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# The role of cities in the transition to the Electric Vehicle:a coevolutionary approach

Ferloni Andrea

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FACULTÉ DES GÉOSCIENCES ET DE L'ENVIRONNEMENT

INSTITUT DE GÉOGRAPHIE ET DURABILITÉ

# The role of cities in the transition to the Electric Vehicle:

## a coevolutionary approach

THÈSE DE DOCTORAT

présentée à la

Faculté de géosciences et de l'environnement
de l'Université de Lausanne

pour l'obtention du grade de

Docteur en géographie

par

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intitulée

## THE ROLE OF CITIES IN THE TRANSITION TO THE ELECTRIC VEHICLE: A COEVOLUTIONARY APPROACH

Lausanne, le 30 juin 2023

Pour le Doyen de la Faculté des géosciences et de l'environnement

Marie Elodie Pe

Professeure Marie-Elodie Perga

# Summary

The transition to Electric Vehicles (EVs) is underway, and it requires adaptations across several sectors including automotive, electric, and chemical ones. The outcome of this transition can be *geographically uneven*, as urban regions face the challenge of restructuring their productive base and attracting new innovative jobs.

In this thesis, I frame the EV transition as a *coevolutionary process*, considering invention and production of EV-related technologies in large urban regions. This research provides elements to understand how geographical proximity and local networks can support the emergence of *complementarities* between automotive, battery, and smart grid sectors during transitions.

Socio-technical transitions are radical changes in social organization that involve the replacement of established technologies for new ones, with their social, productive, and institutional ramifications. Transition research is increasingly focusing on the *multi-sectoral* dynamics that characterize contemporary transitions. Insights from economic geography suggest that geographical proximity between innovative actors, and *relatedness* of co-located activities can support technological recombinations. Thus, it is meaningful to combine these literatures, to understand how local relations and specificities can support the emergence of new technologies, and to frame this dynamic in a context of systemic change.

During transitions, previously unrelated technologies become related. The knowledge and inputs that are required to produce them become more connected. Increased *technological proximity* can result in *geographical proximity*, as interdependencies between inventors and firms from different sectors begin to build up and coevolve with local innovation networks. Using data on patents and multinational ownership networks, this research examines how coevolution between different technologies is connected to the emergence of *inventive and productive activities* related to EVs across urban regions.

This investigation brings evidence of increasing relatedness in time — both technological and geographical — between EV, battery, and smart grid technologies. Thus, the transition to EVs implies that inventions in these technologies are more frequently connected and co-located. Traditional automotive cities retain a key role in EV innovation, but the regions that are specialized in battery and smart grid are those where EV patents grow the most. This suggests that path dependence with traditional car making is important, but emerging competences in related sectors might be more central to innovation. Specific applicant firms and multinational producers play a key role in this coevolutionary process, by connecting locally and worldwide different technologies and urban regions through their activities.

## Résumé

La transition vers les véhicules électriques (VE) est en cours et nécessite des adaptations dans plusieurs secteurs. Le résultat de cette transition est géographiquement inégal, car les régions urbaines sont confrontées au défi de restructurer leur base productive et d'attirer de nouveaux emplois innovants.

Dans cette thèse, j'aborde cette transition comme un processus coévolutif, en considérant l'invention et la production de technologies liées aux véhicules électriques dans les grandes régions urbaines. Cette recherche fournit des éléments permettant de comprendre comment la proximité géographique et les réseaux locaux peuvent favoriser l'émergence de complémentarités entre les secteurs de l'automobile, des batteries et des « smart grid ».

Cette recherche s'appuie partiellement sur les théories des transitions qui se concentrent de plus en plus sur les dynamiques multisectorielles qui caractérisent les transitions contemporaines. Ces théories soulignent dans quelles mesures les transitions sociotechniques impliquent le remplacement de technologies établies par de nouvelles, avec leurs ramifications sociales, productives et institutionnelles. Parallèlement, les enseignements de la géographie économique suggèrent que la proximité géographique entre les acteurs innovants peut favoriser les recombinaisons technologiques. Il est donc utile de combiner ces littératures pour comprendre comment les relations et les spécificités locales peuvent favoriser l'émergence de nouvelles technologies, et afin d'inscrire cette dynamique dans un contexte de changement systémique.

Au cours des transitions, des technologies qui n'étaient pas liées auparavant deviennent liées. Les connaissances nécessaires à leur production sont de plus en plus similaires. La proximité technologique accrue peut se traduire par une proximité géographique, car les interdépendances entre les inventeurs et les entreprises de différents secteurs commencent à se développer et à coévoluer dans les réseaux locaux d'innovation. À l'aide de données sur les brevets et les réseaux multinationaux, cette recherche examine comment la coévolution entre technologies est liée aux inventions relatives aux VE dans les régions urbaines.

Les résultats empiriques confirment une corrélation croissante au cours du temps entre les technologies des VE, des batteries et des réseaux intelligents. La transition vers les VE implique que les inventions dans ces technologies deviennent connectées et co-localisées. Les villes traditionnelles de l'industrie automobile conservent un rôle clé dans l'innovation, mais les régions spécialisées dans les batteries et les réseaux intelligents sont celles où les brevets relatifs aux VE augmentent le plus. Ceci signifie que les compétences émergentes dans les secteurs connexes pourraient être plus importantes pour l'innovation que le secteur automobile lui-même.

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Thank you all again!

Andrea Ferloni

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## Attached articles

**Article 1 :** Ferloni, A., 2022. Transitions as a coevolutionary process: The urban emergence of electric vehicle inventions. Environmental Innovation and Societal Transitions 44, 205–225. https://doi.org/10.1016/j.eist.2022.08.003

**Article 2:** Ferloni A., Bida M., and Rozenblat C.**,** 2023. The emergence of Electric Vehicle transition in cities: technological coevolution and spatial colocation. *Progress in Economic Geography*. Submitted.

**Article 3:** Ferloni, A. and Rozenblat, C., 2023. Relatedness and colocation in Electric Vehicle production networks: a coevolutionary network approach. *Papers in regional science*. In progress.

# Introduction

The transition to Electric Vehicles (EVs) has started, and their diffusion is taking off, sustained by the need to quickly reduce emissions and switch to renewable energies (IEA, 2022). Traditional combustion cars are rooted within a global “system of automobility” based on oil (Urry, 2004). Replacing them involves not only introducing electric engines powered by batteries, but to realize profound transformations in the sphere of production and in the cultural, symbolic, and institutional domains (Geels, 2002). The whole automotive value chain will be transformed as many suppliers of engine-related components will be redundant and other modules will become crucial such as the electric motor, battery, and software (Alochet et al., 2022). This transition in production must be accompanied by the deployment of recharge infrastructure, which will modify driving and refueling habits and require adaptations in grid arrangements and further integration of renewable sources (Richardson, 2013). Thus, the EV transition is not simply about adoption and diffusion of an innovation, but it’s a coevolutionary process wherein many technologies, sectors and institutions influence each other and adapt. Yet not all places will be equally able to support the invention, production, and adoption of EV innovations, so the EV transition is likely to involve cities and regions very differently.

Issues of uneven regional development are key to comprehend the conditions that drive regional transitions towards new productive paths. Understanding the spatial emergence of new industrial paths and the restructuring of existing ones can help to steer them with appropriate policy measures, because phasing out existing technologies can cause job losses and social marginalization, particularly in already peripheral territories (Skjølsvold and Coenen, 2021). In turn, this can cause the defense of vested interests, power struggles, and a negative framing of transitions in public debates (Egli et al., 2022). This thesis aims to improve the conceptual and empirical tools at our disposal to investigate how the changes triggered by transitions can impact regional economies, by unveiling the networks of interdependencies that support the creation of EV-related innovations.

This thesis is driven by a general question: to what extent are the technological complementarities that emerge in transitions accompanied by urban colocation of inventors and producers? The goal is to put forward a coevolutionary approach to explain how technological complementarities and colocation are related. The intuition behind it is that during the EV transition, different technologies that were previously unrelated are becoming connected: growing interconnection should be accompanied by colocation, because increased geographical proximity is known to favor innovation. To reach this goal, I distinguish three main technologies that are coevolving: electric vehicle, battery, and smart grid. Then, I study the dynamics of invention and production in three different articles:

1) First, I investigate invention by tracing the path which includes the main patents in these three technologies, and I compare them to assess the extent to which they became increasingly similar in time and co-located in the same urban regions. In this first article, I identify the main features of a coevolutionary approach.

2) Second, I expand the view by studying all patents in EV, battery, smart grid, and combustion engine, and the cities where they were invented. I assess to what extent the evolution of technological relatedness is followed by geographical one, and I distinguish the cities where coevolutionary interactions between these technologies are stronger.

3) Third, I explore the dynamic of production networks by analyzing inter-firm ownership relations in the production of vehicles, batteries, electric motors, and smart grid equipment. I evaluate to what extent firms from these sectors are becoming increasingly connected in time and co-located in the same urban regions.

In this introduction, I provide an overview of the conceptual and empirical background that motivated and inspired this thesis, of the methodological choices taken and I critically elaborate on the main results obtained and the perspectives for future research.

# 1. Coevolution and the electric vehicle

Even if EVs are not prevalent yet, they are constantly increasing their market share over conventional cars (IEA, 2022). Improvements in battery cost/performance, declining prices of renewable energy, and European policy decisions to ban fuel car sales altogether by 2035, suggest that a transition to electric vehicles is well underway. Several technologies must be combined to enable this transition, establishing complementarities among many sectors including but not limited to automotive, chemical, digital and electronics (Golembiewski et al., 2015; Markard, 2018). In this perspective, EVs are central because while benefitting from improvements in their main inputs (batteries and electricity generation), they provide demand and impulse for further innovation and cost reduction in these technologies.

