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Research article

Transitions as a coevolutionary process: The urban emergence of electric vehicle inventions

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ABSTRACT

This paper combines a multi-sectoral approach with a perspective on the geography of transitions. The concept of coevolution is used to bridge these contributions as it allows to see mutual influences and adaptation between sectors while acknowledging spatial embeddedness and its economic, institutional and social aspects. The argument is discussed using the case of the transition to Electric Vehicles (EVs) and the connections between three technologies: EV, battery, and smart grid. Patent citations are used to construct three main paths allowing to geolocate key inventions and to elaborate on the role of cities in supporting knowledge recombination. The case study suggests that a coevolutionary perspective can contribute to understanding the geography of transitions in three ways: by relating emerging socio-technical configurations to changed power relations and opportunities along the value chain, by exposing the spatial embeddedness of interdependent sectors and by clarifying the role of actors and networks.

1. Introduction

In the past decade, research on socio-technical transitions has expanded into a diversified and interdisciplinary field that has greatly advanced our understanding of how technological change can trigger major societal reconfigurations (Köhler et al., 2019). While this literature has often sidelined geographical issues (Hansen and Coenen, 2015), a coherent agenda has emerged recently with the aim to build more systematic insights on the geography of transitions beyond the observation of “topical concerns” (Binz et al., 2020). This perspective underlines that not only the technologies that support transitions diffuse differently across places, but also that their production implies establishing new paths of industrial development that are embedded in regional production systems and constituted across scales (Binz et al., 2016).

This paper connects these contributions to recent insights on inter-sectoral dynamics showing that transition processes involve exchanges across a plurality of sectors beyond a focal one (Andersen et al., 2020). Even though a coevolutionary approach has often been applied to the relations between regimes and institutions, markets and other societal domains (Geels, 2005), research on transitions has mostly focused on cases involving single regimes and single technologies (Rosenbloom, 2020). Yet contemporary transitions imply a complex interplay and integration of complementary technologies (Markard, 2018). Accordingly, if we admit that the technological *path*-dependencies that characterize transitions are embedded into forms of *place*-dependence (Boschma et al., 2017), successful regional diversification in new technologies requires building to some extent on already localized industries and competences. Thus, the combination of different sectors into new sociotechnical configurations requires the integration of localized innovative capabilities so that some forms of *path-interdependence* are likely to emerge in space through co-location, global networking, or

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combinations of both (MacKinnon et al., 2019).

The goal of this article is to improve our understanding of how the technologies that uphold transitions emerge in specific urban regions through coevolutionary interactions across different sectors. To show the evolution of intersectoral linkages in space and time, I explore the empirical case of Electric Vehicle (EV) technologies and their relations with battery and smart grid ones. Recently, declining prices of li-ion batteries and cheaper clean energy sources have contributed to EVs becoming more widespread (IEA, 2021). EV diffusion calls for major adaptations in electric infrastructures, to manage loads and integrate renewables via smart grid and stationary batteries (Richardson, 2013). Research has found that EV diffusion promoted a change in focus in battery patents (Malhotra et al., 2021). However, we do not know if this holds true also for smart grid patents, and whether convergence between EV, battery and smart grid technologies might correspond to co-localization of patenting activities in the same urban regions. Patent co-location could suggest that geographical proximity plays a role in the development of transition technologies,[1] by favoring knowledge exchanges between inventors and firms from different sectors. In turn, these localized interdependencies at the phase of invention are likely to condition technology production and diffusion, being highly relevant to understand the uneven geography of socio-technical transitions across phases.

I explore the interplay between co-location and inter-sectoral coevolution through patent citation networks, because they indicate knowledge flows and can be geolocated through the address of inventors (Jaffe and Trajtenberg, 2002). The key patents for EV, battery and smart grid are identified using main path analysis (Hummon and Doreian, 1989). Then, I investigate empirically to what extent patents in these technologies share increasingly similar concerns in time, whether they appear in the same urban regions, and the role of applicant firms in this process. This study hopes to advance our comprehension of the coevolutionary dynamics that involve multiple technologies and sectors in the spatial emergence of transitions, and their consequences in studying local development.

2. Theoretical framework

This section connects a multi-sectoral perspective to the literature on the geography of transitions. The former approach sheds light onto the many sectors and phases of the value chain that interact during transitions, but it gives limited attention to spatial issues (Andersen et al., 2020). The latter concentrates on geographical embeddedness at multiple scales but considering only individual sectors (Binz et al., 2020). A coevolutionary perspective can join these two stances, highlighting the role of urban regions with their distinctive productive structures, institutions and networks, in supporting knowledge flows and interactions between different sectors. Coevolution allows to explore how these local specificities relate to the uneven geographical circulation of transition technologies. Besides, it can also help explaining how the regions that create these innovations are able to diversify their economies and build new industries from existing productive sectors. Thus, a coevolutionary perspective offers a broad framework to integrate both approaches and account for socio-technical transitions as spatially grounded, inter-sectoral phenomena.

2.1. The geography of transitions

Research on transitions has engaged with Geography only partially (Coenen et al., 2012; Hansen and Coenen, 2015). The spatial variability of transition trajectories across different locations has been exposed, particularly in cities and developing countries (Köhler et al., 2019). These contributions have brought abundant empirical evidence, but they have often been found to be of limited generalizability beyond the scope of the different case studies. In other words, "the consensus is still *that* place-specificity matters while there is little generalisable knowledge and insight about *how* place-specificity matters for transitions" (Hansen and Coenen, 2015, p.105, original emphasis).

Recently, an articulated agenda has formed around the “geography of sustainability transitions” (GoST) with the aim to move beyond topical concerns and conceptualize issues of scale, place and space more precisely (Binz et al., 2020). In this perspective, cities are key nodes in socio-technical transitions because they are the sites where different sectors and domains of application intersect and novel solutions can be more easily deployed and experimented with (Frantzeskaki et al., 2017).

Moreover, the emergence of localized transition trajectories is contextualized within a multi-scalar perspective acknowledging that in the same way as dominant rationalities are embedded into global socio-technical regimes (Funfschilling and Binz, 2018), the alternative configurations that challenge them also connect cities and regions across scales (Sengers and Raven, 2015; Miorner and Binz, 2021). Not only *diffusion* of transition technologies is being addressed but also increasingly their *invention and production*. In fact, the innovation networks that produce transition technologies require a “strategic coupling” between productive assets that are embedded in specific socio-institutional settings on one side, and global actors and flows on the other (Binz et al., 2014; Murphy, 2015). In other terms, transitions involve not only adopting new technologies and devising the corresponding societal adaptations, but also the emergence of new productive sectors to replace incumbent ones.

Issues of uneven regional development are taking center stage in a geographical approach to transitions, to understand the conditions under which regions are capable to transition towards new, socio-environmentally sound productive paths. Research in Evolutionary Economic Geography (EEG) has shown that relatedness - or some degree of similarity in the skills that sustain different

[1] I use this term throughout the article to indicate, when considering contemporary innovations whose diffusion is not obvious, those technologies with the potential to uphold deep socio-technical transformations, regardless of a judgement on their environmental merits. While it could be argued that the transition potential of specific technologies is debatable, I find terms such as “sustainable” or “clean” technology less fitting to my argument and equally questionable on multiple grounds (Shove and Walker, 2007).

industries – is required in order to renew and diversify regional economies (Neffke et al., 2011; Boschma, 2017; Whittle and Kögler, 2020). In this perspective, existing technological rigidity or path-dependence is linked to place-dependence, and conversely the establishment of new socio-technical configurations involves the creation of new regional growth paths (Boschma et al., 2017). The spatial emergence of new industrial sectors and the restructuring of existing ones are crucial topics to understand transitions, because these processes trigger resistance and power struggles with incumbent interest groups that can delay change and contribute to negatively frame the adoption of new technologies in public debates (MacKinnon et al., 2019).

While observers have warned against the risk of selectively importing simplified geographical concepts into transition studies (Schwanen, 2018), the emergence of an increasingly coherent and substantiated field around the geography of transitions (Binz et al., 2020) suggests that both sides have much to gain by deepening interactions and mutual exchanges. On the one hand, transitions are enabled by new technological combinations, produced within Global Innovation Systems that are embedded in multi-scalar configurations featuring different degrees of geographical 'stickiness' (Binz and Truffer, 2017). EEG can help explain spatial concentration, particularly via the role of localized knowledge exchanges and proximity (Maskell and Malmberg, 1999), and provide an avenue to interpret regional trajectories of diversification and path-creation. On the other hand, a transition approach permits to see that relatedness is a dynamic concept because pressing societal challenges can call for radically new solutions wherein inputs and knowledge that are not linked can become related (Boschma, 2017).

This article suggests that local dynamics can play a role in inter-sectoral coevolution in at least two ways. First, geographical, institutional and other forms of proximity in cities (Boschma, 2005), can foster the recombination of heterogeneous knowledge across sectors. Second, the locations where existing activities have some degree of relatedness to emerging ones might be quicker and more successful than others in supporting new inter-sectoral connections. This article provides a coevolutionary background where these place-specific dynamics can be connected to the emergence of the new inter-sectoral configurations that support transitions.

2.2. Coevolution and multi-system dynamics in transitions

Research on socio-technical transitions has shown that some innovations trigger deep transformations that go beyond the sphere of economy, affecting institutions, social practices, infrastructures (Geels, 2002). This idea came from the literature on the social construction of technological systems (Bijker et al., 1987), and implied that "the evolution of technology and the evolution of society cannot be separated, and should be thought of in terms of coevolution" (Rip and Kemp, 1998: 337). Accordingly, several contributions focused their analysis of transitions on coevolution between a socio-technical regime and its different dimensions. Examples include Geels (2005) on technology and society, Quitzow (2015) on the coevolution of innovation systems and Edmonson et al. (2019) on policy mixes. This study focuses on coevolution of technologies and sectors, suggesting that co-location can promote interactions among inventors, firms, and research institutions and strengthen reciprocal influences between sectors. This approach focuses on the structure of technological relations to explain why some sectors can be considered as coevolving, but it leaves room to integrate the contribution of culture, policy, and other system dimensions to this multi-sectoral dynamic.

Technology is a complex system in which new inventions result from a recombinant search process in which existing modules, or bundles of technologies, are assembled into new configurations (Fleming and Sorenson, 2001; Arthur, 2009). Technologies have varying degrees of interdependence so that a breakthrough in one field can greatly alter conditions in others, creating new growth opportunities and reinforcing coevolutionary feedbacks between them (Kauffmann and McReady, 1995). In the context of transitions, this means that for major transformations to occur, distinct sectors are likely to mutually adjust and interact forming new "development blocks" (Dahmén, 1988). In the case of the Danish wind industry, for example, research showed that through interactions between the agriculture, marine engineering and renewable technology sectors, the cluster became a global leader, pointing at the confluence of unrelated activities into a coevolutionary field (Cooke, 2014). Technology coevolution has been rarely addressed in the transitions literature (some exceptions on multi-regime interactions include Raven, 2007; Raven and Verbong, 2007; Sutherland et al., 2015), and the study of multi-system dynamics is a major research gap (Rosenbloom, 2020).

