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Survey

Mexico's renewable energy innovation system: Geothermal and solar photovoltaics case study

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ABSTRACT

This paper evaluates the impact of changes in Mexican energy policies on the Mexican innovation systems ability to support renewable energy technologies, through a comparative case study on geothermal and solar photovoltaic technologies. The study examines the effectiveness of government policy in each case by exploring how changes in policy have affected the development of their respective innovation systems. The analysis is facilitated by a technology innovation system framework. The main source of data is primary data from an online survey of 61 experienced energy experts in Mexico in 2019, complemented with desktop research. Results suggest that changes in government priorities have a strong influence on the development of these two technologies. The development of these technologies in Mexico is determined by their innovation systems resilience and adaptability to the changing policy landscape. Policy instruments that encourage knowledge formation serve as critical for the continued development of renewable energy technologies in Mexico. This study contributes to the literature on innovation systems in Mexico, on comparing two renewable energy technologies, and on developing countries policy and innovation contexts.

1. Introduction

The core objective of the paper is to determine the effectiveness of the Mexican energy innovation systems (IS) in promoting renewable energy (RE), in the midst of changing and conflicting public policy priorities. The paper describes the development of geothermal and solar photovoltaic (PV) capabilities and finds both commonalities and differences characterising their IS. A comparative case study is presented to understand how the IS for these two technologies have developed, and to examine the effectiveness of government policy in each case to gain insight on the wider RE sector.

Technological innovation plays a significant role in enabling civilisations to benefit from the natural capital around them. Even though Mexico has an abundance of RE resources, public policies have historically locked Mexico into fossil fuels to meet the country's energy demand (Everhart and Duval-Hernandez, 2001). Technological innovation plays a fundamental role in increasing RE penetration (N., 2019). Innovation, can not only improve efficiency and reduce costs, but it is necessary to address the challenges presented by a high-share of variable RE in the power grid (IRENA, 2019a). According to recent United Nations (UN) 2019 recommendations, in order to encourage renewable energy technologies (RET), governments require solid IS frameworks tailored to their national and regional contexts as well as to their unique institutional and regulatory environments. This underlines Mexican policymakers' key role in fostering the expansion and diffusion of RE production and use.

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The current Mexican administration of President Andres Manuel Lopez Obrador, in power since December 2018, has shifted its priorities away from RE. For instance, the federal government cancelled a fourth electricity auction scheduled for November 2019, despite the success of the first two in 2016 and the third in 2017, that brought with it record breaking low energy prices (PwC, 2018). The administration also cancelled two major transmission line projects, which had a direct negative impact on grid accessibility for RE generation sites (CENACE, 2019). These modifications to the program set out by the previous government, portray differing priorities which pose a serious risk to the long-term development of RETs.

While the government is an enabler for ISs to flourish, it is not the only factor impacting RE ISs. Resource availability, functional infrastructure, technology know-how, and markets are examples of other factors impacting the system. This paper demonstrates both the robustness and fragility of Mexican energy IS amid changing public policy priorities by using the Technological Innovation System (TIS) framework established by Bergek et al. (2008). This framework was selected as the most adequate tool to capture the effectiveness of Mexico's local and international actors in developing the RE TISs.

This paper primarily uses survey results gathered by the authors in 2019, which are then complemented with desktop research amassed from secondary data of other scientific reports to obtain the data required to conduct a comprehensive analysis on the Mexican RE TISs. An intentional effort was made to underline the variety of contextual structures present in the RE TISs in Mexico.

Compared to other reports on Mexico's new energy policy landscape, this paper probes a broader perspective by gathering the views of a wider demographic group of stakeholders in one survey, thereby allowing for a holistic and up-to-date opinion on the evolving IS. This paper uses Bergek et al. (2008)'s TIS framework as the basis to evaluate Mexico's RE IS, thus facilitating comparison with other papers, but also incorporates some of the suggestions proposed by other TIS literature on defining the "contents" of the functions. Since there is no existing literature specifically focused on RE TISs in Mexico, this paper examines geothermal and solar PV IS and draws comparisons to find characteristics of the wider RE sector. The framework proves to have few limitations when applied to middle-income and low-income country contexts, such as Mexico, despite the different modifications suggested by some authors to adapt the TIS to a middle-income country context (Arocena and Sutz, 2000). Reflections are made on the application to a developing country context in section 6.

This study offers three contributions. First, it contributes to the few regional TIS studies within Latin America and other developing countries. Secondly, it evaluates the resilience of solar PV and geothermal development amid changing political context. Lastly, it contributes to the growing TIS literature by comparing two technologies in the same country.

Section 2 reviews the existing literature on ISs and presents the most appropriate framework to evaluate the RE TISs in Mexico. Section 3 presents the methodology used to obtain the primary data for the analysis and lays out the sources that complement the survey. Section 4 presents the Mexican context and describes the different characteristics of the selected technologies. Section 5 selectively presents and discusses the survey results accompanied by secondary data. Section 6 presents the conclusions, puts forward policy proposals, and reflects on the limitations of the study.

2. Theory

2.1. Innovation system (IS) framework

The IS approach developed to assist in understanding and evaluating different IS. It is considered to have emerged with the convergence of *national systems of innovation* by (Freeman, 1987), and (Nelson, 1988) and *technological systems* by (Carlsson and Stankiewicz, 1991) (Edquist, 1997, p.3). Since its formation, variations continue to be improved and adapted to suit different needs. The new versions incorporate complexity and a non-prescriptive nature, resulting in an improved understanding of IS. Although various frameworks define their boundaries differently, they are complementary and interrelated systems used to investigate ISs (Markard and Truffer, 2008).

2.2. Technological innovation system (TIS)

The TIS framework first emerged with Carlsson and Stankiewicz in 1991. Their work defined a Technological System as a network of agents interacting in the economic or industrial area under an institutional infrastructure and involved in the generation, diffusion, and utilisation of technology (Carlsson and Stankiewicz, 1991, p.94). Considering the case where Carlsson and Stankiewicz analyse the effects of automation on Sweden while considering the international context (e.g. the manufacturing of solar PV panels abroad), it is evident that their TIS is able to incorporate international context into the analysis. This therefore, suggests the framework's adequacy to evaluate geothermal and solar PV technologies in Mexico, as they are technologies affected by global trends.

Since the first emergence of the Technology System framework, TIS have subsequently evolved by focusing on *functions* of a system rather than on *components* (Johnson and Jacobsson, 2001). The new evolution presented in Johnson and Jacobsson (2001) made the TIS more distinctive and prescriptive. Centering *functions* focuses on the *key processes* involved (Bergek et al., 2008), bringing the narrative away from the composition of the system towards the actual functioning of the system. This shift facilitates an analysis that better considers the effects of lobbying, opposition, and external events on a system (Hekkert et al., 2007, p.418). This new focus also better depicts the reality that Mazzucato 2013 presents, in which different actors, such as the government, banks, and private sector, can play multiple roles within IS. Focusing on *functions* is a better way to identify the underlying strengths and weaknesses of the system (Hekkert et al., 2007; Lundvall et al., 2002), and therefore, allow for practical policy advice to result from this approach. The quality of the *functions* and the interaction between them better describe the system's capacity to innovate to meet a specific goal,for example, decarbonization. In general, a technology-focused study describes dynamic systems, as can be seen with the case of solar PV support in Germany (Jacobsson et al., 2004), suggesting that TIS *functions* can be used to understand complex innovation policies in Mexico. The benefits of using TIS are twofold. Firstly, there are considerably fewer actors, networks and institutions, making it more bounded than other frameworks. Secondly, the comings and goings of some institutions within the Mexican IS favours a framework that focuses on *functions*, not on composition (for reference, compare institutions listed in Dutrenit et al. (2008, pp.35–52) and Elizondo-Noriega et al. (2017, p.3)).

Although the number of *functions* differs from framework to framework, there is an overlap that Johnson (2001, p.11) systematically details. The most cited TIS framework has seven *functions* from Bergek et al. (2008)) which is similar to the next most cited from Hekkert et al. (2007). This research will use Bergek et al. (2008)'s framework, given the extensive literature utilising this version to examine RET in different countries, and its unique *function* number seven, which considers the interaction between *functions*- something that will be useful to evaluate the effectiveness and the robustness of Mexico's RE TISs. Bergek et al. (2008) propose seven *functions* that can be evaluated by using a set of indicators set out in the 3 section.

2.3. TIS for developing countries

Different authors who use the TIS framework demonstrate varying extents of the need to develop new frameworks when examining developing countries, which is a worthwhile pursuit when considering the socio-political factors hindering IS development to a greater extent relevant in developing countries e.g. inequality, corruption, armed conflict. For example, Kebede and Mitsufuji (2017) consider the TIS framework to evaluate the diffusion of solar PV in Ethiopia. Similar to the proposition by Casadella and Uzunidis (2017), they highlight the need to modify the focus of TIS on the diffusion of already existing technologies, rather than emphasise the creation of new technologies, matching the country's context. Edsand (2017) uses TIS to identify the barriers facing wind energy in Colombia. Edsand (2017) adds to his TIS *functions* "inequality", "corruption" and "climate change awareness", which had important repercussions on the diffusion of wind in the context of Colombia, a country socioeconomically comparable to Mexico (Solleiro et al., 2018). Moreover, Tigabu et al. (2015) compare the evolution of TIS for bio-digesters in Kenya and Rwanda by looking at the "accumulation of *functions*". Their effort in showcasing the evolution of the *functions* comes at the expense of critical analysis on the interaction between *functions*. The shortcomings of the TIS mentioned are in line with papers that question the validity of IS for developing countries (Arocena and Sutz, 2000). Arocena and Sutz (2000) argue that an IS approach is an *ex-post* analysis for industrialized countries, and that no systematic framework will consider the socioeconomic reality and existing dynamics of Latin America. All these perspectives need to be taken into consideration when using the TIS framework, and like van Alphen et al. (2008, p.166) indicate, "[the TIS functions framework] cannot be used without modifications" when applied to a developing country. This paper keeps the original framework without alteration, but has incorporated suggestions of the literature when defining the contents of the function to take advantage of lessons learned from efforts to analyse TISs in developing economies. The aim of this paper is to capture the changes experienced by two technologies within the similar developing country socioeconomic reality. Because of this, an exhaustive description and analysis was done on the Mexican context to capture elements not in the original framework, addressing the criticisms of how the original framework captures developing countries' realities (Solleiro et al., 2018). Additionally, *functions'* sensitivities to corruption, inequality and climate change awareness were considered in the analysis.

