Energy transition, innovation, and direct uses of geothermal energy in Mexico: a thematic modeling analysis

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Abstract

This article analyzes factors of the development and diffusion of knowledge and innovation for technologies associated with direct uses of geothermal energy (DUGE) in Mexico, within the context of energy transition policies during the period 2008-2019. The Technological Innovation Systems (TIS) approach was employed for this analysis, given its usefulness in identifying the mechanisms that determine the development and diffusion of an emerging technology in a system. The analysis also involved the elaboration of two thematic models of Latent Dirichlet Allocation (LDA), the results of which showed that TIS for DUGE in Mexico is in a formative stage and is driven by science and technology.

Keywords: Technology Innovation System; energy transition; direct uses of geothermal energy; innovation drivers; functions.

1. INTRODUCTION

Over the last two decades, one thing that has gained greater relevance in communities dedicated to studying development, innovation systems, transitions, sustainability and energy systems is the study of energy transition and the role played by innovation and technology in developing solutions for energy sufficiency and in countries' development (mainly emerging economies) (Sandoval, 1998; Santoyo-Castelazo *et al*., 2014; Vázquez, 2015; Araújo, 2014; Wieczorek, 2018). According to the International Renewable Energy Agency (IRENA, 2017), energy transition (ET) is the path to decarbonize the global energy system and making it zero-carbon. Under the assumption that the accelerated deployment of renewable energies and ET would have an impact on countries' development, especially in emerging economies, it is assumed that developing appropriate technological solutions creates greater societal well-being by creating jobs and improving the quality of life (IEA, 2019). In socio-technical systems' process of change and with the goal of promoting the competitiveness and sustainability of domestic economies (Coenen and Díaz López, 2010), innovation is a key factor in driving ET processes through the development and dissemination of knowledge of renewable energy technologies which allow one to diversify applications beyond generating and distributing electricity (Araújo, 2014).

Based on the above, the Mexican government has set medium- and long-term goals to promote renewable energies so it makes up a greater part of the electrical grid. They hope to achieve this by means of various public policy instruments aimed towards this end; the Energy Transition Law proposed that 35% of electricity generated in the country would come from clean energy sources by 2024 (SENER, 2013).

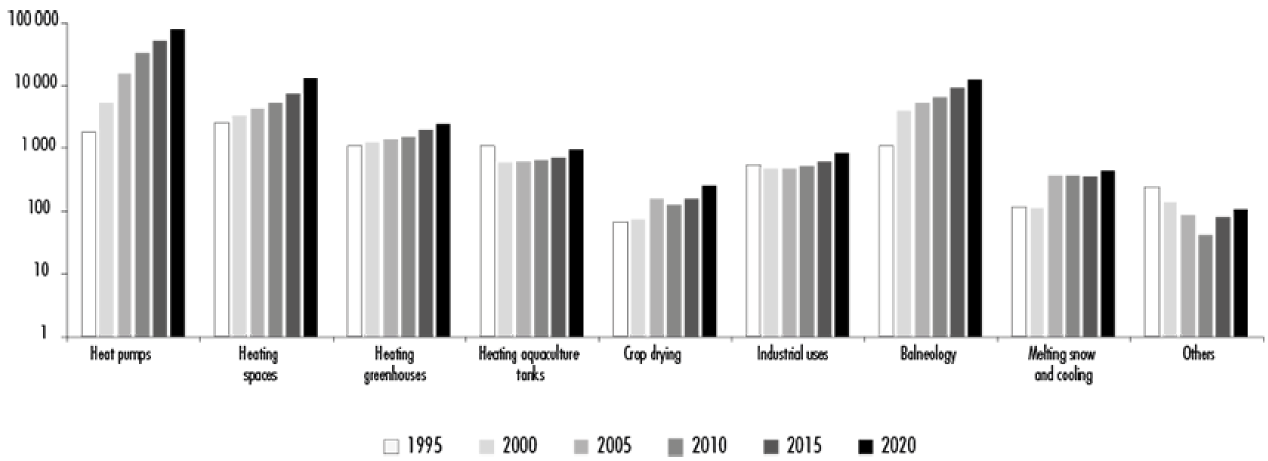
At the international level, the ET discourse focuses on analyzing the role played by solar and wind energy. In recent years, the topic of ET based on clean and sustainable technologies has had greater weight in Mexico, especially in exploring emerging patterns in other areas such as bioenergy, ocean energy, and even low-carbon hydrogen (Morales *et al*., 2017; Silva, 2019). Surprisingly, entities such as the International Energy Agency (2019) consider geothermal energy a renewable energy source with great potential for technological development, though there it has had little penetration in the global energy network compared to other means of generating electricity from renewable sources. There is great potential in Mexico to take advantage of geothermal energy in various forms, nevertheless, its use is limited to recreational applications (balneology) and therapeutic treatments (Hiriart, 2011; Santoyo *et al*., 2012).

This article focuses on analyzing the state of development of the Technological Innovation System (TIS) for direct uses of geothermal energy (DUGE) in Mexico by studying its components (actors and institutions) and proposing the insertion of DUGE in ET analysis as an option drive diversification in the energy sector. Said diversification can be achieved through the use of DUGE in industrial processes, cooling systems for food and warehouses, heating systems at the district level, HVAC for buildings, crop drying, providing energy to greenhouses and in intelligent aquaculture, among others (Sircar *et al.,* 2016; Lund and Toth, 2020).

According to the International Energy Agency's (IEA, 2019) Geothermal Energy report for Mexico, in 2019 Geothermal Energy (GE) had a probable and proven potential installed capacity of 1005.8 MW at a national level. That same year, DUGE reported 156 MW, with a total used heat of 1,162.1 GWH/year distributed in over 160 locations in 19 states of the Mexican Republic (Romo-Jones *et al*., 2020). These resources are mainly hot water with an average temperature of 50 °C and an installed capacity of 155.8 MW, which represents a small fraction of its potential (Santoyo-Gutiérrez and Torres-Alvarado, 2010).

