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SMART GRID DOMAIN: TECHNOLOGY STRUCTURE AND INNOVATION TRENDS

Elona Marku*
University of Cagliari
Viale Fra Ignazio 74 – 09123
Cagliari, Italy

Maryia Zaitsava
University of Cagliari
Viale Fra Ignazio 74 – 09123
Cagliari, Italy

Abstract

Smart grids are an impactful emerging technology in the Information and Communication Technology (ICT) field. Different from prior research, the present study aims at providing a comprehensive overview of the smart grid domain by disentangling the technology structure, depicting the technology landscape, identifying the innovation trends, and highlighting the major players. Specifically, using a patent co-classification analysis and examining the U.S. patents granted from 2010 to 2017, we identified three different technology structures: (1) *core* structure, (2) *supportive* structure, and (3) *complementary* structure. The last two can be conceived as layers that encompass on and gravitate around the core technology of the smart grid. The framework provided can offer insights into a deeper understanding of entry dynamics and standards emergence.

Keywords: Innovation, smart grid, technology structure, technology trends, ICT, patents

Introduction

Smart grids or "intelligent grids" are an impactful emerging technology in the Information and Communication Technology (ICT) field (Chen, Huan, & Chen, 2012; Ho & O'Sullivan, 2017; Gouvea, Kapelianis, & Kassicieh, 2018). The smart grid consists of a modern electric power network capable to increase exponentially the energy efficiency via automated control and modern communication infrastructure (Mohsenian-Rad et al., 2010; Farhangi, 2010; Güngör et al., 2011; Fang et al., 2012; Siano 2014; Li et al., 2017; Kanran & Chanana 2018). The difference with the existing power grid is vivid since the latter converts only one-third of fuel energy into electricity while along transmission lines a significant part of the output is wasted (Farhangi, 2010). The relevance of this convergent ICT domain is not only in its direct effect on the climate change and greenhouse gas emissions but also in its impact on the way policymakers drive regulation, firms invest, and consumers behave (Güngör et al., 2011; Van Der Schoor & Scholtens, 2015; Tricoire, 2015; Ho & O'Sullivan, 2017).

A key challenge is making the smart grid system a reality, but this process requires essential prerequisites such as interoperability and adoption of widely accepted standards (Güngör et al., 2011; Ho & O'Sullivan, 2017). Indeed, the lack of standards has become a focal point in many economy and policy agendas involving the National Standards Institute, the European Union Technology Platform, the Ontario Energy Board, and the Third Generation Partnership Project among others. Also, timing and appropriateness of standards are critical because if standards are timely and well-designed, they provide support for innovation, in contrast, if inappropriate they can hinder innovation (Ho & Sullivan, 2017). So, on the one hand, national and international organizations have the urge to define standards, while on the other hand, firms struggle to develop efficient smart grid networks.

Although the interest of scholars, practitioners, firms, and policymakers in the smart grid field has grown fast, most of the research has focused on the definition of technical attributes, the identification of potential opportunities for firms (Farhangi et al., 2010; Mohsenian-Rad et al., 2010; Güngör et al., 2010; Fouda et al., 2011; Fang et al., 2012; Siano, 2014; Reka & Dragicevic, 2018; Kanran & Chanana, 2018) and value for customers (Clastres, 2011; Gangale, Mengolini, & Onyeji, 2013; Al-Ahmadi & Erkoc, 2018). However, less attention has been drawn to providing a comprehensive overview of the domain regarding its technology structure and landscape, and potential future trends.

Moreover, the current growing ferment scenario opens up great opportunities for ICT firms (and not only them) to enter the smart grid market, even contrasting incumbents that oppose the energy transition (Planko et al., 2017). The uncertainty perceived by firms is empowered by both the absence of defined standards and the intrinsic technology complexity of the smart grid infrastructure, including its interconnected systems and components (Chen, Huang, & Chen, 2012). For instance, the technologies' divergence inside smart grids could be perceived as an advantage for the technical efficiency, but it brings ambiguity about the future the smart grid sector and how smart grid technologies will evolve (Verbong, Beemsterboer, & Sengers, 2013).

