs, Negro, & Kuhlmann, 2007). These functions are an excellent approach to analyzing technological change and drawing decisive processes that foster technology development. Empirical studies have used the functions of innovation systems to deliver explanations for the success or failure of technological trajectories of sustainable energy technologies in different countries (Jacobsson, 2004; Negro et al., 2008; Suurs &

Hekkert, 2009). Table 4 shows a list and description of the functions of innovation systems.

Innovation systems can be analyzed at multiple levels of analysis: technological innovation systems (TIS). sectoral innovation systems (SIS), national innovation systems (NIS), and regional innovation systems (RIS) (Jacobsson & Bergek, 2011). In this chapter, the focus is the TIS for green hydrogen within Mexico. However, it is important to recognize that these systems are nested, such that the TIS for green hydrogen exists within the larger SIS for clean energy technologies, as well as the NIS in Mexico more broadly (Aguiar-Hernandez & Breetz, 2022b). For this reason, the initiatives recommended to strengthen the TIS are not necessarily specific to green hydrogen. The innovation system approach has been applied in Mexico at the national level (Cimoli, 2000; Dutrénit Bielous, 2010; Solleiro & Castañón, 2005), regional level (Garcia & Chavez, 2014), the agriculture sector (Hellin, 2012), and the sustainability-oriented innovation system (Kılkış, 2017). To the best of my knowledge, only Aguiar-Hernandez & Breetz (2022b) have applied this approach to the energy sector.

Research Methods

This study applies the functions of innovation systems to understand the functionality and dynamics of the green hydrogen TIS in Mexico. Additionally, I identify possible solutions to strengthen this IS and improve its operation. The solutions proposed are connected to each of the functions of innovation systems and could be transformed into policy, regulation, and systemic instruments.

The object of study is the green hydrogen TIS in Mexico and initiatives to strengthen its functioning. The technological innovation system approach is utilized as an analytical framework to investigate the status of the green hydrogen TIS, providing data on the fulfillment of each of the innovation systems functions. The chapter also explores possible solutions that could play a role in strengthening one or more IS functions, uncovering mechanisms for different purposes, and leading organizations.

Data collection was conducted using scientific literature, reports, and 12 expert semi-structured interviews (see Appendix B). The interviews were conducted in Spanish and recoded by Zoom, using only audio. The recordings were transcribed, and the coding and analysis was conducted in Spanish. After analysis, the results were translated into English. I consider 12 expert interviews to be sufficient to reach saturation with the collected information. The interviews were carried out between October and December 2021 and lasted between 1 and 1.5 hours. Experts were asked to express their views on the functioning of the green hydrogen TIS and their perspectives on improving it. The questionaries were structured by applying the functions of innovation systems described in Table 4. Experts were divided into four categories: government, companies, non-governmental organizations, and universities and research centers. Three experts per category were interviewed, and all responses regarding the functionality of the green hydrogen TIS analyzed were analyzed critically to guarantee that nothing was neglected or looked after.

For data analysis, I utilized Bergek et al. (2008) framework to assess the data concerning the seven functions of innovation systems presented above. Then, I analyze how the TIS for green hydrogen operates using the data described before, aiming to identify how well each system function is fulfilled and possible solutions for their improvement; these solutions are presented as policy and technology management recommendations that I have defined as initiatives. After this deductive process, I used two categories to classify the initiatives: policy instrument purposes and organizations leading or executing the initiatives. The former categorizes them by demand-pull and technology-push policies, the latter by government and non-government organizations.

Results

This section analyzes the functions indicated in Table 4, evaluating the TIS for green hydrogen in Mexico. The results are shown by each function of innovation systems.

Entrepreneurial Activities

> "In Mexico, there is no way for the State to assume the risks and take advantage of the benefits of having assumed those same risks, because there is a total aversion towards new technologies that are not proven."
>
> (W. Jensen, personal communication, Dec 1, 2021)

Hydrogen has been studied, produced, and used in Mexico for decades, but grey hydrogen has dominated in the past. However, the interest in green hydrogen is growing, mainly in the private and academic sectors. These two sectors are leading the development and adoption of green hydrogen technologies, but most interviewees found that the quality and type of their entrepreneurship are not enough to advance green hydrogen in Mexico. Various companies can be identified as actors or potential actors in the green hydrogen sector, but only a few are working on it. Most of these potential actors understand the industry and the technology, but they are not entirely developing technologies or projects, reflecting knowledge creation and diffusion but limited entrepreneurial activities. The level of activity in the green hydrogen sector in Mexico is low, even in companies utilizing hydrogen for their processes, like cement and steel companies, which are using hydrogen produced from fossil fuels but without capturing CO_2. The technology is not mature enough and has high costs. Still, according to Cryo-Infra (D. Femfert, personal communication, Nov 24, 2021), a private company part of the primary chemical manufacturing industry, and one of the three companies with the entire current hydrogen market in Mexico (HINICIO, 2021a), these costs will decline as adoption increases, as happened with cell phones and televisions.

There are two NGOs that cluster most of the actors in the green hydrogen TIS and are communicating the benefits this technology could bring to Mexico's decarbonization efforts and its sustainable development: the Mexican Society for Hydrogen (SMH for its acronym in Spanish) and the Mexican Hydrogen Association (AMH for its acronym in Spanish). The former was created in 1999 and has between 120 and 140 members, 85% are academic members; the latter was created in 2021 to promote the hydrogen industry in Mexico, grouping primarily private companies and other organizations. These two organizations, their members, and other NGOs have been crucial to understanding better the green hydrogen sector and its potential impact on Mexico's energy and productive sectors. Local governments are also playing an essential role in developing the green hydrogen sector. They are filling the gap the federal government is leaving in terms of new energy technologies, by establishing regional and international markets, supporting pilot projects, and developing additional strategies for mobility and industry powered by green hydrogen.

The low involvement of the federal government is reflected in the absence of a national strategy, roadmaps, standards, specific policy, or regulation. Because of this, Mexico is perceived as behind similar countries, such as Chile and Colombia. Multiple interviewees discussed how Chile created an entrepreneurial agency that encourages research in green hydrogen technologies among Chilean organizations and in collaboration with Germany and other countries. The role of the government is crucial in these technology stages, creating regulations and mechanisms to promote green hydrogen projects, as well as public investments in R&D and entrepreneurship (IRENA, 2020).