Internationally one of the most common applications of DUGE is district heating. In countries such as Iceland and China, DUGE are used to solve the problem of low temperature with a technology which allows them to provide constant heat at a low cost and with a lower carbon footprint (Tomasini-Montenegro *et al*., 2017). Elsewhere it is used for a wide variety of industrial purposes; e.g., in Italy DUGE are used to make beer and pasteurized milk (Kiruja, 2011; Líndal, 1992; Link *et al.,* 2015; Lund and Boyd, 2015; Ragnarsson, 2003). Figure 1 shows the evolution of DUGE's installed capacity according to its application.

Figure 1. Evolution of DUGE's installed capacity according to application (1995-2015)



Source: created by the authors based on Lund and Toth (2020).

In addition to generating electricity, DUGE can create added value in various economic sectors; a few cases have been documented in Mexico with domestic companies which use geothermal solutions to generate electricity. Among these are the projects developed by Grupo Dragón, which in October of 2014 installed a commercially operational geothermal plant in San Pedro Lagunillas, Nayarit, and, in 2018, a Geothermal Food Dehydrator that functions with DUGE in conjunction with the National Autonomous University of Mexico's (UNAM) Institute of Engineering's Desalination and Alternative Energies (iiDEA).[1]

We turn to look at the literature on TIS functions and innovation drivers to analyze the formation of a system which promotes the development of technologies for various DUGE applications. This perspective indicates that technological developments take place within the context of a system composed of a network of actors, institutions, technologies and the relationships created between them (Carlsson *et al*., 2002). Nevertheless, as TIS are formed gradually, emerging technologies will go through a formative stage before they can be expected to enter a market distribution stage (Jacobsson and Bergek, 2004b). The performance of TIS can be analyzed through the so-called system functions which correspond to various drivers and are defined based on the dominant activities within it, while also considering its components' level of development. Several studies have used the TIS framework to analyze key mechanisms which explain the innovation system's dynamics and their effect on the development and diffusion of technology (Bergek *et al*., 2008; Markard and Truffer, 2008).

The research questions to be developed in this work are the following: "What are the functions involved in the formation of the DUGE TIS and how are they defined?" and "to which innovation drivers do DUGE's TIS functions belong?" To answer them, this research develops a theoretical modeling of the functions involved in forming a system for emerging technologies and an empirical estimate was carried out using topic modeling, a fully automated approach to text analysis.

Automated analysis of large volumes of text using qualitative data mining methods is a growing area of interest in political science and research into public policy with recent applications in the areas of eco-innovation and sustainable transitions (Díaz López and Montalvo, 2015a and 2015b; Coenen and Díaz López, 2010). According to Nowlin (2016), this method tries to categorize and draw conclusions from documents in a systematic way, a technique that facilitates this categorization is topic models.

The objective of this paper was to identify the existing functions in the DUGE TIS to determine the degree of the system's development and determine to which innovation driver its development pertains. The topic modeling (TM) approach was used by applying the Dirichlet Latent Allocation (LDA) algorithm to establish which functions were carried out in the period of 2008-2019. Two models were created to analyze the latent representative issues of the functions carried out in the TIS for the system's components: institutions and actors.

The article is divided into four sections after the introduction. The first takes on the theoretical discussion of TIS in the formative stage, functions and innovation drivers. The second contextualizes DUGE in Mexico at the institutional stage and the applications and technologies developed in that period. The third describes the method and data used for the study. The fourth section shows the results obtained and their analysis by component, as well as the conclusions.

2. TECHNOLOGICAL INNOVATION SYSTEMS IN FORMATIVE STAGES AND INNOVATION DRIVERS

According to Edsand (2019), the TIS framework can be used to analyze the formation and growth of innovation systems. In emerging countries, the analysis tends to focus, in most cases, on the formative stage. The focus of TIS has as its goal to analyze the performance of the system and the factors that affect its performance (Hekkert *et al.*, 2007) and its recent theoretical contributions have contributed to the discussion on the role played by sustainability oriented technological development in stimulating the energy transition.

This approach has been used in several works to analyze renewable energy in emerging countries. For example, Tigabu *et al.* (2015) apply it to analyze the emergence of a biogas TIS in Rwanda. Sawulski *et al.* (2019) study how a TIS is generated in technologically “follower” countries in the case of offshore wind energy in Poland. On the other hand, Bento and Fontes (2015) research the construction process of a new TIS based on wind energy. There they highlight the need to improve the ability to assimilate the technologies in the case of Portugal; while Perrot (2015) applies the TIS approach to track the evolution of agents, networks and institutions which have influenced the generation and diffusion of solar and wind technology in South Africa and India.

Technological Innovation Systems

TIS literature highlights that technologies will go through a formative stage before they can be subjected to a market environment (Jacobsson and Bergek, 2004). In this stage, the actors incorporate themselves into the TIS in order to trigger the creation of networks and the design of institutions which make technology adapt itself to its surrounding structures. Various necessary components for establishing the TIS are outlined during the formative stage, e.g., the accumulation of knowledge and institutional configurations (Edsand, 2019).

The TIS creation process is conceived from the functions which represent essential activities for developing a system which will promote technological advancement. The functions drive the accumulation of the TIS and accelerate the system’s growth through mechanisms of the functions’ positive feedback. This process was named cumulative causality (Suurs, 2009; Suurs and Hekkert, 2009a; Suurs *et al*., 2009b) and refers to how with time the system’s functions interact and strengthen each other. In TIS literature, this process is known as innovation drivers and is analyzed in light of the system’s structure and functions. Both elements need to be thought of as two individual aspects of the topic being analyzed.