For a better understanding of the dynamics related to the innovation scenario of the smart grid field, the present study aims at providing a comprehensive overview by disentangling the technology structure, depicting the technology landscape, identifying the innovation trends, and highlighting the major players. We analyze the information extracted by the U.S. patent documents granted under the Patent Cooperative Treaty between 2010 and 2017 classified in the Y04S subclass. By adopting a patent co-classification analysis and using the Gephi software (a visualization tool), we map and visualize not only the structure of the smart grid technology but also the links between the different technology elements, highlighting boundary and core technologies.

The remainder of the paper is structured as follows. In the next session, we present the literature background on smart grid technologies and patent analysis. Then we describe the method, the dataset, and the tools applied. We conclude by discussing the results, the main implications as well as the contributions and limitations of the present work.

Literature Background

Smart Grid Technologies

Since its development in the early 1990s, the interest on the smart grid technology has grown exponentially among scholars, practitioners, firms, and policymakers (Gurstein, 1991; Mohsenian-Rad et al., 2010; Farhangi, 2010; Güngör et al., 2011; Fang et al., 2012; Siano, 2014; Lee et al., 2016; Kanran & Chanana, 2018; Reka & Dragicevic, 2018). This attention is highly connected to the disruptive change that this technology embodies especially as a solution to the climate change issues. In particular, recent studies have focused on the identification of the most suitable and efficient ICT technologies to be used in the smart grid field, the emergence of standards and how these standards will affect the development of related technologies (Ho & Sullivan, 2017). Another stream of research has highlighted the evolution of regulation to foster efficient business models and technology platforms, but as long as the smart grid is an emerging technology itself, its components are not defined as ultimate solutions (Clastres, 2011; Giordano & Fulli, 2012; Tricoire, 2015). Furthermore, smart grid infrastructure is characterized by a plethora of different elements that communicate with specific paths and sensors to allow interoperability via distribution and transmission (Güngör et al., 2011). In this vein, it becomes salient to investigate the phenomenon using a wide-range approach.

More specifically, the global climate change continually generates demand for sustainable and renewable electric energy requiring alternative sources and smarter autonomous power management (Güngör, Lu, & Hancke, 2010). One of the most significant problems of renewable energies is that they are not always available where and when needed (Hossain et al., 2016). The integration of the renewable energy sources into existing grids comes with a whole new set of barriers since the system of the existing grids is a one-way pipeline without real-time information (Fan, 2013). As businesses move to the cyberspace not only communication, goods selling but also data storages, transactions and money transfers, exchange, auctions and many more, reliable and sustainable power is seen as a significant competitive advantage. Moreover, the cost of blackouts and failures becomes enormous for businesses. Thus, the existing grid is a-mile-less-than-ideal, especially at the light that it converts only one-third of fuel energy into electricity, without recovering the waste of heat. Only 20% of generation capacity can meet the peak demand, and along transmission lines, almost 8% of output is wasted (Farhangi, 2010). In contrast, smart grids represent the key to efficient use of extensive energy resources as they enable “bidirectional flow of communication and electric power between suppliers and consumers, thanks to the pervasive incorporation of information and communication technologies—ultimately transforming the traditionally passive end-users into active players” (Gangale, Mengolini, & Onyeji, 2013: pp. 621; Hossain et al., 2016). Besides, the smart grid delivers and monitors electricity consumption using multi-directional technologies that allocate and meter power flows dynamically to ensure efficiency, savings, and reliability. For this reason, smart grids are characterized by a progressive complexity due to the large volumes of information handled (Chen, Huang, & Chen, 2012).