Of recent, however, several empirical contributions are advancing a multi-sectoral or multi-technology perspective to explain the interdependencies that uphold transitions (Andersen and Gulbrandsen, 2020; Andersen and Markard, 2020; Mäkitie et al., 2022). These studies share a concern for identifying the plurality of sectors that interact around a focal one, and they do so by mapping in detail the components of a main technology of interest and the value chains to which they belong. This approach shows that the adoption of new technologies has different impacts and enables inter-sectoral connections differently according to the parts of the value chain that are considered. This has four major implications: first, it widens the analysis beyond the diffusion phase to include upstream activities of the value chains; second, it nuances the idea that transitions imply radical discontinuity and permits to identify relatedness between incumbent activities and emerging ones in detail. Third, and related to this, it offers a way to reflect on the economic and societal impact of technological change so that sounder policy implications can be sketched. Fourth, even though the cited studies do not have an explicitly spatial dimension, the multi-sectoral approach provides valuable tools to unpack the territorial embeddedness and relatedness dynamics that can affect local productive systems in transitions (Andersen et al., 2020).

Research on socio-technical transitions is increasingly aware that regime change implies not only the alignment of societal domains beyond the economic, but also interactions between productive sectors and technologies. A coevolutionary perspective allows to identify the processes of mutual influence and adaptation between sectors as a result of the interactions between clearly defined categories of actors (Murmann, 2003). At the same time, it allows to accommodate institutional, social and spatial arguments into the analysis (Gong and Hassink, 2019), thereby permitting to frame transitions as multi-dimensional processes that are spatially embedded. To illustrate the relevance of a coevolutionary approach, I consider inter-sectoral linkages in the development of EV, battery and smart grid inventions.

2.3. Inter-sectoral dynamics around EVs

EVs are an old invention, and at the beginning of the 20th century they were already diffused on the streets of New York, London, or Amsterdam, before being replaced by fuel cars (Larminie and Lowry, 2012). After decades of failed attempts at promoting EV adoption (Hoogma et al., 2002), diffusion has accelerated sharply in the last few years, and in 2020 global sales of EV increased by 41% while conventional cars dropped 16% (IEA, 2021). This is likely not a conjunctural event, because technological developments have made EVs increasingly competitive with fuel cars. In fact, developments in consumer electronics have driven battery prices down improving performance (Nykvist and Nilsson, 2015a), the cost of renewable energy has decreased, and "smart grid" systems are being developed to avoid grid overload, route energy demands and integrate intermittent sources (Richardson, 2013; Yong et al., 2015). EVs are therefore implicated in a dynamic of convergence between several sectors including the automotive, chemical, and electric ones (Golembiewski et al., 2015).

Transitions scholars have provided ample empirical evidence on EVs, accounting for their speed of adoption (Köhler et al., 2009; Dijk et al., 2016), the actors and coalitions supporting mobility scenarios (Marletto, 2014), the role of virtual user communities (Meelen et al., 2019) and support policies in different countries including Sweden (Nykvist and Nilsson, 2015b), Norway (Skjølsvold and Ryghaug, 2020), Germany and the U.K. (Mazur et al., 2015). Still, the EV transition has rarely been investigated as a coevolutionary process: exceptions include Haley's (2015) study of the linkages between EVs and the hydroelectric industry in Québec, and Augenstein (2015) who discusses adaptation to EVs in the German innovation system in terms of coevolution. Furthermore, transition-oriented research on EVs has largely ignored invention and production, focusing mostly on diffusion (see Mirzadeh Phirouzabadi et al., 2020, for an exception using patent data).

2.4. Conceptualization and research questions

The goal of this study is to explore inter-sectoral coevolution in the transition to EVs and its spatial embeddedness, both in specific urban regions and within interurban networks. Research has shown that the emergence of the EV market and use environment was associated to a discontinuity and re-orientation in the battery knowledge trajectory, hinting at the existence of coevolutionary feedbacks between the EV and battery technologies, and across stages of the value chain (Malhotra et al., 2021). EV diffusion is also creating incentives to the adoption of renewable energy and smart grid solutions, and the other way around (Richardson, 2013). This is likely to feed-back to the upstream parts of the value chain, by promoting a shift in the focus of patenting and production in the electric sector. Inter-sectoral interactions around the deployment of EVs are likely to feed back to affect invention and production, but I do not address these linkages here, concentrating on invention only.

I consider EV, battery, and smart grid patents. These are complex technologies, whose production involves many components. Each technology is produced within a focal sector, which is defined as "an aggregation of actors having similar production competences and outputs" (Stephan et al., 2017, p.711). Sectors are characterized by their respective core outputs, but they exchange components and finished products with other sectors, so that complex technologies feature multi-sectoral value chains. For example, batteries are a key component of EVs, and smart grid systems can include vehicle-to-grid arrangements: their production involves at least the automotive, electrochemical, and electric sectors. Multi-sectoral interdependences are established at the production phase but are likely to be mirrored also in the knowledge generation process.

This paper considers the EV, battery, and smart grid main paths of patent citations independently, identifying the key patents in the trajectory towards contemporary inventions. Patents are grouped into relatively coherent technology fields whose main concerns and focus of invention can be similar across different main paths. These similarities can imply enhanced exchanges of knowledge and ideas between inventors from different backgrounds, which can be favored by spatial proximity (Maskell and Malmberg, 1999), and lead to increased patent concentration in space. More generally, the geography of inventions indicates what locations support different technology paths and favor multi-sectoral interactions, to what extent they do so for extended periods of time and whether new inventive regions are emerging while others decline. Lastly, patent applicants are exposed: they are major firms or research laboratories that often participate to many patents in different technologies and are connected to several urban regions. The composition of their networks can provide clues on the extent of multi-sectoral integration and the multi-scalar configurations through which they are organized.

Accordingly, I propose three empirical research questions, and a conceptual one. By answering them, this study provides an empirical application of a coevolutionary framework in which the interdependencies that are required by new multi-sectoral arrangements become central to interpret the spatial emergence of transitions.

Empirically, I ask:

1- To what extent does the evolution of key inventions and technology fields in the electric vehicle, battery, and smart grid main paths of patent citations suggest growing cross-sectoral interconnections in time?
2- Which urban regions are most supportive of inventions in the EV, battery and smart grid paths and are they capable of doing so regularly or only during certain periods of time?
3- What inter-sectoral and inter-urban connections emerge in the analysis of the city-applicant network and who are the key actors in it?

Conceptually, I ask:

1- How can a coevolutionary perspective connect the analysis of multi-sectoral interactions in transitions to their embeddedness in regional development trajectories, and what insights can we obtain from it?

3. Constructing technology paths and exploring their urban roots

Patent data are used to investigate inter-sectoral coevolution. Patents are legal titles protecting an invention and granting their owner rights of exclusivity (OECD, 2009), and they are a standardized, easily accessible, and quantifiable tool to measure innovation. Patent data have been used to study EV technology (Oltra and Saint Jean, 2009; Borgsttedt et al., 2017; Mirzadeh Phirouzabadi et al., 2020), focusing on different low-emission technologies such as hydrogen, electric and hybrid vehicles to comprehend the strategies and networks of car manufacturers. However, most patents do not have economic value and only few of them end up being used in successful innovations. By analyzing patent citations, we can get insights on their relative value and on the knowledge spill-overs—along with their geographical scope—that contribute to their emergence (Jaffe and Trajtenberg, 2002; Jaffe and de Rassen-fosse, 2017).

Yet citation counts are not necessarily a measure of patent importance. Therefore, this paper adopts the methodology of main path analysis to identify the most significant knowledge flows in citation networks and make sense of the strategic position and roles of patents (Hummon and Doreian, 1989). This approach is based on reconstructing citation networks in time, then finding the links with a strategic position, i.e., those that serve to connect the highest number of alternative paths between *sources* of citations with recipients of citations or *sinks*. Main path analysis permits to study the cumulative process of knowledge construction dynamically, as it evolves through different technology traditions, and the role of individual inventions in it. Furthermore, it permits to simplify many relations between patents by finding those that matter the most in terms of knowledge connectivity.

Many studies have applied main path analysis to patent networks (Mina et al., 2007; Verspagen, 2007; Barberá-Tomas et al., 2011; Epicoco, 2013). Recently, de Paulo et al. (2020) applied this methodology to EV patents to identify the most promising green vehicle technologies. However, their analysis remains highly aggregated at the national level and no study to our knowledge has used main path analysis to study the emergence of EV inventions at the urban or regional level. In this article, main path analysis permits to assess to what extent the key focus of invention becomes increasingly similar for different technologies, by evolving towards increasingly related applications in time.

3.1. Data and procedure

To build citation networks, I started by selecting technology codes. Several IPC (International Patent Classification) codes can cover a technology, and a patent can be attributed to many codes (OECD, 2009), so I decided to select only one code for each technology (EV, battery, smart grid) but to do so at a high level of aggregation.[2] These codes do not allow a precise delimitation of technologies: by following their patent citations through a snowball method, in fact, it was possible to gather related patents belonging to several other patent codes.

The general IPC subclasses that were identified are the following:

- For EV, Code B60L: “*Propulsion of electrically propelled vehicles*” (WIPO, 2021)
- For battery, Code H01M: “*Processes or means,* e.g.*, batteries, for the direct conversion of chemical energy into electrical energy*” (WIPO, 2021)
- For Smart Grid there is no specific code in the IPC so the Cooperative Patent Classification (CPC) tag Y04S was considered, that refers to “*Systems integrating technologies related to power network operation, communication or information technologies […],* i.e. *smart grids*” (EPO, 2021).

Patents with these codes were extracted from the OECD dataset on triadic families (OECD, 2021a), which includes patents taken at the European Patent Office (EPO), Japanese Patent Office (JPO) and US Patent and Trademark Office (USPTO). Patents in triadic families have been submitted to the world’s leading jurisdictions at the same time and therefore they are considered particularly relevant technologies (Dernis and Khan, 2004).

Because the analysis is centered on patent citations, I decided to consider only US patents. In fact, while the USPTO requires in-ventors to provide all known references to related inventions (“duty of candor”), the EPO does not (Webb et al., 2005). Hence, US patents always include many citations whereas EPO ones often do not contain any. As a result, I decided not to mix patents from different citing traditions and to consider only those from USPTO which is also arguably the most competitive and innovative patent jurisdiction.[3] Also, only granted patents were included because they represent a safer indicator of relevant inventions compared to patent applications which can be abandoned or rejected.

After extracting the first sample of patents, an SQL script was applied to browse recursively the citation dataset (OECD, 2021b) looking for all patents they cited and for all subsequent citations, ending the search only when no additional patents were added. This

[2] The codes selected are subclasses, which are the third hierarchical level of the IPC after the eight main sections and the subsections.

[3] Although the choice of considering only USPTO patents seems limiting, it is important to note that most of the documents at step 1 have a correspondent registration in the EU and Japanese patent offices, so that inventions produced in these two jurisdictions are mostly accounted for. Furthermore, inventors of USPTO patents are located all over the world.