The structure of TIS consists of three components: actors, institutions and technology. *i)* Actors bring about the involvement of organizations which contribute to rise of emerging technology, among them are developers, adopters, financiers, etc. *ii)* The definition of institutions is based on North (1990) and consists of laws, regulations and norms which govern the context. *iii)* Technologies are the artifacts and technological infrastructures in which they are integrated (Suurs *et al.*, 2009b). The processes that occur within the system are represented by seven functions that must be fulfilled in order to generate technological development and diffusion.

TIS functions and sustainable innovation drivers

The functions represent activities necessary for TIS accumulation; Table 1 provides an overview of what they imply and the events with which they can be associated so that they may be identified. The work uses Hekkert *et al.*’s (2007) functional analysis proposal to analyze the empirical case.

Table 1. TIS Functions and associated events

Function		*Events*
[F1]	Entrepreneurial activities	Projects with commercial purposes, start-ups, established companies, combination of companies from the public and private sector.
[F2]	Knowledge development	Publications, patents, research projects, national projects, basic knowledge research, technological development research.
[F3]	Knowledge diffusion	Workshops, conferences, exhibitions, international networking, technological collaborations, industrial-academic relations.
[F4]	Guidance of research	The government’s development of a vision and objectives, development of priority areas, incentives, support, and complementary standards.
[F5]	Market formation	Competitive market advantages by means of incentives and backing, government purchases, alignment of national economic and trade policies.
[F6]	Resource mobilization	Specialized human resources, investment in public and private R&D, incubators, technology parks, specialized research centers.
[F7]	Creation of legitimacy	Development of specialized regulations and institutions, norms, intellectual property rights.

Source: Hekkert et al. (2007).

In TIS formative stages, the system's functions present specific dynamics defined by its components' level of development. In other words, performance is conditional on maturity, e.g., if the actors are identified and technological development is present, there must be an institutional adjustment that accompanies these innovations so that technological diffusion is promoted in the long-term.

The definition of drivers is based on the dominant functions which take place in the system and the elements' level of development. They serve to explain how these systems are formed in the presence of various characteristics. It is important to mention that the system's functions do not interact directly but rather through the innovation drivers, i.e., the system's actors act according to existing institutional and technological conditions, creating and supporting events which contribute to the development of TIS in general (see Table 2).

Table 2. Sustainable innovation drivers

Driver	*General characteristics*
Technology Push (TP)	Dynamics are characterized by a strong fulfillment of the functions of knowledge development [F2], knowledge diffusion [F3], guiding research [F4] and resource mobilization [F6]. The engine starts with guidance [F4], relies on resource mobilization [F6], resulting in the development and dissemination of knowledge needed for emerging technology [F2, F3], the cycle ends there and returns to [F4] where it originally began. A second cycle goes from [F4] to [F6] to [F1] to [F4], but this new feedback stage is usually weak. Market Formation [F5] is absent, since in this part business activity does not play a big role, in addition to the fact that the driver can continue its dynamics even without the industry's support. A shared vision arises, providing the technological field with direction. Furthermore, the number of scientists and companies increases and their relationships become stronger, sheltered under the establishment of official support institutions.
Business	Identified by a strong fulfilment of the functions of knowledge development [F2], knowledge diffusion [F3], guidance of the research [F4] and resource mobilization [F6]. What differentiates the Business driver from the TP is the strong presence of the legitimizing function [F7] and entrepreneurial activities [F1] in particular. The sequence of events which characterizes this driver begins with companies, public services and/or local governments that enter the TIS and begin innovative projects [F1], adoption experiments or proof-of-concept projects in general, as they see business opportunities [F4] and with these conditions the actors put pressure on the government [F7]. If the results are positive there is a mobilization of resources [F6]. The results provide feedback and determine the dynamics as they provide a characterization of the setting so that other actors integrate into the system.
System's construction	Implies the participation of all the functions proposed in the literature. The important addition is market formation [F5] which was barely present in the TP driver. The sequence of events associated with this driver begins with companies and other actors venturing into innovative projects, typically proof-of-concept, sometimes with successful results [F1, F4]. As part of these ventures, these actors organize themselves to create platforms where they can share knowledge, but also communicate and coordinate subsequent technological development [F2, F3, F4]. With these platforms, they also push for resources [F6, F7]. This engine results in the national government and large companies becoming an integral part of the system. In the energy sector, such companies often control important infrastructures. The actors of the system form strong networks that induce further development, in addition to needing specific institutional backing to accompany the technology.
Market	Characterized by a strong contribution to Entrepreneurial Activities [F1], Knowledge Development [F2], Knowledge Diffusion [F3], Guidance of Research [F4], Resource Mobilization [F6] and Market Formation [F5]. All the system's functions have a strong presence except for the support of Advocacy Coalitions [F7], which is not so important for this driver. The main reason is that Market Formation [F5] is no longer a matter of policy; a market environment has been created as a result of formal regulations. Instead, Market Formation [F5] is adopted as part of regular business activities, i.e., marketing and promotional strategies which are directly linked with Entrepreneurial Activities [F1].

Source: created by the authors based on Suurs and Hekkert (2012).

Drivers are related to structural factors and some tend to be based on the prior existence of others. This feature causes TIS to develop in more complete and complex structural configurations, which in turn are likely to stimulate the development of more advanced drivers and thereby reach the growth stage. The mechanisms of each driver are not linear, and involve a variety of functions connected through relationships of varying intensity which create feedback. The TIS do not necessarily experience all of these stages, as they can collapse and stop developing. Understanding the system's functions and the drivers that explain its formation is of great import in analyzing DUGE'S TIS's characteristics in Mexico.