Accordingly, I propose a coevolutionary hypothesis in which firms from the automotive, battery production and electric distribution sectors are involved in a dynamic of mutual influence, resulting in vehicle technologies becoming increasingly related to innovations in battery, renewable energy, smart grid, and recharge among others. This thesis explores these coevolutionary interdependencies between sectors and their geographical emergence. Section 1.1 accounts for the history of EVs. Section 1.2 digs into the technical issues that have limited their diffusion and elaborates on coevolution, while section 1.3 discusses the general questions and standing issues that inform this study.

## 1.1 Electric cars: a long trajectory

The possibility to use an electric engine to drive a carriage began to be explored as early as the 1830s. At the end of the 19th century, electric cars were diffused in the main cities of Europe and the USA and competed with gasoline and steam cars. Their quietness, simplicity and ease of maintenance made the electric option particularly suited to urban environments in which frequent stops on short distances were required. At the beginning of the 20th century, fleets of electric taxis crowded the streets of New York, London, or Amsterdam (Larminie and Lowry, 2012). Electric cars were as a successful option for urban use including as a taxi and for promenade in urban parks, whereas fuel vehicles encountered more success for racing and for leisure trips in the countryside. However, Ford model T reached the market in 1908, providing a dominant design that became the basis for incremental improvements, and that started to be mass-produced at declining prices. Innovations such as the electric starters contributed to remedying previous shortcomings of gasoline vehicles, and electric vehicles could only briefly resist in a luxury niche for urban transport, before being completely replaced (Geels, 2005).

Starting from the 1970s, environmental concerns and the oil crisis brought attention back on the virtues of electric vehicles. Several research institutes and companies worldwide started working on experimental projects to develop and promote them (Callon, 1980; Hoogma et al., 2002). Despite being well received by the public opinion, these attempts encountered little commercial success and were quickly abandoned. At the same time, different alternatives to conventional cars were developed including hybrid, fuel cell and fully battery-powered vehicles, and they were alternatively promoted or dismissed following cycles of hype and disillusion (Dijk et al., 2016). In the last twenty years, problems of air pollution and global warming have taken center stage in western countries, resulting in tighter control of emissions and fuel consumption, and culminating in an historical decision by the European Union to ban the sale of all combustion engine cars altogether by 2035[1].

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[1] https://ec.europa.eu/commission/presscorner/detail/en/IP_22_6462 accessed on November 22, 2022.

As of today, electric vehicles represent around 9% of yearly sales globally, but their diffusion has multiplied by 4 since 2019 (IEA, 2022). We can distinguish two main families of electric vehicles: battery Electric Vehicles (EVs) depend on the electricity stored in a battery whereas Fuel Cells Vehicles (FCV) continuously produce electricity through the reaction of hydrogen stored in a tank with oxygen from the air (Larminie and Lowry, 2012). Nowadays, EVs have acquired an important edge over hydrogen cars: in fact, while electric cars are available already from a variety of carmakers and their diffusion is growing, hydrogen ones have only been championed by few constructors and their diffusion is negligible. For this reason, this thesis project focuses exclusively on EVs and does not consider hydrogen ones. Finally, hybrid cars are often counted as electric vehicles, because they have electric engines, and they sometimes provide fully electric range capabilities. Even though this thesis concentrates on fully electric vehicles, I acknowledge the importance of innovations developed to support hybrid solutions to the growth and development of electric cars.

The transition to EVs has been studied from various scientific perspectives. Scholars of economics, business, management (Egbue and Long, 2012; Steinhilber et al., 2013; Sierzchula et al., 2014; Rezvani et al., 2015) but also psychology (Franke et al., 2012) have studied consumer preferences, support policies, attitudes, and perceptions towards EVs. They found that high costs, lack of infrastructures, and several subjective factors such as “range anxiety”, can influence consumers’ choices negatively. Transitions scholars have studied EV speed of adoption (Köhler et al., 2009; Dijk et al., 2016), the actors and coalitions supporting EVs (Marletto, 2014), the role of virtual user communities (Meelen et al., 2019) and policies in different countries including Sweden (Nykvist and Nilsson, 2015b), Norway (Skjølsvold and Ryghaug, 2020), Germany and the UK (Mazur et al., 2015). Still, the EV transition has rarely been investigated as a coevolutionary process between different sectors. 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 Germany in terms of coevolution.

Transition-oriented research on EVs has largely ignored invention and production, focusing mostly on adoption of innovations. Some exceptions include Mirzadeh Phirouzabadi et al. (2020), who used patent data to explain interactions between different powertrain systems. Malhotra et al. (2021) also analyzed patents, showing that the emergence of the EV use environment influenced the focus of inventions related to lithium-ion batteries. Others have studied the role of policies in the emergence of the Chinese EV-related battery industry (Gong and Hansen, 2023). Yet there are no studies, to the best of my knowledge, that investigate the economic geography of EV invention and production. In a context of policy initiatives that aim at support battery production and EV diffusion such as the EU battery alliance[2], the EU "Green Deal Industrial Plan[3]" or the "Inflation Reduction Act" in the USA[4], it is increasingly important to provide empirical elements to make sense of the spatial emergence of the EV transition.

## 1.2 Relatedness and coevolution around electric vehicles

Contrary to previous hype and disillusionment cycles that involved alternative vehicles, the recent uptake of EVs is backed by advancements in the sectors of battery production and renewable energy, which provide favorable conditions by reducing input costs and improving performance. In fact, developments in consumer electronics have driven battery prices down (Nykvist and Nilsson, 2015a), the cost of renewable energy has decreased, and "smart grid" innovations are being devised to avoid grid overload, route energy demands and integrate intermittent sources (Richardson, 2013; Yong et al., 2015). Within this perspective, EVs are likely implicated in a dynamic of convergence between several sectors including the automotive, chemical, and electric ones (Golembiewski et al., 2015; Markard, 2018). There is still a long way to go to scale up EV diffusion, particularly to deploy extensive recharge infrastructures and radically change energy production and diffusion systems (IEA, 2022). This will likely imply even stronger complementarities between these sectors to be able to innovate and adapt to the challenges that will emerge during the transition process.

When technologies become more related, as it is the case for electric vehicles, battery, renewable energy, smart grid, and recharge technologies, the knowledge that is required to produce them becomes more similar and complementary. Growing technological relatedness results in technological coevolution, or the emergence of a shared body of knowledge, so that integration of different technology fields and their competences becomes necessary to innovate. For example, recent studies have shown that increased complementarities between EV and batteries at the diffusion phase has influenced the focus of battery inventions (Malhotra et al., 2021). This means that battery inventions become increasingly tailored to EV necessities, but also that EV inventions need to integrate gradually more knowledge of battery, smart grid, recharge, and other technologies. The advantages of localization economies and knowledge spillovers provide positive feedback to co-located agents, so increasing technological

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[2] https://single-market-economy.ec.europa.eu/industry/strategy/industrial-alliances/european-battery-alliance_en Accessed on February 16, 2023.
[3] https://ec.europa.eu/commission/presscorner/detail/en/ip_23_510
[4] https://www.whitehouse.gov/cleanenergy/inflation-reduction-act-guidebook/

relatedness is likely to result in growing geographical proximity of inventors and firms, as their technological interdependencies become embedded within local networks and institutions.

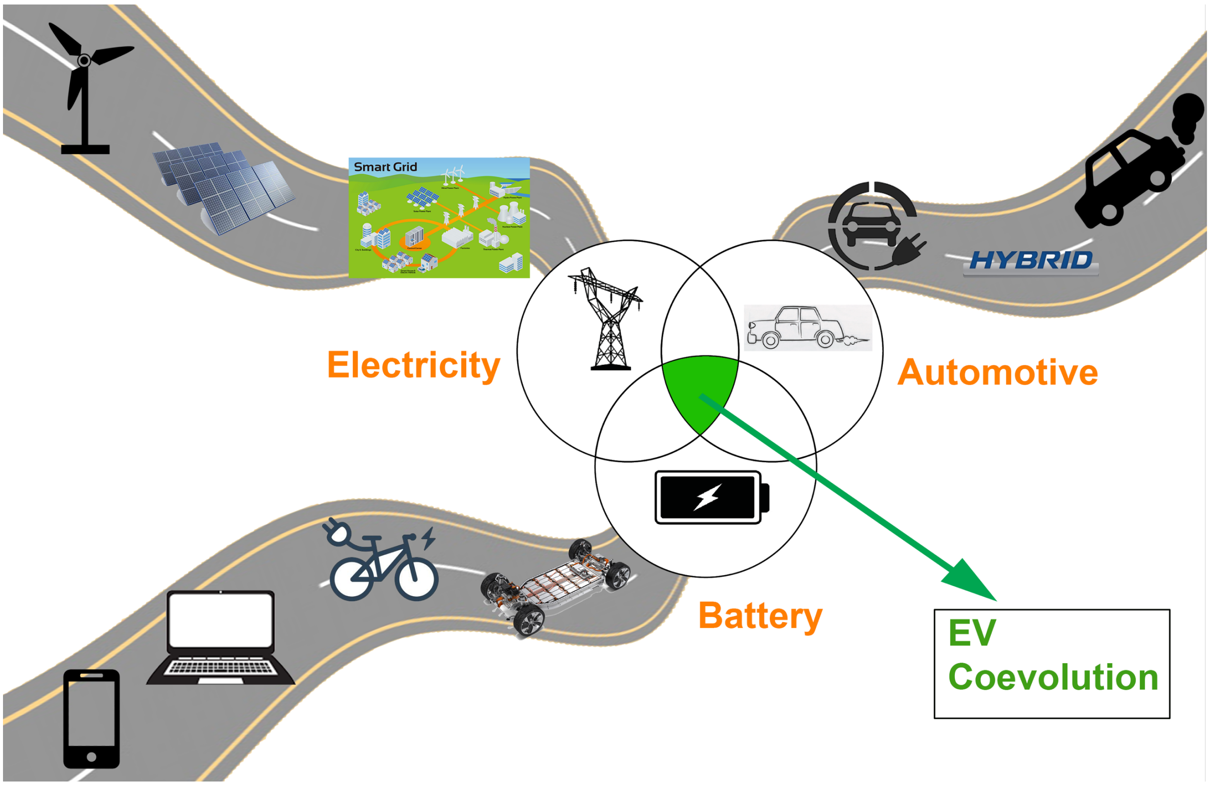

***Figure 1****: three coevolving systems around Electric Vehicle's transition*

In the transition to EVs, we can identify groups of actors that belong to three separate systems: 1) automobile production 2) battery production 3) electricity generation and distribution (Fig.1). This research proposes that these systems developed independently but that they became increasingly connected and interdependent. While it is true that EVs require batteries, and that smart grid systems can use EVs for vehicle-to-grid arrangements, their evolution can be considered as separate. In fact, lithium-ion batteries were first developed for laptops, mobile phones, toothbrushes, or e-bikes. Before smart grid arrangements, it was necessary to refine wind turbines, photovoltaic panels and begin integrating them into the grid. Similarly, even though electric cars were invented long ago, innovation in hybrid engines and experiments with different energy sources such as hydrogen or natural gas contributed to the evolutionary history of cleaner mobility solutions. Thus, these three sectors can be considered as developing along separate, but increasingly interrelated, trajectories. Technological improvements and cost reductions in each of them create demand and stimulate innovation in the others so that, following Kauffmann and McReady (1995) and Murmann (2013), my assumption is that:

*The productive systems of automobile, battery production and electricity are coevolving together in the emergence of EVs because the independent adaptive moves of actors that participate in each of them reciprocally alter the landscape to which actors in other systems are confronted.*

To recognize coevolution, it is necessary to identify distinct populations of actors and the processes of reciprocal influence through which they change together (Murmann, 2013). In this thesis, coevolution is inferred by analyzing patent data and ownership networks of multinational companies. On the one hand, the general evolution of technological proximity between EV, battery and smart grid technologies is analyzed to comprehend the general dynamics of their mutual relatedness. Then, their colocation in space is taken as a proxy for coevolution because it indicates that there might be increasing exchanges and interdependencies being established between actors from different sectors in the phases of invention and production. This thesis proposes a general framework and conceptualization of coevolution based on which specific interactions can be more precisely analyzed.

## 1.3 The implications of coevolution: open questions

A coevolutionary approach can improve our empirical and conceptual tools to imagine the economic and societal transformations of the EV transition. This thesis contributes to frame three wide open questions:

1) Which new technological complementarities could emerge during the EV transition?
2) What are the implications of coevolution for policies of local diversification and smart specialization?
3) Which socio-institutional changes are necessary to accompany the EV transition?

In this thesis I investigate interrelations between three technologies: Electric Vehicle, battery, and smart grid. Yet other innovations are likely coevolving with EVs including chargers, photovoltaic modules, autonomous driving systems, and many more. Which new complementarities might emerge as energy systems switch to renewables and cars become electric, connected, and autonomous? To begin answering this question we need to better comprehend how different technologies and the economic sectors that support them are connected, and to do so we need a finer analysis of value chain relations and multi-sectoral interdependencies.

The entire EV value chain should be considered because inter-sectoral constraints, opportunities, and complementarities can emerge anywhere along the chain. For example, raw materials such as cobalt and lithium are key to battery chemistry, and their strategic importance is apparent in the EU promotion of mining projects (European Commission, 2017). These projects could help create jobs in certain regions, but they also have environmental consequences, and they might not help secure higher quality jobs if other manufacturing tasks — such as cell making or battery assembly — fail to locate in proximity. Also, the strategic importance of materials such as lithium could decline if new battery chemistries are invented. On the other hand, mining strategic rare earth elements (REE) could enable to participate to other industrial sectors where these are needed such as in the production of magnets, electric motors, and defense applications (Lewicka et al., 2021). The EU is also supporting the establishment of battery "gigafactories", that hold the premise of creating thousands of workplaces across Europe (Eddy et al., 2019). Attracting them can boost regional development not only because of their direct impact but also by promoting related and ancillary activities. At the end of the value chain, recycling batteries will be key to re-use valuable raw materials, but it can also open new applications and possibilities as batteries can be adapted for stationary storage applications and support the deployment of renewable energies and smart grids.

Governments face the complex task of managing the decline of existing automotive productions — some of which will be inevitably abandoned as combustion engines are phased out — and stimulate the establishment of new productive sectors. However, they also need to maintain a diversified economic base and avoid becoming locked into lower value-added activities, as technological innovations can always change relations along the value chain. The coevolutionary approach proposed here merely scratches the surface of these topics, by exploring the colocation of EV-related sectors, but it sets the stage to further account for the complexity and multi-sectoral relatedness of contemporary transitions (Markard, 2018), and design appropriate policies to support them.

Coevolution also involves the emergence of new complementarities when innovations are adopted, calling for changes in institutions, regulations, and social practices. The diffusion of EV charging stations, for example, modifies automobile practices and enables the development of new economic activities, as longer and more frequent stops are required to recharge EVs. New regulations will be necessary for the battery sector, not only in the key phases of raw material sourcing and battery recycling, but also to manage the risks of fire in battery packs and adapt firefighting practices accordingly. Autonomous vehicles also call for regulatory responses to determine the nature of individual or manufacturers' responsibilities in case of accident. The examples and questions discussed above show just few of the ramifications involved in the EV transition and illustrate the relevance of a coevolutionary approach that invites to think in terms of the interdependencies that exist (or that might become apparent in the future) among different sectors and domains of applications.

# 2. Innovation as a coevolutionary process?

Beyond the case of the Electric Vehicle, this thesis widely considers innovation as a coevolutionary process. Innovation is a key driving force of capitalist economies, but the ability to create new solutions has been an essential feature of human history. Major innovations such as printing, fire weapons or the steam engine set in motion changes that revolutionized many social and productive domains. In this section I conceptualize innovation from a coevolutionary perspective, reviewing the main contributions from the literature.

I reflect on three main aspects: first, innovations can transform and reconfigure the societal domains in which they are embedded. Second, when emerging technologies are created, new interactions and mutual interdependencies can form between existing sectors, implying coevolution. Third, innovative capabilities are geographically concentrated, so that spatial proximity can be crucial to promote the circulation of complex knowledge and enable multi-sectoral interactions. While the role of innovation to promote economic growth has been often studied, we still lack a deeper understanding of its transformative role: how can we map and represent the complex networks of interconnections that are enabled by technological innovations? How are coevolutionary complementarities embedded in different cities and regions? How to devise policies to support innovation while considering this complexity?

## 2.1 What is innovation? Three insights from the literature

Joseph Schumpeter (1934) was the first to theorize the central role of innovation in economic growth. The essence of capitalism, in his view, was the process of creating "new combinations" that could give entrepreneurs an edge over competitors. His intuitions were rediscovered in the 1970s, when the period of sustained post-war growth gave way to a time of instability. Schumpeter's description of capitalism as "creative destruction" became popular, and innovation became a key notion to interpret and steer economic dynamics (Fagerberg, 2004).

Innovation can be defined as "*an idea, practice or object that is perceived as new*" (Rogers, 1983:11). This can comprise different forms of novelty, so it should be clarified what kind of innovation I investigate. As Schumpeter noted (1934:66), innovations comprise the introduction of new products, reorganizing production processes, opening new markets or setting up new forms of industrial organization. Furthermore, innovations are more than productive objects because they can be based on symbolic and cultural elements (Jeannerat and Crevoisier, 2011). This research focuses on technological innovations, adopting a definition of technology as the entire collection of devices, components and practices that are available to fulfill human purposes (Arthur, 2009). By starting from technological innovations, it is possible to distinguish specific inventions, their functional interdependence with other artifacts and practices, and to establish a firm ground onto which to investigate technological coevolution and its consequences. Three key insights are worth presenting here about the nature and consequences of innovation.

First, some innovations are *incremental* improvements on existing technologies, while others imply a *radical* departure from existing knowledge (Freeman, 1994). These two categories are often seen as complementary and connected by a cyclical dynamic in which radical innovations start a new trajectory of incremental exploration and refining, followed by another phase of breakthrough. Mokyr (1990) argues that without continuous improvements — what he calls *microinventions* – radical innovations such as the steam engine – which he calls *macroinventions* — would have rapidly been abandoned. Yet what makes innovations radical is not only their novelty content but also their transformative potential with respect to established ways of thinking and doing. Nelson and Winter (1982) called this dominant paradigm a technological *regime*, and defined it as a concept "*relating to technicians' beliefs about what is feasible or at least worth attempting*" (p. 258). Dosi (1982) described it as: "*a set of procedures, a definition of the relevant problems and of the specific knowledge related to their solution*" (p. 148). The interest in regimes as structuring mechanisms resonated with Kuhn's (1962) notion of scientific paradigms that are challenged and eventually changed during scientific revolutions. Likewise, Abernathy and Clark (1985) observed the emergence of a *dominant design* around major technological innovations, as in the case of the Ford model T car which set a standard for subsequent improvements in car design. Thus, the first question that this literature inspires about emerging technological innovations is: do they belong to established regimes with their accepted practices, or to competing paradigms based on different operating principles and visions?

Second, innovations are *socially embedded* objects, and their adoption has consequences beyond the productive domain. Sociologists had already begun to think of science not as an objective reality but as the product of a purposeful construction involving heterogeneous (human and non-human) elements (Callon et al., 1986; Latour, 1987). Other scholars added that technological artifacts are also socially constructed, and their diffusion should be contextualized by studying the social groups that support them and their contested meanings (Bijker et al., 1987). Hughes (1987, p. 51) added that "*Technological systems contain messy, complex, problem-solving components. They are both socially constructed and society shaping*". The second contribution of the innovation literature is that innovations must be contextualized within wider technical systems of which they are part and that support them. Yet societal domains — cultural, political, institutional — can be affected in different ways by innovation diffusion, and they can themselves influence the speed or extent of technology uptake. How to account for mutual influences and feedback loops from technology to society and back?