Table 1
Patent numbers at each step by technology.

Key steps in main path construction	Electric Vehicle	Battery	Smart Grid
Step 1: first extraction (search technology codes in triadic families)	7′539	26′758	697
Step 2: build the full network (snowball citations of patents)	Nodes: 2.9 million Links: 13.9 million	Nodes: 3.1 million Links: 17.7 million	Nodes: 2.9 million Links: 14.4 million
Filter networks by keywords	Nodes: 20′446 Links: 47′350	Nodes: 142′960 Links: 469′263	Nodes: 5′820 Links: 9′295
Main paths of patent citations	Nodes: 54 Links: 55	Nodes: 42 Links: 44	Nodes: 50 Links: 57

yielded three large citation networks, that sometimes included very different technologies than those I was interested in. Thus, full networks were filtered by selecting only granted patents and searching for documents that contained relevant keywords in the database Patentsview (2021), containing all USPTO patents with titles and abstracts.[4] Table 1 summarizes the key steps and the number of documents found for each class.

To calculate main paths, I applied the Search Path Count algorithm (SPC), which counts all paths from source to sink nodes and calculates traversal weights as the proportion between the number of paths in which a link appears with respect to the total number of paths (de Nooy et al., 2018). Traversal weights measure the relative importance of citations in connecting two patents and keeping the network connected. Then, the ten key routes with highest traversal weights were selected, so that it was possible to reconstruct the main path linking source and sink patents along with several secondary paths that might have contributed to the main one. Because recent patents can cite very old ones, the main paths were traced until the early 20th century.[5] However, the citation dataset included documents starting only from 1976, which means that backward citations for documents before this date could not be retrieved.

3.2. Patent geolocation

The address of inventors is usually considered as the safest indicator to geolocate a patent, because applicants can have multiple addresses and headquarters in different countries (OECD, 2009). However, patents can have multiple inventors in different cities, which prevents a univocal assignation. To account for multiple inventors' locations, fractional counts were used, assigning an equal share to each inventor's location. The dataset published by de Rassenfosse et al. (2019) was mobilized to rely on accurate location data, and for the few main path patents for which information was missing, I manually searched within patent files to geolocate their inventors. When applicants had many locations, I considered them connected to the locations of inventors.

After geolocating patents, the paper accounts for the fact that, although the address corresponds to a small town or residential neighborhood, inventors usually gravitate around a major metropolitan area in which their workplace and connections are. To this end, I used the concept and related dataset of Large Urban Regions (Rozenblat, 2020), defined all over the world on the basic concept of Mega-city region (Hall and Pain, 2009), which describe the fact that economic dynamics transcend administrative boundaries forming large regional systems of workers and firms around urban agglomerations. One of the key features of LURs is that they also represent the gateway to long-distance connections, so the main airports are considered as the geographical center of the LUR. Hence, inventors were assigned to LURs with an algorithm that calculated the distance between an inventor's address and LUR centers, choosing the closest one.

4. Results

In this section, the main paths of patent citations are presented for the three technologies of EV, battery, and smart grid. The technology fields that compose each path are distinguished based on their main focus and position along the path, and the relative centrality of patents is exposed to understand their role in connecting different groups of inventions together. Then, patent locations are analyzed, zooming on the urban regions where technologies emerged. Finally, I elaborate on the role of applicants in connecting cities through their global networks and supporting long-term inventive capabilities in the regions where they operate. Patents from 1920 to 2020 are included, permitting a reflection not only on *where* inventions emerge but also *when*. With these results, the empirical research questions are answered, before turning to the conceptual one in Section 5.

4.1. Three main paths of patent citations

The main paths of patent citations represent the key knowledge flows and connections on which contemporary inventions build

[4] The Electric Vehicle citation network was filtered by selecting only patents that contained "Electric(al) Vehicle (s)" in either the title or abstract of the patent. The battery citation network was filtered by selecting only the patents that contained the words "Batter*", "Anode" or "Cathode" in the title or abstract. To identify the key words in the smart grid citation network I proceeded to a textual analysis within the smart grid patents (tagged Y04S). From this I decided to select all patents in which the word "grid" was combined in the title or abstract to any of the following: "smart", "network", "energ*", "power", "load", "renewable", "current", and "storage".

[5] Patents were dated using the date of the first publication of the application document.

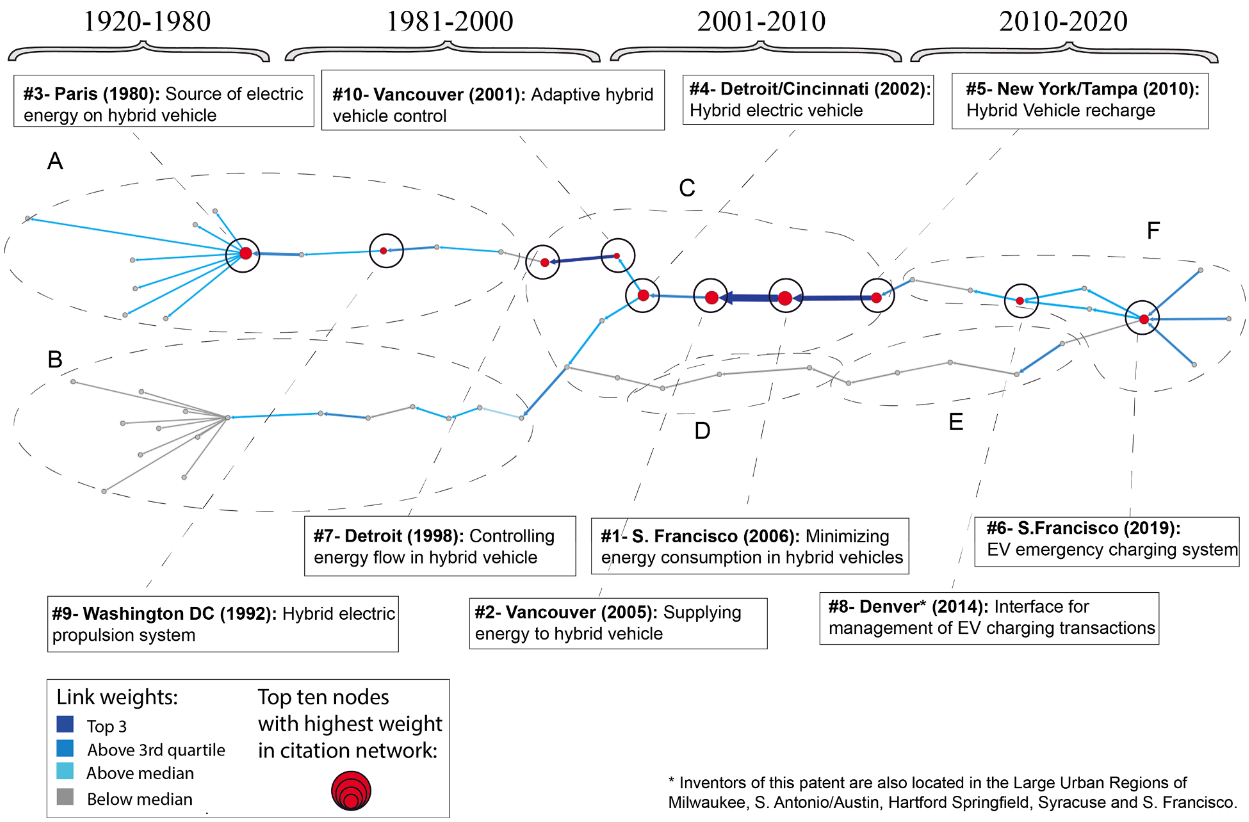

Fig. 1. Electric Vehicle main path in time with the ten most central patents in the citation network and six key technology fields.

upon. When patents share a similar technology focus, it is possible to group them into clusters along the path, that are distinguished by letters (A, B, C, etc.). Furthermore, we can compare link weights—or the strategic position of patent citations in connecting patents together—to evaluate the importance of different nodes and branches of the path. The 10 patents with highest citation weights[6] are highlighted, along with their rank, location, year, and summarized title. This information is essential to contextualize the technology developments that characterize the path, with the patents and locations that contributed the most to it. All three graphs should be read from left to right following the historical periods that are indicated on top.[7]

4.1.1. Electric vehicle main path

Groups A and B (Fig. 1) include the key building blocks that permitted the development of hybrid vehicles. Group A reunites patents related to propulsion systems and their capability to use different power sources and switch between them, while group B features inventions related to automatic vehicle transmission and regenerative braking capabilities. Patents in group C built on these contributions and created several highly central inventions in hybrid vehicle technologies. These patents represent the core of the EV main path because hybrid cars incorporate most technologies that are required for a fully electric vehicle, the main difference being that the latter do not have a combustion engine and have enhanced battery capacity. Group D and E are part of a secondary branch that includes, respectively fuel cell vehicle patents and inventions related to EV frame and structure (such as a battery holder). Finally, group F features patents about recharge interface, battery swap technologies and recharge methods. As EVs gradually become a more viable option, these patents embody a clear shift in focus towards providing a safer and quicker recharge process for fully Electric Vehicles.

4.1.2. Battery main path

The battery main path (Fig. 2) does not display a clear separation into branches of different importance. In fact, the main patent group A unfolds from 1978 to 2010 and comprises inventions that have to do with monitoring battery conditions and state of charge. Group B deals with security issues during recharge, and group C includes battery applications to electric tools. Group D features the highly ranked patents #2 and #4, related to battery recharge and battery swapping technologies applied mostly to electric motorbikes.

[6] Patent (node) weights are attributed by summing the weights of the edges to which they are connected.
[7] Refer to appendix for the full patent list for each main path.