To strengthen the function of entrepreneurial activity, many interviewees suggested a need for greater federal support, including public funding of pilot and demonstration projects to advance knowledge and public procurement to promote private-sector investment and deployment. An interviewee from the private sector mentioned that the Mexican government, through the Federal Electricity Commission (CFE for its acronym in Spanish) , avoids adopting new energy technologies, and CFE usually invests in technology when it becomes mature. The most recent version of the Program for the Development of the National Electric System (PRODESEN for its acronym in Spanish) mentioned that CFE aims to blend blue hydrogen with natural gas in some combined cycle power plants, as part of its strategic development plan for the next 14 years. The introduction of hydrogen in PRODESEN suggests an adoption strategy from the Mexican government, but not fast enough to stimulate the innovation activities in the green hydrogen sector, as the change from blue to green hydrogen would still be required. Lastly, a few interviewees mentioned a cultural resistance to collaboration between academic and private sectors, suggesting more robust entrepreneurial and technology transfer programs in universities and research centers, as well as international collaboration could help encourage green hydrogen startups by researchers.

Knowledge Development

> “At the moment, in Mexico, the research organizations are the ones doing this work [knowledge development], but on the other hand, I do believe that much more technology transfer will eventually come from these [international] companies in the future.”
> (I. Hurtado, personal communication, Dec 16, 2021)

Academia is perceived as the leading actor in creating knowledge for the green hydrogen TIS. For more than 20 years, several universities and research centers in Mexico have researched hydrogen. More recently, industry and governmental actors are approaching academia to know more about different processes and technologies for green hydrogen production, storage, transportation, and usage. The academic sector is recognized for its basic knowledge and small projects; the private sector is characterized by its market and large project knowledge. Some limitations of the academic sector are the way researchers are evaluated, making the research chapter production more important than patents and technology transfer, and the barriers for researchers to work with startups or create them.

The private sector also has a long history of working with hydrogen, and now companies producing and commercializing hydrogen are starting to evaluate the transition to green hydrogen. This transition will require knowledge creation from both the academic and private sector, as well as other supporting actors such as Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, which created reports about the potential of green hydrogen in Mexico, including the integration to the Mexican grid, opportunities for Mexican Petroleum (PEMEX for its acronym in Spanish), CFE and the private sector, application in the transport sector, and export potential (HINICIO, 2021a).

Local and federal governments have different approaches to the green hydrogen sector. Some local governments actively promote this technology; the most notable cases are Puebla, Tamaulipas, Guanajuato, and Nuevo Leon. For example, the State of Tamaulipas is approaching some wind projects that have been affected by the federal government's position for private and clean electricity generation to propose producing green hydrogen, using it for mobility and industrial usage. In coordination with GIZ, this same State produced a report on the potential for production and usage of green hydrogen in Tamaulipas. On the other hand, the federal government is having conversations with experts and collecting information but not taking the actions required from this level of government. The passiveness of the Federal Government is perceived as a barrier to the development of green hydrogen.

The following are some recommendations made by several interviewees intending to improve the knowledge development function: more investments in public R&D and changes in the collaboration between the academic and the private sector. Although local governments support the green hydrogen sector, most of the R&D funding comes from the federal government and the energy regulation associated with this technology. R&D funding should also respond to the long-term characteristics of innovation, and more interdisciplinary and open collaboration among universities and companies is required. Innovation policies that stimulate the mobility of researchers and knowledge among academia and companies will be crucial for knowledge creation and transformation into usable technology.

Knowledge Diffusion

“[Green hydrogen knowledge diffusion] is bilateral, there is no established system or program [...] knowledge is given to whoever asks and it is bilateral, the search for knowledge in hydrogen is quite manual.”

(J. Gutierrez, personal communication, Nov 17, 2021)

Different mechanisms have been identified for knowledge diffusion in the green hydrogen TIS, such as forums and conferences, research articles, reports, and direct training. Forums and conferences are perceived as the primary mechanisms and are organized by different actors or sectors, depending on the topics and specialization level. An interviewee mentioned that participants only share certain parts of the knowledge they have in conferences, reserving part of the information for future developments. Research articles and reports are less direct than conferences without the reserving problem. Agencies of the federal government have requested direct training for other actors. Interviewees refer to CFE, the Energy Regulatory Commission (CRE for its acronym in Spanish), and the Secretary of Economic requesting training to better understand green hydrogen's opportunities and potential in the Mexican context.

Knowledge exchange across sectors and technologies is crucial for the green hydrogen TIS, as it is about technology integration and different sectors working together. For example, the national mobility strategy does not consider hydrogen, and changing this strategy will require coordination from several agencies and support from academia. Although interviewees mentioned that knowledge diffusion for green hydrogen is isolated in Mexico and that more international coordination is important, being proactive with international cooperation will be crucial to improve capacities and produce more specialized human resources.

As green hydrogen is an early-stage technology that needs a robust knowledge diffusion, most of the interviewees recommended that society, government, private and academic sectors should be involved in sharing knowledge across the entire society and cooperation with other countries and regions. Policymakers should have enough information for planning and designing policies and regulations for the green hydrogen sector. Universities could play a vital role diffusion of knowledge across the entire system, training specialized human resources for the whole IS, and establishing proactive international cooperation.

Guidance of the Search

"There is no national hydrogen strategy, there is no roadmap, there are no regulations on the matter and there are no standards, we have to work on all these."

(I. Hurtado, personal communication, Dec 16, 2021)

"The decrease in costs is subject to people consuming it, so they produce more and as more is produced, it leaves more money for innovation and development, there is more progress, and this acts as a chain reaction that lowers the price of technology. If that does not happen in Mexico, it does not mean that we will not use hydrogen, it will arrive when natural competitiveness arrives, then, if we do not work on hydrogen, it will arrive one day, but it will arrive too late."

(D. Femfert, personal communication, Nov 24, 2021)

The expectation is that the demand for cleaner solutions will define the technological route for green hydrogen in Mexico. The federal government's role has not been evident in determining if public policies will drive this technology. Although, as mentioned before, the most recent version of PRODESEN includes blue hydrogen, this will happen between 2029 and 2035 and only for 1.31% of additions of electricity generation, representing a low goal for the green hydrogen sector and almost no incentive for the current efforts. PRODESEN is the only public procurement goal set by the

Federal Government in terms of hydrogen, reflecting the low guidance the Federal Government is providing. Local governments aim to support the development and deployment of green hydrogen technologies, establish regional and international markets, and recognize that energy policy and regulation are managed at the federal level.