Patent analysis

Patents grant to their owners a limited-life monopoly power to exclude others from making, using or selling the claimed invention, as such, they play a crucial role in preserving the R&D efforts (Oh, Cho, & Kim, 2014). The innovation literature has broadly recognized the role of patent analysis as a useful method for transforming the information included in patent documents into useful insights for assessing the firm innovation performance (Trajtenberg, 1990; Hagedoorn & Cloodt, 2003; Valentini & Di Guardo, 2012; Di Guardo & Harrigan, 2016; Harrigan & Di Guardo, 2017; Harrigan et al., 2017; Harrigan, Di Guardo, & Marku, 2018), identifying the different dimensions and components of technology (Hall, Jaffe, & Trajtenberg, 2001; Harrigan, Di Guardo, & Cowgill, 2017), tracking the technology evolution and trends, and depicting technology structure (Archibugi & Pianta, 1996; Curran & Leker, 2011; Tseng et al., 2011; Chen, Huang, & Chen, 2012; De Rassenfosse et al., 2013; Karvonen & Kässi, 2013; Suh & Sohn, 2015; Han & Sohn, 2016; Niemann, Moehrle, & Frischkorn, 2017; Lee, Park, & Kang, 2018).

Furthermore, the innovation literature proposes two techniques to map and visualize science and technology structure, namely, patent citation analysis and patent co-classification analysis (Curran & Leker, 2011; Di Guardo & Harrigan, 2012; Karvonen & Kässi, 2013; Jeong, Kim, & Choi, 2015; Castriotta & Di Guardo, 2016; Loi, Castriotta, & Di Guardo, 2016; Marku, Castriotta, & Di Guardo, 2017). While on one hand patent citation analysis allows a more in-depth investigation of the technology flows between different elements (i.e., at inventor level), patent co-classification is more suitable to map and visualize the technology structure and the connections between two or more technologies within a broad technological space (Leydesdorff, 2008; Luan, Liu, & Wang, 2013).

Patent co-classification exploits the information based on the classification codes of a patented invention, in particular, the Cooperative Patent classification system (CPC) encompasses fine-grade information through multiple classification codes assignments (Luan et al., 2013; 2014). The rationale behind it is that if two or more technologies have generated an invention, the relatedness between these components is stronger. Looking more profound in the technological space and examining a broad set of patented inventions, the links between the different technologies and their degree of centrality allow the emergence of specific structures of the sector or industry (Park & Yoon, 2014; Lee, Kang, & Shin, 2015).

Method

Sample and data

In this paper, we examine the smart grid domain because it represents an emerging technology for the next-generation energy delivery (Chen, Huang, & Chen, 2012). Indeed, since the electricity enters all levels of our lives, the cost of blackouts and failures becomes enormous, more and more everyday tools from plagues for our mobile phones to electro vehicles and from

PCs to data storages with billions of servers are dependent on reliable power. For this reason, the smart grid technology is moving very fast, and it is full of uncertainty. Therefore, providing a clear picture of these dynamics can provide new and additional insights into the phenomenon.

Patent information was retrieved using the Derwent Innovation Database. We searched for patents granted by the U.S. Patent and Trademark Office (USPTO) under the Cooperative Patent Treaty that were classified in the Y04S classification code in the time interval that goes from 2010 to 2017. The timespan is particularly important because it is a turning point in this technology field. Our final dataset consists of 4.519 patents.