Third, innovation is a product of collective interactions. Carlsson and Stankievicz (1991) coined the term Technological Innovation Systems to describe "*a network of agents interacting in the economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology*" (p. 94). Such systemic interest for innovation has generated several approaches on National (Lundvall, 1992), Regional (Cooke et al., 1997) and Sectoral Innovation Systems (Malerba, 2002). These contributions show that innovation is a systemic activity based on networks of economic actors, universities, public institutions, regulatory agencies, user groups and more. Similarly, Dahmén (1988) suggested that when technological transformations unfold, structural tensions or disequilibria can arise because emerging innovations are not supported by complementary technologies, infrastructures, and institutions. To resolve these tensions, actors from different technological sectors and social domains can come together and form "development blocks" that can support the innovation diffusion. Hence, the third main insight is that innovations emerge from interactions between different economic and institutional actors. Yet how can we represent and investigate these complex networks of connections that surround technological innovations?

## 2.2 Innovation and (co)evolution

Creating innovation is a basic evolutionary process because it serves the purpose of improving our wellbeing and adaptability. As such, apart from being a key economic asset in today's global economy, the ability to develop new tools and techniques has always been a defining feature of humans throughout history (Mokyr, 2002). Since the invention of agriculture and writing till modern computers, our capacity to invent has transformed societies and the environment leading to an impressive accumulation of knowledge. Thus, we could gain a deeper understanding of contemporary innovation dynamics if we conceptualize it in simpler terms: how is innovation related to our essential capacity to find new solutions to problems and transmit them to the following generations?

Innovation can be framed as an evolutionary process based on the Darwinian dynamics of *variation, selection* and *retention* (Hodgson and Knudsen, 2010). Individual technologies are arranged within a hierarchical structure made of systems, sub-systems and components, with a modular and nested architecture. The evolutionary cycle acts at all levels by adding new technologies, replacing components, and passing on the most successful solutions while older ones are abandoned (Murmann and Frenken, 2006). During this process, inventions are never completely new, because they originate from a recombinant search process in which existing solutions are assembled into new configurations (Fleming and Sorenson, 2001; Arthur, 2009). But if this is the case, is it necessary to be skilled in existing technologies to produce innovations? This is likely the case, because "What we think of as a single innovation is often the result of a lengthy process involving many interrelated innovations. This is one of the reasons why many students of technology and innovation find it natural to apply a systems perspective rather than to focus exclusively on individual inventions/innovations" (Fagerberg, 2004, pp. 5-6).

Technological coevolution can be defined as:

> *A process of coupled, deforming landscapes where the adaptive moves of each entity alter the landscapes of its neighbors in the ecology or technological economy. Such landscape deformation among coevolving technologies creates knowledge spillovers and new growth opportunities as modified product designs usher in new bursts of technological learning and open new markets (Kauffmann and McReady, 1995, p. 27)*

For coevolution to be observed, it is necessary to identify different populations that undergo change through processes of variation, selection, and retention, and where some form of bidirectional influence connects their evolutionary trajectories (Murmann, 2013).

We can distinguish two main perspectives on coevolution (Schamp, 2010): one that aims at the identification of bidirectional interactions between actors, and another that designates wider system-level influences that can include sectors and technologies but also the institutions, policies, and symbolic elements that accompany their emergence. Following Gong and Hassink (2018), I contend that the pairwise and systemic understanding of coevolution are both useful and complementary to our understanding of innovation. In fact, a systemic approach carries the risk of seeing coevolution everywhere without clearly specifying why, but it also provides a framework to understand the regulatory, political, and societal elements that are key to the innovation diffusion. When different technologies become increasingly interdependent, new organizational routines (Nelson and Winter, 1982) are likely to emerge, to stabilize their interactions in research laboratories during invention, to adapt production processes to new technological requirements, and through the rise of new social practices and institutions at the diffusion phase (Martin, 2000). Routines represent sets of capabilities and instructions to enact behavioral patterns according to different conditions (Hodgson and Knudsen, 2004). Coevolution permits to inquire into routine emergence by pointing at the pairwise or multi-wise interactions that form the basis of new technological solutions, but also to investigate the systemic conditions that enable new social routines.

To sum up, in this thesis I explore technological innovation as an evolutionary process undergoing variation, selection and retention: this allows going beyond analogies and assume an evolutionary ontology (Hodgson, 2002). I adopt a multi-wise understanding of coevolution by studying the emergence of specific technologies and identifying the actors that embed them in their inventive and productive routines. I explore coevolution directly, using technological classifications, and indirectly by accounting for the geographical location of inventors, applicant firms, and producers. In fact, this research conceptualizes coevolution as a geographical process, in which localized networks and institutions play a key role in enabling interactions between inventors and firms from different sectors. But through which mechanisms can geography play a role in coevolution?

## 2.3 The role of space in innovation: relatedness and path interdependence

The role of space in innovation is a key object of research in Economic Geography. Interest in innovation arose when the Fordist landscape began to be replaced by the fragmented geographies of flexible specialization. Production had been disintegrated according to the comparative advantages that territories can offer, and organized through global production networks (Feenstra, 1998; Coe et al., 2008). Yet geographers found that while traditional industrial regions such as the Ruhr or the American Mid-West were declining, growth was concentrating in new regions such as the Silicon Valley or the Third Italy (Scott, 2000), which featured dense networks of small, interdependent firms, and an industrial atmosphere of the kind described by Marshall (1890). Paradoxically, what happened in localized industrial regions regained importance just when advances in communication and transport technologies seemed to herald the success of a "*space of flows*" over a "*space of places*" (Castells, 1996).

Geographers have tried to explain this paradox by viewing cities and regions as nexus of "*untraded interdependencies*" (Storper, 1995) where firms benefit of traded externalities (input-output connections, skilled workforce, shared infrastructures) but also of the exchange of ideas, knowledge and *savoir faire*. Michael Polanyi (1962) had talked about *tacit knowledge* which cannot be easily standardized and communicated. In the context of a knowledge economy where innovation is the key productive asset, scholars saw spatial clustering as a way to enhance the exchange of the tacit knowledge that is prevalent in new industries (Maskell and Malmberg, 1999; Gertler, 2003). This, however, left open the question of how much proximity was necessary — or even desirable — and of what kind? Torre and Rallet (2005) and Boschma (2005) showed that geographical proximity can be substituted or complemented by various kinds of organized proximity that do not imply clustering. Besides, in line with Grabher (1993), they suggested that too much proximity ― of all kinds — can be detrimental to innovation because it can lead to the *lock-in* of established practices and the failure to explore new ones.

In relation to this, it is important to introduce the concept of path dependence, which is rooted in the observation that the choices taken by economic agents set in motion a self-reinforcing process that limits the range of possible paths that these actors will be able to choose from in the future. Economic geographers have used this idea to understand how regions can avoid being locked into the activities they have been traditionally performing and how they can adapt and renew their productive base (Martin and Sunley, 2010). By turning towards path-dependence we can ask : to what extent can the socio-technical and productive routines that are concentrated in certain places (Boschma and Frenken, 2006) adapt and transform to uphold new kinds of economic activities?

Path dependence is tightly connected to the idea of relatedness, or the observation that products, economic sectors, or technologies can have varying degrees of complementarity with each other, or of similarity in the inputs that are required to generate them (Hidalgo et al., 2018; Farinha et al., 2019). Relatedness is linked to the concept of absorptive capacity applied to organizations, or the fact that "the ability to evaluate and utilize outside knowledge is largely a function of the level of prior related knowledge." (Cohen and Levinthal, 1990, p. 128). When relatedness is applied to cities, regions or nations, it means that the establishment of new inventive or productive activities can be facilitated if the new knowledge, skills and productive capabilities that are required by the emerging sectors have a certain degree of similarity or complementarity with those that are already present. Relatedness has been measured on products (Hidalgo et al., 2007), industries (Neffke et al., 2011; Boschma et al., 2013; Tanner, 2014), input-output relations (Essletzbichler, 2015), knowledge (Rigby, 2015; Kogler et al., 2017), skills (Neffke and Henning, 2013), and jobs (Muneeperakul et al., 2013; Farinha et al., 2019). Empirical results have shown that relatedness positively influence employment growth and branching into new technologies and industries.

These studies have contributed to relatedness becoming a staple in policy initiatives, particularly in the European Union "Smart Specialization Strategy" which advocates for "diversification through the local concentration of resources and competences in a certain number of new domains that represent possible paths for transformation of productive structures" (Foray, 2014, p. 493). Despite being criticized for being an ambiguous concept and for providing unclear policy recommendations (Hassink and Gong, 2019), smart specialization frameworks can likely benefit from the robust empirical contributions received from relatedness and complexity-oriented studies in recent years (Balland et al., 2019; Balland and Boschma, 2021). Still, work on relatedness could be improved in several respects, and this would enhance its value as a policy instrument (Boschma, 2017).

First, as relatedness has been measured in several ways, its definition is not always clear: does it involve similarity between different capabilities, complementarity, or the establishment of local synergies between activities? (Farinha et al., 2019). Second, what role do unrelated combinations play? related diversification is the most common trajectory for regional development, but a diversified portfolio of unrelated activities could support radically new combinations and promote regional resilience and adaptability (Frenken et al., 2007; Grillitsch et al., 2018). Third, and related to the previous point, what is the role of extra-regional linkages in accessing unrelated capabilities? Extra-regional or extra-national resources could help bridge the lack or related competences, which calls for improved ways to account for the role of global networks and connections (Binz and Anadon, 2018; Neffke et al., 2018). Fourth, relatedness is not fixed but it is dynamically evolving, so what happens when unrelated technologies and sectors become related over time (Castaldi et al., 2015; Juhász et al., 2020)?