International companies in Mexico could move into the green hydrogen sector, creating a market and providing guidance. In the beginning, some green hydrogen projects could be developed without policies and regulations because no regulation does not mean that it is prohibited, and different industrial sectors have been using grey hydrogen for decades. However, for the creation of an industrial sector, regulation is going to be required, as technology and regulation need to be developed at the same time, and different regulation is needed for each of the uses and stages of this energy carrier: production, transportation, vehicles, industrial, electricity production. Interviewees refer to industrial policies, information campaigns, improvement of the rule of law and infrastructure, a national strategy, standards, technology roadmaps, and other policies as feed-in-tariffs and carbon taxes as the primary instruments to guide the green hydrogen TIS.

Aiming to strengthen the function guidance for the search, interviewees suggested cost reduction as one of the main drivers of green hydrogen adoption. Therefore, different efforts in the TIS for green hydrogen need to address cost reduction, including R&D and deployment activities. In addition, it is expected that the federal government will increase the funding for green hydrogen research, support the investigation of new components and materials, and the generation of specialized human resources.

Market Formation

“We are making board plays, playing without the ball, but this is how all industries start.”
(I. Hurtado, personal communication, Dec 16, 2021)

“The green hydrogen market in Mexico does not exist yet.”
(R. Gonzalez, personal communication, Nov 18, 2021)

The potential market for green hydrogen in Mexico is enormous. Different industrial sectors, transportation sector, power generation, electrolyzer manufacturing, refineries, hydrogen production, and transportation are some of the productive sectors mentioned by interviewees. Transportation is perceived as the sector that would be a first adopter, and this adoption will happen at the same rate as cost reduction. According to GIZ reports, Mexico would be a prominent player in the green hydrogen market worldwide.

The private sector is developing a green hydrogen market by requesting low-carbon solutions for its processes. This market is under construction, and the demand for green hydrogen is increasing as more companies set emission goals, more decarbonization efforts, and more environmental challenges, such as the Conference of the Parties (COPs), climate change, and other international forces. As this market grows, the financial sector is positively reacting and expecting to finance green hydrogen projects. Export is highly mentioned by interviewees, specifically exporting green hydrogen to Europe, Japan, and South Korea. In addition, Germany developed a green hydrogen strategy considering Latin America as a critical partner, and Mexico should consider this as an opportunity.

Lack of regulation and support for green hydrogen projects are the main threats to the market formation, increasing uncertainty. In addition to this, green hydrogen production requires renewable energy, and the federal government is not supporting these kinds of energy sources, weakening the development and deployment of renewable energy sources such as solar and wind. An interviewee mentioned that the Federal Government is not afraid to cancel renewable energy contracts or permits and pay the penalties of withdrawing them. If this scenario continues, the green hydrogen sector and its investors would prefer other Latin American countries like Chile, Colombia, Costa Rica, and Peru instead of Mexico.

Some interviewees mentioned the federal government's position toward renewable energy projects as an opportunity for green hydrogen developments. Renewable energy projects focused on green hydrogen production do not require a grid interconnection. The energy required can be directly delivered to the electrolyzers; the Federal government's permits and contracts would not be needed, avoiding the obstacles mentioned above. This uncertainty could create a possible positive externality.

Resource Mobilization

"Many funds or will be available, many international funds, especially from international development banks, to finance both pilot projects and projects on a commercial scale". "[By its manufacturing capacity,] Mexico is very well positioned to enter the hydrogen economy even without producing it."

(W. Jensen, personal communication, Dec 1, 2021)

"In Mexico, more people are learning about green hydrogen than positions [available] in the green hydrogen industry."

(J. Gutierrez, personal communication, Nov 17, 2021)

Currently, financial resources are scarce, and the expectation is that more funds will be mobilized, primarily from development banks such as the Inter-American Development Bank and the World Bank. These international financial institutions have approached multinational corporations to offer to fund green hydrogen projects. On the contrary, Mexican banks are not ready to invest in this new technology. Moreover, the Mexican government's lack of regulation and support will harm the competition for these international funds. Countries with green hydrogen policy and regulations, national strategies, roadmaps, and other instruments would be better positioned to get international funding.

Interviewees agreed that Mexico has well-trained personnel for the green hydrogen sector. Universities and research centers have trained human resources in the hydrogen knowledge; the problem is that most of these personnel are in the academic sector or other sectors, as the hydrogen industry is not offering enough positions. Many trained people ended up teaching in high schools or other sectors, and these well-trained personnel would be an excellent opportunity for the green hydrogen TIS. Although these well-trained personnel, the perception is that more training is required in the public sector, regulators, energy agencies, and other actors of the TIS, as well as personnel in universities not directly working with hydrogen projects. This broader training program will reduce the misinformation and create a more knowledgeable society that could improve resource mobilization.

Infrastructure resources were mentioned by interviewees in two different aspects: research and productive infrastructure. Research infrastructure is perceived as enough, but it needs to be prioritized or administered better, and it would need significant investments as the green hydrogen sector grows. This infrastructure and the human resources mentioned above are enough to produce more than 130 scientific articles per year on hydrogen-related topics. Demonstration projects and a national lab for certifying and validating equipment are required to advance green hydrogen research in Mexico, moving from small prototypes to medium and large-scale projects. Productive infrastructure is also seen as adequate. Natural gas pipelines, refineries, ports with liquefaction, natural gas regasification, and manufacturing capacity.

To strengthen this function, several interviewees recommended improving the capacity to receive funding, which will be critical for the functioning and dynamics of the green hydrogen TIS in Mexico. For international funds, Mexico needs to develop the instruments mentioned in section 4.4., aiming to improve its competitiveness and management of different initiatives and projects created. Furthermore, additional training programs beyond the academic sector will be crucial to expand the public knowledge, jointly with demonstrative projects to generate a better environment for resource mobility into the system.