2.4. TIS Framework theoretical challenges

Utilising the TIS framework requires striking a balance between focusing on the technology and keeping in mind the relevance of what is outside the boundaries set, or *context* per (Wieczorek et al., 2015). Carlsson et al. (2002) highlight the challenging task to properly define the *product*, in this case solar PV and geothermal, to be analysed and its boundary. As was previously discussed, RETs are part of a whole global system. Defining the boundary within Mexico is in fact excluding an entire global ecosystem, which (Wieczorek et al., 2015) warns us may overestimate the role of a national government. This risk comes with the benefit of being able to analyse the TIS in greater depth to identify local changes across time. In addition, this paper looks at two different TISs to avoid tunnel vision and reveals the changing relevance of different actors and policy in Mexico, seeking to bring out their role in the overall RE TIS. This paper implements the suggestion by Coenen (2015) to conduct a wider analysis to the context of RE in Mexico to better capture structural dynamics and functioning of the TIS, as well as to avoid making sharp and definite distinctions between what is "inside" and "outside" the TIS. However, this paper does not go in depth to consider technology developments in other countries, but rather focuses on the local context, a limitation which Bergek et al. (2015) conclude "to be key to explaining societal transitions." Though the concept of "context" encompasses various topics, this paper only looks at the political context, seeking to provide the reader with the awareness of the apparent relevance on the TISs.

3. Methodology

This paper carries out a comparative case-study on the IS of geothermal and solar PV to evaluate the Mexican RE TISs, using Bergek et al. (2008)'s TIS framework as the main basis for analysis. The comparative case study approach was selected given the ability to address a salient contemporary topic such as RET in Mexico (Yin, 2018, p.13). Additionally, a mixed-method approach to triangulate the TIS is followed, which provides for a "stronger array of evidence than can be accomplished by any single method alone" (Yin, 2018, p.13) The analysis focuses on the period between 2012 and 2019, spanning two different presidential administrations.

The principal basis for the analysis is primary data from an exploratory survey of stakeholders and experts, involved in the generation, diffusion and utilisation of geothermal and solar PV technologies in Mexico (see Appendix B). Babbie (1990, p.53) considers an exploratory survey method appropriate when beginning an inquiry into a topic. Because of the inaccessibility of recent data despite a concurrent interest to gather the latest stakeholder and expert perspectives, and the consensus that indicators alone do not sufficiently describe the complexity of an IS (Dosi, 1988, p.222), the exploratory survey was best suited to effectively explore the Mexican RE IS and evaluate geothermal vis-à-vis solar PV using the most recent perspectives from those involved in the energy sector.

The survey structure is summarised in Fig. 1. It begins with general questions and gravitates towards questions of a more personal nature (i.e. professional career). Questions on professional information are placed at the end of the survey as suggested by ONeil et al. (2003), to encourage honesty and participation. The survey starts with an interview protocol in accordance with the European Union General Data Protection Regulation (GDPR).

The survey questions are based on the *functions* and indicators proposed by Bergek et al. (2008) (Table 1). Likert-type questions and open questions are used. Closed questions are included to measure the levels of agreement with statements, allow coverage of topics within a short time, increasing participation, and setting the context to provoke thoughts and ideas so that the participants can tackle the open questions. Open questions are also included in the survey to allow participants to describe their experience and freely express their personal opinions.

One hundred and twenty experts were invited to participate in the survey, which was open from May 2019 to August 2019 on *Opinio*. Those invited to participate were those agents involved in the economic or industrial area under an institutional infrastructure involved in the generation, diffusion and utilisation of geothermal and solar PV technologies as Carlsson and Stankiewicz (1991, p.94) describes. 61 experts participated. The experts were found through LinkedIn, online reports, market research of technology providers and through mutual networks. To ensure there is wide representation by the experts, before seeking experts to participate in the survey, as recommended by Maxwell (2008), four large sectors and twelve sub-sectors were established (Fig. 2). There was at least one respondent for each of the subcategories previously established. To ensure anonymity during the analysis of the survey, respondents self-categorised themselves during the survey with a different set of aggregated options than used to categorize the experts before inviting them (e.g. private sector instead of consultancy).

The survey results are complemented with desktop research amassed from secondary data of reports from international institutions, academic papers, government data, and news articles. Secondary sources complement the survey to analyse the Mexican RE TISs (Table 1) using suggested indicators by Bergek et al. (2008). This data is primarily used to create the context Bergek et al. (2015) warn must be explicitly considered to provide a basis for the classification, generalisation, and transfer of findings from one TIS to another. This comparative approach using survey data and additional sources allows one to address the difficulties in obtaining data for all the indicators proposed and to identify commonalities between the two TISs, thereby enabling a characterization of the RE Mexican IS.

4. Mexican context

4.1. Policy evolution in mexico

Today, over 90 per cent of Mexico's primary energy consumption comes from fossil fuels (OECD, 2019b), making Mexico the country with the largest share of fossil fuel in total primary energy consumption in Latin America (IEA, 2018). This high share is driven primarily by Mexico's role as an oil-producing nation. Even though Mexico has an abundance of RE resources, its policies have historically locked Mexico into fossil fuels to meet its energy demand (Everhart and Duval-Hernandez, 2001).

Amid declining fossil fuel production in the 2000s, Mexico's Secretariat of Energy (SENER) became increasingly proactive in promoting the deployment of RET. The Mexican government made its first strong articulation of interest in RET in 2008. The state passed a set of laws that allowed for a RE market to emerge (GoM, 2008). These laws, along with incentives such as transmission fee exemptions and accelerated depreciation, increased the uptake of solar PV generation (Fig. 3). In 2012, the Mexican government continued to promote RET. Through the *General Law on Climate Change* (LGCC) (GoM, 2012), Mexico became one of the first countries to integrate climate change legislation directly into its national policy (Vance, 2012).

The federal government has historically controlled Mexico's electricity sector. Up until the 2013 constitutional energy reform, the state-owned Federal Electricity Commission (CFE) had a monopoly over electricity trading and generation (GoM, 2013a). The Mexican IS had no market competition necessary for utilities to be motivated to become more efficient (Batlle, 2013). The 2013 reform allowed for this competition in the energy market, particularly through several constitutional amendments that opened the energy space to private investment and promoted competition within the wholesale electricity market. A year later, the independent National Energy Control Centre (CENACE) was established to oversee the newly competitive energy market. The liberalization of the power generation sector saw immediate growth in RET deployment, increasing the RE installed capacity by 61 per cent from 2011 to 2018 (IRENA, 2019c). This made Mexico one of the fastest-growing markets for RET in the region, with high expectations to continue this way (Vazquez et al., 2018). A large part of this growth was due to international companies starting to participate in Mexico, as will be discussed later. The role of other countries in the technology development in Mexico should not be ignored (Wieczorek et al., 2015), and merits its own research.

Between 2008 and 2015, the Mexican government put in place successful policy and economic instruments to create an environment which encouraged foreign companies and investment to promote RET in Mexico. Among the most notable incentives is the requirement for major power consumers to source a percentage of clean energy through power purchase agreements (PPA) or clean

Fig. 1. Survey structure.

Table 1
Indicators recommended by Bergek et al. (2008) and those used for this investigation .

Function	Recommended by Bergek et al. (2008)	Indicators used
Knowledge Development and Diffusion (Function 1)	• number of professors, patents, workshops and conferences • bibliometrics • number and size of R&D projects • assessments by managers • learning curves	• number of conferences and workshops (desktop research) • bibliometrics • investment in R&D (reports) • perceptions of number of academics and knowledge base*
Influence on the Direction of Search (Function 2)	• incentives from factor/product prices • articulation of interest by leading customers, e.g. targets • regulatory pressures • beliefs in growth potential	• incentives (regulatory framework) • articulation of interest (government targets) • regulatory pressure* • beliefs in growth potential*
Entrepreneurial Experimentation (Function 3)	• number of new entrants • diversification activities of incumbent actors or experiments with the new technology	• number of new entrants (market research) • diversification activities*
Market Formation (Function 4)	• number, size and type of markets formed • timing of market formation • actors' strategies, the role of standards and purchasing processes	• number, size and type of markets formed (reports) • drivers for market formation*
Legitimation (Function 5)	• attitudes towards the technology among different stakeholders • rise and growth of interest groups • extent of lobbying activities • political debate in parliament and media	• attitudes from stakeholders* • extent of lobbying*
Resource Mobilisation (Function 6)	• volume of capital and venture capital • volume and quality of human resources • volume and quality of complementary assets	• volume of capital and venture capital (reports) • accessibility to capital* • human resources*
Development of Positive Externalities (Function 7)	• strength of political power of TIS actors • activities aiming at uncertainty resolution • existence/development of specialised intermediates and/or a pooled labour market • information and knowledge flows	• general commentary on TIS*

*From survey

energy certificates (CEL), that can also be used to finance energy projects. Other incentives include the long-term power auctions that led to some of the lowest prices for utility solar PV globally. The staunch commitment from the government to promote RE was enacted with the *Energy Transition Law* (LTE) (GoM, 2015). This law mandated that 35 per cent of national electricity production must be from clean sources[1] by 2020 and for that share to rise to 50 per cent by 2050. During 2018, the solar PV installed capacity grew 280 per cent to 2.5GW (IRENA, 2019c), describing significant growth in RET deployment.