Multivariate analysis and software

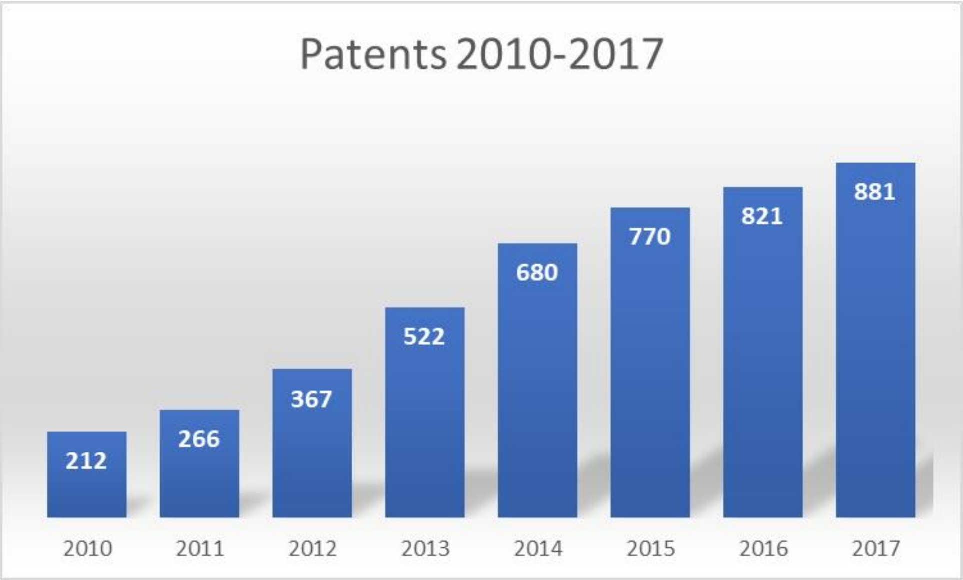
In this study, we applied the patent co-classification method using the CPC codes. Operationally, we built a co-occurrence matrix of the whole smart grid field considering the frequency that two different CPC codes were included in the same patent document. We then performed a multidimensional scaling (MDS) technique to find a structure in a set of proximity measures between objects or elements (Kruskal, 1977). In such a way, using visualization software, it was possible to produce a map in a low dimensional space that optimizes distances between those elements according to a similarity measure (Leydesdorff & Vaughan, 2006).

To map and visualize the technology structure of the smart grid domain, we used the Gephi Graph Visualization and Manipulation software (version 0.9.2; NetBeans 8.2) and chose the Fruchterman-Reingold graph layout algorithm which disposes nodes in a gravitational way, and further applied the nonoverlap and expansion options to make the map clearer. The basic descriptive analyses were performed to produce an indication of the nodes (CPC codes) and edge numbers that represent the relationship between nodes. We performed additional analyses regarding the network diameter, average path length, density (proportion of the potential network connections that are actual connections), average degree (an average calculation of the number of edges connected to each node), among other calculations.

Results

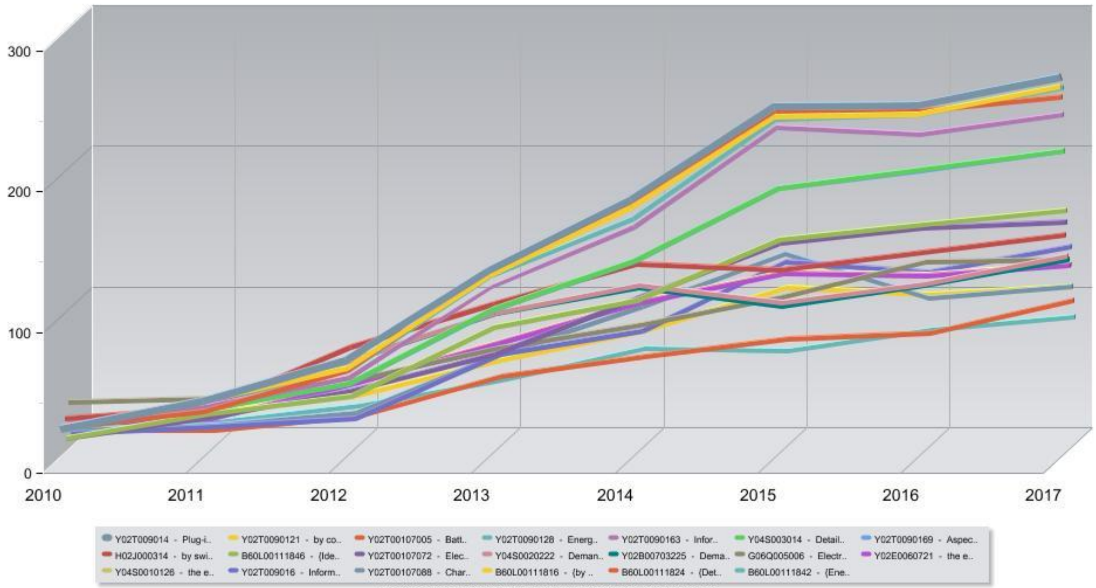
Descriptive analysis and technology trends

The increasing importance of the smart grid technologies emerges clearly by observing the number of patented inventions granted by the USPTO over time. As depicted in Graph 1, the number of patents goes from 212 in 2010 to 881 in 2017.