This thesis aims at providing a contribution to the conceptualization of relatedness as dynamic, because during transitions — such as the one towards EVs — the bases of relatedness between technologies are shaken and rearranged around new socio-technical aggregations. Furthermore, the empirical evidence that I present can help comprehend how the evolution of relatedness can be supported by multi-sectoral interactions that are spatially localized but organized across globally spanning networks. The challenge is therefore to explain how path-dependent processes of routine concentration can transform into *path-interdependent* trajectories in which different technologies interact and reinforce mutually (MacKinnon et al., 2019). So, what are socio-technical transitions and why is coevolution relevant to study them?

# 3. Coevolution and the geography of transitions

Geels has famously defined transitions as "major technological transformations in the way societal functions such as transportation, communication, housing, feeding, are fulfilled" (2002, p. 1257). They are triggered by technological innovations and characterized by deep changes in many social domains. Coevolution is key to comprehend them because they often involve interactions between different sectors. But how can a geographical perspective shed light on coevolutionary interactions in transitions?

## 3.1 Socio-technical transitions as multi-level processes

The acknowledgement that technological innovations are transformative, and socially embedded objects is the basis of the literature on *socio-technical transitions* (Kemp et al., 1998; Hoogma et al., 2002). Transition scholars turned their attention to the technologies with a potential to address environmental or social issues — such as the electric vehicle — and asked the question of why these are not widely adopted and how to enhance their diffusion. They proposed the concept of *niche* to define the space where promising technologies can be tested, improved, and experimented with, while being protected from market competition. What starts as a *technological niche* through research or policy programs can develop into a *market niche*. Emerging innovations challenge the established *technological regime*, defined as the established rationale, rules and institutions that guide the activities of engineers and structure technical change (Dosi, 1982). A socio-technical *transition* can follow, wherein technical replacements are accompanied by adaptations in the institutional, economic, and social dimensions. Transitions unfold over a period of years or decades, following an S-shaped curve that involves pre-development, take-off, acceleration, and stabilization (Rotmans et al., 2001). Transitions are not linear, but they can follow different pathways ranging from simple technological substitutions to a profound dealignment and realignment of regime structures around novel technologies and priorities (Geels and Schot, 2007).

This approach was refined in a Multi-Level Perspective (MLP) that added one more level to the explanation (Geels, 2002; Smith et al., 2010). Besides the niche and regime, the MLP added the *landscape* to indicate the wider trends and circumstances — such as a financial crisis, war, or environmental event — that influence the possibility for niche innovations to challenge the existing regime (Fig.2). Besides being multilevel (niche, regime, landscape) and multiphase, Geels also stressed that transitions are multidimensional because they involve several social dimensions beyond the economic such as the cultural, political, industrial, and scientific ones.

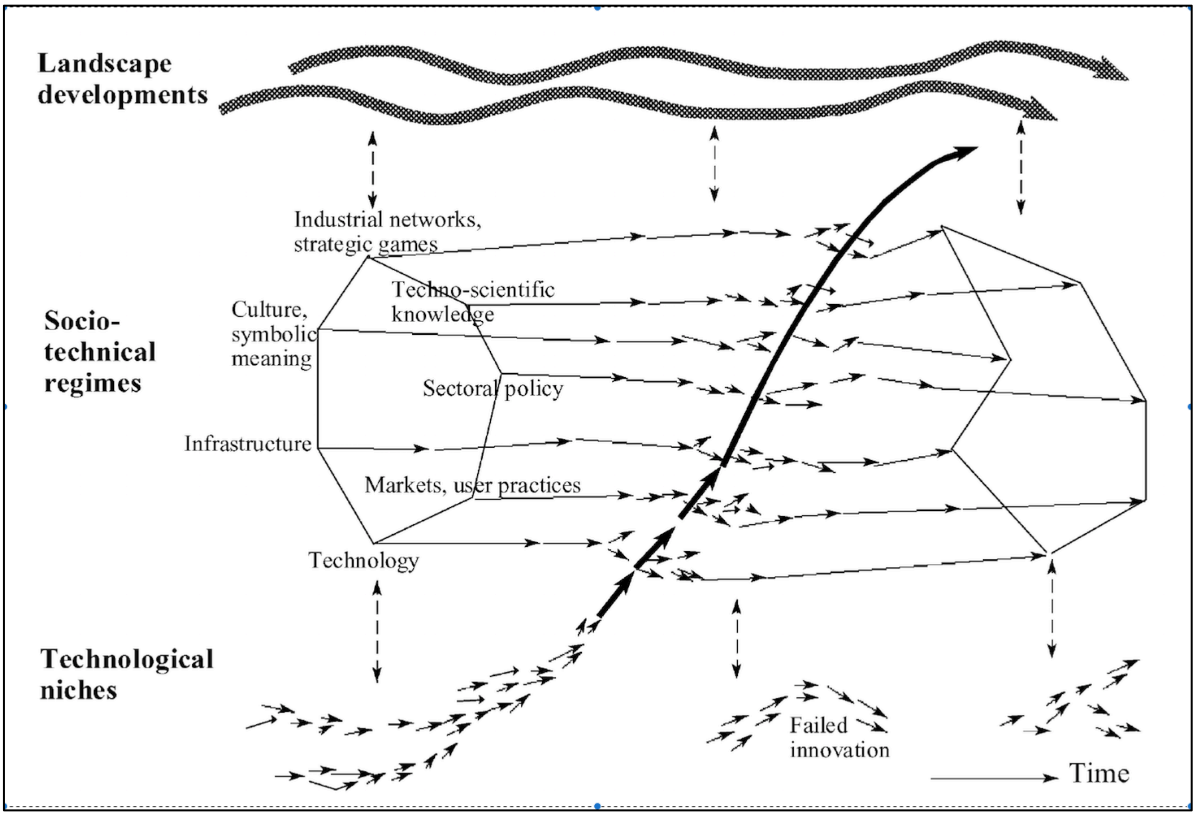

***Figure 2:** the multilevel model of socio-technical transitions (Geels, 2002, p. 1263)*

A large research field has continued to grow around the study of transitions (Markard et al., 2012; Köhler et al., 2019), with the contribution of different approaches besides the MLP, such as the literature on Technological Innovation Systems approach (TIS), Strategic Niche Management (SNM), and Transition Management (TM). Growing concerns for environmental and social problems have steered scholars towards studying *sustainability transitions*. However, it is hardly feasible to pilot transitions towards a specific outcome, not only because of the complexity of the issues at play, but for our ignorance of what the most sustainable option is (Shove and Walker, 2007). Thus, in this research I adopt the term of *socio-technical transitions* instead of *sustainability transitions*, to focus the attention on the transformative potential of technologies rather than on their purported environmental merits. Still, by framing issues of innovation in terms of transitions we can see that technological evolution occurs along trajectories that provide "gradients of force" (Geels and Schot, 2007: 403), opportunities and constraints which condition the kind of novelty that is produced by agents of innovation, its impact and possibility to be incorporated in existing regimes at a given time.

Research on transitions has greatly contributed to our understanding of how technology evolution can contribute to transform and rearrange society at large, both conceptually and with many empirical studies. In particular, it has provided insights on issues of politics and power, governance, culture and social movements, new industry emergence, everyday life and practice of transitions, the geography of transitions, ethical aspects, and it has done so by using different methodological approaches (Köhler et al., 2019). Despite the amount and diversity of these contributions, transition studies have limitations, and this thesis aims to contribute at remedying two of them, namely the lack of attention to multi-sectoral dynamics in transitions (Rosenbloom, 2020) and the limited treatment of geography (Hansen and Coenen, 2015).

## 3.2 Multi-sectoral transitions and coevolution

Transition research has often brought coevolution at the center of theorization, but it has generally applied it to wide system-level influences between technologies and societal dimensions, overlooking multi-regime and multi-technology interactions. Since the contributions of the literature on the social construction of technical systems (Bijker et al., 1987), the idea has been 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, p. 337). Studies focused on coevolution between a socio-technical regime and its dimensions (Geels, 2005), on the embeddedness of firms into different external environments (Geels, 2014), on innovation systems (Quitzow, 2015), or policy mixes (Edmonson et al., 2019). The idea behind this interpretation of coevolution is that many different dimensions and external resources need to be aligned and work together to favor technological change, but it does not address the question of: how do *different* technologies and systems coevolve together?

Studying coevolution between technologies, regimes, sectors, or systems, remains a major gap in transitions research (Rosenbloom, 2020). Research has shown what happens when different regimes coevolve such as waste and electric ones thanks to bioenergy applications (Raven, 2007) or the natural gas and electricity regimes in combined heat and power systems (Raven and Verbong, 2007). Previous work had conceived the existence of multimode interactions between technologies that can be not only complementary but also in competition (Pistorious and Utterback, 1997). Transition scholars have expanded on this suggesting that the range of interaction modes between technologies can be even wider, and involve different socio-technical systems because, by their own nature technologies are inherently "bundles of value chains" (Sanden and Hillman, 2011). The establishment of complementarities across regimes can thus enable the emergence of new systems from their combination. Hacklin et al. (2009)

have observed this process from a management perspective and described it as convergence, using the case of the ICT industry as combination of phones and computers and expanding the argument to nanoscience and biotechnology sectors. Papachristos et al. (2013) discussed the case of functional foods as combination of food and pharmaceutical systems, and claimed for integration of multi-system perspectives into the MLP.

Recently, a multi-sectoral research perspective has emerged focusing on the complementarities that support transitions (Andersen et al., 2020). These contributions argue that to understand socio-technical change we should acknowledge the interactions that occur *around* a main technology: *above and below*, in the value chains that are responsible for providing subcomponents and using outputs, and *sideways* as different sectors, and parts of their value chains, interact together (Fig.3). Within this framework, Markard and Hoffmann (2016) studied photovoltaics, offshore wind, and electric vehicles, showing that complementarities can be positive or negative, and that they vary according to technological requirements and the degree of maturity and diffusion of new solutions. Andersen and Gulbrandsen (2020) studied the offshore petroleum sector in Norway and mapped complementarities with sectors that require similar capabilities in offshore infrastructures such as wind energy and aquaculture. Mäkitie et al. (2022) explored inter-sectoral complementarities (positive or negative) around the coastal shipping sector in developing zero-carbon technologies such as electric ships or hydrogen and biogas fuels.