The 2013 energy reform catalyzed the Mexican IS for RET, which this paper captures by examining the geothermal and solar PV evolution since 2013, up to the policy changes in 2019. In 2019 the change in government administration ushered in new priorities

[1] The Mexican government defines *clean energy* as electricity from wind, solar, geothermal, biomass, hydro, nuclear and efficient co-generation.

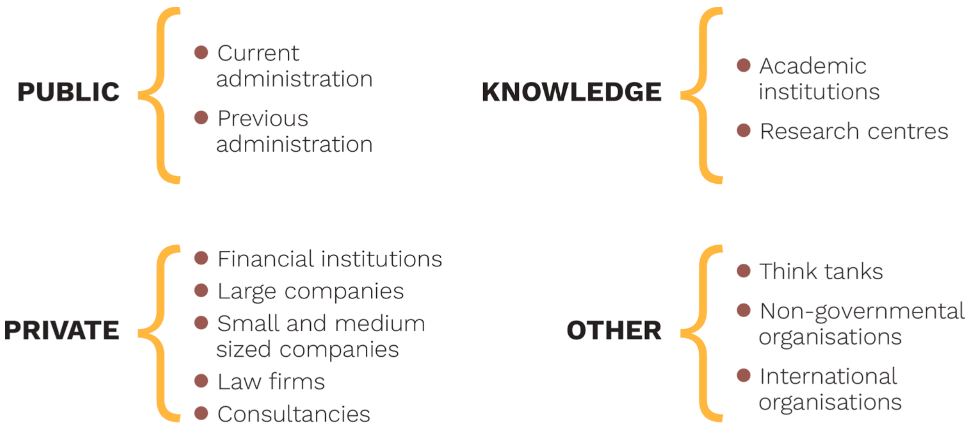

Fig. 2. Survey respondent categories.

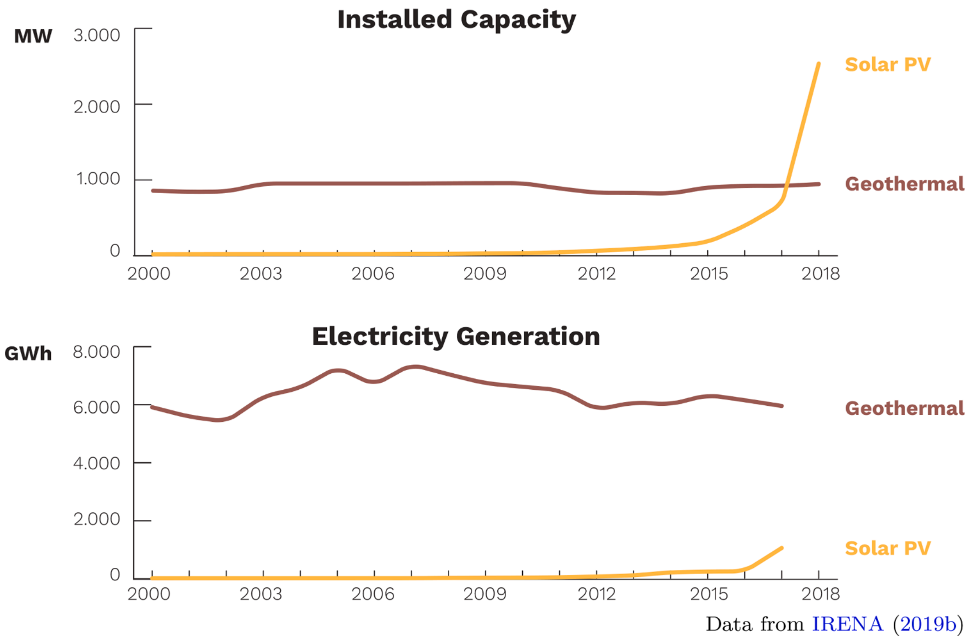

Fig. 3. Installed capacity (top) and electricity generation (bottom), line-graph.

seemingly opposed to creating an enabling environment for RE.

The apparent hostility against RE from the Lopez Obrador administration can be understood from both the statements and actions the government has taken. During the presidential campaign leading up to 2018, Lopez Obrador spoke openly against the 2013 energy reform — the key enabler for clean energy to flourish (Obrador, 2016). Furthermore, once in power, President Lopez Obrador took actions to revoke and hinder the RE benefits obtained in the past years. Those actions include the cancellation of a fourth energy auction which favoured cheap, clean technologies and the cancellation of the tender for transmission lines to ensure sufficient capacity between the national electricity system and the south of Mexico, where most of the country's wind plants are located (CENACE, 2019). An amendment on the regulation defining how CELs are established was passed in 2019, allowing old CFE generation plants to be eligible to generate CELs, generating an oversupply of CELs in the market, causing the price of this instrument to plummet and thereby no longer serving as an incentive to build RE projects (GoM, 2019a). Another amendment created additional requirements for RE to connect to the grid which limited the participation of RE in the national grid (GoM, 2020). Other actions, such as increasing the CFEs annual budget to modernise old thermal power stations, building an oil refinery and rescuing the national oil company PEMEX, one of the most indebted oil companies in the world, are all contrary to enabling RE growth in Mexico (Bloomberg, 2019; GoM, 2019b; 2019d; Obrador, 2019). The question remains whether the apparent government hostility is against market liberalization, foreign companies and their investment in Mexico, or whether it is indeed a situation of intentionally prioritising oil and gas over RE. The answer to this question will determine whether there is a need for RE TISs to circumvent the Lopez Obrador government.

4.2. Geothermal and solar PV

Geothermal and solar PV RET have developed distinctively within Mexico and both have unique technical and financial characteristics. The former has a long history in Mexico, and the latter a relatively short one. Geothermal exploitation requires a long list of permits and licenses; solar panels can be easily acquired at a retailer. While geothermal utilisation entails high exploration risks, solar utilisation carries practically none. While solar energy may be more accessible, it is also less productive in absolute terms. A geothermal plant can run 24 hours a day, all year round, thereby having an average availability of 90 per cent, while solar PV can have an average utilisation factor of around 20 per cent (Hernandez-Escobedo et al., 2020; IRENA, 2017a). In terms of cost, geothermal plants are considerably more capital intensive than solar PVs, though the former also have low and predictable operating costs.

Despite a number of fundamental differences, a commonality of both these technologies is that Mexico contains abundant natural resources for implementing both, and that they have both benefited from international know-how. Comparing them will shed light on the RE TISs. Solar PV and geothermal generation represent over 40 per cent of clean energy generation, while the other 60 per cent originates from wind and bioenergy. Solar PV and geothermal represent 55 per cent of the added clean energy capacity between 2015 and 2020 (IRENA, 2019b).

Geothermal energy, up until 2012, was Mexico's second-most preferred source of RE after large-scale hydropower (SENER, 2013). Between 2012 and 2017, solar PV investments totalling USD 3 billion multiplied solar PV installed capacity four-fold (BloombergNEF, 2018; REN21, 2019). This resulted in the installed capacity of solar PV being three times greater than geothermal by the end of 2018 (REN21, 2019). Nonetheless, the role of geothermal is still important. According to the latest available data, geothermal energy accounts for 1.7 per cent of the total electricity produced, compared to 0.1 per cent from solar PV (BloombergNEF, 2018).

Mexico benefits from both large geothermal and solar resources (IRENA, 2017a; Mundo-Hernndez et al., 2014). To harness them, the government must foster its RE TISs (MorganStanley, 2017). This paper analyses the changes in the Mexican RE TISs, illustrating areas of opportunity to increase the chances of Mexico meeting its obligations stemming from the LTE and the targets set under the Paris Climate Agreement to reduce national greenhouse gas emissions by 22 per cent by 2030.

5. Results and discussion

The analysis considers 61 survey replies, 36 of whom are self-identified experts in geothermal and 53 in solar PV. Fifty-nine per cent of the respondents had experience in at least two sectors listed in Fig. 2. At least one respondent from each of the stakeholder types completed the survey (Table 2). Secondary data complements this analysis (Table 1). This section divides the findings into the seven *functions* set out by the TIS framework proposed by Bergek et al. (2008).

5.1. Function 1: Knowledge development and diffusion

The first *function* is *knowledge development and diffusion*, which is at the core of a TIS, and a fundamental resource for an IS (Lundvall, 2010, p.1). The *knowledge development* originates from academic and firm research and development (R&D) in addition to *learning-by-doing*, which will only be effective at a system level, if there is knowledge diffusion.

5.1.1. Knowledge base

Mexican geothermal and solar PV research activities began in the 1960s and late 1970s, respectively (Mercado and Fernandez, 1988; Rincón-Mejía and Pereyra, 2006). Since the 1960s, scattered geothermal projects have been carried out, in contrast to the continuous developments in solar PV. Knowledge diffusion mechanisms within the TIS for solar PV started with the first National Reunion for Solar Energy in 1980. The National Association for Solar Energy (ANES) was created at the first of these summits, which to this day is responsible for organising the annual conference that brings together academics, researchers, and private stakeholders. This conference highlights scientific knowledge-flows across Mexico's borders in the early stages of solar PV development in Mexico.

Since 2012, the number of solar PV R&D projects has dropped while the rate of large-scale deployment has increased. The change from smaller *projects* to larger scale *deployment* suggests the TIS was creating *market knowledge* (5.4), demonstrating that the market can facilitate demand, supply and sufficient resources and market knowledge to execute. The growth in the deployment of larger projects can be explained by the confluence of growing market and regulatory knowledge and the increasing awareness by stakeholders of the implications of the energy reform. The emergence of forums within the last few years attests to the TIS facilitating events where

Table 2
Table showing the frequency of how survey participants self-identified. Note that survey participants could select more than one category .

Category	Frequency
Academic	12
Public Sector	21
Private Sector	21
Entrepreneur	3
Other: International Cooperation	1

technical and market information is exchanged between actors.