Graph 1: Number of U.S. granted patents published in the time span 2010-2017

A more in-depth analysis on firms that operate in the field showed that the major players are: General Electric (253 patents), IBM (123 patents); Toyota Motor Co Ltd (123 patents), Iron Inc. (92 patents), Toshiba (78 patents), Panasonic (71 patents), Sony Corp (68 patents), Witricity Corp (61 patents), LG Electronics Inc (60 patents), Siemens AG (55 patents).



Source: Derwent Innovation®, www.derwentinnovation.com

Graph 2: Trend of the top-20 technologies in the smart grid field from 2010 to 2017

To track more in detail the evolution of the elements that comprise the smart grid field, Graph 2 shows the top-20 technologies that include: systems characterised by the monitored, controlled power network equipment involving electricity-based vehicles (i.e., power aggregation of electric vehicles or hybrid vehicles) and interoperability (i.e., vehicle recognition, authentication, identification or billing); plug-in electric vehicles, electric charging stations, ICT for improving the operation of electric vehicles and for charging station selection, ICT for supporting the interoperability of electric or hybrid vehicles (i.e., smart grids as interface for battery charging of electric and hybrid vehicles), energy storage for electromobility, batteries (lithium, lead acid); ICT mediating in the improvement of the carbon footprint of electrical power generation, transmission or distribution (i.e., smart grids as enabling technology in the energy generation sector) focusing on the end-user application control systems characterised by the aim of the control (demand response systems); circuit arrangements for distribution networks by changing a characteristic of the network load by switching loads on to, or off from, network (i.e., progressively balanced loading); electric propulsion with power supplied within the vehicle using power supply from primary cells, secondary cells, or fuel cells by conductive energy transfer (i.e., connectors); methods for the transfer of electrical energy or data between charging station and vehicle (identification of the vehicle), energy stored in the vehicle is provided to the network (i.e., vehicle to grid arrangements), details of charging stations (i.e., vehicle recognition or billing). Consistent with the expansion of the smart grid domain, the technology trends seem to grow continually with few temporary decreases.

Technology structure

Figure 1 depicts the technology structure of the smart grid domain highlighting the links between different technology elements. The field has a very centric structure characterized by a core and two different layers that encompass it, explicitly, we distinguished them as (1) *core* structure, (2) *supportive* structure, and (3) *complementary* structure.

The *core* structure is composed of three technology elements. Not surprisingly, the first component is classified in the class **Y04**, information or communication technologies having an impact on other technology areas, the core of smart grids. This technology element (**Y04)** allows the system to interact and adjust in real-time mode, ICT is an essential distinctive part of smart grids as it makes the different elements of the infrastructure communicate with each other. The second element of the *core* structure is represented by **Y02** classification code, technologies or applications for mitigation or adaptation against climate change. This class is particularly important because it gave the first input to the change of the existing grids and favored the rise of the smart ones. The third technology is included in the **H02** classification code—generation, conversion or distribution of electric power—which is the primary function of any power grid. Thus, the *core* structure includes three milestones of the smart grid domain and enable the functioning of the whole smart grid system. These three technologies are firmly interconnected to each other influencing their development. At the same time, they have multiple linkages and connections with other technologies that gravitate around. As it can be observed, these connections are gradually spread throughout layers. However, there are some exceptions, which can be explained by the specificity of the field. For example, **Y02** technologies responsible for the climate change were historically connected mostly with vehicles emission. Hence, we can observe the most substantial connection on the whole technology map between **Y02** and **B60** (vehicles wheels).