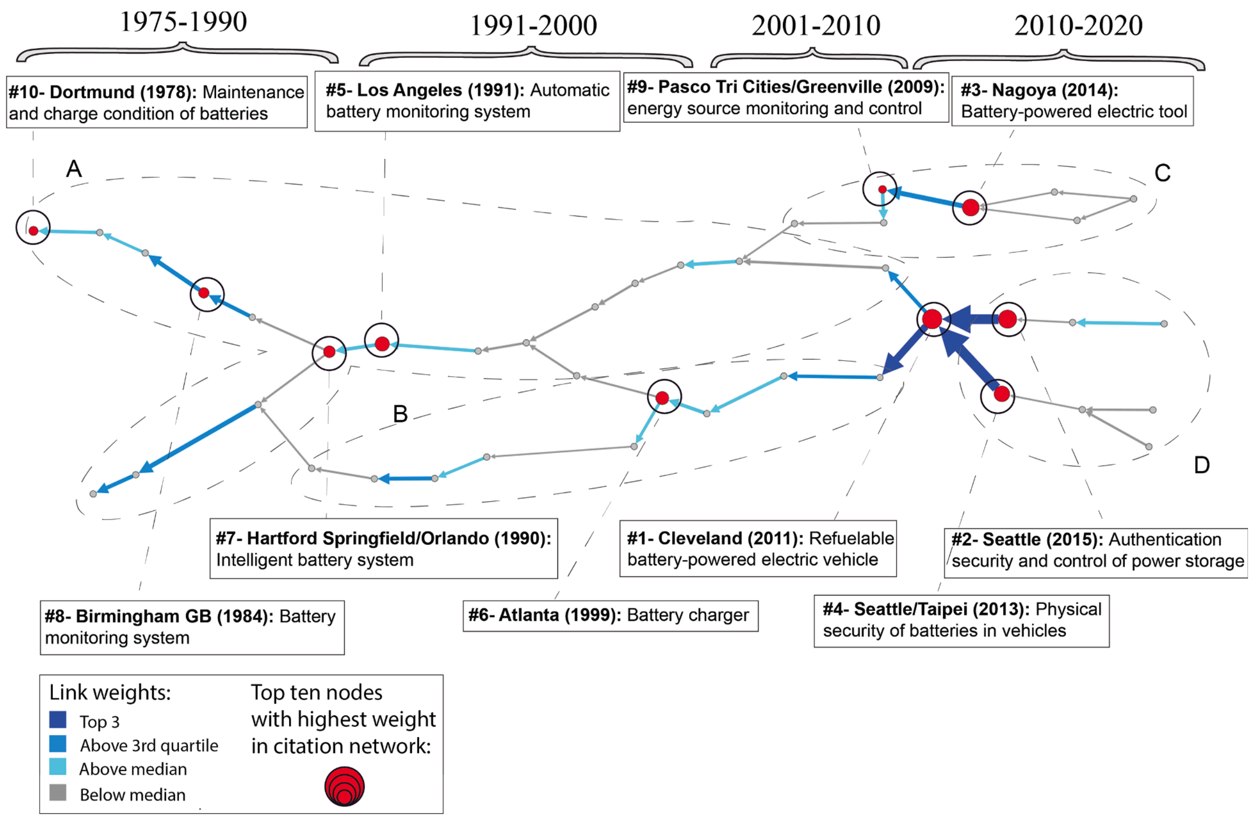

Fig. 2. Battery main path in time with the ten most central patents in the citation network and five key technology fields.

Even if these inventions do not directly refer to electric cars, it is reasonable to assume that after being already applied to electric scooters, battery swapping might find an application to EVs in the future.[8] Furthermore, it is important to remark that patent #1, the most central invention in the battery path, is directly concerned with the EV recharge process.

4.1.3. Smart grid main path

The smart grid main path can be divided into three main patent groups (Fig. 3). Group A comprises several patents that have to do with voltage regulation, control of electric lines, electric generators, and circuits for control of induction furnaces. Group B is the core of the smart grid path and reunites inventions associated with wind energy generation. Patents #1, #2 and #6 are the most central in the path because they contributed to the development of generators that can cope with variations in rotor speed. The capability to accommodate fluxes coming from different energy sources is crucial also in group C technologies: while some of these patents still have to do with wind turbine controllers, the majority tackles the issue of controlling distributed energy sources and their interaction with the power grid. Specifically, the four patents in the highlighted EV subgroup have to do with EV recharge, but one of them deals with vehicle-to-grid systems, whereby EV can stabilize grid loads and stock renewable energy by charging and releasing electricity according to demand.

4.1.4. Main paths and inter-sectoral connections

The analysis of the main paths of patent citations has provided elements to support the assumption that there are increasing similarities in the main technology focus of EV, battery, and smart grid patents. Specifically, we have seen that the trajectory of EV inventions is rooted in the key contributions of hybrid vehicle technology in the areas of electric propulsion, regenerative braking, energy control and recharge. While this is true until 2010, the newest part of the path shows a clear change in orientation towards improving battery performance and charge process, to allow independence from combustion engines. At the same time, patents related to fuel cells appear in a secondary branch of the main path, which suggests that the bulk of inventive efforts are concentrating around improving battery EVs over competing solutions. The heightened centrality of batteries for EVs is mirrored by the fact that the most central patent in the battery path is an EV invention (patent #1) and other central contributions (patents #2 and #4) relate to battery swap methods that are also featured in group F in the EV main path. In the smart grid path, EV patents do also appear in recent years in

[8] Gogoro, the Taiwanese company that applied for these patents, has deployed an extensive network of battery swap stations for electric scooters in Taiwan.

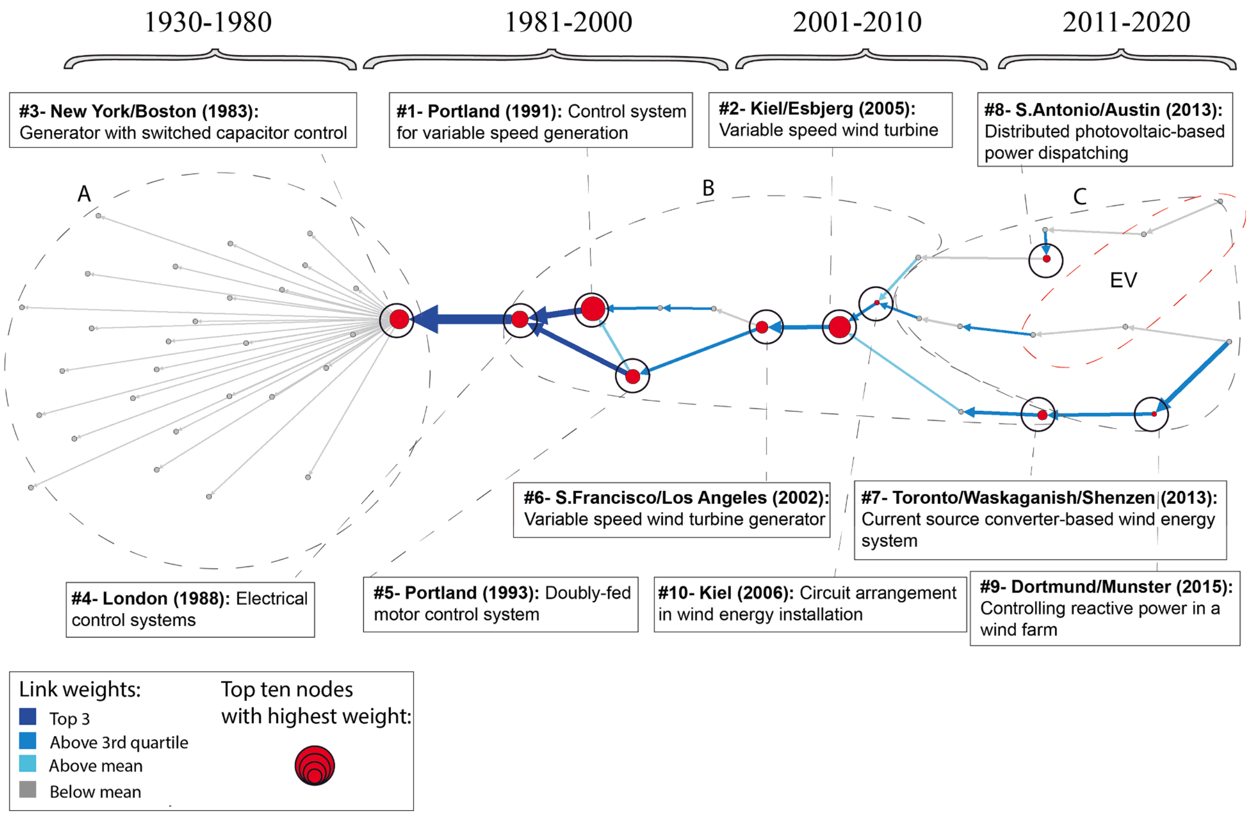

Fig. 3. Smart Grid main path in time with the ten most central patents in the citation network and three key technology fields.

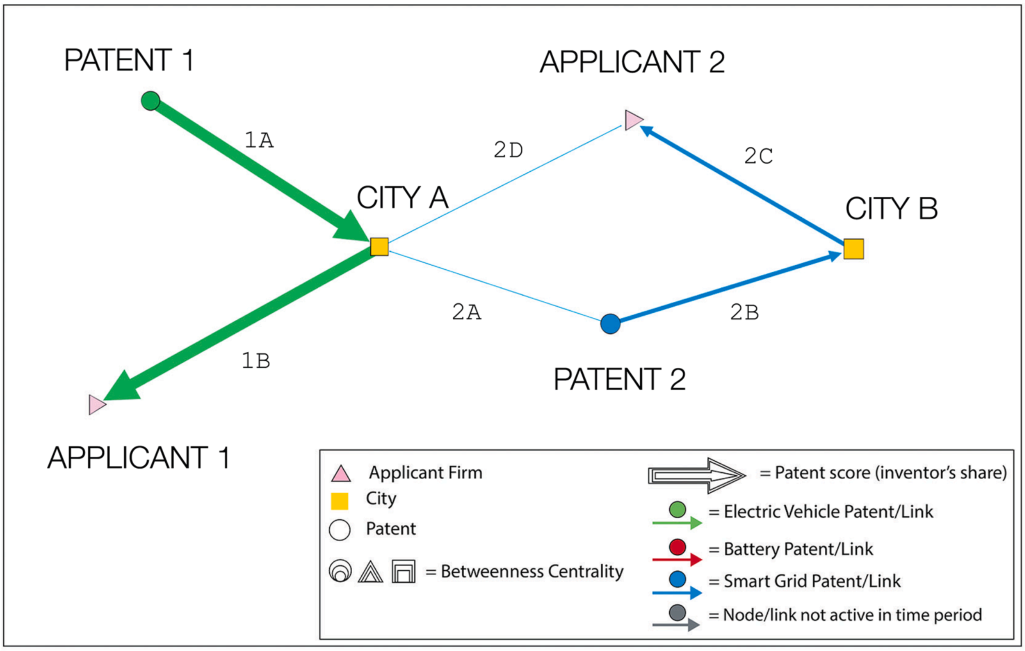

Fig. 4. Link weights in the patent-city-applicant network.