International organisations have historically contributed to the Mexican knowledge base around geothermal and solar energy. Their presence has contributed to knowledge spillovers through projects aimed at increasing *legitimation* of RET. Casadella and Uzunidis (2017) consider the inward flow of knowledge as characteristic of *receivers* of technology, which they attribute to developing countries. However, this term implies a one-way knowledge flow, which is untrue in the case of Mexico. This can especially be seen in the case of geothermal energy, where Mexican R&D specialists share their skills and spread knowledge to projects in other countries.

5.1.2. Bibliometrics and investment in R&D

The bibliometrics computed for the number of geothermal and solar PV-related publications (Fig. 4) are low compared to other smaller countries with comparable solar PV and geothermal renewable resources. Mexico's research, largely by institutions within Mexico, contributes to less than 2 per cent of the global publications on these topics. The comparably small number of publications is in line with the low support from the government towards scientific research (OECD, 2009). Since 1980, annual investment in research and technological development has been less than 0.5 per cent of Mexico's gross domestic product (GDP); this figure is well below the Organisation for Economic Co-operation and Development (OECD) member states' 2.3 per cent average (CONACyT, 2014; OECD, 2019b). The 2019 8 per cent budget cut to the National Council of Science and Technology (CONACyT) (TEC, 2020), implies this trend will not immediately change despite the small increase in publications at the time of the energy reform, which exemplifies the interdependence of *functions* (i.e. knowledge development and diffusion and resources).

5.1.3. Survey results

Survey respondents perceive that technological and scientific knowledge is weak in both TIS (Fig. 5). Additionally, survey respondents believe that there is a scarcity of qualified academics in the TIS, which complements the data illustrating a low number of geothermal and solar PV-related publications. One respondent considers Mexican technical knowledge as "antiquated and ill-informed." Almost half of the respondents consider market knowledge as the strongest knowledge, which supports the solar PV growth experienced in the last six years; Mexico ranked ninth in solar PV installed capacity in 2018 (REN21, 2019). This growth was not witnessed in the geothermal TIS. Geothermal experts blame the nonexistence of financing mechanisms —an element of *market knowledge* (5.4)— as the culprit for its failed growth.

5.2. Function 2: Direction of search

The second *function* is *influence on the direction of search*, which is a direct result of incentives and competition, a *function* that the latest reports from the OECD (2019a) on Mexico suggest are weak and need to be addressed. Firms, large or small, must have some incentive to enter a new TIS. These incentives can originate from governments, markets, or firms, and can also originate from changing economic, environmental or normative values (Geels, 2002).

5.2.1. Policy direction

In response to a national need to diversify energy sources, laws promoting RET (4.1), *entrepreneurial activity* (5.3) started to appear, like they had in other countries where *guidance* and *market* concur (Hekkert and Negro, 2009). This is especially true for sustainable technologies (Hekkert et al., 2007).

The LGCC in 2012, and the energy reform in 2013 drastically improved the prospects for cleaner energy (ProMexico, 2017) and increased *legitimation* (5.3) of clean energy technologies, thereby mobilising *financial resources*. The 2013 reform ended the CFE monopoly of the power sector that had restricted other actors from generating or trading electricity. Solar PV flourished in the ensuing new regulatory environment. The 2013 energy reform did not have the same impact on geothermal energy as on solar PV, even when the National Electricity System Development Programme (PRODESEN) estimated that geothermal capacity would double by 2030 (SENER, 2015). To reach that goal of doubling geothermal energy, SENER proposed additional regulation such as a geothermal law, to supplement the energy reform to facilitate private participation in geothermal projects (GoM, 2014). Although the initial target has since been reduced, the target and regulations were clear signs of government support for geothermal energy.

5.2.2. Survey results

Survey respondents asserted that a clear direction for RET had been mapped out and was being followed, until the presidential

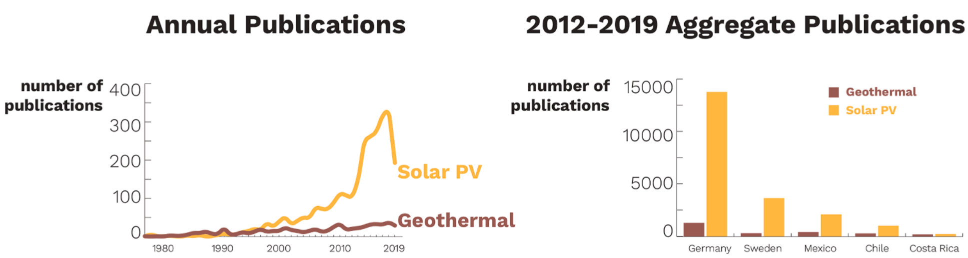

Fig. 4. Bibliometric results of geothermal and solar PV publication in Mexico, mixed-graph.

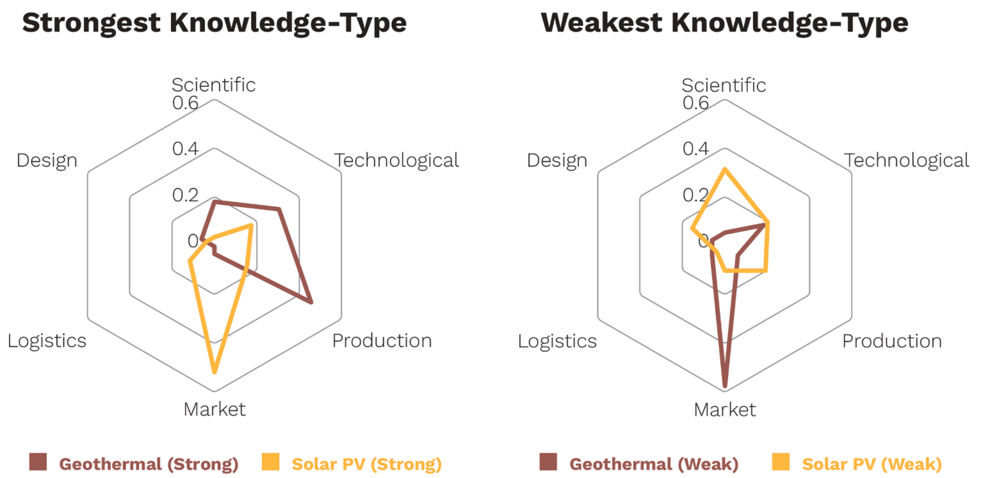

Fig. 5. Survey results, shown in percentage of survey respondents, on the strongest-perceived knowledge (left) and the weakest-perceived knowledge(right), radar.

administration change in 2018. Commonly cited examples of this clear direction included the CEL obligations and the three successful long-term electricity auctions, which resulted in one of the world's lowest bids (IRENA, 2017b). However, the outlook later turned bleak. The survey responses highlighted that the current administration favours fossil fuels, creating uncertainty at all levels of the RE TISs (Fig. 6). The latest National Development Plan (PND) 2019c mentions RE only briefly. One respondent describes the frustration of private firms not knowing whether SENER will allow them to participate in new geothermal exploitation, while another respondent describes the cancellation of the fourth long-term energy auction in January as "nonsense." As Tigabu et al. (2015) highlight, *direction and search* are not necessarily cumulative and some capabilities may be lost if they are not actively sustained.

Despite the current government's hostility to the energy reform and it backtracking public efforts to meet its legal obligation to promote clean energy, there is general optimism that both geothermal and solar PV implementation can progress. Respondents listed numerous incentives still in force, although a few suggested that without government intervention, geothermal capacity will not grow further. This is a different reality to that of solar PV, which now has a competitive market and perhaps needs fewer government incentives to continue growing.

5.3. *Function 3: Entrepreneurial experimentation*

The third *function* is *entrepreneurial experimentation*, which counterbalances the uncertainties that are normal in new technologies and markets. The number of experiments taking place can indicate the potential of an IS, provided that as greater number of experiments fail, more learning will take place. This is the basic principle of *learning-by-doing* which fosters innovation. Lindholm-Dahlstrand et al. (2018, p.243) describe the particular difficulty of measuring this *function*.

5.3.1. *Number of entrants*

Due to limiting regulation, only a few actors existed in the electricity sector before the 2013 energy reform. Since the reform, the liberalised energy generation market allows for new solar PV actors. Around twelve solar PV manufacturing plants have been built in Mexico since 2013, exemplifying the deployment and expected growth in solar PV demand (see Appendix B). The largest growth was first seen in distributed solar PV, which was later shadowed by utility-scale capacity (Fig. 7). The lack of accessible data on the number and size of solar PV companies created makes it difficult to quantify this growth. Expositions and forums have increased in the last years, serving as a proxy for this missing information. For example, the first business-to-business exhibition on solar PV was held in 2019 and had over 78 exhibitors (Notimex, 2019). To further continue benefiting from this growth, the Mexican government established The Mexican Centre for Innovation in Solar Energy (CeMIE-Sol) in 2013 funded by the CONACYT-SENER Energy Sustainability Fund to encourage academic and research institutes to launch projects in the market (GoM, 2013b). An outcome of the increased number of actors in the solar PV TIS was the competitive prices being bid for the long-term energy auctions (IRENA, 2017b).

5.3.2. *Survey results*

General attitudes contradict the optimism suggested by solar PV deployment of recent years. Survey respondents cite what they believe to be excessively centralised power, which favours personal interests above any other. The latest OECD 2019a Mexican Competition Assessment includes recommendations that regulation be open to private investment and be unbiased towards local companies. This is particularly salient for geothermal energy, which is still state-controlled and has failed to successfully open the market to private companies. Survey respondents note that most of the new entrants for solar PV have been in the installation market segment. For solar PV, small companies being formed in Mexico are selling PV panels to residents, while larger, more established international companies are addressing larger projects.