Legitimacy Creation

"There is a favorable opinion, without getting into the technology and costs, simply the fact that it contributes to combating climate change is already a favorable topic."

(I. Hurtado, personal communication, Dec 16, 2021)

"The opposition at the moment is the financial profitability of using hydrogen."

(A. Leon, personal communication, Dec 13, 2021)

Overall, Mexican society is misinformed about the benefits, risks, production, and usage of green hydrogen. This technology requires a certain level of technical and economic knowledge that is not widely available, although the efforts of some NGOs, companies, and local governments to communicate green hydrogen information. As green hydrogen is becoming a more common topic and an option for cleaner processes in several industries, society will perceive it as an opportunity for sustainable development.

Effective communication about the benefits and functionality of green hydrogen technologies will be crucial for creating legitimacy.

Interviewees mentioned a few organizations creating legitimacy for this technology: Secretary of Environment and Natural Resources (SEMARNAT for its acronym in Spanish), National Institute of Ecology and Climate Change (INECC for its acronym in Spanish), Instituto Mario Molina, GIZ, AMH, SMH, National Institute of Electricity Clean Energies (INEEL for its acronym in Spanish), universities doing hydrogen research, some local governments, private companies, and NGOs. SENER and CONACYT could support the creation of legitimacy by funding green hydrogen studies and projects. So far, the participation of these two federal government agencies has been minimal. Even though hydrogen is included in the PRODESEN, the top management of CFE will not adopt it in the short term, as CFE is not even considering solar PV viable.

An obstacle to creating legitimacy for green hydrogen technologies in Mexico is the dependency on fossil fuels and the perception that the country has many other priorities as an emerging economy, such as health, infrastructure, poverty, education, etc.). The fossil fuel sector in Mexico opposes green hydrogen; this is not a transparent and clear opposition but behind closed doors. This is early-stage technology, and it is hard to identify direct opposition or question something so nascent. Disinformation campaigns could be expected to block green hydrogen, similar to disinformation campaigns against wind and solar technologies. Ideology plays a vital role in the legitimacy of green hydrogen, as fossil fuels are critical in Mexico's energy, social, economic, and cultural aspects.

Interviewees proposed demonstration projects, specific research projects, and information campaigns for strengthening this function. Demonstration projects are perceived as initiatives to improve the communication efforts to legitimacy creation, presenting the operational aspects of the technology, and communicating with information produced by the project. In addition to demonstration projects, research offering the emission reduction based on green hydrogen technologies would increase its validity. As seen above, multiple organizations from different sectors contribute to the legitimacy creation of this technology; balancing interventions across the entire green hydrogen sector, specifically from the government, will produce a more knowledgeable society towards this technology. Lastly, including a circular economy in the green hydrogen discussion will change society's perspective, as humans can create a substitute for fossil fuels that do not require millions of years to be produced.

Discussion

This chapter analyzes the green hydrogen TIS and identifies initiatives to strengthen its operation. Twenty-two initiatives were identified by interviewees in order to support the functionality of Mexico's green hydrogen TIS. The numbers associated with each initiative indicate which of the seven functions would be supported. Some initiatives apply to different functions, showing interdependencies across the seven functions.

I categorized these initiatives in two ways: type of policy instrument (demand-pull versus technology-push) and type of actor leading or executing these initiatives (government versus non-government). Demand-pull and technology-push are categories conventionally used to classify relevant instruments or measures for socio-technological change (Rennings, 2000). Policies tackling environmental externalities are often called demand-pull policies, and policies addressing knowledge market failures are frequently called technology-push policies (Popp, 2019). Non-incremental innovation is more responsive to technology-push policies; incremental innovation is more likely to respond to demand-pull policies (Dosi, 1988) but demand-pull and technology-push policies have been widely used (Nemet, 2009) and are complements rather than substitutes (Gallagher et al., 2012). Table 6 presents the initiatives mentioned above and the categories into which they were divided.

Demand-pull Policies

Demand-pull policies typically include intellectual property protection, tax credits, rebates for consumers of new technologies, government procurement, technology mandates, regulatory standards, and taxes on competing technologies. This kind of policy aims to foster innovation by supporting the use of technologies on the demand side (Guerzoni & Raiteri, 2015; Nemet, 2009).

The green hydrogen sector in Mexico is in its early stages. Information is diffused in a limited and market regulation has not been developed. These two factors were identified across multiple functions, reflecting their importance for demand-pull policies. Information campaign for the entire society is a crucial element mentioned by interviewees and the most repeated across functions. I can identify it in both kinds of organizations, government and non-government. The former is in the form of information for policymakers for policy and regulation design, the latter as information campaigns for the entire society. Although information campaigns could be in charge of the government, interviewees identified companies, universities, and NGOs as leaders in this domain. Information flows across the system but by request and is not openly available as in other markets such as Chile and Europe.

Table 6

Matrix of Initiatives for Strengthening the Green Hydrogen IS in Mexico

	Demand-pull policies	**Technology-push policies**
Government	Feed-in-tariffs, carbon taxes, standards, and a national strategy (4, 6) Industrial policies, improve rule of law and infrastructure (4, 6) Local government supporting regional and international markets (4) Public procurement and other new technology adoption strategies (1) Information for policymakers for designing policy & regulation (3) Balance government intervention (bringing together all the actors) (7)	Pilot projects to demonstrate the technology and promote investments (1, 6) Support cost reduction research (4) Create technology roadmaps for green hydrogen (4) R&D policies and knowledge exchange with foreign universities (3) Long term R&D policies for green hydrogen innovation (2) Increase R&D funding (2) Create startups led by researchers (2) Policies to move the research from basic to the development (innovation policies) (2)
Non-Government	Support renewable energy projects affected by the positions of the Federal Govt (5, 6) Setting agenda and strategies to improve competitiveness for international funds (6) Information campaigns for the entire society (1, 3, 4,7) Private market creation (1, 5)	Studies to provide evidence of the impact of green hydrogen on emission reduction (7) Use international cooperation to improve academia's capacities (2, 3) Train specialized human resources (energy agencies, universities, and other actors) (3, 6) Proactive international cooperation (3)

On the other hand, policy, regulation and infrastructure that focus on green hydrogen activities was highly mentioned. This includes taxes, subsidies, standards, strategies, industrial policies, and infrastructure; these factors remain a government responsibility, even though the contributions of non-government organizations in this area. The main concern about developing these instruments is that other Latin American countries are advancing faster than Mexico, mostly Chile and Colombia, making them more attractive to receive funding, technology, and pilot project from global leaders in terms of green hydrogen. This readiness is required to position Mexico as a destination for green hydrogen investments. Most of the interviewees refer to the passivity and lack of leadership of the Federal Government as the main obstacle to creating an attractive destination for green hydrogen technology and investments.