3. DIRECT USES OF GEOTHERMAL ENERGY (DUGE) IN MEXICO

In Mexico, Article 2 of the Regulatory Law for Geothermal Energy (DOF, 2014), defines direct uses as those in which geothermal energy can exploit geothermal energy but are separate from the generation of electricity, such as: heating districts or greenhouses and the drying of agricultural or industrial products, among others. Mexico has a great geothermal resource potential which for the most part is used for generating electricity.

At the institutional level, Mexico revitalized the development of renewable energies (RE) in the period of 2008-2019. In this stage, changes were made in the institutional energy framework which favored the development and dissemination of REs and thereby increased their share of the national energy matrix. This led to the promulgation of laws, agreements, treaties and financing that establish the direction taken by energy transition and aid its development at the national level.

The Fund for Energy Sustainability (FSE)[2] was created in 2013 with the main goal of promoting science, technology and innovation in the field of energy sustainability by a variety of actions and prioritizing connections with various actors in the system. That same year saw the publishing of the Law for the Exploitation of Renewable Energies and the Financing of the Energy Transition (LAERFTE),[3] which established a goal of 35% of electricity generation as coming from RE by 2024. To achieve this, the development of RE knowledge and technologies was proposed.

The FSE served to create the Mexican Centers for Innovation in Renewable Energy (CEMIE)[4] , starting with CEMIE-Geo, an industrial-academic undertaking with the support of the Secretariat of Energy (SENER) and the National Council of Science and Technology (CONACYT).[5] It had as its objective promoting and accelerating the use and development of geothermal energy (Jones and Kretzschmar, 2017). The academic institutions that made up the consortium were as follows:

i) the Ensenada Center for Scientific Research and Higher Education, CICESE, *ii)* Mexico's National Institute for Electricity and Clean Energy, INEEL, *iii)* University of Gudalajara, UDG, *iv)* Michoacan University of St. Nicholas of Hidalgo, UMSNH, *v)* Geo-sciences Center, UNAM, *vi)* Renewable Energies Institute, UNAM, *vii)* Geophysics Institute, UNAM, *viii)* Geology Institute, UNAM, *ix)* Engineering Institute, UNAM, *x)* Polytechnic University of Baja California, UPBC, *xi)* Advanced Technology Center CIATEQ and private companies.[6]

CEMIE-Geo developed a Specialized Laboratory System (SLS), where they used various lines of research to deepen their knowledge of the resource; one of these lines was DUGE. From 2014 to 2018 these laboratories carried out projects which shared the general goal of developing technological capabilities and generating knowledge associated with the technologies for various applications of this resource (see Table 3).

Table 3. CEMIE-Geo projects for the direct use of geothermal heat 2014-2018

Application	*Technology*	*Location*	*Actors*	*Stage of development*	*Type of development*
Building HVAC	GHP	Morelos	INEEL	Market research and pre-project	TA
Laboratory HVAC	GHP	Baja California	INEEL and UPBC	Under construction	TA
Climate control for spaces, schools and health centers	GHP	Puebla	INEEL and CFE	Proof-of-concept	TA
Climate control for spaces (hotels)	GHP	Guerrero	Private enterprise	Commercial	TA
HVAC system	GHP	Mexico City	II, UNAM	Proof-of-concept	TD
Greenhouse HVAC	GHP	Baja California	INEEL and UPBC	Proof-of-concept	TA
Buildings' HVAC	GHP	Michoacán	UMSNH	Proof-of-concept	TD
Food dehydrator	FD	Nayarit	Grupo iiDEA	Operational	TD
Office HVAC	GHP	Michoacán	CFE	Operational	TA
Vegetable greenhouse	GHP	Jalisco	CEO Hortalizas	Commercial	TA
Seawater desalination	DS	Baja California Sur	Grupo iiDEA	Proof-of-concept	TD
Food dehydrator	FD	Michoacán	UMSNH	Pilot	TD

Notes: GHP: geothermal heat pump; FD: food dehydrator; DS: seawater desalination; TA: technological appropriation; TD: technological development.

Source: created by the authors based on interviews.

The center's creation and the financing for the development of these DUGE projects show the direction taken by research for the development of technologies related to the geothermal industry. The actors of the DUGE's TIS promoted the development of knowledge and from 2008 to 2019 bachelor's and master's theses on technologies and applications of direct uses articles were published, as were articles for scientific publications and for mass consumption. In 2011, various technological and economic studies were carried out in regards to this resource in conjunction with international organizations such as the Inter-American Development Bank. Starting in 2014, short courses were offered in different geothermal disciplines and dissemination of knowledge was encouraged by means of connecting with experts through various projects and by holding congresses, symposia and national and international workshops on DUGE. In terms of generating specialized human capital, curricular plans were included in graduate programs in the academic institutions that made up CIMIE.

4. METHODOLOGICAL OVERVIEW: EVENT HISTORY ANALYSIS AND TOPIC MODEL

The objective of this paper is to identify the functions present in the DUGE TIS in order to determine to what degree the system has developed and determine which is the corresponding innovation driver. First, we made a map of the main activities and historical processes related to DUGE TIS. The Event History Analysis (EHA) proposed by Van De Ven and Poole (2005) was adopted in order to achieve this. This methodology allowed us to operate and measure the functions of the system by relating them to events, which are defined in terms of the topics discussed in the documents analyzed. The events helped to identify representative categories of functions present in the system. The interaction between system functions was measured by tracking sequences of events which were repeated throughout the period of 2008-2019.

To measure the above we applied the classification technique with unsupervised methods of topic modeling (TM). This involves the automated processing of a body of texts to determine the underlying topics in them (Blei *et al.*, 2003; Mohr and Bogdanov, 2013). TM algorithms are statistical methods which analyze: *i)* the words in the original texts in order to discover the latent cross-textual topics; *ii)* how these topics connect to each other, and *iii)* how they change over time (Blei *et al.*, 2012).