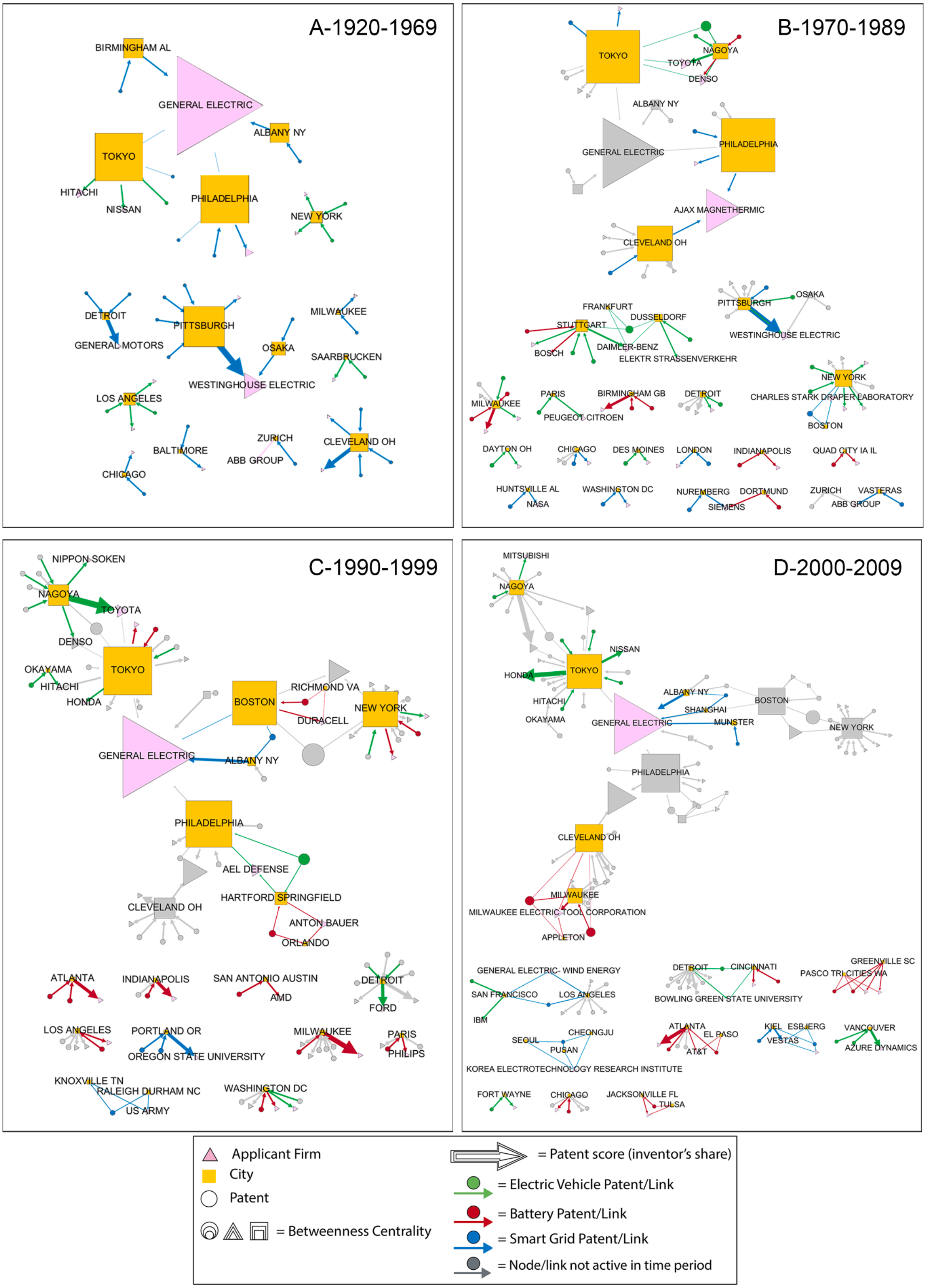

Fig. 5. ***(A-D)***: the patent-city-applicant network from 1920 to 2009.

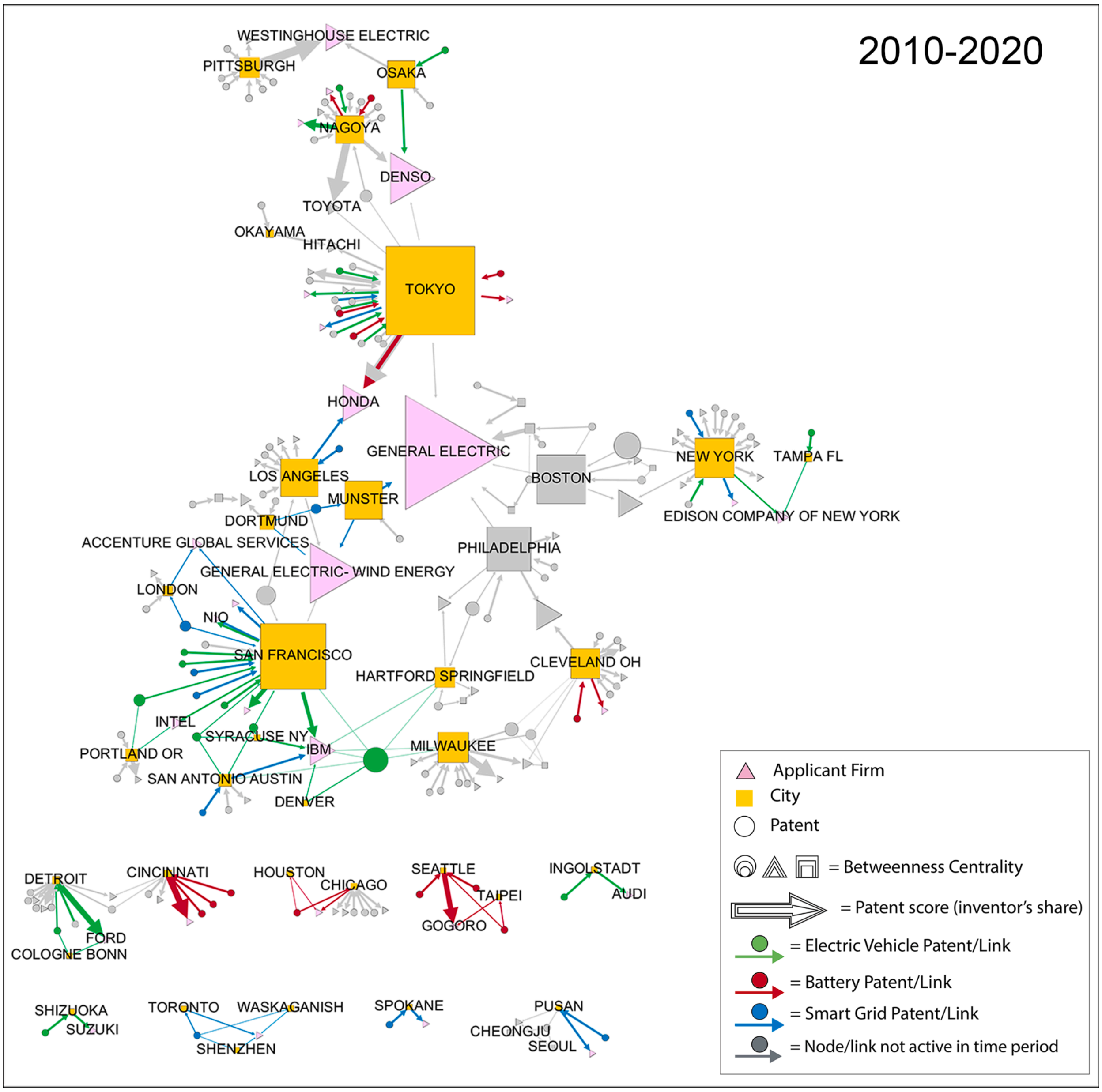

Fig. 6. The patent-city-applicant network from 2010 to 2020.

the subgroup highlighted in red. Even if they do not have a central position in the trajectory, they are directly concerned with EV recharge and with the role of EVs as stabilizers in the context of smart grid management systems.

Answering the first research question, we can say that, while battery-related inventions are increasingly central for EVs, EV-related patents are also more present, particularly in the battery path but also, albeit to a lesser extent, in the smart grid one. This result confirms the findings of Malhotra et al. (2021) that the knowledge trajectory in battery technology is increasingly oriented towards EV-related applications. Extending their argument, results suggest that, especially starting around 2010, increased interconnections with EV applications are also developing in smart grid technology.

4.2. *Technology co-location in cities and the role of inventors/applicants*

To account for urban co-location of EV-related technologies, I constructed a patent-city-applicant network that covers the last 100 years in five time periods. Patents are located according to the address of inventors, and patent applicants—usually firms or research laboratories—are also connected to the city of inventors. Indeed, although their official address could be at their headquarters'

Table 2
Top 10 patenting LURs for each technology (all years together).

	Electric Vehicle		Battery		Smart Grid	
Rank	Large Urban Region	Score	Large Urban Region	Score	Large Urban Region	Score
1	TOKYO	7.18	MILWAUKEE	4.37	PITTSBURGH	5
2	NAGOYA	6.66	CINCINNATI	3.99	CLEVELAND OH	4
3	NEW YORK	5.65	TOKYO	3.97	SAN FRANCISCO	2.89
4	SAN FRANCISCO	5.54	ATLANTA	3.66	PHILADELPHIA	2.5
5	DETROIT	3.49	SEATTLE	2.5	CHICAGO	2
6	STUTTGART	2.33	NAGOYA	2	DETROIT	2
7	VANCOUVER	2	BIRMINGHAM GB	1.99	PORTLAND OR	2
8	LOS ANGELES	1.99	INDIANAPOLIS	1.99	ALBANY NY	1.91
9	DUSSELDORF	1.33	CHICAGO	1.7	MUNSTER	1.65
10	MILWAUKEE	1.13	CLEVELAND OH	1.33	LOS ANGELES	1.6

locations, they often have research facilities in many different cities, so it is more straightforward to assume that applicants are connected to the cities in which their inventors reside.

For each period, the active nodes and links are presented, as schematized in Fig. 4. They are colored according to the main path they belong to: EV in green, battery in red and smart grid in blue, and they are grayed when they are no longer active during that period, but they were active before. Links have different weights according to the number of inventors that contributed to a patent. For example, in Fig. 4, patent 1 has only one inventor that resides in city A, so links 1A (patent to city) and 1B (city to applicant) both weigh 1. Patent 2, instead, has three inventors, two in city B and one in city A. Thus, links 2B and 2C weigh 0.66 while 2A and 2D only 0.33. City-applicant link weights are cumulative, so they are summed across periods to account for the persistent role of an applicant in an urban area. Finally, the size of nodes (patents, applicants or cities) is proportional to their betweenness centrality in the network, which is calculated including all nodes (active and inactive) at each time step.

4.2.1. Urban invention patterns in time

Figs. 5 and 6 show the evolution of the patent-city-applicant network. The first thing that we can notice is that the most central cities vary in time: Philadelphia and Boston lose centrality, Tokyo maintains a central position in all periods, and San Francisco moves on to the second most central city in the last period after being nearly absent previously. This suggests that—apart from the case of Tokyo—the capacity of cities to produce highly relevant inventions in these three technologies has been variable in time, and that the urban region of San Francisco has emerged as a leader over others in recent years.

The second observation relates to the most important cities in the EV main path and the extent to which they overlap with those in the battery and smart grid paths. Some cities are connected to EV inventions in most periods, and these are Tokyo, Nagoya, New York, and Detroit. Nagoya and Detroit are the main cities in their country's automotive industry, and they are strongly linked to EV inventions. Detroit is also connected to smart grid patents, while Nagoya to battery ones. Tokyo and New York, on the other hand, are global cities that support patents in all three technologies, although they both host a higher proportion of EV patents, and Tokyo more battery patents than New York.

The cities of Stuttgart, Los Angeles, Vancouver, Dusseldorf, and Milwaukee also appear in the top EV patenting cities, but they only produce EV patents in one or two periods. Los Angeles, however, also hosted battery and smart grid patents in other periods. Finally, the city of San Francisco appears in the path only in the last 20 years ranking 4th overall in EV patents and 3rd in smart grid ones (Table 2).