The fact that green hydrogen production includes renewable energy, its production is perceived as an opportunity for those renewable energy projects affected by AMLO's administration towards renewable energy and private energy projects (Aguiar-Hernandez & Breetz, 2022b). Furthermore, green hydrogen creation can operate without interconnection to the grid, working. At the same time, the renewable energy power plant produces electricity; this out-of-the-grid characteristic would not require permits from the Federal Government and, therefore, avoid the restrictions implemented by the Mexican Federal Government.

Technology-push Policies

Technology-push policies aim to stimulate technological change by reducing the private cost of creating new technology. They usually involve government-sponsored R&D, tax credits for companies investing in R&D, enhancing the capacity of knowledge exchange, support for education and training, and funding demonstration projects (Nemet, 2009). The quality of the knowledge and technological capabilities developed through R&D activities are determinant aspects of the production and diffusion of environmental innovations (Costantini et al., 2015).

Pilot projects, international cooperation in the academic sector, and training specialized human resources are the technology push policies mentioned across multiple functions in the analysis, covering and impacting different functions in the TIS. Pilot projects are designed to demonstrate how the technology works in the local environment, providing data that can be utilized for research and attracting commercial projects. Usually, governments oversee pilot projects, while they require public funding to test an early-stage technology that is not widely available (IEA, 2011).

In charge of a non-government organization, I identified international cooperation in the academic sector and training specialized human resources for energy agencies, universities, and other actors. Both initiatives are related to the academic sector, which has done a great job generating trained human resources for the academic sector. Still, hydrogen experts are required in other areas, such as energy agencies, companies, and NGOs. This connects with the demand-pull initiative mentioned above, reflecting on the information for policymakers, while their training will be crucial for the design of green hydrogen policies and regulations.

Although hydrogen technologies have been studied in Mexico for several years, the most advanced technologies regarding green hydrogen have been developed by other countries. Therefore, collaborating with their universities and research centers will provide a technology advantage if Mexico wants to be part of the green hydrogen economy worldwide (HINICIO, 2021a).

Balancing demand-pull and technology-push

Although the optimal balance between technology-push and demand-pull policy is difficult to find, researchers agree that both policies are essential drivers of technological change (Cantner et al., 2016; Costantini et al., 2015; Rogge & Reichardt, 2016). This balance will be an essential piece for the proper design, plan, and operation of the green hydrogen TIS while reflecting the role of the government and the rest of the actors. The participation of all the actors, including the society, will draw the potential success of this technology in the Mexican context.

Based on the results presented above and summarized in Table 6, I created a diagram (Figure 7) that visually described the 22 initiatives result of this analysis, their different categories (policy instrument purposes and organizations leading or executing), and functions of innovation systems that each initiative attends. Demand-pull and technology-push policies are evenly distributed. The actors leading or performing them reflect the perspective of the experts interviewed for this analysis and the importance of working together with the government and the rest of the actors in the TIS. This is not the case when I analyze how the initiatives are distributed across the functions of innovation systems, where certain functions cluster more initiatives than others, implying the level of priority for some activities in this early-stage period of the TIS. Guidance of the search and resource mobilization are the most impacted by the initiatives; market formation has the smallest number of initiatives. Green hydrogen technologies are not incumbent and require specific activities for their development; most of these activities are included in the innovation systems functions guidance of the search and resource mobilization. This aligns with the results presented by Breetz et al. (2018), in which research and demonstration are more significant for new technologies than market formation.