These studies account for complementarities between sectors and value chains, contributing to an improved conceptualization of the interdependencies that enable transitions. They provide four key contributions. First, transition studies have seldom addressed dynamics of invention and production, focusing mostly on diffusion: a multi-sectoral approach enlarges the analysis by including upstream activities of the value chains. Second, it nuances the idea that transitions imply radical discontinuity by identifying relatedness and complementarities between incumbent and emerging sectors. Third, and related to this, it allows to reflect on the economic and societal impact of technological change so that sounder policy implications can be sketched to accompany transitions and mitigate the societal impact of industrial restructuring. 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.

This research builds on all these contributions by giving center stage to invention and production and by studying complementarities between incumbent technologies such as combustion engine, and emerging ones such as EV, battery, and smart grid. In particular, I expand this approach and link it to contributions in the geography of transitions and economic geography, because a multi-sectoral perspective tells us that many different sectors associate during transitions, but a geographical one explains how localized relations and networks enable these interactions.

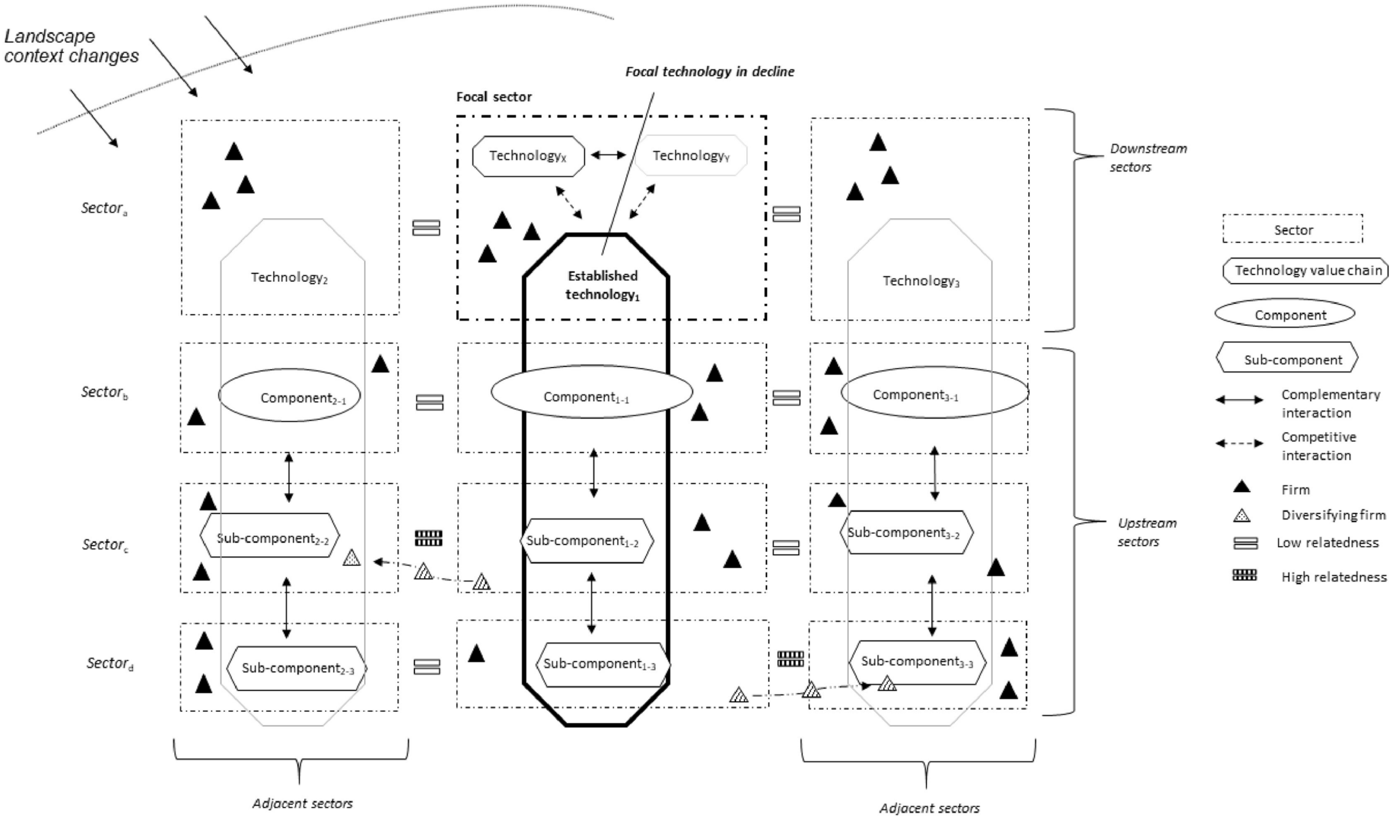

***Figure 3:*** *Multi-sectoral interactions in transitions (Andersen and Gulbrandsen, 2020, p. 4)*

## 3.3 Relatedness and path dependence in the geography of transitions

The path-dependent concentration of capabilities in related technologies, and the advantages of geographical colocation in facilitating interactions, are key elements to explain why certain regions support the emergence of transition technologies and others do not. By combining a coevolutionary approach with economic geography we can explain how localized capabilities, networks and institutions can enable and sustain the recombination of different technologies. A coevolutionary perspective on transitions permits to go beyond a general acknowledgement that spatial proximity benefits innovation by focusing on the recombination of specific technologies in the context of wider processes of change.

The role of geography has only partially been addressed in the literature on transitions (Coenen et al., 2012; Truffer and Coenen, 2012; Hansen and Coenen, 2015). Spatial heterogeneity has been exposed by studying how local specificities inform specific transitionary trajectories in cities and developing countries (Köhler et al., 2019). These contributions have brought empirical evidence, but their results are not easily generalizable 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).

Of late, an articulated agenda has cohered 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 hubs in transitions because they are the places where different sectors and domains of application can associate, and novel solutions can be implemented and tested (Frantzeskaki et al., 2017). But these processes are not only local. The emergence of localized trajectories of change is contextualized within a multi-scalar perspective showing that while dominant rationalities are embedded into global socio-technical regimes (Funfschilling and Binz, 2018), the alternative configurations that challenge them also relate cities and regions across scales (Sengers and Raven, 2015; Miorner and Binz, 2021). Not only *diffusion* of transition technologies is being explored, but also 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). Thus, transitions involve not only implementing new technologies and adapting to them, but also the emergence of new sectors which are invented and produced by actors that draw on local resources, but are globally connected.

Insights from economic geography show that the *path dependence* that supports existing technological regimes is linked to *place dependence* because it is based upon capabilities that are the product of localized knowledge, institutions, networks, and cultural values (Maskell and Malmberg, 1999). When transitions unfold, these territorial dependencies need to be 'unlearned' and new regional growth paths emerge based on new socio-technical configurations (Boschma et al., 2017). The literature on relatedness provides a solid base to study the emergence of new sectors (Whittle and Kögler, 2020), and how it is embedded in local capabilities and development paths.

A geographical perspective to transitions builds on these insights and complements them in several respects. First, it allows to contextualize innovation within a structural framework in which the transformative opportunities of transitions impact different technologies and regions at the same time. Local responses can be heterogeneous, but socio-technical transitions are global phenomena, so they permit to establish similarities between localized innovation trajectories. Second, it shows that as socio-technical conditions change, relatedness between sectors and technologies also evolves (Juhász et al., 2020). Third, it acknowledges that external networks and connections can be important sources of unrelated diversification, overcoming an agglomeration-centered view of relatedness (Binz and Anadon, 2018). Fourth, it highlights the importance of "smartly" diversifying local competence bases by developing the interconnections with the highest relatedness potential between existing and emerging sectors (Andersen and Gulbrandsen, 2020).

## 3.4 Contributing to the geography of transitions

The contribution of this thesis is to improve the engagement and exchanges between economic geography and transition research (Boschma et al., 2017; Binz et al., 2020). I pursue this engagement through a coevolutionary perspective that connects the emergence of inter-sectoral complementarities during transitions, to the spatial structures and resources that enable them. This approach has three main advantages. First, it relates transitions to generalized dynamics of technological change in which technologies emerge and are selectively retained, and in which coevolution improves chances of success by promoting bundles of interrelated solutions. Second, it enriches the societal relevance of economic geographic analysis by going beyond innovation as a growth engine and specifying how smart specialization or the promotion of related diversification might be connected to wider transformations that invest different sectors and social domains. Third, it sheds light on the interplay between global networks and localized productive systems (Binz et al., 2016).

Economic geography helps us explain the role of agglomerations and global networks in promoting coevolution, while transition studies frame this into a wider perspective. Colocation can favor the recombination of heterogeneous knowledge from different sectors by reinforcing cognitive and institutional proximity (Boschma, 2005). Yet sometimes very different inputs are required than those available locally, and they can be accessed by drawing on global resources and connections (Binz and Anadon, 2018). The emergence of transitions is a path-interdependent process in which cross-sectoral connections are enabled by complementarities between local networks institutions, productive systems, and global ones (MacKinnon et al., 2019). This approach allows studying the localized emergence of new inter-sectoral configurations and how the ‘transition hotspots’, where these novelties are invented and produced, are globally connected. In turn, this allows to pose increasingly urgent questions such as: how can policymakers support the establishment and growth of transition-related sectors? Does the presence of related sectors matter? Does the presence of incumbent industries favor or hinder the development of emerging ones?

# 4. Conceptual framework and research questions

The goal of this research is to propose a coevolutionary perspective to interpret the emergence of multi-sectoral interactions in transitions and how these are supported by geographical connections and interdependencies. To reach this goal, I explore the invention and production of EV, battery and smart grid technologies and I pose questions about how growing technological relatedness between them translates into geographical colocation. In this section I present the conceptual framework that drives the thesis and the research questions.