The second research question asked which cities are most supportive of inventions in EV, battery and smart grid technologies, and to what extent they can do this regularly in time. Table 2 shows a summary of the urban areas that patented the most in each main path. Overall, Tokyo and New York have hosted patents in all three technologies and across different periods. Nagoya and Detroit have also been constant in time but mostly in the EV sector, with Nagoya also patenting battery technologies and Detroit smart grid ones. San Francisco has appeared in the main path only in the last two periods but with many patents in EV and smart grid.

This result suggests us that global cities like New York and especially Tokyo, play a major role in patent networks likely because of their sheer economic size and diversity, and their role of innovation hubs. Nagoya and Detroit, on the other hand, are the national automotive leaders and they support EV inventions even if their productive base is rooted in combustion vehicles. Finally, the emergence of San Francisco as a major pole of EV invention in recent years indicates that while EV patents have been rooted into a handful of traditional automotive cities, things might be changing and other urban regions with competence in related technologies such as battery and smart grid might attract an increasing share of EV patents in the upcoming years.

4.2.2. The role of patent applicants

Patent applicants play a key role in the network displayed above, because they allow to trace the urban roots of a technology for a longer period. Especially when considering a relatively small number of patents as in this case, it is relevant to know which applicants have participated to many patents across various technologies and urban regions. Through applicant networks we can grasp the contours of an interurban system where knowledge and resources are exchanged, and transitions emerge.

In Figs. 5 and 6, we can distinguish a main network component in the center that gets bigger as new cities and patents add to it, and several separate applicant-city groups. Within the main component, a central cluster forms around Tokyo and Nagoya with the firms Nissan, Honda, Mitsubishi, Toyota, Denso, Hitachi, Sony, Subaru, and General Electric. Tokyo and Nagoya participate of an interconnected and diverse urban network in which the firm Honda is the only one to participate to all three technologies. Denso, an automotive supplier partly controlled by Toyota, participates to both the EV and battery technology. Not only they applied for several EV patents, but they also founded Nippon Soken, a joint research institute that patents technologies related to fuel cells, hybrid vehicles and power systems among others.[9] Thus, the urban regions of Tokyo and Nagoya are key locations in which EV coevolution might be occurring, and the network visualization offers the possibility to elaborate further on the role of cities that are directly or indirectly connected to it such as Osaka, Okayama, Pittsburgh and Los Angeles.

The other key cluster in the main component is around San Francisco. Contrary to cities such as Philadelphia, Boston or New York, that were more active and central in the first periods, San Francisco became central only in the past 20 years, participating to a high number of EV and smart grid patents. The key applicants here are IBM, that invented the most central EV patent in the path, and the US branch of Chinese EV producer NIO. Both firms participate to the EV and smart grid paths and IBM appears at the center of an extended urban network because their inventors are located in five other cities (Denver, Milwaukee, San Antonio/Austin, Hartford Springfield and Syracuse). The role of General Electric is also important because through their wind energy branch they produced a key smart grid patent in San Francisco/Los Angeles and via their network they provide connections to Münster, Dortmund, and several other global cities.

Outside the main network component, we find Ford and General Motors in Detroit, Audi in Ingolstadt or Peugeot-Citroen in Paris for the EV main path. In the battery path, we find AT&T and Total Battery Management in Atlanta, Siemens in Dortmund and Paris, and Ethicon—a producer of surgical tools—in Cincinnati. In the smart grid path, the utility Westinghouse Electric is a key actor in Pittsburgh, and the Danish producer of wind turbines Vestas in the cities of Kiel (Germany) and Esbjerg (Denmark).

University and research institutions are also important. For example, patent #4 in the EV main path (Fig. 1), was invented by a group of researchers at Bowling Green University, Ohio, who built a prototype of electric racing car to be used in the “Formula Lightning” student competition. The car, called “Electric Falcon,” was constructed and improved during a decade, with the help of students and private partners, and this effort yielded a patentable invention related to a hybrid bus project (Palumbo et al., 1997). Oregon State University is another main university from the smart grid path, with two patents ranking first and fifth in centrality (Figs. 3 and 5-C). Other public actors and research institutes include the Charles Stark Draper Laboratory (an MIT research venture) and the NASA (Fig. 5-B), the US Army (Fig. 5-C), and the Korea Electrotechnology Research Institute (Fig. 5-D).

Finally, an interesting network developed in Germany in the 1970s around the cities of Dusseldorf, Frankfurt and Stuttgart (Fig. 5-B). Mercedes-Benz and Bosch are the two main firms here, patenting, respectively in EV and battery technologies. An inter-sectoral dynamic might have been in place in these cities involving the applicant Electric Road Transport Society[10] (GES). GES was a public-private partnership between the Rhine-Westphalia electric company (RWE) and some major German car makers, that researched EV technologies and developed prototypes based on existing car models. GES’s efforts led to the deployment by the mid-1980s of electric and hybrid buses in a few German municipalities and of more than 150 electric test cars and vans in 25 cities (Horstmann and Doring, 2018). The project finalized at the end of the 1980s, but it is a telling case of how sectoral boundaries can become blurred in the development and experimentation of new socio-technical solutions, by involving public bodies (electric utility, municipality and regions) and private firms from different sectors (VW and Mercedes for cars, Varta for batteries).

The third research question asked what inter-sectoral and inter-urban connections emerge in the city-applicant network and who are the key actors in it. We can answer that the cities in which we find a high diversity of applicants and technologies that might favor inter-sectoral linkages are Tokyo, Nagoya and San Francisco. In particular, the key applicants in this dynamic are the firms Toyota with a network that includes affiliated companies (Denso) and dedicated research institutes (Nippon Soken), with connections to Tokyo and Nagoya. Honda has patents in all three technologies and connections with Tokyo and Los Angeles. IBM is a key applicant in San Francisco and is linked to many north American cities, while the Chinese EV maker NIO, also connected to San Francisco, has patents in EV and smart grid. General Electric appears to be a particularly central applicant in the smart grid path because it is connected to inventors located in Tokyo, several north American cities, Shanghai and Münster. Other applicants appear to be locally relevant but, if it’s difficult to reach conclusive evidence about their centrality, the network visualization allows to detect significant inter-sectoral experiments in which also research bodies and public institutions played a key role (Bowling Green University, Rhine-Westphalia Electricity).

5. Discussion

In the previous section, I exposed the increased similarity in the key focus of patents in the EV, battery, and smart grid technologies. Several urban regions were identified where inter-sectoral relations in the development of EV, battery and smart grid patents might be taking place, along with the actors that are involved in this process. These results do not allow to formulate clear-cut conclusions on the geography of the EV transition. However, they are useful to show three ways in which a coevolutionary approach might advance our understanding of how the multi-sectoral interactions that support transitions are embedded in regional development paths.

5.1. New socio-technical configurations, different centralities

To understand contemporary transitions, we must turn to the evolutionary trajectory through which some technologies emerged

[9] www.soken-labs.com/english/company/index.html

[10] The original name was Gesellschaft für elektrischen Straßenverkehr.

and were selected. By doing so, we can identify the building blocks in the development of different technologies, how they were combined, and how different domains of application became increasingly related in time. For example, in the battery and smart grid main paths (Figs. 2 and 3), we observed not only an increased number of EV-related patents in the last ten years, but also a general convergence towards applications that are highly related to EVs such as battery recharge infrastructures and distributed electrical systems. By making sense of how the relative centrality of different technologies varies in time, we can get better insights on the conflicts between actors and interest groups that are inevitable as transitions change power geometries between technologies (Markard, 2018).

In our case, automotive firms are key actors in EV invention, but central patents in the future might have more to do with battery chemistry, autonomous drive, and smart recharge than with traditional automotive components such as transmission or engine. The empirical results showed the key position of a digital company such as IBM in the EV main path. When it comes to production, Google and Apple have already started programs to build their own autonomous cars (Harris, 2015) but other major companies of the digital economy such as Uber and Amazon are likely to participate in the race, and this can affect the distribution of rewards and incentives along the value chain lessening the centrality of automotive firms. Further empirical evidence would be necessary to ground these claims. However, this discussion shows that a coevolutionary approach exposing network interactions opens promising research directions to explain the inter-sectoral arrangements that can characterize transitions.

It is thus relevant to move beyond an exclusive focus on the diffusion of transition technologies by accounting for the phases of invention and production and the inter-sectoral dynamics they are involved into. This can allow to map more thoroughly relatedness in terms of knowledge, skills and inputs between incumbent and emergent sectors, to identify and target with specific policies the new inter-sectoral configurations that might emerge from the transition (Andersen and Gulbrandsen, 2020). A coevolutionary framework allows to address these topics but also how institutional, regulatory and societal forces intervene in the deployment phase, and how these interactions may feed-back to influence the phases of invention and production (Malhotra et al., 2021). Besides, it permits reflecting on the economic and social imbalances that might emerge as entire productive sectors disappear and points to the spatial embeddedness of inter-sectoral dynamics.

5.2. *The spatial emergence of transitions*

As outdated technologies begin to be phased out, regions face the challenge of renewing their knowledge base and production infrastructure. In Section 4 we have seen that the urban regions of Tokyo, Nagoya, Detroit and New York show a persistent capacity to generate key inventions, while most of the other cities do so intermittently. The fact that traditionally automotive cities such as Nagoya and Detroit have a crucial role in EV patenting suggests that path dependence is important. Thus, although EVs are often opposed to traditional fuel vehicles, incumbents retain the skills, expertise and strategic interest to produce EV patents. On the other hand, we have also seen the recent growth of San Francisco, a region that had not appeared in any path before the year 2000, and that is usually associated to the ICT industry more than the automotive one. A geographical perspective on transitions can contribute to explaining what the main drivers in the spatial emergence of new growth paths are, to what extent the influence of incumbent sectors conditions this process and how to address lock-in and decline.

Insights from economic geography have shown that when regions try to expand and diversify their productive base, related diversification is the rule and unrelated diversification the exception (Whittle and Kögler, 2020). Yet relatedness is a dynamic concept (Boschma, 2017), so in the context of transitions regions might face new opportunities and constraints to diversify into emerging industries, as new socio-technical combinations become possible. Results have shown that traditional motor regions retain a role in EV innovation, but other locations might surpass them because, as discussed above, traditional automotive competences might become less central to novelty generation. More in general, the acceleration of transitions can exacerbate existing social tensions and deepen the cleavage between core and peripheral territories (Skjølsvold and Coenen, 2021). Thus, the problem is not only one of diversifying local competence bases, but of enabling path creation through the establishment of novel interconnections between existing sectors or their reconfiguration and phase-out (Andersen and Gulbrandsen, 2020).