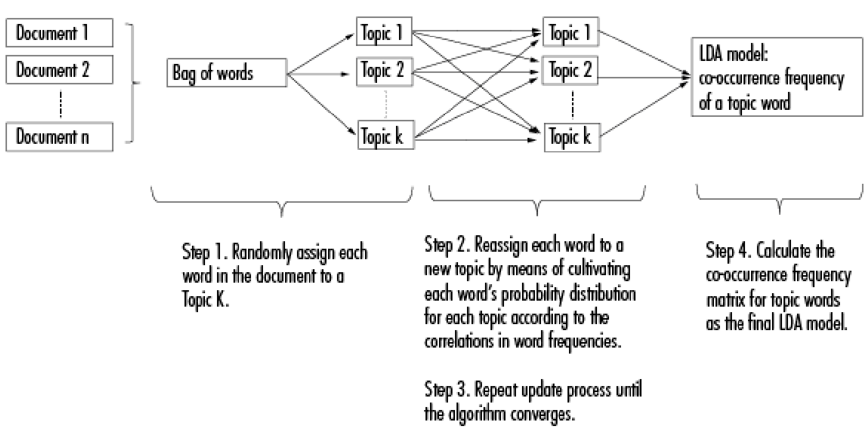
The TM looks for recurring patterns in the content of the texts and does so based on word frequencies. This technique makes it easier to identify latent topics which make up a *corpus* (Blei *et al.*, 2012). There are several algorithms for carrying out TM, including: Latent Dirichlet Allocation (LDA), Pachinko Allocation, Hierarchical LDA, among others (Nowlin, 2016).

LDA Models

LDA models are a useful tool for analyzing TIS functions and are defined as a statistical language model in which each document within a set or *corpus* is seen as a bag of words produced according to a mix of topics that the author sought to discuss. Each topic is a distribution of all the words observed in the *corpus,* such that terms strongly associated with the dominant topics within the document have a higher probability of being selected. In order to run the LDA model the development of an algorithm is needed in the appropriate language to use Rstudio for graphical and statistical computations.

Among the results the LDA model produced is a set of topic distributions by words that associate a probability with each pair of topic words and a similar set of distributions of documents by topic, these describe the probability of choosing a particular topic for each *corpus*' documents. The structure obtained is latent, which implies that topic distributions by words are not associated with an explicit topic label, but with a set of probabilities for words which, when sorted by decreasing probability, are often closely related and therefore considered to be "topics." Figure 2 summarizes the steps in an LDA model.

Figure 2. Schematic diagram demonstrating the sequence used in developing the LDA model



Source: created by the authors, designed with the methodology proposed by Ding et al. (2018).

DUGE's TIS data in Mexico

We analyzed 125 documents related to DUGE TIS from the period of 2008-2020, 60 of which include laws, regulations and strategies developed by the government to accelerate the energy transition and development of REs. The rest of the documents (65) cover information created in the same period related to the development and dissemination of DUGE knowledge and technologies.

In order to study the institution component, we looked at laws, norms and strategies proposed by the government for REs. On the other hand, in order to analyze the actor component, we gathered information related to the development and dissemination of DUGE knowledge and technologies in the same period. We can see their classification in Table 4. These were used to develop two models that gather the largest number of events in the period studied. Data from different sources were triangulated to ensure accuracy (Yin, 2009).

Table 4. Documents scanned

Type of Document	*Number of documents*	*Model*
Programs, strategies, guidelines and regulatory frameworks in the field of renewable energies.	48	LDA-Institutions
Official documents related to technologies for DUGE.	12	
Articles for mass consumption and workshops/conferences.	29	LDA-Actors
Scientific articles.	11	
Evaluations of DUGE technologies.	16	
Interviews with key actors: CEMIE-GEO DUGE project leaders, external consultants from the Federal Electricity Commission and the Mexican Petroleum Institute.	9	

Source: created by the authors.

The results obtained from the models were coded into the functions using the events proposed in Table 1. To that end, we reasoned that the fact that an event was classified into a particular function represented proof that that function existed and that, once a function was established, its impact persisted over time. Functions are therefore considered to be additive and accumulate over time, increasing the actors' and the system's ability as a whole to perform the functions.