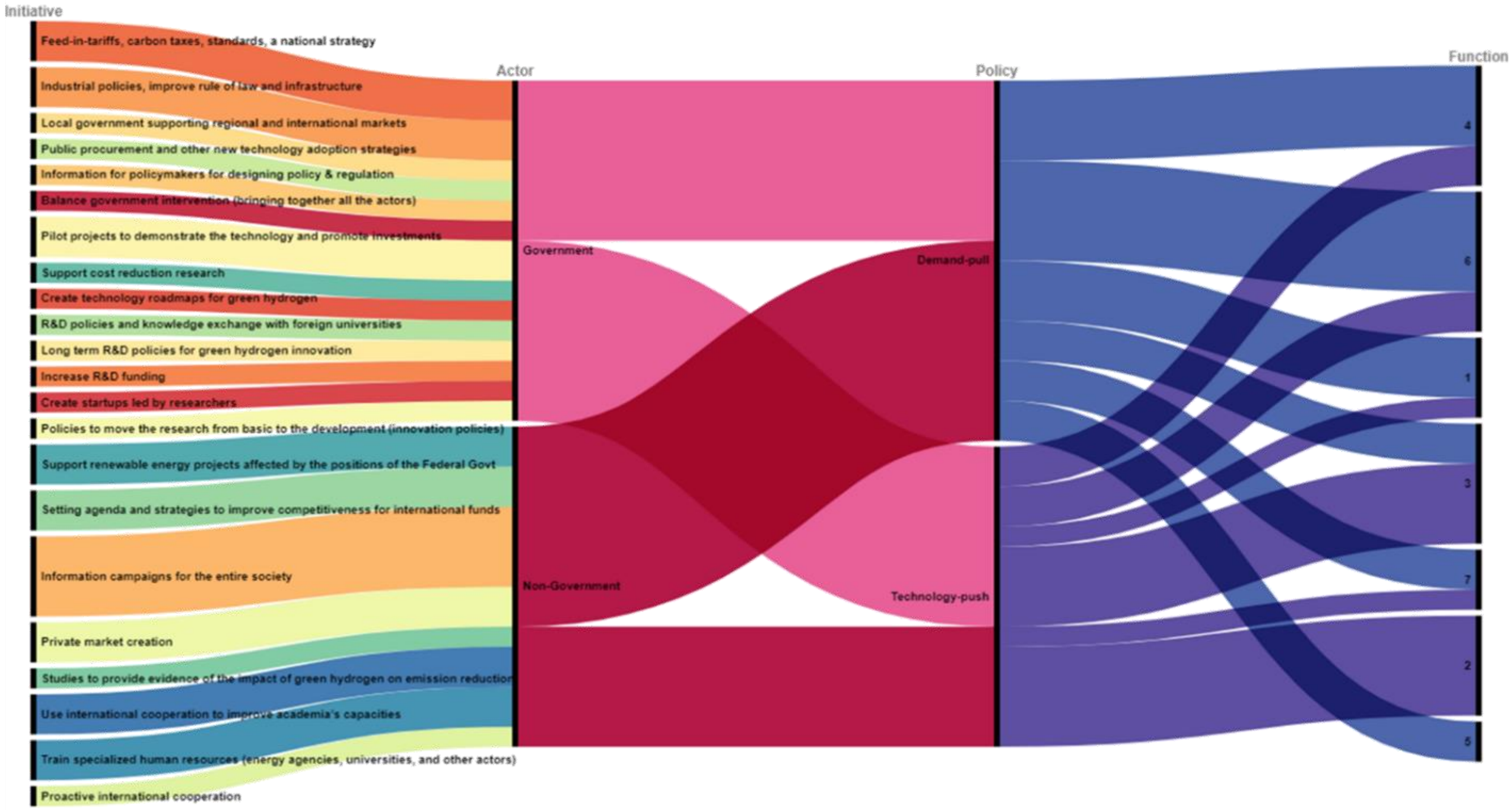


Figure 7. Classification of Initiatives for Strengthen the Green Hydrogen IS in Mexico.

Conclusions

This chapter aims to analyze the green hydrogen TIS in Mexico and uncover the mechanisms that would strengthen the development and diffusion of green hydrogen technologies. Using the innovation systems approach, the chapter addresses the case of the green hydrogen TIS in the context of an emerging economy that is expected to have a significant role in the global hydrogen economy. This is relevant because of the role green hydrogen will play in the decarbonization of different industries such as light and heavy industries, transportation, power, and gas sectors, and supporting the integration of other technologies such as energy storage, grid operations, and synthetic fuels. Hence, the participation of emerging economies like Mexico is expected to grow at a fast pace starting in this decade (HINICIO, 2021a).

This research provides the status of the green hydrogen TIS and identifies initiatives to strengthen its functionality. I categorized these initiatives by the functions that are affected, the policy instrument purposes (demand-pull and technology-push policies), and the organizations leading or executing the initiatives (government and non-government organizations). Twenty-two initiatives were identified and classified, some of which affect multiple functions of TIS, showing various solutions by a single initiative and priorities among the processes, implying broader impacts in strengthening the performance of the green hydrogen TIS. Information campaigns, different regulation (e.g., standards and industrial policies) and policy instruments (e.g., taxes, subsidies, and strategy), and infrastructure were the most repeated initiatives categorized as demand-pull. On the other hand, the initiatives classified as technology-push, pilot projects, international cooperation in the academic sector, and training of specialized human resources were mentioned more frequently. Both categories denote the importance of knowledge production and diffusion, guidance, and collaboration, aligning with Aldrich & Fiol (1994) regarding the institutional environment for emerging industries.

The initiatives analyzed are balanced along with the four categories mentioned previously, reflecting the importance of demand-pull and technology-push policies and government and non-government organizations leading or executing these solutions. The combination of demand-pull and technology-push has been proved to drive and shape the speed of technological change, as they closely interact (Costantini et al., 2015; Mowery & Rosenberg, 1979; Nuñez-Jimenez et al., 2019); as the study reflects on both kinds of policies, I imply that it covers a combination for development and deployment of green hydrogen innovations. In terms of the actors leading or executing the initiatives identified in this research, innovation system approach provides a new rationale for policy making and implementation, suggesting, among other, the engagement of multiple actors in the policy making, policy implementation and in the innovation process (Flanagan et al., 2011; Meissner & Kergroach, 2019). Having a multiple actor approach would allow the green hydrogen TIS in Mexico to function properly and generate synergies across the system.

The findings connect the initiatives identified to strengthen the green hydrogen TIS with each of the TIS functions, showing the priority level for some activities under the current context of the green hydrogen TIS. Guidance of the search and resource mobilization are the innovation systems functions with the most significant number of the identified initiatives, reflecting the priorities of the green hydrogen TIS in this formation stage in the country. On the other hand, the market formation has the smallest number of initiatives, indicating the reality of this market and the fact that "The green hydrogen market in Mexico does not exist yet". The differences across the functions and initiative priorities are consistent with the findings presented by (Breetz et al., 2018; Foxon et al., 2005; Grubb, 2004; Junginger et al., 2010), in which research and demonstration are more significant for new technologies than market formation.

Overall, green hydrogen could provide a solution for the renewable energy projects affected by AMLO's administration towards renewable energy and private energy projects (Aguiar-Hernandez & Breetz, 2022b). This is because the equipment for green hydrogen production can operate off the grid and only while the renewable energy power plant is running, avoiding the restrictions implemented by the Mexican federal government. Furthermore, the wind and the solar market will flourish by strengthening green hydrogen production, as these are Mexico's most common renewable energy technologies.

Mexico is part of the countries with renewable energy potential that plan to be a main exporter of green hydrogen to adopters like Japan, South Korea, and the European Union. At the same time, Mexico has certain conditions that make it an attractive market for green hydrogen technologies. The following are characteristics shared by countries with excellent market conditions for these technologies: decarbonization efforts, energy independence, supply diversification, grid flexibility while introducing renewables, development of a green economy, and development of new value chains in the energy sector (HINICIO, 2021a). At the beginning of 2021, more than 30 countries, which accumulate more than 50% of the global GDP, have published a roadmap or a strategy to promote and integrate hydrogen in their energy systems (Hydrogen Council, 2021). Therefore, Mexico needs to develop a hydrogen roadmap or national strategy and additional instruments such as pilot projects, international cooperation, training, regulation, and information campaigns, to have the conditions to be part of the global hydrogen economy and participate not only as an exporter but as an important market.