A coevolutionary approach illuminates path-interdependence, or the fact that inter-sectoral dynamics are embedded in the history and specificities of local configurations and coupled with external networks (MacKinnon et al., 2019). Co-location can importantly favor the creation of new paths through processes of *mindful deviation* and bricolage (Simmie, 2012) because the recombination of heterogeneous knowledge might be supported by cognitive and institutional proximity (Boschma, 2005). Yet recent contributions have shown that path creation involves anchoring global resources in local productive systems (Binz et al., 2016) so that coevolution occurs across multiple scales. As a result, unrelated diversification should not be seen as a regionally or nationally bound phenomenon but rather as a multi-scalar process because the access to very different inputs and knowledge can be obtained by drawing on global networks and resources (Binz and Anadon, 2018). Hence, the second contribution of a coevolutionary perspective is in making clear that the possibilities for cities and regions to engage in the development paths that are enabled by transitions are linked to their capability to support new inter-sectoral configurations between local actors or to draw on extra-local connections to access them.

5.3. *Transitions and networks*

The third contribution of a coevolutionary approach is to draw attention onto the actors and networks that sustain transitions. In Section 4.2 several key applicants were identified, with the cities and technologies they are connected to. Honda, for example, was the only firm to patent in all three technologies, and the only case of Japanese firm with inventors in the US, in Los Angeles. Toyota and IBM were also at the center of diverse and extended networks in Japan and the US, respectively. Empirical results have corroborated the findings of Stephan et al. (2017) that EVs are at the center of cross-sectoral collaborations between Japanese battery manufacturers, automotive firms and universities, and that the government plays an important role in supporting these interactions. In fact, transition technologies are anchored in the networks of global firms, but they emerge in the resources developed locally by universities, research centers, and government agencies among others.

In line with Binz et al. (2014), this study has found that a network perspective can illuminate how innovation systems connect firm and non-firm actors within and across cities, adding that this process spans different sectors and technologies. If we can identify the agents that enable and nurture coevolutionary interactions, such as the GES society in Germany or Nippon-Soken in Japan, we can follow their networks to better comprehend what localized advantages are provided by different urban regions. A coevolutionary approach permits to comprehend how the interactions and interdependencies among specific actors are embedded into wider networks with their different spatial and socioeconomic characteristics.

5.4. Limitations and perspectives

This research has several limitations. First, patents are good indicators of the knowledge generation process, but there is a lag of several years between invention and publication, even more so if only granted patents are considered. This applies particularly to contemporary invention patterns, so recent trends must be interpreted with caution. Second, main path analysis is an effective methodology particularly for studying well delimited technologies. When the scope is widened to include more diverse patent networks, results become harder to interpret and filtering decisions are likely to affect the outcome. Third, the choice of USPTO patent jurisdiction was motivated by the need to stick to a coherent citing tradition but implied leaving out inventions produced in other potentially relevant patent offices, which limited the scope of the analysis. Overall, results could vary if a different set of criteria were chosen, including technology codes, filtering keywords, and patent jurisdictions.

This paper aimed at discussing the general dynamics of technology coevolution in urban regions, so it could not treat any specific urban case in depth, although a few concrete examples were picked out to illustrate the argument. Accordingly, future research could explore inter-sectoral linkages more in depth by focusing on invention networks in one or few urban areas. Future studies could also address the emergence of inter-sectoral arrangements in production and diffusion of EV innovations and how these phases are connected to invention. For example, several very influential producers have not been retrieved through main path analysis, including Tesla, BYD, LG Chem., CATL, or Samsung. This might be due to drawbacks in the methodology, but it might also signal that these actors are not central in the inventive process, or perhaps more inclined to use secrecy than patent. Accordingly, future research could address explicitly the linkages and feedback loops that exist between these phases.

6. Conclusion

This paper has proposed to use the concept of coevolution to combine a focus on the multi-sectoral arrangements that support transitions with a geographical perspective that can explain their embeddedness in regional development trajectories. To illustrate how this framework might be applied, I exposed the key patents and technology fields in EV, battery and smart grid technologies, analyzing in which urban regions they were invented, and asking to what extent spatial co-location of inventions might suggest coevolution. By focusing on the role of applicants, the paper disclosed some of the actors and mechanisms that might be driving this process and the urban networks in which they are embedded.

These empirical insights illustrated three main contributions of framing transitions as a coevolutionary process. First, by making sense of inter-sectoral connections along the evolution of technologies we can better comprehend the new power geometries between technologies that are implied by transitions and analyze opportunities for (un)related diversification along the value chain. Second, these inter-sectoral linkages are spatially embedded: it is crucial to understand how regions can support emerging technologies and how to avoid unpromising growth paths. Third, the actors and networks that uphold transitions are also spatially situated, transcend technology boundaries and often emerge at the intersection between private and public. The study of ongoing transition processes is challenging but highly relevant to research and policy. If—as it seems likely—the EV transition consolidates further, this will have deep implications in all domains of society. Particularly, local economies face the task of adapting their production base and develop the routines and infrastructure to accommodate EV diffusion while mitigating the negative consequences in terms of employment and social cohesion. Transition research can provide tools to make sense of this complexity and inform policy decisions, and this study aims to contribute to this task.

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Data availability

The datasets that support the claims made in this paper can be downloaded at the repository: https://zenodo.org/record/5534093

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.

Data availability

I have shared the link to my data at the end of the article.

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Appendix

Tables 3–5

Table 3
Electric Vehicle patents in the main path.

#	US patent	Year	Title	LUR	Applicant
1	1,790,635	1923	Self-charging electric vehicle	New York	N/A
2	3,216,541	1961	Control System For Operating The Drive Clutches Of Motor Vehicles	Saarbrucken	Saarbergtechnik GMBH
3	3,503,464	1968	Control System For A Battery And Hydrocarbon Powered Vehicle	New York	Michel N. Yardney
4	3,719,881	1969	Device For Charging Storage Battery	Tokyo	Nissan—Hitachi
5	3,732,751	1969	Power Train using Multiple Power Sources	Los Angeles	Trw Inc.
6	3,572,167	1969	Transmission Combining Gearset With Planetary Gearing	Los Angeles	White Motor Corp.
7	3,673,890	1970	Auxiliary Transmission	Milwaukee	Allis Chalmers Corp.
8	3,792,327	1972	Hybrid Electrical Vehicle Drive	Detroit	Waldorf L
9	3,905,252	1972	Automatic Planetary Gear Change-speed Transmission For Motor Vehicles	Stuttgart	Daimler-Benz AG
10	3,861,485	1972	Electric Motor Vehicle And Drive System Therefor	Dusseldorf	Elektr. Strassenverkehr Ges
11	3,915,251	1973	Electric Vehicle Drive Utilizing A Torque Converter In Conjunction With A Field Controlled Motor	Pittsburgh	Westinghouse Electric Corp.
12	3,991,357	1976	Storage battery monitoring and recharging control system with automatic control of prime mover driving charging generator	Dayton OH	Stolle Research & Development Corporation
13	3,984,742	1976	Electric motor drive for trackless vehicles	Stuttgart	Deutsche Automobilgesellschaft mbH
14	3,938,409	1976	Control system for automatic transmissions of automotive vehicles	Nagoya	Toyota
15	4,042,056	1977	Hybrid powered automobile	New York	Automobile Corporation of America
16	4,021,712	1977	Control system for automatic transmission for electric automobiles	Nagoya Tokyo	Toyota Denso
17	4,153,128	1979	Drive aggregate for electric vehicles	Frankfurt Stuttgart Düsseldorf	Daimler-Benz AG
18	4,187,436	1980	Device for regulating the source of electric energy on a hybrid electric vehicle	Paris	Peugeot-Citroen
19	4,306,156	1981	Hybrid propulsion and computer controlled systems transition and selection	New York	Alexander Mencher Corp.
20	4,419,610	1983	Reversible regenerating electric vehicle drive	Des Moines	Sundstrand Corporation
21	4,928,227	1990	Method for controlling a motor vehicle powertrain	Detroit	Ford
22	5,172,784	1992	Hybrid electric propulsion system	Washington DC	Arthur A. Varela
23	5,215,156	1993	Electric vehicle with downhill electro-generating system	New York	Nathan Stulbach
24	5,359,308	1994	Vehicle energy management system using superconducting magnetic energy storage	Hartford Springfield Philadelphia	AEL Defense Corp.
25	5,287,772	1994	Transmission control system in electric vehicle	Tokyo	Honda
26	5,476,310	1995	Braking apparatus for electric vehicle	Okayama	Hitachi
27	5,654,887	1997	Braking force controller for electric vehicle	Nagoya	Nippon Soken Denso
28	5,650,931	1997	Generator output controller for electric vehicle with mounted generator	Nagoya	Toyota

(*continued on next page*)

Table 3 (*continued*)

29	5,820,172	1998	Method for controlling energy flow in a hybrid electric vehicle	Detroit	Ford
30	5,984,034	1999	Hybrid vehicle	Nagoya	Toyota
31	6,137,250	2000	Controller for electric vehicle and electric vehicle using the same	Tokyo	Nissan
32	6,242,873	2001	Method and apparatus for adaptive hybrid vehicle control	Vancouver	Azure Dynamics
33	6,186,253	2001	Brake activated torque disable in hybrid electric vehicles	Fort Wayne	Navistar International Transportation
34	6,484,830	2002	Hybrid electric vehicle	Detroit Cincinnati	Bowling Green State University
35	6,378,637	2002	Fuel-cell-powered electric automobile	Tokyo	Honda
36	6,909,200	2005	Methods of supplying energy to an energy bus in a hybrid electric vehicle	Vancouver	Azure Dynamics
37	6,874,588	2005	Fuel cell electric vehicle and a fuel cell system box	Tokyo	Honda
38	7,013,205	2006	System and method for minimizing energy consumption in hybrid vehicles	San Francisco	IBM
39	7,533,748	2009	Vehicle mounting structure for fuel cell	Tokyo	Honda
40	7,610,978	2009	Battery unit mounting structure for electric vehicle	Nagoya	Mitsubishi
41	7,693,609	2010	Hybrid vehicle recharging system and method of operation	New York Tampa FL	Consolidated Edison company of New York
42	7,654,352	2010	Electric vehicle	Nagoya	Mitsubishi
43	7,991,665	2011	Managing incentives for electric vehicle charging transactions	San Francisco San Antonio-Austin Syracuse NY	IBM
44	8,210,301	2012	Battery mounting structure for vehicle	Tokyo	Subaru
45	8,531,162	2013	Network based energy preference service for managing electric vehicle charging preferences	San Francisco San Antonio-Austin Syracuse NY	IBM
46	8,789,634	2014	Electric vehicle	Shizuoka	Suzuki
47	8,836,281	2014	Electric vehicle charging transaction interface for managing electric vehicle charging transactions	Denver Milwaukee San Francisco San Antonio Austin Syracuse NY Hartford Springfield	IBM
48	9,120,506	2015	Subframe for a motor vehicle	Ingolstadt	Audi
49	9,738,168	2017	Cloud access to exchangeable batteries for use by electric vehicles	San Francisco	Emerging Automotive
50	9,925,882	2018	Exchangeable batteries for use by electric vehicles	San Francisco	Emerging Automotive
51	10,220,717	2019	Electric vehicle emergency charging system and method of use	San Francisco	NIO USA
52	10,333,338	2019	Charging method and assembly utilizing a mule vehicle with a storage battery	Cologne-Bonn Detroit	Ford
53	10,461,551	2019	Charging support device	Osaka	Denso
54	10,688,874	2020	Vehicular inductive power transfer systems and methods	San Francisco Portland OR	Intel

Table 4
Battery patents in the main path.