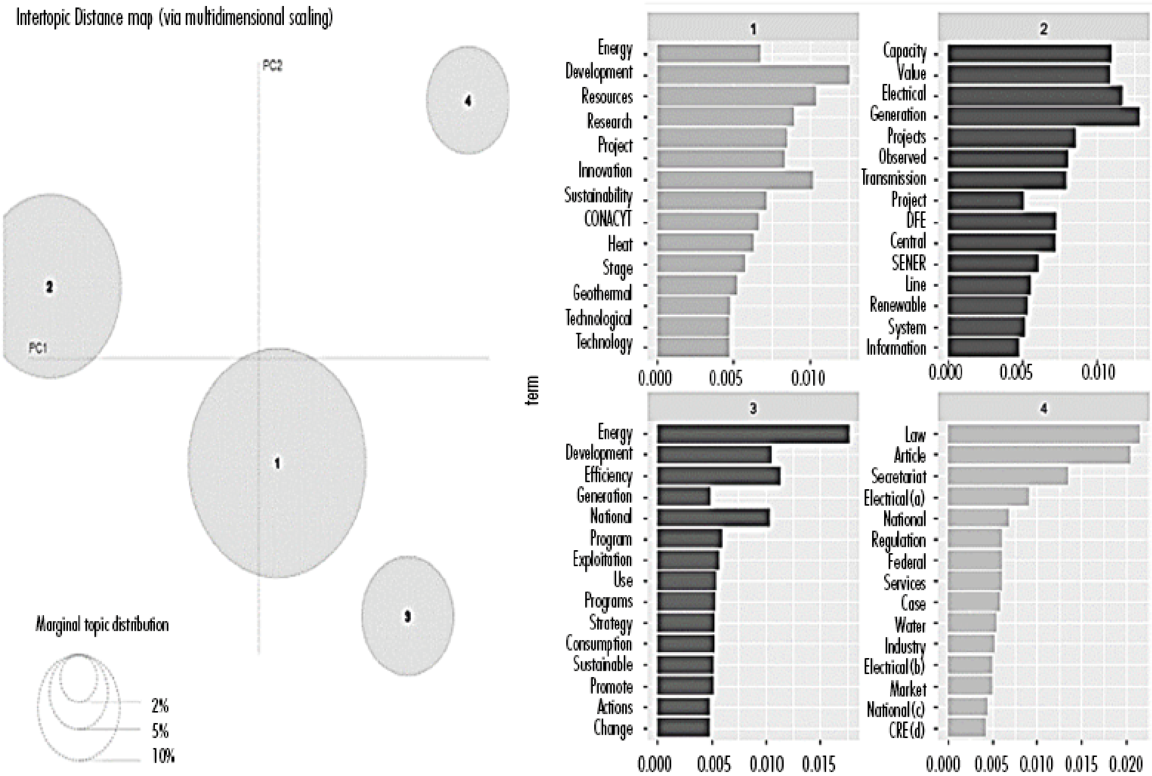
The ideal number of topics (k) was calculated according to Blei *et al*. (2003); determining the value of k is one of the biggest challenges when using topic modeling as, in unsupervised approaches, the researcher is responsible for making sure that the categories derived from the model can be justified based on what they want to prove. For a topic to be representative it must have semantic validity, this means that each topic has to have a clear and coherent meaning which can be detected by the association of terms in that topic (Grimmer and Stewart, 2013). The ideal number of k should be selected based on the research question and guided by the theory. After running several models with k>4, where the results were not representative nor contributed to the explanation, it was determined that k=4 as this was representative for the analysis.

5. ANALYSIS OF THE RESULTS

Two LDA models were created. The first analyzed institutions involved in the TIS development. The second examined the documents related to the performance of the system's components, that is the performance related to knowledge development and dissemination. Both models analyzed were used for the period of 2008-2019. The goal was to understand and characterize at a structural level the performance of the functions and thereby understand the sustainable innovation drivers which dominate in DUGE TIS.

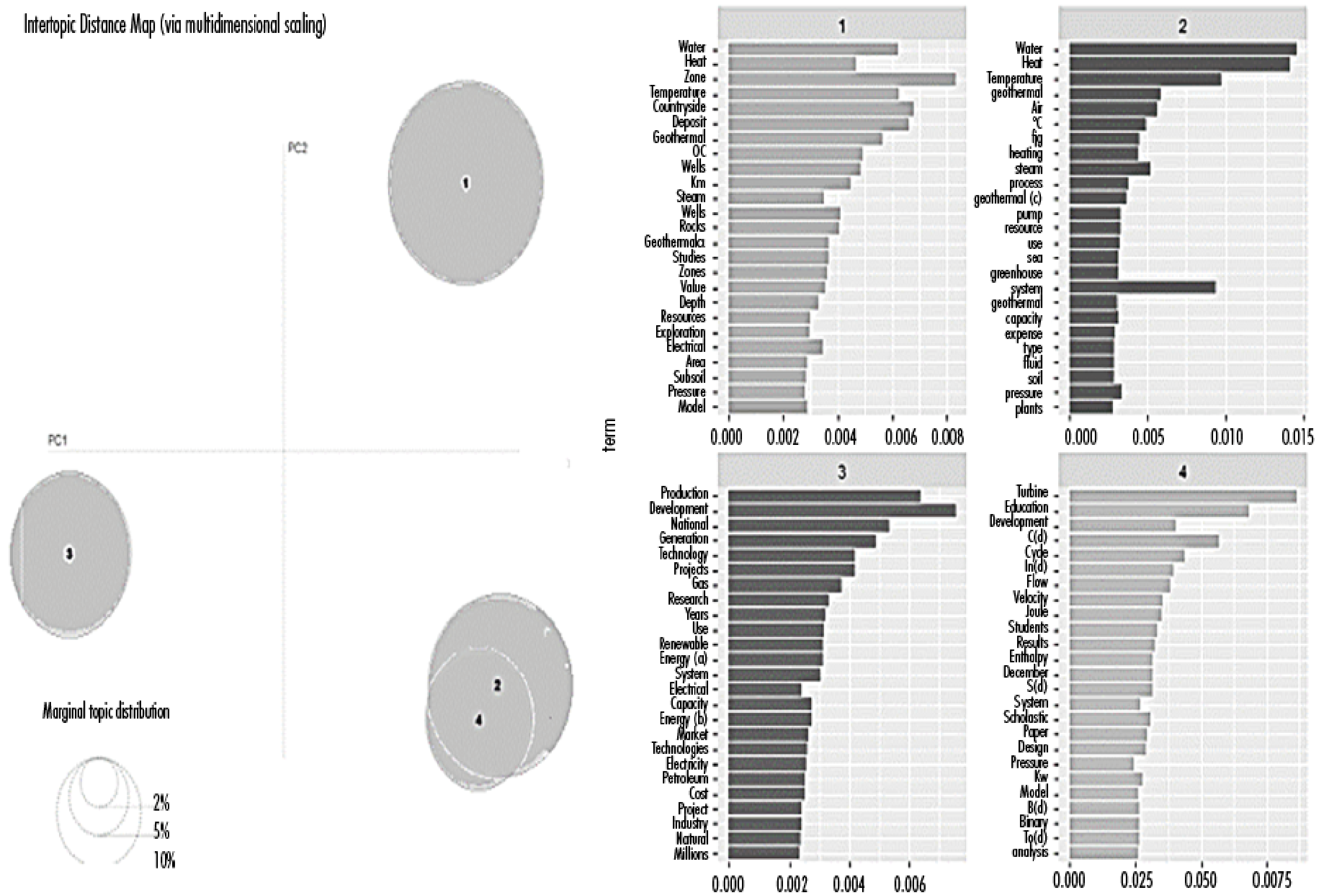
Figures 3 and 4 present the TM results of the developed models. On the left side the themes are displayed as circles in a graph with size indicating the relevance of each one. The right side shows a horizontal bar graph representing the individual terms which were most useful in interpreting each topic.