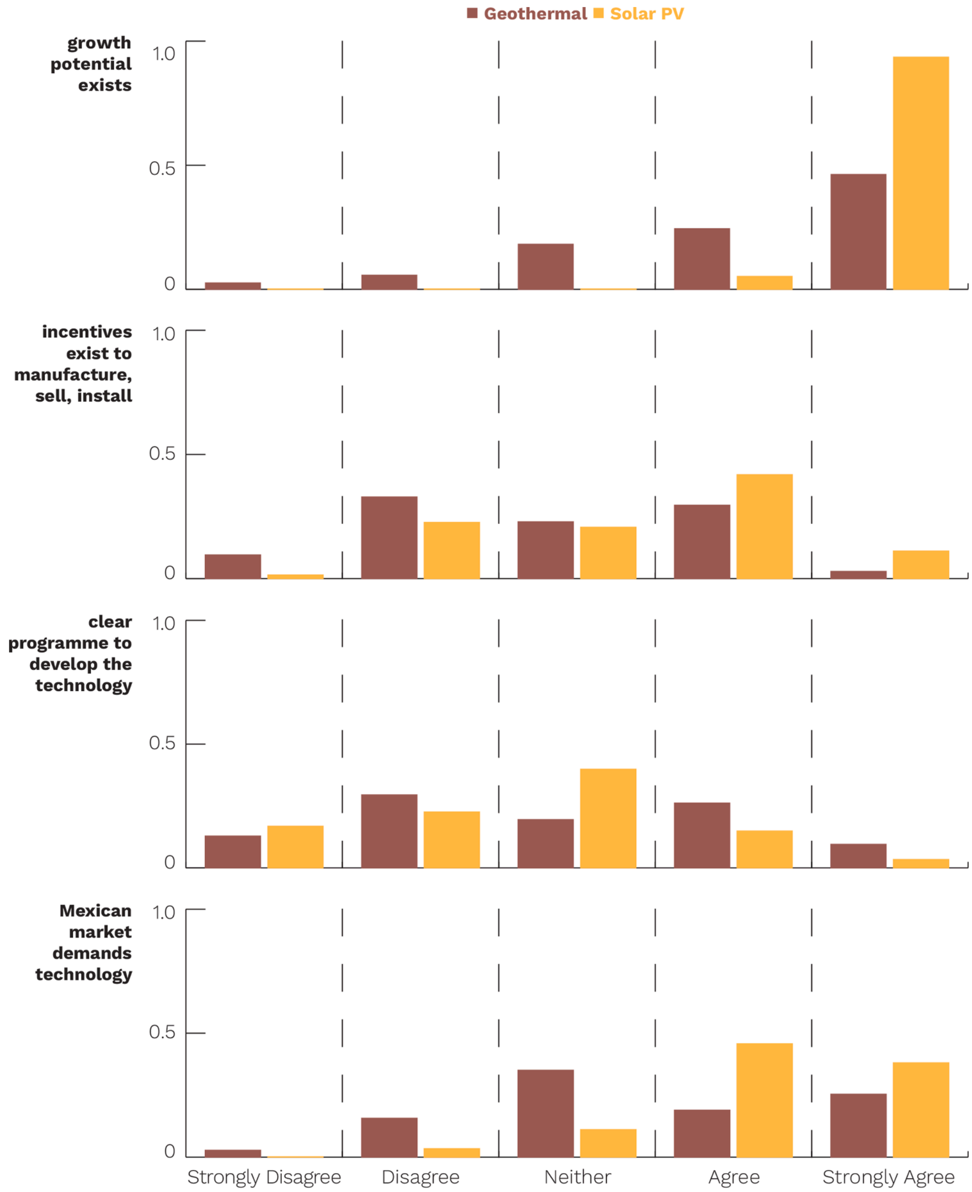

Fig. 6. Survey results on direction, bar-charts.

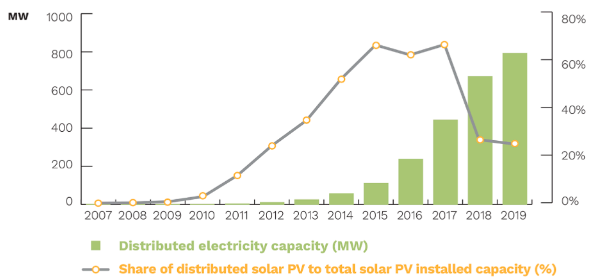

Fig. 7. Distributed installed capacity (MW) and the share of distributed to total solar PV installed capacity (%), mixed-graph. *99% of distributed electricity originates from solar PV Data from IRENA (2019b) and CRE (2019).

Geothermal generation is dominated by CFE, with the unique exception of *Grupo Dragon*, which became the first private company to manage a geothermal generation facility in 2015. The long-term energy auctions and, the 26 exploration permits and six concessions given to private companies in line with the geothermal law (SENER, 2018) were indicators of new actors entering the Mexican geothermal TIS, possibly triggering a set of actions and reactions in the IS (Carlsson et al., 2002; Jacobsson et al., 2004). However, nearly half of the respondents expressed dwindling hope for innovation within the Mexican geothermal TIS in the years to come due to the combination of a monopolised sector and declining government interest in developing geothermal projects. Survey respondents expressed two needs to encourage entrepreneurial activity. First, there is a need to innovate finance mechanisms to keep geothermal innovation afloat. The high upfront costs and high risks make geothermal installation unattractive for investors. Second, survey respondents said that private participation in energy projects is necessary, despite a recent statement from president Lopez Obrador stating that he wants CFE to maintain 54 per cent of the nation's electricity generation (Martínez, 2019). This could limit the level of innovation, which Jacobsson and Bergek (2011) suggest would cause the TIS to stagnate.

5.4. *Function 4: Market formation*

The fourth *function* is *market formation*. This *function* describes the need for a learning space where different actors can learn how to utilise the technology and further develop it. This can be done either by entrepreneurs who identify market segments which value the advantages over the cost, or by policymakers who promote certain technologies. Casadella and Uzunidis (2017) determine the ability to use and adapt existing technologies in developing countries as more important than developing new technologies, highlighting the increased relevance of this *function* to Mexico's TISs.

5.4.1. *Current phase of market*

Geothermal and solar PV in Mexico have contrasting development histories. Mexico was the first country in the Americas to develop geothermal electricity in 1950. Conversely, it was a latecomer in commissioning its first utility-scale PV plant in 2013. Within the last ten years, Mexico's global ranking in geothermal capacity has fallen, displaying an opposite trend to that of solar PVs, which has increased five-fold just in 2018, pushing Mexico into the top ten countries with solar PV capacity (REN21, 2019). This growth implies that there is a market in Mexico for both technologies, though one is stagnant and the other is increasing in size.

Today, the geothermal generation market is practically non-existent, despite the permit granted to *Grupo Dragon* by CFE to operate a geothermal plant (Flores-Espino et al., 2017). There was an expectation of an increase of geothermal players after the first energy auction, but these hopes dwindled as the two winners of the second auction were CFE and later auctions were canceled by the Lopez Obrador government. The dominant player continues to be CFE, managing all geothermal plants except for the *Domo San Pedro* plant.

The solar PV market has national and international company participation. Large international companies dominate the utility scale, while national companies take on most of the distributed-scale supply, principally assembling solar PV sets. A respondent explained that nationally produced solar cells are too expensive for utility-scale projects.

5.4.2. *Survey results*

Two respondents suggest that international companies are wary about their future participation in Mexico. They foresee limited demand growth for utility-scale solar PV, given the government's opposition to energy auctions and the lengthy and opaque procurement processes. This was identified by a survey respondent and backed by an OECD report (2019a). Survey responses also warn that because of government statements hostility towards projects from international companies can raise amongst those who believe that these companies are taking advantage of Mexican resources, negatively affecting *legitimation* (5.5) of the sector.

Two respondents noted subsidies in electricity consumption as being a market-barrier for RET. The 2013 energy reform abolished such subsidies by liberalising the price. The current administration reintroduced the subsidies, as their removal had been heavily criticised. A likely explanation for why electricity consumption subsidies are considered to be a market barrier is twofold. First, those energy consumers interested in distributed solar PV had less of an incentive to install solar panels on their roofs. Second, subsidising electricity consumption, in fact, indirectly subsidises fossil fuels, which is the prominent fuel generating most of that electricity in the country. To keep electricity prices artificially low, it will require increasing subsidies as fossil fuel plants become older and more

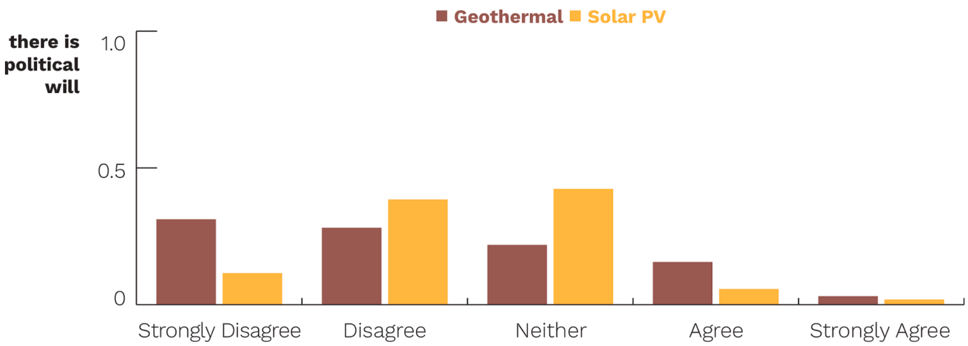

Fig. 8. Survey results on political will, bar-graph.

expensive to run. The risk though of decreasing subsidises is an increase in power theft, a common problem in developing countries (Antmann, 2009). Other drivers for the market are described in *direction of search* (5.2).

5.5. Function 5: Legitimation

The fifth *function* is *legitimation* where new technologies need to be considered appropriate and must be desired. Government strategies or policy statements can send a signal that a particular technology is seen as important or a priority. *Legitimation* is evaluated by the actors of an IS and is achieved through deliberate action by different actors, because there can be resistance to accepting new technologies.

5.5.1. Context

Historically, government support for RET has been overshadowed by political interests to protect the fossil fuel industry (5.2). In 2010, policy changes increased the *legitimation* of RE as an important part of Mexico's energy mix, but recent changes under the Lopez Obrador administration have started to erode this *legitimation* (Fig. 8). The magnitude of the government's role is illustrated by noticing the consensus on the advanced maturity of geothermal and solar PV (Fig. 9) and the minor deployment up until the government relinquished some of its control in 2013 (Fig. 3) (see Appendix B for the historical evolution of government institutions).