#	US patent	Year	Title	LUR	Applicant
1	4,080,560	1978	Method and apparatus for determining the maintenance and charge condition of lead storage batteries	Dortmund	Siemens
2	4,210,855	1980	Apparatus for regulating the current drawn from an electric battery	Stuttgart	Bosch
3	4,193,025	1980	Automatic battery analyzer	Milwaukee	Globe Union
4	4,308,492	1981	Method of charging a vehicle battery	Nagoya	Denso
5	4,322,685	1982	Automatic battery analyzer including apparatus for determining presence of single bad cell	Milwaukee	Globe Union
6	4,484,130	1984	Battery monitoring systems	Birmingham GB	Lucas Industries
7	4,558,281	1985	Battery state of charge evaluator	Birmingham GB	Lucas Industries
8	4,709,202	1987	Battery powered system	Quad City IA IL	Norand Corp.
9	4,746,854	1988	Battery charging system with microprocessor control of voltage and current monitoring and control operations	Indianapolis	Span
10	4,965,738	1990	Intelligent battery system	Hartford Springfield Orlando	Anton Bauer
11	5,049,803	1991	Method and apparatus for charging and testing batteries	New York	AlliedSignal
12	5,047,961	1991	Automatic battery monitoring system	Los Angeles	Simonsen Bent P.
13	5,153,496	1992	Cell monitor and control unit for multicell battery	Washington DC	Baxtrer International Inc.
14	5,321,627	1994	Battery monitor and method for providing operating parameters	Milwaukee	Globe Union

(*continued on next page*)

Table 4 (*continued*)

15	5,304,915	1994	Overcharge preventing device and overdischarge preventing device for a secondary battery	Tokyo	Sony
16	5,459,671	1995	Programmable battery controller	San Antonio Austin	AMD
17	5,563,496	1996	Battery monitoring and charging control unit	Indianapolis	Span
18	5,606,242	1997	Smart battery algorithm for reporting battery parameters to an external device	Boston Richmond VA	Duracell
19	5,729,116	1998	Shunt recognition in lithium batteries	Atlanta	Total Battery Management
20	5,825,156	1998	System for monitoring charging/discharging cycles of a rechargeable battery and host device including a smart battery	Paris	US Philips Corp.
21	5,900,718	1999	Battery charger and method of charging batteries	Atlanta	Total Battery Management
22	6,043,631	2000	Battery charger and method of charging rechargeable batteries	Atlanta	Total Battery Management
23	6,118,248	2000	Battery having a built-in controller to extend battery service run time	Cincinnati	Procter & Gamble
24	6,324,339	2001	Battery pack including input and output waveform modification capability	Jacksonville FL Tulsa	Eveready Battery Company
25	6,624,616	2003	Portable battery recharge station	Atlanta El Paso	AT&T Intellectual Property
26	6,950,030	2005	Battery charge indicating circuit	Chicago	Credo Technology Group
27	7,580,803	2009	Energy source monitoring and control system	Pasco Tri Cities WA Greenville SC	Techtronic Power Tools Technology
28	7,508,167	2009	Method and system for charging multi-cell lithium-based batteries	Milwaukee Appleton Cleveland OH	Milwaukee Electric Tool Corporation
29	7,504,804	2009	Method and system for protection of a lithium-based multicell battery pack including a heat sink	Milwaukee Appleton Cleveland OH	Milwaukee Electric Tool Corporation
30	7,496,460	2009	Energy source monitoring and control system for power tools	Pasco Tri Cities WA Greenville SC	Eastway Fair Company
31	7,948,207	2011	Refuelable battery-powered electric vehicle	Cleveland OH	Scheucher Karl Frederick
32	8,560,147	2013	Apparatus method and article for physical security of power storage devices in vehicles	Taipei Seattle	Gogoro
33	8,813,866	2014	Electric tool powered by a plurality of battery packs and adapter therefor	Nagoya	Makita Corp.
34	9,182,244	2015	Apparatus method and article for authentication security and control of power storage devices such as batteries	Seattle	Gogoro
35	10,084,329	2018	Power pack vending apparatus system and method of use for charging power packs with biased locking arrangement	Chicago Houston	NRG Energy
36	10,159,483	2018	Surgical apparatus configured to track an end-of-life parameter	Cincinnati	Ethicon
37	10,345,843	2019	Apparatus method and article for redistributing power storage devices such as batteries between collection charging and distribution machines	Seattle	Gogoro
38	10,201,364	2019	Surgical instrument comprising a rotatable shaft	Cincinnati	Ethicon
39	10,650,444	2020	Battery reservation device and battery reservation method	Tokyo	OMRON Corp.
40	10,759,299	2020	Management device management system and computer-readable storage medium	Tokyo	Honda
41	10,613,149	2020	Managing apparatus computer-readable storage medium management method and production method	Tokyo	Honda
42	10,687,806	2020	Adaptive tissue compression techniques to adjust closure rates for multiple tissue types	Cincinnati	Ethicon

Table 5
Smart grid patents in the main path.

#	US patent	Year	Title	LUR	Applicant
1	1,940,295	1933	Regulating System	Birmingham AL	General Electric
2	1,931,644	1933	Method And Mechanism For Removing Reactances	Philadelphia	Ajax Electrothermic Corp.
3	2,078,667	1937	Automatic Control System For Phase-advancing Means	Osaka	Westinghouse Electric
4	2,243,584	1941	Voltage Regulation	Tokyo	General Electric
5	2,293,484	1942	Control System	Philadelphia	General Electric
6	2,451,939	1948	Automatic Switching System	Pittsburgh	Westinghouse Electric
7	2,436,302	1948	Alternating Current Motor Starting by Means Of Capacitors	Pittsburgh	Westinghouse Electric
8	2,484,575	1949	Phase Controlled Switching System	Albany NY	General Electric
9	2,460,467	1949	System Of Controlling Electric Lines	Milwaukee	Line Material Company

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Table 5 (*continued*)

10	2,705,301	1955	Dual Voltage Capacitor Bank	Pittsburgh	Westinghouse Electric
11	2,881,376	1959	Induction Motor Control System	Detroit	General Motors
12	2,871,439	1959	Induction Generator Power System	Detroit	General Motors
13	3,002,147	1961	Remote Capacitor Switching Apparatus For Power Distribution System	Baltimore	Charles Wasserman
14	3,002,146	1961	Remote Capacitor Switching System	Chicago	Motorola
15	3,043,115	1962	Method And Apparatus For The Generation Of Electric Power	Pittsburgh	Carrier Corp.
16	3,185,811	1965	Automatic Induction Furnace Control	Cleveland OH	Ohio Crankshaft
17	3,419,792	1968	Device For Controlling The Power Factor In The Output Circuit Of A Generator	Cleveland OH	Ohio Crankshaft
18	3,391,329	1968	Apparatus For Compensating Wattless Power Component Of Inductive Power Consumers	Zurich	BBC Brown Boveri & Cie
19	3,375,433	1968	Device For Controlling The Output Frequency Of A Generator Driven By A Wound Rotor Induction Motor	Cleveland OH	Electric Products Company
20	3,530,370	1970	Flicker Preventing Circuit	Tokyo	Sanken Electric Co Ltd
21	3,675,117	1972	Asynchronous Generator Device	Washington DC	Reimers Eberhart
22	3,731,183	1973	Power Control And Phase Angle Correcting Apparatus	Philadelphia	Inductotherm Corp.
23	3,855,519	1974	Voltage Controller For Synchronous Electric Machines	Nuremberg	Siemens
24	3,832,625	1974	Electrical Power Generating Arrangement And Method Utilizing An Induction Generator	Pittsburgh	Westinghouse Electric
25	3,829,758	1974	Ac-dc Generating System	Chicago	Borg Warner
26	4,052,648	1977	Power factor control system for AC induction motors	Huntsville AL	NASA
27	4,162,442	1979	Capacitor equipment	Vasteras	Asea Aktiebolag (now ABB group)
28	4,139,723	1979	Power control unit for a single phase load with slightly changing impedances	Cleveland OH	Ajax Magnethermic Corp.
29	4,417,194	1983	Induction generator system with switched capacitor control	New York Boston	Charles Stark Draper Lab.
30	4,791,309	1988	Electrical control systems	London	Thamesmead Engineering
31	4,994,684	1991	Doubly fed generator variable speed generation control system	Portland OR	Oregon State University
32	5,239,251	1993	Brushless doubly-fed motor control system	Portland OR	Oregon State University
33	5,652,485	1997	Fuzzy logic integrated electrical control to improve variable speed wind turbine efficiency and performance	Knoxville TN Raleigh Durham NC	US. Army
34	5,907,192	1999	Method and system for wind turbine braking	Albany Boston	General Electric
35	6,420,795	2002	Variable speed wind turbine generator	Los Angeles San Francisco	General Electric— Zond Energy Systems
36	6,933,625	2005	Variable speed wind turbine having a passive grid side rectifier with scalar power control and dependent pitch control	Kiel Esbjerg	Vestas
37	7,102,247	2006	Circuit arrangement and methods for use in a wind energy installation	Kiel	Vestas
38	7,253,537	2007	System and method of operating double fed induction generators	Shanghai Albany	General Electric
39	7,276,807	2007	Wind turbine dump load system and method	Munster	General Electric
40	7,579,702	2009	Electric power converting device and power converting method for controlling doubly-fed induction generator	Cheongju Seoul Pusan	Korea Electrotechnology Research Institute
41	7,679,208	2010	Apparatus and system for pitch angle control of wind turbine	Pusan	Samsung Heavy Industries
42	8,319,358	2012	Electric vehicle charging methods battery charging methods electric vehicle charging systems energy device control apparatuses and electric vehicles	Spokane	Demand Energy Networks
43	8,352,091	2013	Distributed grid-interactive photovoltaic-based power dispatching	San Antonio Austin	IBM
44	8,521,337	2013	Systems and methods for operating electrical supply	New York	Calm Energy
45	8,350,397	2013	Current source converter-based wind energy system	Toronto Waskaganish Shenzhen	Rockwell Automation Technologies
46	9,046,077	2015	Reactive power controller for controlling reactive power in a wind farm	Munster Dortmund	General Electric—Wind Energy
47	9,457,680	2016	Vehicle-to-grid control	Los Angeles	Honda
48	9,766,671	2017	Electric vehicle distributed intelligence	London San Francisco	Accenture Global Services
49	10,532,663	2020	Electric vehicle overhead charging system and method of use	San Francisco	NIO Usa
50	10,686,314	2020	Power grid saturation control with distributed grid intelligence	San Francisco	Xslent Energy Tech

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