Figure 3. Topics and relevant terms for the LDA-institutions model



Note: (a)feminine; (b) masculine;[7] (c) plural;[8] (d) Energy Regulatory Commission (Comisión Reguladora de Energía)
Source: created by the authors.

Figure 4. Topics and relevant terms for the LDA-actors model



Note: (a) feminine adj.; (b) masculine adj.;[9] (c) plural; (d) left in the original Spanish.[10]
Source: created by the authors.

LDA-Institutions

The institutional analysis clearly demonstrates that topics do not overlap as they address different functions of the system. This is true in both general and specific terms in the sense that in this analysis the *corpus* is composed of national strategies for developing renewable energies and promoting clean technologies as set forth in the Climate Change Law, National Water Law, Electrical Industry Law, Geothermal Energy Law, etc., and by specific DUGE institutional instruments (such as roadmaps and technological and capacity diagnoses). At the institutional level, the Energy Transition Law (ETL) was brought forward, establishing the Transition Strategy to Promote the Exploitation of Cleaner Fuels and Technologies. This guided national policy for clean energy. As much of the national strategy is based on the improvement of energy efficiency through knowledge and technological improvements, the relevance in analyzing these documents was getting to know how science and technology were presented in order to ensure an increase of RE’s share.

Figure 3 shows how topic 1 is the most representative and discussed throughout the set of documents and constitutes the function of “guiding the research.” This is so as the government defined the parameters with which it sought to promote the ET; for this purpose it defined long-term goals and instruments that would help to meet them. Topic 2 is next in importance and characterizes the function of “creating legitimacy” as it was necessary to create norms which would validate these efforts. Topic 3 represented the function of knowledge development and dissemination and as was previously mentioned, the strategies proposed were based on promoting innovation and knowledge development for REs. Topic 4 corresponds to the knowledge development function for ER and the energy sector in general. The right side of the image shows the top 15 terms for each topic.

Table 5 summarizes the most representative terms for each topic and the function they fulfill based on the semantic validity each one presented. In the specific case of DUGE, legislation promoted identifying and unifying actors relevant to TIS, through the CEMIE-Geo, as with the consortium’s creating a network where participants could interact, thereby promoting and strengthening the link with the industry. This was important, as before the center existed, DUGE's development efforts in Mexico were disjointed.

Table 5. Relationship between TIS topics and functions derived from the institutional LDA

Topic	Terms	Function represented
1	Energy, efficiency, development, national, program, exploitation, use, program, strategy, consumption, sustainable, projects, promote, generation, actions, change, technologies, transition.	Guidance of research
2	Law, article, secretariat, national, regulation, federal, services, water, industry, electrical, market, national,[a] CRE, use, rights.	Creation of legitimacy
3	Development, resources, project, research, fund, innovation, energy, sustainability, CONACYT, heat, geothermal, technological, report, national, sectoral, CEMIE, uses, direct.	Development and diffusion of knowledge
4	Generation, capacity, value, projects, transmission, system, SENER, system, project, information, CFE, resources, millions, distribution, power, gas, national.	Development of knowledge for the energy sector's infrastructure

[a] TL note: plural adjective in the original Spanish.

Source: created by the authors

LDA-Actors

Based on the fact that at the institutional level they sought the development of knowledge and technologies for DUGE, one can see in Figure 4 that topic 1 represents the function of "guidance of research in terms of development, creating knowledge and innovation. The projects aligned with the pursuit of energy efficiency and an energy sector renewed by this type of resource. Topic 2 represents the "development and diffusion of knowledge," and talks about innovation, applications and technologies to exploit DUGE. Topic 3 represents mobilization of resources, both financial and specialized human capital; education and project development were found to be relevant. Topic 4 constituted the knowledge development function, specifically in regards to the resource. Terms such as heat, temperature, steam and water were common among topic 2 and 4, as both topics discuss the development of knowledge, one focused on the resource (geothermal and DUGE) and the other on the resource's technologies or applications (heat pumps, greenhouses, etc.) This is important in developing TIS as, given that both functions are in the formative stage, they are of great import in building the system's foundations.

Table 6 summarizes the most representative terms for each topic and the function they represented based on the semantic validity each one presented. One can see that the research's orientation led the system's actors to both research the technologies for exploiting DUGE, as well as the potential commercial applications. This is relevant as DUGE do not compete directly with electrical generation from solar or wind energy but have the advantage of being applied in various economic sectors. This is why topic 2 provides such clarity where the actors' efforts in developing knowledge was focused.

Table 6. Relationship between topics and TIS functions derived from the actors' LDA

Topic	Terms	Function represented
1	Development, production, national, generation, gas, technology, renewable, research, energy, market, industry, emissions, innovation, natural, costs.	Guidance of research
2	Water, heat, temperature, system, air, heating, geothermal, steam, greenhouse, pumps, desalination, sea, process, drying, humidity.	Development and dissemination of technological knowledge for the resource's applications
3	Education, development, flow, students, results, analysis, state, system, scholastic, work, cycle, school, higher, design, model.	Resource mobilization, in this case reference is made to specialized human capital
4	Zone, countryside, deposit, temperature, water, geothermal, well, heat, rocks, steam, studies, depth, resources, exploration, subsoil, pressure.	Resource-specific knowledge development

Source: created by the authors.