## 4.1 The role of path dependence and relatedness in the evolution of EV technology

Technological evolution is a process that, while having its own specific features, can be framed within the general evolutionary dynamics of variation, selection, and retention. Accordingly, transitions are conceptualized as a process of routine construction that begins when new technological routines are developed (invention), continues when some of them are selected and embedded into production routines (production) and follows when socio-technical routines are created that incorporate the new technology in their functioning (adoption). These phases are seen sequentially, because without invention and production there cannot be adoption. Yet this does not mean that this process is linear because through trial-and-error, changes are likely to feedback from production and adoption towards invention, recursively.

The production of complex technologies such as EVs involves joining many different components. Each technology is produced within a main sector, which can be defined as “an aggregation of actors having similar production competences and outputs” (Stephan et al., 2017, p. 711). Sectors are thus defined by their main outputs, but they are themselves exchanging components and finished products with other sectors. As a result, complex technologies are at the center of multi-sectoral value chain arrangements, so that EVs, for example, participate to the dynamics of the battery sector (including chemical and extractive sectors), the automotive and the electric one (including electricity generation and distribution, and the wider production of electric devices, motors, connectors, etc.). Interdependencies and cross-sectoral connections are manifest at the production and adoption phase because it is where new arrangements involving different technologies start working together, but they are likely to emerge already at the invention phase. This thesis focuses on the first two phases of the EV transition: invention and production. Each of these phases involves the creation of specific routines that are studied using patent data and information on ownership networks of multinational firms. The phase of adoption could not be studied in this thesis, but I acknowledge its importance, and it will be the object of further investigations afterwards.

| | ***Invention*** | ***Production*** | ***Adoption*** |
|---|---|---|---|
| **Unit of analysis** | Technological routines and their geographical location | Production routines and their geographical location | *Socio-technical routines and their geographical location* |
| **Units of observation** | Patent citation networks. Patent locations. Inventors and applicant firms. Technology classifications. | Ownership networks. Location of firm establishments. Production classifications. | *For example recharge networks between utilities, car companies, consumers' groups, service providers.* |
| **Technologies** | Patents related to electric vehicles, battery, smart grid, and internal combustion engines. | Firms that manufacture conventional and electric vehicles, batteries, electric motors, electricity distribution and control apparatuses. | *For example: Electric Vehicle Supply Equipment (EVSE) in different specifications. Renewable energy generation.* |

***Table 1***: *Three phases of the EV transition.*

In this research I assume that multi-sectoral interactions are organized spatially through a combination of dense, localized exchanges that can support the co-creation of new knowledge around EVs, and global network linkages that allow this knowledge to circulate (Maskell and Malmberg, 1999). During transitions, new interdependencies are established between technologies. The emerging geography of transitions will depend on the extent to which these new multi-technology configurations find support and complementary conditions in the innovative capabilities of specific urban regions. Technological and geographical spaces coevolve (Fig. 4).

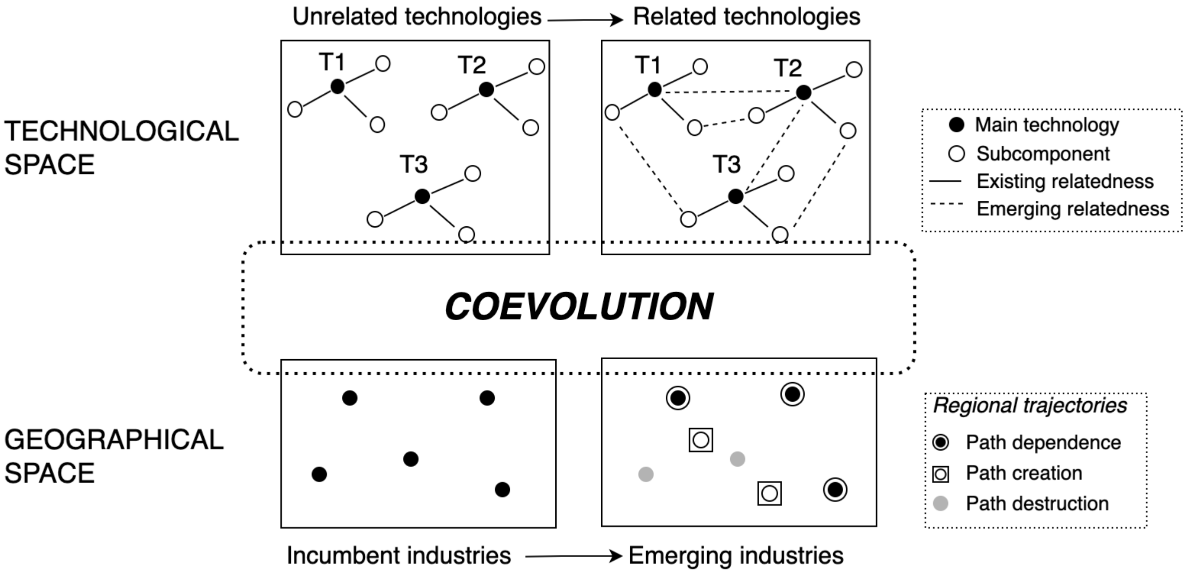

***Figure 4***: *Coevolution between technological and geographical space during transitions*

The *technological space* is characterized by differences in relatedness, or proximity, between technologies. Some of them are related because they are frequently associated or because the inputs they use are similar (*i.e.,* boats and radar systems or planes and space rockets). Others are unrelated because they are not usually associated or their inputs are dissimilar (i.e., tractors and violins, or ovens and t-shirts). Relatedness between technologies has often been represented as a network where the strength of connections between nodes is given by their technological proximity (Boschma et al., 2015). During transitions, new links emerge between disconnected technologies, and the whole network is reconfigured. As a result, new inputs, know-how and productive capabilities become relevant to generating innovation.

These resources are unevenly distributed in *geographical space*, so that not all urban regions are able to host EV-related patents or productions. In our case, I expect path dependence to play a key role: because automotive capabilities are related to EV ones, the urban regions that innovated in conventional cars should also be innovative in EVs. Yet this might not be always the case: automotive regions might be unable to create EV innovation and experience path destruction and the loss of existing competences. Otherwise, new regions without an established automotive base could develop EV competences and create new regional paths where they were absent.

I view *coevolution in transitions* as a matching process between emerging technological networks with their new relations of relatedness, and the urban regions that support them with their innovative and productive competences. In this thesis, I account for coevolution between technologies by exploring interactions between inventors and firms. This conceptualization does not allow to draw generalizable conclusions, but my contention is that by exploring invention and production networks we can build a structure of relations between technologies, sectors, and cities. On this framework, we can articulate wider questions on coevolution between technologies and space, or between different phases of the innovative process from invention to adoption. Thus, the goal of this research is not to treat coevolution fully, but to provide a way to explore it empirically, and to sketch the contours of a conceptual framework where coevolution connects innovation, geographical differences, and transitions.

## 4.2 The main path towards EV inventions: a coevolutionary framework

The first article proposes the key features of a coevolutionary perspective capable to connect the study of multi-sectoral interactions in transitions with the localized networks and capabilities that enable them. To illustrate the argument, I build patent citation networks that account for what previous inventions were cited by subsequent ones, reconstructing the long-term trajectory by which technological knowledge was selected and accumulated in time. Then, I simplify this network and identify the main nodes that contributed to inventions in electric vehicles, battery, and smart grid technologies. The first research question is:

**RQ 1.1:** *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?*

The idea is that even though these technologies can be largely considered as independent, their innovative claims and main contributions are likely to become increasingly similar in time and possibly joined in common inventions and products. This increasing convergence of technological interests could be mirrored by increasing colocation of patents from different sectors in the same urban regions. In fact, the development of complex knowledge can be favored by face-to-face interactions between inventors and firms. Hence, I ask:

**RQ 1.2:** *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?*

The first part of the question aims at identifying the cities where coevolution between these sectors might be favored by their colocation. The second part of the question hints at the fact that path dependence could play a key role in this so that established centers of invention, particularly in the automotive field, might be able to attract patents in EVs but also in related battery and smart grid fields. On the other hand, the diversity of the knowledge base required by these emerging technologies might favor the appearance of new growth paths in rising urban regions. Patents are localized through the address of inventors, but applicant firms can support many different inventions, so they connect different urban regions through their activities. I analyze the inter-urban networks that they form, and ask:

**RQ 1.3**: *What inter-sectoral and inter-urban connections emerge in the analysis of the city-applicant network and who are the key actors in it?*

Cities where different technologies co-locate are likely to favor their recombination and coevolution. Applicant firms can operate in different cities, connecting them in practice and supporting inter-urban knowledge flows and coevolution. The last question is conceptual:

**RQ 1.4:** *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?*

By answering these three empirical and one conceptual research questions, I provide support for the identification of some key features of a coevolutionary approach to transitions, before applying it further to study invention and production dynamics in more detail.