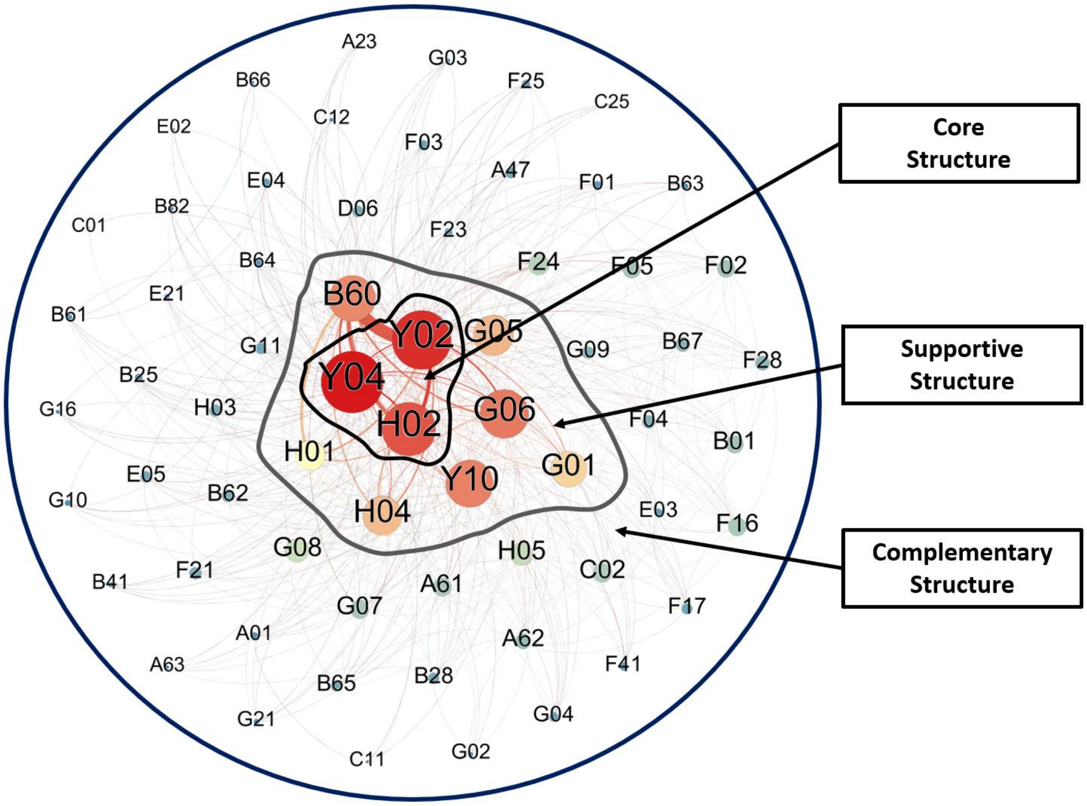


Figure 1: Technology structure and links between the technology elements

The *supportive* structure supports the *core* structure and improves the overall efficiency of the smart grid infrastructure, including its elements: communication, energy management, and climate change influence. This bunch of technologies emerged as the response to the *core* structure needs. Looking at the *supportive* structure, it is larger than the core one; this is logic since going far from the core the diversity of technologies increases to meet the different technology applications. The components embodied in this layer answer to the question *"how"* smart grid operates. *Supportive* structure provides backup functions, vitally important for the smart grid performance. Technologies on computing, calculating and counting (**G06**), measuring and testing (**G01**), controlling and regulating (**G05**) make the grid system intelligent, helping to measure and control performance, to program real-time adjustments in the system. Electric communication technique (**H04**) and basic electric elements (**H01**), literally bring to life cyber communication within the system by enabling its physical form. There are also, technical subjects covered by former USPC (**Y10**) and vehicle wheels (**B60**). As the system expands, the linkages between the technologies within the *supportive* structure become more various. In the case of the smart grid domain, they are gradually spread and do not show strong dependency bias on each other. They are relatively independent one from another suggesting that they could coexist in parallel. However, *supportive* technologies still have a strong relationship with the *core* structure technologies, they gravitate around them with a strong dependency. The case of **B60** (vehicle wheels) and **Y02** (technologies or applications for mitigation or adaptation against climate change) groups discussed above is distinctive.