As for future research, I suggest that researchers investigate the implications of the initiatives identified in this study, specifically in the context of emerging economies in Latin America. This region should be focused not only on green hydrogen production but also on participating in the global supply chain, creating a market environment, and innovation and technology efforts; at the same time, aiming for a regional approach to creating a regional market and identifying collaborations and opportunities across the region. Further work could connect these findings with the policy mix approach. The green hydrogen TIS denotes a multi-level, multi-actor, and complex system with multiple policy instruments intended to achieve different policy goals (Flanagan et al., 2011). This approach would provide a better policy process and implementation, improving the impacts of the innovation process.

Limitations of this chapter

Green hydrogen is an early-stage technology with a limited market, resulting in a limited analytical process to evaluate its innovation system. Although multiple reports about green hydrogen have been created, the study of a technology-specific innovation system in an emerging economy has limitations regarding its methodological approach, specifically the data collection process.

CHAPTER 5

CONCLUSION

This dissertation examines three aspects of energy innovation, mainly in the Mexican context, and advances the research on innovation system by identifying policies and other inducements to accelerate energy innovation in emerging economies. It contributes to energy transition and innovation studies by expanding our understanding of energy innovation in an emerging economy. The emissions intensity of electricity sectors in emerging economies is high (IEA, 2020d). These countries also do not fully capture the benefits of their innovation, disincentivizing their clean energy innovation efforts (Samant et al., 2020); these factors, added to the constant increase in energy demand for their development, represent a primary challenge for the energy transition worldwide.

In this concluding chapter, I expand on the findings mentioned in previous sections, aiming to provide broader insights about what these studies collectively contribute to our understanding of energy transitions, innovation systems, and the policy mix concept.

Innovation for Energy Transitions

One comprehensive insight from this research is that **enabling technologies** and **emerging economies** are two often-overlooked factors that will have profound impacts on global energy innovation and decarbonization. This is an important contribution, because the energy innovation and energy transition literatures overwhelmingly focus on renewable generation technologies, especially in the Global North.

Enabling technologies are critical for supporting the transition to renewable energy. They provide flexibility to the electricity system, and hydrogen in particular can further contribute by decarbonizing sectors that are challenging to electrify, such as transportation, chemicals, iron and steel, and cement. As for how to accelerate innovation in enabling technologies, Chapter 2 found that policies aimed at stimulating renewable energy generation have spillover effects on innovation in enabling technologies. However, it also suggested that more targeted policies may be needed for enabling technologies, given the urgency and scale at which they are needed for decarbonized energy transitions. It further emphasized that we need to take innovation in enabling technologies seriously, with further research to understand its innovation and deployment compared as distinct from renewable generation. Chapter 4 further showed the importance of green hydrogen in decarbonization efforts and how emerging economies could play a key role in different aspects of energy transitions worldwide. Additionally, it shows the value of collaboration between government and non-government organizations, as well as the complementary of policies in terms of demand-pull and technology push, consolidating a more robust innovation system for early-stage technologies, like green hydrogen.

Another broader insight from this dissertation, specifically from studying enabling technologies, is the difference between the price and value of these technologies. Although this is not explicitly mentioned in this dissertation, studying the nexus of energy transition and innovation provides a better perspective of how value can be created in the energy sector and how distant it is from the price. Value is created collectively, reflecting how different components interact; as enabling technologies to support increasing the amount of renewable energy we produce and decarbonizing different sectors, their participation is restricted in terms of price and needs to be rethought. Markets lack mechanisms to make decisions based on value, having a short-term specification based on price; energy markets could incorporate additional metrics to evaluate the value of their components, considering environmental and social value added to the system. The systemic characteristic of innovation and the fact that the innovation systems deal with various unpriced but highly valued components such as knowledge represent an excellent approach for enabling technologies or any other component adding unquantified benefits to the energy system.

In addition to highlighting the value of studying enabling technologies, this dissertation emphasized that emerging economies are important actors in global energy transitions and energy innovation. Emerging economies demand a massive amount of energy for their development, representing a considerable portion of the energy produced worldwide. The decisions that they make for the adoption of clean energy technologies have global implications. But emerging technologies are more than energy consumers; they also have innovation capabilities that can advance technological change. Chapter 3 found that innovation in emerging economies needs institutional changes to progress, as some cultural and social blocking mechanisms are present; part of these changes involve more participation of the government in the innovation system, and improve the international collaboration. For example, seven emerging economies mentioned in chapter 3 are part of the global initiative Mission Innovation, which contributes to R&D

and demonstration to make clean energy affordable and accessible (Mission Innovation, 2021). Knowledge creation and diffusion can increase international collaboration, as knowledge is the center of innovation; main innovation activities could come from this form of collaboration. In chapter 4, I present some hydrogen reports mentioning Latin America as one of the regions expected to have lower production costs for green hydrogen, further reflecting how emerging economies have opportunities to contribute to the global energy transition and move from recipients of technology to partners in innovation and development.

At the same time, this research highlighted challenges for emerging economies. Chapters 3 and 4 discussed how Mexico needs to strengthen its innovation systems and participate in the global energy transition. While Mexico has many innovation assets, it is challenged by gaps and instability in federal policy. In addition, the mindset toward innovation remains poor and, in most cases, many actors continue to wait for the technology from other countries.

Innovation Systems

Thinking in systems provides a rich understanding of the actors, structures, and functions that support the system's performance. Before the Mexican energy reform, the energy sector in Mexico was operated by two government-owned companies managing the oil and electricity sectors, PEMEX and CFE, respectively. This monopolistic structure might be the reason for the lack of prior research on innovation systems and energy innovation in Mexico. However, one of the interviewees stated that after the liberalization of certain electricity activities (part of the energy reform), conditions were created to increase entrepreneurial and R&D activities, stimulating the innovation system for renewable generation technologies, allowing multiple actors to interact matters for innovation. This dissertation set out to discover how these institutional changes affected innovation for clean energy and hydrogen, using an innovation systems lens to capture the participation of numerous actors and institutions. This systems perspective enabled me to identify not only a range of formal institutional and policy factors affecting innovation, but also the informal cultural norms that affect innovation. This is highly relevant not only for Mexico, but also potentially for other emerging economies.