5.5.2. Survey results

Based on the survey results, energy experts today strongly support both geothermal and solar PV for several reasons, including decarbonising the energy sector whilst ensuring national energy security with cheaper alternatives to fossil fuel. Two respondents emphasised geothermal energy's unique ability to provide low-carbon invariable energy for heat and electricity.

Most surveyed agree with the need for public support in developing geothermal and solar PV (Fig. 10), per the conclusions of Fairhead et al. (2012). Experts suggest the reason to be a low public awareness of the benefits of RET. Steurer and Bonilla (2016) highlight that climate-related topics are of secondary priority for Mexican citizens, possibly explaining a low interest altogether in clean energy. This perhaps explains survey respondents low expectations for increasing public support, especially for geothermal energy. A respondent explains that geothermal has faced increased resistance by local communities due to past abuses. There have been numerous conflicts recorded in Mexico originating from large scale renewable energy projects. The abuses involved expropriating large plots of land, providing negligible benefits to local and indigenous communities and not taking them in consideration during the execution of the project (Avila, 2018).

International bodies have been involved in Mexico's RE TISs since the 1970s. For example, *PROSOLAR*, the most cited project by the respondents, was executed by the German state development agency, GIZ. Among other benefits, it resulted in co-creating regulation to promote solar PV, contributing to the legitimation of RET.

Only international actors that have supported the legitimation of RET have been identified i.e. no international actors have been identified in Mexico delegitimizing solar PV/and geothermal. On the other hand, national actors can be sorted into those favouring and those resisting RET development. Academic institutions such as ANEL or the Mexican Centre of Innovation (CeMIE) have strongly promoted these technologies since the 1980s. As mentioned earlier, (*5.2*), previous administrations have also demonstrated favour. However, most respondents indicated that the current government has no interest in geothermal development and actively resists solar PV growth. The respondents highlight the radical shift in government support, which ignores the success of recent developments (*Function 4* and *Function 2*). The responses indicate scant optimism towards a change, which is in line with the absence of any mention of RET in the PND (GoM, 2019c) submitted to Congress and the limited public budget allocated to geothermal restoration. A few survey

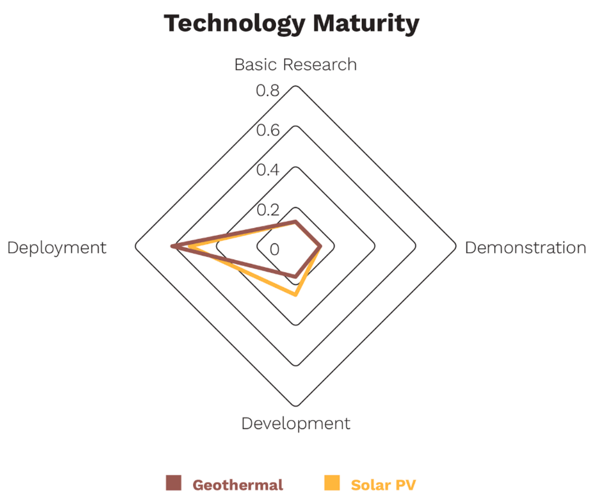

Fig. 9. Survey results, shown in % of survey respondents, on maturity of technologies, radar.

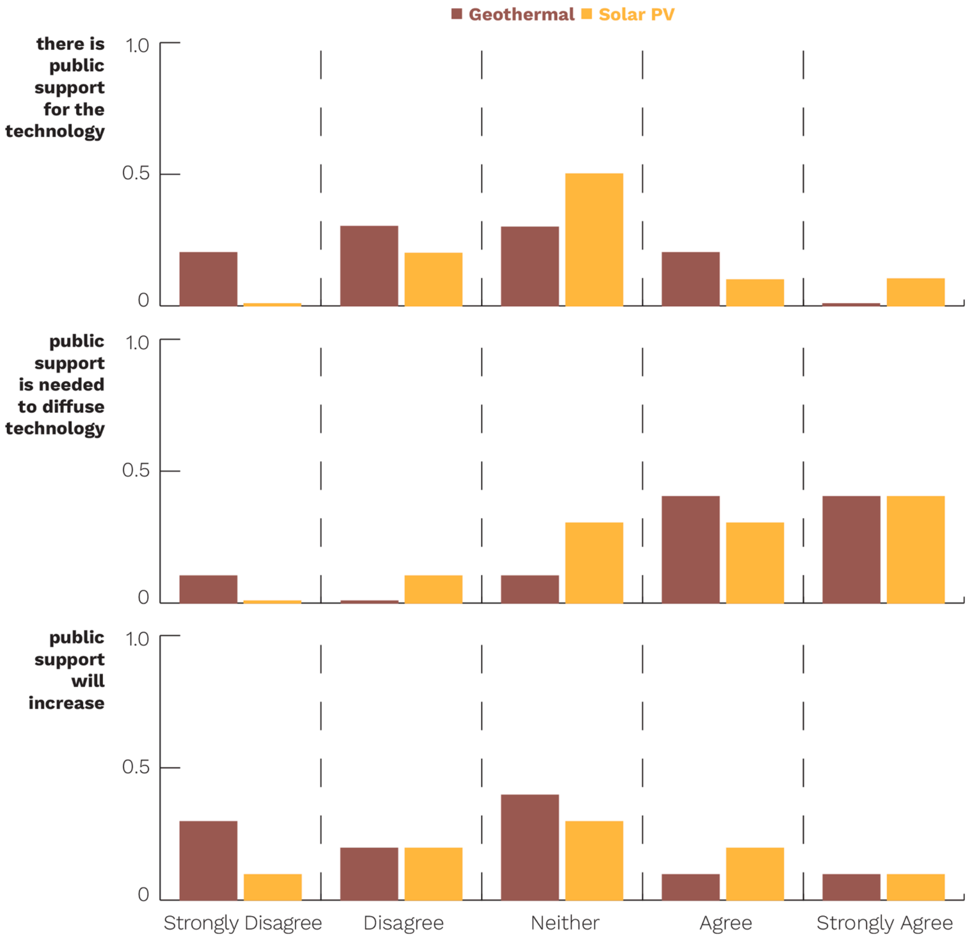

Fig. 10. Survey results on public support, bar-chart.

respondents claim that the government's apparent hostility towards distributed solar PV originates from a fear of losing authority and profits coming from CFE.

As highlighted by seven respondents, rural and indigenous communities also play an important role in *legitimation.* Agreeing with the results from Avila (2018), opposition is not oriented towards the technology but rather against the ways that land is expropriated. As a survey respondent wrote, "the local community always benefits the least." Some responses alluded to academic and social-rights groups denouncing private geothermal and solar PV developments on the basis that they are taking undue advantage of national resources that are vital to the livelihood of rural communities. Without safeguarding local communities' sovereignty, the long-term sustainability of the IS is at risk. The climate crisis is increasingly shedding light on the relevance of ethical and political decisions in addressing the climate change equitably. Beyond companies fulfilling their obligations to shareholders, safeguarding the rights of indigenous communities, and including them in due diligence processes is an opportunity for companies to obtain social license, reduce construction delays because of protests, and ensures that the RE IS maintains public support. The government must ensure rule of law so that good intentions translate to good practices. On one side of the spectrum, regulation can be good intentions without the due process to guarantee fundamental fairness and justice and on the other side of the spectrum, regulation can cause extortion and abuses of the same system intended to protect those rights.

Lastly, survey responses alluded to a competition between the hydrocarbon industry and the RE industry. In fact, President Lopez Obrador has openly stated that there must be a strategy put in place to protect the national oil company, PEMEX, and the state utility, CFE (Obrador, 2019). The president presents numerous reasons which includes the case, discussed above, that international firms abuse local and indigenous communities (Obrador, 2020). Although abuse is not a problem exclusive to international firms, these arguments have justified the changes in regulation to favour national actors (GoM, 2019a) (*Function 2*), changes in budget allocation compared to previous years (GoM, 2019d)(*Function 6*), and changes in mandates to independent organisations (GoM, 2020) that have had direct repercussions on the development of solar PV and geothermal. The impact has been less pronounced for geothermal, given that it is mostly state-owned and therefore does counter the narrative push for national sovereignty. Though the difference in the political support between the previous administration and the current one might seem like an apparent competition between the RE sector and the hydrocarbon sector, the market structure now favouring private companies (i.e. RE) is what is predominately being contested. Based on arguments in defence of national sovereignty presented by the current administration, it could be expected that if most RE projects were state owned, RE would be thriving would it be benefiting the state owned utility (Obrador, 2020). The problem lies in that government does not have sufficient money to invest in all the RE required to meet its climate targets (ElPais, 2020). This suggests that the measures put in place to exclude private sector participation goes against RE, and that though the effort to gain control over the national energy system will cost the country, the direction set by the current administration (*Function 5*) has more relevance in the Mexican RE IS, over any economic evidence.

5.6. *Function 6: Resource mobilisation*

The sixth *function* is *resource mobilisation*. The resources considered can come from human capital, financial capital, and complementary assets.

5.6.1. *Investment context*

Mexico has attracted substantial foreign financial investment since 2012. In 2015, Mexico was among the top 10 destinations for clean energy investments (BloombergNEF, 2018). The magnitude of the investments is exemplified by the USD 6.5 billion (Zarco, 2019) investment in solar PV. Most investments were primarily directed toward wind and solar, leaving out geothermal. For geothermal, investments have been deficient in amount. However, there have been a few glimmers of hope: In 2014, *Grupo Dragon* invested USD 170 million to develop a geothermal plant (Garcia, 2015). Secondly, 26 exploration permits were granted to private companies, thereby bringing private investment into the geothermal TIS.