The *complementary* structure is represented by technologies at the frontier of the smart grid domain. Without influencing the overall ecosystem dramatically, these technologies cover the niche needs of a particular field and complement existing technologies from the *core* and *supportive* groups. *Complementary* structure brings to the smart grid technology tailor-made or bespoke solutions enabling the smart grid efficient performance in different areas and fields. This group of technologies answers to the question *"where"* or in which fields the smart grid can be functional. Thus, **E04** is responsible for the technologies applied in buildings, **C12** corresponds to the solutions in brewing and beer, **B01** covers physical or chemical processes, or apparatus in general, **G04** works with horology, **A01** technologies are applied in agriculture, forestry, animal husbandry, hunting, trapping, fishing and many more. Logically, the patents' classes variety in the *complementary* structure is vast, and interestingly, it covers all the sections under the Cooperative Patent Treaty (A, B, C, D, E, F, G, H, Y). Consequently, the links between *complementary* and *core* technologies and *supportive* structure are various but they are spread gradually and symmetrically, without clear relationship bias.

Discussion and conclusion

In this paper, we examined the smart grid domain by unveiling its technology structure, innovation trends, and major players. We also proposed a framework for a more in-depth investigation of the smart grid technology structure distinguishing three different components, namely, (1) *core* structure, (2) *supportive* structure, and (3) *complementary* structure. It is interesting to note how the output of the smart grid field consists of a combination of these three structures.

The positioning of the smart grid technology (**Y04**) in the *core* structure signifies that the disruption in this sector has already occurred, the main point is how the repercussions of the entrance of this disruptive innovation are going to affect the *supportive* structure and the *complementary* structure. We expect that there is a substantial direct effect on the *supportive* structure as the technologies are trying to adapt to the smart grid technology (**Y04**). If a firm wants to enter the smart grid market, it first needs to know where its technology is positioned in the technological space; then it needs to acquire competencies in the other two structures; this may also lead to partnerships or mergers and acquisitions.

In particular, *the supportive* structure shows a wider variety of technologies which enable the functioning of the whole system. This structure presupposes having competencies also in the *core* structure, for instance, firms with measuring and testing technologies in their portfolios, are more likely to win the market if they have a partnership (or engage in an acquisition) with at least one firm that possesses technology from the *core* structure. These partnerships will make a new entry stronger and more stable on the market. In contrary, technologies with no linkages with the core or at least with the same *supportive* structure technologies will more likely fail on the market as they provide more general and less specialized solutions and can be easily jeopardized by a stronger player. Moreover, the absence of standards in the *supportive* structure makes it appealing to new entries. At the same time, it brings overall uncertainty into the smart grid technology and puts barriers on the governmental level to implement the smart grids.

The *complementary* structure is the most interesting from the point of view of the entry dynamics. Not only it represents the most significant variety of technologies, which emerged as the response to the market need for specialized solutions, but also shows that standards are only starting to shape. If in the *supportive* structure we could observe a competition for standards, in the *complementary* structure some of the technologies are so young that there is not even a reason to talk about standards. Thus, golden opportunities for firms willing to enter the market of the smart grid are salient. It is worth mentioning that technologies in *complementary* structure become specialized covering niche solutions.

The contributions of this study can be summarized as follows. First, it contributes to the innovation and technology literature by proposing a framework for the investigation of the structure of a domain and by pointing out entry strategies based on the technologies possessed by the firm. Second, it contributes to the smart grid literature by disentangling the technology structure of this domain, identifying its major players and innovation trends. Third, managerial contributions can be highlighted, being aware of the positioning of the technology in a scenario with high uncertainty is essential for the gaining of competitive advantage.

Future studies could apply our framework in other technology fields and look if they present a similar technology structure or not, other works might focus for example on the interaction of smart grids and blockchain technologies. Finally, despite the contributions, a limitation of our study is related to the use of patents; some inventions are not patented because firms choose to keep secret some R&D outcomes.

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