Within this innovation system, all three chapters of this dissertation emphasized the critical role of national-level policy. Chapter 2 showed the importance of dedicated renewable energy policy at stimulating innovation in both renewable generation and enabling technologies. Although these policies may be enacted by subnational states (e.g., in the United States), they are most often enacted by national governments. Focusing on Mexico, Chapters 3 and 4 show some of the challenges created with the national government is not focused on renewable energy. Although there are many private companies, research institutes, and subnational governments in Mexico who are working on energy innovation and deployment, the federal government is not supporting the process, slowing down the entire SIS for wind and solar technologies. Governments need to increase their participation in the energy innovation process, as they tend to assume that the private sector, in collaboration with other actors, will create the knowledge and value required to advance clean energy innovations. However, this research shows that the innovation process is slowed or paralyzed without government involvement. Government can work beyond fixing market failures and have a more dynamic role in the IS through public procurement and improving public-private partnerships, this applies for advance, emerging, and developing economies.

Policy Mix

The policy mix concept has been mentioned to describe some of the results of this research. Chapters 2 and 4 use this concept to partially explain their findings due to the complexity of innovation systems, with multiple market failures affecting energy innovation and different policies needed to address technologies at different stages of development. I use the policy mix concept to tie together multiple actors, instruments, and institutions, aiming to increase the interaction between energy and innovation policies and balance technology-push and demand-pull policies. Given the importance of innovation for energy transitions and how the complexity of energy systems and their technological change keeps increasing, the policy mix concept will become essential for policy formulation and implementation and policy interactions.

Although this research focuses on technological innovation, it also shows that social and institutional innovations are required to advance the energy transition. Several of the recommendations from this dissertation could be classified as addressing social and institutional innovation. Factors such as history, culture, education, political and institutional organization, and economic structure determine the capacity of a society to generate and use new ideas and knowledge, highlighting the importance of social and institutional features in addition to economic or technical capabilities. Therefore, the policy mix for clean energy technologies should consider these features to develop new technologies and use technology from other countries or sectors. The uses of the policy mix concept mentioned above could be employed across all countries, as they share similar complexities in their energy and innovation sectors.

Conclusion

Harnessing knowledge and turning it into something new, useful, and legitimate that reduces emissions, supports energy transition, solves energy problems, or decarbonizes our economy could be the most critical challenge we will face as a society in the following decades. From an innovation perspective, knowledge is the most fundamental resource in modern society, and learning is the most critical process, as knowledge is transferred through learning. Advancing our understanding of generating and using collaborative knowledge for energy transitions and decarbonization will improve our chances of adapting and mitigating climate change. As this dissertation shows, this knowledge could come from multiple scales, countries, regions, technologies, and sectors. Our capacity to exploit this knowledge and create something valuable from it will determine our future.

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APPENDIX A

LIST OF INTERVIEWEES, WIND AND SOLAR EXPERTS

Name	Institution	Category
Dersu Figueroa	Universidad Autónoma de Querétaro	Universities and research centers
Fernando Rodriguez	Cluster de Energia de Sonora	Non-governmental organizations
Rocio Ruelas	Gobierno de Sonora	Government
Efraim Castellanos	Gobierno de Durango	Government
Aldo Rodriguez	Gobierno de Tamaulipas	Government
Karla Cedano	UNAM-IER	Universities and research centers
Elsa Bernal	REDMEREE	Non-governmental organizations
Jose Hoyo	Instituto Tecnologico de Hermosillo	Universities and research centers
Enrique Koenigue	Siemens Energy	Private companies
Nassif Surus	TAM Energia Alianza	Private companies
Personnel in Mexico	Global wind turbines manufacturer	Private companies
Hugo Cruz	Iniciativa Climatica de Mexico	Non-governmental organizations
Georgina Ortiz	Instituto Mexicano del Petroleo	Government
Jose Eduardo Robledo	Tuto Energy	Private companies
Jose Amaya	GGGI	Non-governmental organizations
Humberto Becerra	INEEL	Universities and research centers

APPENDIX B

LIST OF NTERVIEWEES, GREEN HYDROGEN EXPERTS

Name	Institution	Category
Tatiana Romero	INEEL	Universities and research centers
Maria Valencia	Gobierno de Puebla	Government
Aldo Gutierrez	Gobierno de Tamaulipas	Government
Juan Antonio Gutierrez	Sociedad Mexicana del Hidrogeno	Non-governmental organizations
Rosa de Guadalupe Gonzalez	IPN	Universities and research centers
Dieter Femfert	Cryo-Infra	Private companies
Agileo Hernandez	UNAM-IIM	Universities and research centers
William Jensen	Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH	Non-governmental organizations
Enrique Koenigue	Siemens Energy	Private companies
Pamela Avila	AES	Private companies
Antonio Leon	Gobierno de Guanajuato	Government
Israel Hurtado	Asociacion Mexicana de Hidrogeno	Non-governmental organizations

APPENDIX C

APPROVALS AND PERMISSIONS

APPROVAL: MODIFICATION

Hanna Breetz
CGF-SOS: Faculty & Researchers
480/727-0408
Hanna.Breetz@asu.edu

Dear Hanna Breetz:

On 10/15/2021 the ASU IRB reviewed the following protocol:

Type of Review:	Modification / Update
Title:	Innovation systems for sustainable energy: The case of Mexico
Investigator:	Hanna Breetz
IRB ID:	STUDY00014287
Funding:	None
Grant Title:	None
Grant ID:	None
Documents Reviewed:	• Sample Interview Questions Spanish, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • Sample Recruitment email Spanish, Category: Recruitment Materials; • Sample verbal consent Spanish, Category: Consent Form; • Study Information Sheet Spanish, Category: Recruitment Materials; • Translation Certification form, Category: Translations;

The IRB approved the modification.

When consent is appropriate, you must use final, watermarked versions available under the "Documents" tab in ERA-IRB.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

REMINDER - All in-person interactions with human subjects require the completion of the ASU Daily Health Check by the ASU members prior to the interaction and the use of face coverings by researchers, research teams and research participants during the interaction. These requirements will minimize risk, protect health and support a safe research environment. These requirements apply both on- and off-campus.

The above change is effective as of July 29th 2021 until further notice and replaces all previously published guidance. Thank you for your continued commitment to ensuring a healthy and productive ASU community.

Sincerely,

IRB Administrator

cc: Carlos Aguiar Hernandez
Carlos Aguiar Hernandez