Table 7 shows the findings of this research, identifying the functions related to the events resulting from both LDA models. It highlights that for both components the research's orientation was the most important topic as can be seen in Figures 3 and 4.

Table 7. Functions present in the DUGE TIS by component

Topic	Functions identified in the Actors component	Functions identified in the Institutions component
1	Guidance of Research [F4].	Guidance of Research [F4].
2	Development and diffusion of technological knowledge for the resource's applications [F2 and F3].	Creation of legitimacy [F7].
3	Resource mobilization, in this case specialized human capital is referenced [F6].	Development and diffusion of technological knowledge [F2 and F3].
4	Resource-specific knowledge development [F2].	Knowledge development for energy sector infrastructure [F2].

Source: created by the authors.

To complement the above, we also highlight that in the specific case of DUGE TIS in Mexico, knowledge development is discussed in two aspects for both components: for the actors, knowledge is developed and disseminated in terms of the applications/technology, but it is also important to contribute to knowledge on the characteristics of geothermal resources. The CEMIE-Geo pursues other lines of research which dive deeper into the knowledge of this resource. On the other hand, the institutional component also has two types of knowledge development and it is carried out in terms of technologies, albeit more focused on issues of the energy sector's sustainability and infrastructure.

Based on the above and taking into consideration the functions present in the discourse of each component, one can say that DUGE TIS in Mexico begins with guiding the research [F4], as the government proposed the development of CEMIE-Geo and brought together different actors to create it. To achieve this, it provided financial resources [F6] which allowed the development of research projects and technologies at the prototype level, in addition to providing financial support for specialized human resources. This focuses, at the national level, on the development of knowledge, both technological and resource-oriented. Its dissemination is carried out on a smaller scale due to national and foreign networking events having been promoted, but not prioritized, so the resources in this case determine the presence and strengthening of [F2 and F3], thereby ending the cycle and returning to its original starting point of [F4].

The Market Formation [F5] is absent as entrepreneurial activity does not figure much in this part as this TIS is concentrated and developed within the academic sector and participating companies are spinoffs from academic institutions. In spite of this, they focus on developing the knowledge of applications for commercial purposes. While it is true that the creation of legitimacy [F7] is important at the institutional level, it is logical as the analysis of the component was based on the proposed regulatory framework for encouraging the development of renewable energies. The driver's structural impacts on TIS are related to the rise of a shared vision that provides direction for the technological field. In the period of 2014-2019, the number of scientists and (spinoff*)* companies increased and thanks to the CEMIE-Geo bringing them together in a geothermal specific consortium, the scientists' relationships were strengthened under the establishment of official support institutions. One can then say that the innovation drivers in which DUGE TIS in Mexico finds themselves is the Technology Push and, as a system, in the formative stage, but also seeking the development of its components.

6. CONCLUSIONS

The evidence shows that DUGE TIS finds itself in the formative stage in which its components are not sufficiently developed in order to fulfill the seven functions proposed by the literature. In spite of this, TIS formation responds to four functions directed by the guidance of the research [F4] which gave way to the mobilization of resources [F6], and the combination of both these functions generated the development and dissemination of knowledge [F2 and F3]. This represented the first phase of the system. One can also see that the creation of legitimacy [F7] played an important role as it was the system's formation's main companion in the form of a series of policies and instruments which contributed to its development. This is relevant as it diverges from what was theoretically proposed.

Based on the above, one can say that the driver which defines DUGE TIS formation in Mexico is related to the Technology Push. This mechanism can be highly influential in emerging countries as it creates niches for developing technologies free of market and system failures, such as in the national case. Nevertheless, it is imperative to consider that protected environments have a limit to their growth. This study demonstrates that government support in the form of orienting institutional instruments towards a vision of RE, just like the development of knowledge and technologies, led to the formation of a part of the DUGE SIT, and identified its main actors.

In order to achieve the objectives of the energy transition, it is essential that the State create public policies geared toward a rapid and satisfactory implementation. The developments generated by CEMIE-Geo represent energy alternatives for various economic sectors as they possess the possibility of creating added value by producing goods in a sustainable manner.

The approach adopted by this text represents a methodological contribution for TIS and TS as there is a need to integrate quantitative methods for analyzing these kinds of approaches. The goal of the article was to demonstrate the state of DUGE TIS development in Mexico.

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[1] TL note: from the original Spanish *Instituto de Ingeniería Desalación y Energías Alternas*.

[2] TL note: from the original Spanish *Fondo de Sustentabilidad Energética.*

[3] TL note: from the original Spanish *Ley para el Aprovechamiento de las Energías Renovables y el Financiamiento de la Transición Energética*.

[4] TL note: from the original Spanish *Centros Mexicanos de Innovación en Energía Renovable*.

[5] TL note: from the original Spanish *Consejo Nacional de Ciencia y Tecnología.*

[6] TL note: acronyms from the original Spanish: *Centro de* Centro de Investigación Científica y de Educación Superior de Ensenada, *ii)* Instituto Nacional de Electricidad y Energías Limpias, *iii)* Universidad de Guadalajara, *iv)* Universidad Michoacana de San Nicolás de Hidalgo, *x)* Universidad Politécnica de Baja California, respectively.

[7] TL note: as Spanish is not a gender-neutral language, the word frequency for the feminine and the masculine adjectives differ.

[8] TL note: in Spanish adjectives can be pluralized, resulting in a separate word count.

[9] TL note: as Spanish is not a gender-neutral language, the word frequency for the feminine and the masculine adjectives differ.

[10] TL note: left in the original Spanish.