5.6.2. *Survey results*

At first sight, the survey results indicate a pessimistic view on the accessibility and availability of volume of capital for geothermal and solar PV projects (Fig. 11). For geothermal projects, the high up-front costs in combination with the uncertainties of exploration do not incite loans to be issued. For solar PV projects, credits are deemed by the survey respondents as most relevant (Fig. 12). For utility-

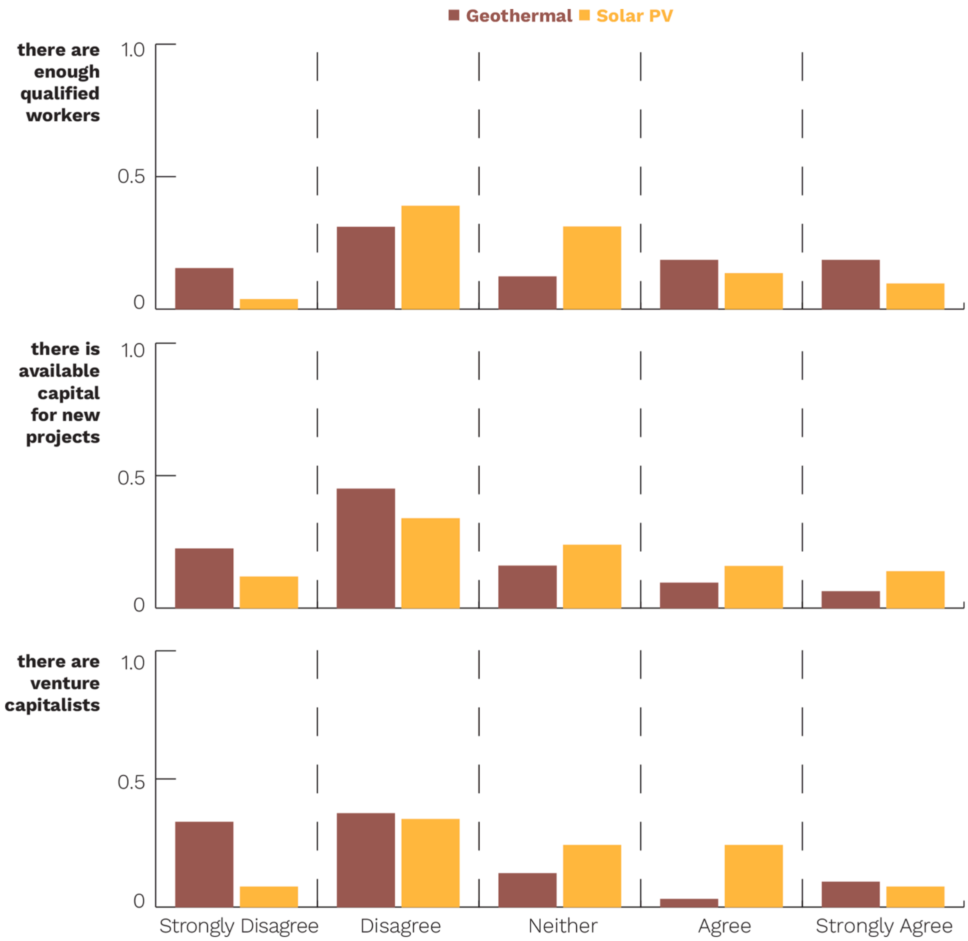

Fig. 11. Survey results on resources, bar-chart.

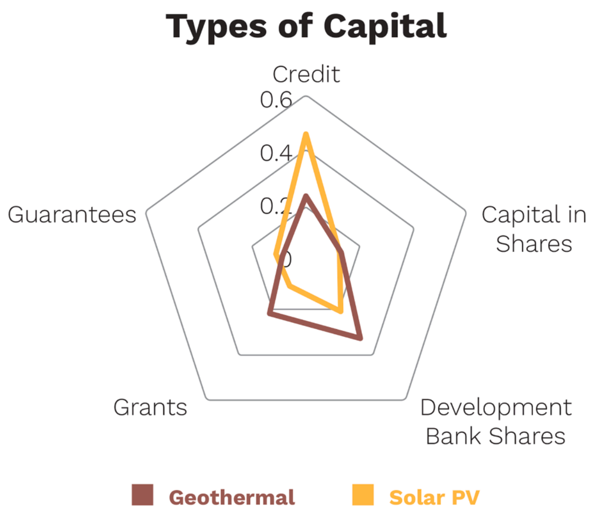

Fig. 12. Survey results, shown in % of survey respondents, on types of capital, radar.

scale solar PV, a respondent described that not having access to cheap capital favours international firms and development banks to be granted utility-scale projects. Survey respondents highlight the role by either the government or financial institutions to address these barriers.

5.6.3. Quantity and quality of human resources

Most survey respondents agree on the poor availability of national human resources for both technologies, and on the fair quality of those available. This conclusion aligns with a report by the International Energy Agency (IEA) revealing the shortage of solar PV-related workforce in Mexico (Villamar and Diaz, 2011). The new government recently cut the budget for the CONACyT-SENER-Energy Sustainability programme which supports Mexican students' study abroad within RET fields (energiahoy, 2019). The budget cuts, along with historically high levels of human capital flight paint an unchanged future (Dumont et al., 2010).

5.7. Function 7: Development of positive externalities

The seventh and last *function*, which is unique to the TIS by Bergek et al. (2008), is *development of positive externalities*. This *function* is an outcome of the rest of the *functions* and indicates the dynamics of the system on a function level (Geels, 2002). As suggested by the previous *functions*, the government through CFE has significant control of the RE TISs, particularly for geothermal. Control over solar PV is still dominated by the government but is slightly more distributed, with other actors playing a growing role in its development. The financial, manufacturing, and marketing sectors play an important role in obtaining financial and human resources, opening the market, and increasing diffusion of the technology. While their success is evident, the recent shift of focus by the government towards gas and oil (5.2) might have significant effects on the evolution of the RE TISs.

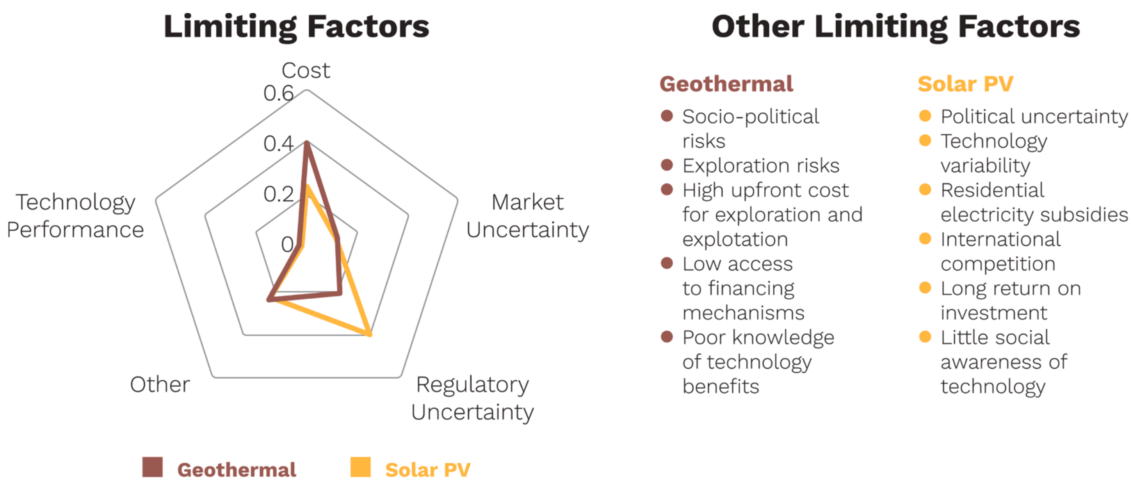

Fig. 13. Survey results on limiting factors, mixed-graph.

5.7.1. Survey results

The survey responses suggest that the current administration opposes RETs in general, resulting in a visible effect in all *functions*. The government has reduced the financial resources for knowledge creation, and instead incentivised the gas and oil TIS. The direction of infrastructure and regulation favours fossil fuels over RET. One respondent suggested that entrepreneurial experimentation needs to find regulatory loopholes to maintain growth in RET deployment. Such comments suggest the government is thwarting the positive externalities that RE can bring to the country.

Nearly all respondents mentioned the element of uncertainty produced by the current government administration as playing an important role in the development of the different function components, thereby affecting their progression of the TIS (Fig. 13). In 2011, efforts to identify and address barriers for solar and geothermal deployment led to the energy reform creating a favourable and more dynamic environment for foreign investment. The current government has been critical of the reform and has halted any further energy auctions, thereby increasing uncertainty. The government is supposed to reduce uncertainty to encourage experimentation, but appears unsuccessful (Bergek et al., 2008). In addition, its control over this space sets the precedent for where and how private entities enter the market. The government prioritises gas and oil, negatively affecting RET *resource mobilisation* (5.6). Since *direction* (5.2), *market formation* (5.4) and *resource mobilisation* (5.6) are components of a TIS, the new characteristics of the Mexican RE TISs suggest little interest in the promotion of RET. In solar PV, the tension is apparent by looking at the high interest of all actors, except the government and some local communities.

5.8. Discussion

This paper evaluates the resilience of two RE technologies amidst a changing political context through the comparison of the solar PV and geothermal TISs. With this comparison, we capture changes across functions, suggesting that the development of the systems is subject to policy support.

For solar PV we notice knowledge development and diffusion (Function 1) and resource mobilisation (Function 6) to be the most sensitive to changing political priorities. Solar PV knowledge creation gained traction at the same time as capital was being injected into solar PV projects. Once the installation trend stopped growing at the same speed, so did publications related to solar PV. This suggests a relationship between funding for solar PV and the output of publications related to the topic. The changing priorities and the reduction of public funds for innovation, universities, or supporting infrastructure, could have blocked the development of solar PV project, and with it knowledge development in Mexico. This situation highlights the space for international capital to develop local *know-how* to realise the full potential of RE in Mexico. Although there is a wide group of professionals educating citizens on RET benefits, public and private efforts are still needed to ensure the benefits that they speak of are safeguarded. In the case of solar PV, the 2013 energy reform addressed the absent competition. Resistance still exists, albeit to a lesser degree for solar PV projects, which is encouraged by the current administration. The success of solar PV can be attributed to the now open market, allowing for *entrepreneurial experimentation* by new entrants and CFE, enabling competition that is consequently lowering prices and encouraging solar PV installations through befitting financial instruments.

For geothermal, given the slower nature of its development, we consider that market formation (Function 4) and legitimation (Function 5) have been the most affected by the changes in priorities from the federal government. The government has instigated through its public communication the importance of saving state owned utilities, of which geothermal energy is almost uniquely state-owned. Therefore, while solar PV and geothermal do not compete directly, the narrative used by the current administration favours the development of geothermal vis–vis solar PV. The absent competition of geothermal developers (Function 4) explains the reduced *entrepreneurial experimentation* (Function 3) in both the execution and financing of geothermal projects, a technology that requires competitive procurement to bring to the table advanced technology to undergo safe and profitable projects. Geothermal capacity growth continues to be impaired because of the scarce financing instruments designed to address the high upfront costs and high apparent risks involved with exploration, therefore making accessibility to capital a barrier for development. A second barrier that geothermal has to address is local community resistance due to misinformation on the health impacts of geothermal plants. Lastly, and arguable the most important one, it must address its affection to local communities due to negative practices and unjust expropriation from project developers.

For both cases, the impact of changes in federal priorities had little impact on the optimism felt by those interviewed (Function 2). It is evident that there still remains a desire to continue developing the RE IS in Mexico, which we argue will be a much stronger driver in promoting RE in the long run. This conclusion should be guardedly considered because this study was not a representative study and it did not consider public opinion concerning these technologies. This is more so relevant as the government continues to propagate resource nationalism with the message that all international energy companies are corrupt and thieves.

The basis of the changes in the development of the TIS seems to rely on developing favourable relationship between actors, allowing them to push for growth in the country in a coordinated matter. In the solar PV case, and presumably in the geothermal case, international actors were key enablers of the IS to thrive. Training programs were provided by international firms interested in exploiting the RE potential in Mexico. The networks in place (e.g. CEMIE), allowed for knowledge to diffuse through the IS, thereby increasing legitimacy and consequently demand. All these inducement mechanisms suggest that *adaptive capacity* (van Alphen et al., 2008) was key to allow for the technology to be implemented in Mexico, but should not be assumed that this was done positively. The cases where communities were opposing firms, largely multinationals, from developing these projects, suggests that absent regulation and enforcement within Mexico could have allowed abuses. With the new policy changes, energy regulation and regulatory agencies became uncertain, naturally driving a deceleration of solar PV and geothermal, which suggests that the *adaptive capacity* was affected by the changes in the federal government. Indeed there were reductions in financing, institutional capacity, no interest in deploying infrastructure, and a narrative from the government depicting all international firms as corrupt. All these actions were at the core of the deliberate changes from the current administration to attenuate the development of RE. However, it is worth remembering that we should not idealise the counterfactual, as not sufficient time was allowed with the institutional infrastructure in place to properly assess how adequate the adaptive capacity was able to manage the market the 2013 energy reform had facilitated. A question remains whether sufficient capacity-building was done, an important element not mentioned by any survey respondent. What can be said is that both private and public institutions are required to bolster different functions to increase adaptive capacity for clean energy to materialise equitably in Mexico. The backlash to the deployment of RE because of the abuses of international companies has revealed probable inequality or transgression experienced by local communities abandoned by the government. This is not exclusive to international firms. But, since most development firms participating in the energy sector are international, it is being used by the current administration as justification for actions favouring national government entities and so, the national fossil fuel industry.

Three points arise from the data analysis. **First,** the Mexican government plays a fundamental role in the geothermal and solar PV TISs through its control over the public financial resources allocated to support RET knowledge development (Function 1). The government is not significantly investing in RET knowledge creation (Function 1), which is an essential condition for a TIS to develop. The dearth of academics and practitioners in the field (Function 6) is indicative of the state's inadequate support. Fortunately, international interest in and collaboration with Mexico's vast amounts of solar and underground heat resources partially make up for the government's low commitment. The 2013 energy reform allowed international firms to participate in the Mexican energy sector, thereby bringing knowledge and financial resources, even when the regulatory environment was not optimal (Function 2 and Function 4), as exemplified by the solar PV case (Function 4). The future of international firms' participation in knowledge formation is uncertain given the unfavourable market conditions, making the state's investment in R&D even more vital, as it is at the heart of a dynamic IS (Lundvall, 2010) (Function 7).

Second, the Lopez Obrador administration's recent shift in prioritization, from RET towards fossil fuels (Function 2), poses a risk to the momentum built up in the geothermal and solar PV TISs. The evolution of TISs in Mexico reflects a cumulative process over a couple decades (Andersen et al., 2002; Dosi, 1988). By looking at the number of publications published and projects deployed, one can infer that the 2013 energy reform contributed to both geothermal and solar PV accumulated learning (Function 1). The accumulated learning, stemming from the investment in RET articulated through regulation and other incentives from the previous administration (Function 2), will most likely continue to direct future learning towards RET (Andersen et al., 2002). However, because of the current government's focus on fossil fuels, the characteristics of the evolving TISs suggest tensions between *direction* and the *knowledge accumulated*. As Carlsson et al. (2002) stipulate, the properties that will determine the endurance of the TISs in the current administration are the TIS' solidity, flexibility, and skills for generating change. While not within scope of this paper, a long list of structural problems such as impunity, lack of education, deficient financial inclusion, and lack of transparency all contributed to fragile TISs context long before the energy reform when the RE TISs were early in their development (OECD, 2019a). Two questions arise: one, whether either TISs have pooled enough resources to endure the change in direction by the government (that is "critical mass" per Carlsson and Stankiewicz (1991, p.107) or "momentum" by Hughes (1987, p.37). Two, whether the already deployed projects and the accumulation of tools, practices, rules, and institutional knowledge gathered over the past years will themselves have an impact on the government's future decisions, as suggested by Latour (1990). In summary, TISs have successfully emerged for both geothermal and solar PV, pulling massive amounts of resources and grabbing international headlines. Yet, changes in the federal government priorities risk jeopardising the future growth of geothermal, and to a lesser extent, of solar PV.

Third, international private capital has been imperative to the evolution of the Mexican RE TISs, but this does not suggest private involvement as a replacement for state participation. As Mazzucato (2013) describes, there is a need to demolish the myth that private firms are efficient and the public sector is inherently inefficient. In Mexico, the complicated public sector history does not negate the role the central government should have across all *functions*, as evidenced throughout this analysis. Both parties must work together, for without an active state, there will be no public or private investment. This research revealed that even though the Mexican government has enabled TIS *functions* to develop, it has done little thus far to be considered an active participant in the RE TISs. Opening the Mexican energy market with the 2013 energy reform was no small achievement, but with it came challenges that required time to diagnose and fix. The transition to an open market required time and investment for actors to learn to operate and best take advantage of the novel situation while protecting the most vulnerable. Had all the changes that came with the 2013 energy reform taken its time, perhaps the state-owned companies might not be as threatened by private sector investment as they are now causing the abrupt changes seen through the *functions*.

6. Conclusion and policy recommendations

6.1. Conclusions

Bergek et al. (2008)'s TIS framework proved adequate in evaluating the resilience of the Mexican RE TISs in supporting RE technologies amid changes in government priorities. The changes in government policy between both administrations were noticeable in the analysis of the functions in the solar PV and geothermal TISs. Both technologies showed weakening characteristics of their respective TIS in several functions. Since solar PV and geothermal generation represent 40 per cent of the 2019 national clean energy generation, the conclusion can be extended to a weakening of the entire Mexican RE sector (IRENA, 2019b). Though differences in system resilience can be inferred between distributed solar PV modules and utility-sized solar PV modules, conclusions are applicable to both. As was noted in section 5, the Lopez Obrador administration policy changes were in favour of national and the fossil fuel economy, thereby impacting RE development generally. A comprehensive national strategy should be put in place to leverage new actors and address the particularities of different RE. This paper contributes to the literature on TIS and innovation in Mexico by collecting primary data and evaluating an emerging economy through the lens of two TISs. It contributes to the work of comparative case studies between technologies, drawing attention to commonalities and differences.

This research strove to remain unbiased by the political situation in Mexico. A future iteration can benefit from the perspective of local communities directly affected by the RE deployment and those in the civic domain to gather an even wider perspective on the RE TISs. Given RET's interaction with law, government, and trade, a political economic lens would shed additional light on the influence of these spheres on the RE TISs.

6.2. Policy recommendations

Based on the conclusions of this work, three policy recommendations follow:

1. The government must take a more active role in promoting RET by communicating a clear and credible pathway for the implementation of RET and addressing uncertainties for both TISs to develop.
2. The TISs for solar PV and geothermal need to facilitate new national actors or welcome international ones that are eager to capitalise on the rich resources Mexico to realise the transition to a low carbon economy. International actors can provide capital and knowledge to finance more complex projects such as geothermal or large-scale solar PV. To encourage an increase in the number of national actors, as seems to be the current government's priority, it is fundamental that there be a strong commitment by the federal government to invest in innovation programmes that foster knowledge creation within the RE TISs. Encouraging new actors will create competition, bringing innovative solutions and pushing costs down. For significant development to happen, the regulatory environment should be foreseeable and stable. The regulatory environment should be welcoming of new actors but should not come at the expense of local communities. Recent structural changes in the energy sector carried out by the government and uncertainty have dissuaded companies from making long term investments in Mexico's RE sector. The political motivations appear to be transient and murky, increasing uncertainty among actors within the RE TISs.
3. The state should recognise the wide socioeconomic benefits of RET in energy security, affordability, and sustainability. Geothermal energy potential, which provides stable and reliable power, should be considered a national natural asset that can enable greater penetration of RET in Mexico.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at 10.1016/j.eist.2022.04.004.

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