## 4.3 Technological coevolution and spatial colocation

The second article applies a coevolutionary perspective to study global patenting in EV, battery, and smart grid across large urban regions. We use the concept of relatedness as an empirical tool to assess proximity between different technologies, and as a proxy for coevolution. Accordingly, we distinguish technological from geographical coevolution, the first being indicated by the co-presence of different technologies in the same patent documents, and the second by the presence of different technologies in the same urban regions. The first research question is:

**RQ 2.1:** *To what extent is technological coevolution between EV, battery, smart grid, and ICE technologies, accompanied by geographical coevolution?*

Technological coevolution is a non-spatial concept, that can give a general indication of the increased relatedness between the technologies that support the transition to EVs. We also include information about Internal Combustion Engine (ICE) inventions, to assess if, as it could be expected, conventional fuel-based technologies become less and less related to EV ones. We expect geographical coevolution to be related to technological one, so that when the latter grows, the former also increases. However, this might not be the case for all these four technologies, and we also check whether this is the case for other technologies that are highly related to EVs. After considering how these forms of coevolution are related, we explore geographical coevolution more in detail, and ask:

**RQ 2.2:** *What do technology colocation patterns across different groups of cities suggest about EV coevolution?*

We expect the four technologies that we study to be unevenly distributed across urban regions. We aim to find where they are more concentrated, both in absolute patent numbers and in relative specialization with respect to other technologies being invented locally. To do so, we group regions together according to their scores in these four patent classes, assessing differences and similarities in their technological trajectories in time. Then, we explore the drivers of colocation by studying the effect of different specializations on EV patenting:

**RQ 2.3:** *Does patenting in battery, smart grid, or ICE influence EV patenting, and does path-dependence play a role?*

Without aiming to identify causal mechanisms, we expect that EV patent scores might be significantly impacted by patenting in related technologies, and that this dynamic might be increasingly apparent as these technologies become more related in time. By answering these three research questions, I aim at contributing to a conceptualization of transitions as spatially grounded phenomena that are driven by complementarities between increasingly related technologies that are locally embedded and likely coevolving, as different domains of knowledge become increasingly localized in the same urban regions.

## 4.4 EV production and coevolution with related sectors

Under globalization, production has been vertically disintegrated and organized through networked forms of coordination (Feenstra, 1994). This has lessened the spatial constraints of production: standardized tasks have become increasingly footloose and outsourceable to the cheapest locations. Yet, to keep a competitive advantage, industry leaders have retained several core productive functions. In the context of the automotive sector, the high capital intensity and vertical integration required by car assembly suggest that key production routines are largely embedded in the material manufacturing process. In this view, path dependence is conditioned by the existence of productive facilities, skilled workforce, and infrastructure. While the geography of invention is expected to be organized around the concentration of highly innovative firms, universities and research institutions, the geography of production will likely gravitate around the existence of major productive nodes.

In this paper, we study coevolution in production by exploring changes in the ownership networks of multinational firms in the period 2010-2019. Recent studies have shown that automotive firms are largely internalizing, or controlling through joint ventures, the production of batteries and electric motors for EVs (Alochet et al., 2022). This behavior responds to the need to maintain control over the strategic steps of the EV value chain, to develop independent innovative skills and to employ existing resources. This brings the question of: where is this internalization happening? Do automotive firms add battery-making or software development functions close to existing plants or they control their production through global networks? Alcácer and Delgado (2016) have shown that firms benefit of internal agglomeration advantages that derive from geographical proximity with same-firm units, for example by improving information exchange and economies of scale. It is important to know more about the role of geographical proximity because regional policies in support of battery, smart grid, and software technologies could help retaining automotive jobs or attracting new ones. Hence, we consider companies that are producing automobiles, batteries, electric motors, and smart grid control systems. We map their ownership networks in time, and we ask:

**RQ 3.1:** *Have the networks of multinational firms in the battery, electric motor and smart grid sectors become increasingly connected to those of automotive firms?*

As EVs become increasingly strategic, main automotive firms — that were previously disconnected from battery or electric motor production — are likely to have become increasingly involved in direct participation to these fields. Recharge systems are key to EVs, so the production of electricity distribution systems for grid control and metering are also expected to become more connected to automotive production in time, albeit to a lesser extent. Increased network connections between firms in these sectors are also expected to be reflected in increased geographical proximity. To verify, we aggregate networks based on the urban regions where firms are located, and we ask:

**RQ 3.2:** *Does the production of automotive, battery, electric motor, and smart grid increasingly concentrate in the same cities?*

The main hypothesis is that existing automotive facilities are increasingly co-located with firms in these coevolving sectors. Yet not all locations where automotive activities take place are producing EVs. Therefore, we investigate if EV production locations are interested by this colocation dynamics more than those where conventional cars are produced. By answering these questions, we assess if there is evidence of growing colocation of production sectors that are related to EVs in the same cities, which could suggest that coevolutionary interactions are one of the reasons for it.

# 5. Data and methods

The goal of this investigation is to make sense of the transition to EVs as a process of routine construction that emerges in space, during the phases of invention and production, through coevolution between different technologies. The main methodological feature of this research is to adopt a network approach that allows to elaborate on the relations between technologies and between the agents that contribute to their creation. By locating these relations in space, we can account for technology interactions within and across urban regions.

Actors such as inventors, firms, universities, and public institutions are responsible for developing the routines in which EV and related technologies are embedded. I access information on their activities and location by studying patents and firm ownership networks, which link them through invention and production networks respectively. With the analysis of network properties and positions, we can understand which actors and linkages are most relevant in the creation of EV routines. A network approach allows to comprehend the structural constraints and opportunities that emanate from different network positions.

To investigate the spatial emergence of transitions, it is necessary to consider the emergence of agglomerations of actors and how these are connected globally, because local and global networks are interdependent (Rozenblat, 2010). To do so, I use information on the geographical location of patent inventors, applicant firms and about firm establishments. I aggregate smaller urban locations into Large Urban Regions, to account for the centripetal effect of major metropolitan areas in attracting innovative activities and in their role of gateways to global economic flows. In sections 5.1 and 5.2 I explain how the data were gathered, treated, and analyzed and which methodological choices drove the research.

## 5.1 The geography of EV invention: articles 1 and 2

### 5.1.1 Patent sources

Patents are legal titles protecting and invention and granting their owner rights of exclusivity over an invention (OECD, 2009). The use of patents to measure innovation is well established because they offer quantitative and systematic insights, even though they suffer from some disadvantages (Griliches, 1990). The OECD regularly publishes several databases on patents, of which this thesis uses the following:

- *Triadic patent families* (OECD, 2021a): includes inventions that have been patented in the USA, the EU and Japan. The fact that inventions have been patented in these three jurisdictions at the same time is considered an indicator of patent quality and relevance. Documents from the EPO and the Japanese patent office also include *patent applications*, whereas data from the USPTO include only *granted patents*.
- *Citations* (OECD, 2021b): the database covers all citations from EPO and USPTO granted patents starting from 1978 and 1976 respectively.
- *Regpat* (OECD, 2022): this database includes information about the geographic location of inventors and applicants assigning them to regions across all OECD countries and several developing ones. Data on technological categories (IPC and CPC) are also included. However, it covers only EPO and WIPO patents.

To complement this information, I included specific data to retrieve inventor's location as well as technology classification codes for US patents. (Patentsview.org, 2021). In Box 1.1 the reader can refer to a word list explaining the patent terms used here.

A general drawback of patent data is that there is always a lag of several years between the moment in which an invention is developed and the actual filing and publication of the patent. In this study we used the publication date to locate inventions in time. This means that results should be interpreted with caution, because the coevolutionary dynamics that the study wishes to identify might have taken place already before patent publication.

**EPO** : European Patent Office

**USPTO**: United States Patent and Trademark Office

**Patent family**: a set of patents (or applications) filed in several countries to protect the same invention.

**Patent grant**: unlike a *patent application*, it provides legal rights to protect invention against infringement.

**Applicant**: The holder of the legal rights and obligations on a patent application. It can be a company, university or an individual. It is equivalent to "Assignee" in the US.

**IPC** : International Patent Classification is the most used international classification system.

**CPC**: Cooperative Patent Classification is an extension of the IPC, jointly developed by USPTO and EPO.

***Box 1.1:*** *List of acronyms and patent terms*

### 5.1.2 Patent codes

To delimit the technology fields that are the object of this study, I employed CPC codes at the four-digit level. In line with other studies on EV and battery topics (Golembiewski et al., 2015; Borgstedt et al., 2017), the following technology codes were identified (EPO, 2022):

- For EV, Code B60L: "*Propulsion of electrically propelled vehicles*".
- For Battery, code H01M: "*Processes or means,* e.g.*, batteries, for the direct conversion of chemical energy into electrical energy*".
- For Smart Grid, the tag Y04S is considered, that refers to "*Systems integrating technologies related to power network operation, communication or information technologies [...],* i.e., *smart grids*".
- For Internal Combustion Engine (ICE), code F02B: "*Internal-Combustion piston engines; combustion engines in general.*"

It should be noted that these codes represent the subclass level, which is a rather aggregate classification that contains 656 codes. This means that these categories can include more inventions than those this research is concerned with. Put differently, these codes do not correspond one-to-one with the technologies we are interested in, but they represent a reasonable approximation. This choice aims at maintaining a balance between the need to precisely delimit technologies and keeping the number of codes at a manageable level. This is backed by several studies that analyze IPC/CPC networks at the four-digit or even higher levels of aggregation (Kogler et al., 2013; Leydesdorff et al., 2017; Yan and Luo, 2017).

### 5.1.3 Patent geolocation

To geolocate patents, the address of inventors is often considered as the safest indicator, because applicants can have many addresses and headquarters (OECD, 2009). Yet patents can have several inventors located in different cities. To address this issue, in the first paper I use data from de Rassenfosse et al. (2019) to geolocate inventors, and fractional counts to calculate the share of inventors that corresponded to each urban area. For example, if a patent was invented by three inventors in three different cities, each city received a score of 1/3. In the second paper, we use *Regpat* data to geolocate patents using the address of inventors. Since we focus on the colocation of inventions, we calculate simple counts every time a city participated of a patent, irrespective of the relative share of inventors per city.

In both cases, each location is matched to the closest Large Urban Region (LUR) to which municipal locations belong (Rozenblat, 2020). LURs are defined all over the world around the concept of Mega-city region (Hall and Pain, 2009), that refers to the fact that economic activities transcend administrative boundaries and form large regional systems around urban agglomerations. A key feature of LURs is that they represent the gateway to global flows, so international airports are considered as the geographical center of the LUR. In the first paper, inventors were assigned to LURs using an algorithm that calculated the closest distance from an inventor's address and LUR centers. In the second article, European and US locations were matched to LURs using a correspondence table (Rozenblat, 2020), while for other countries they were manually attributed. In both cases, almost all patents could be correctly geolocated.

### 5.1.4 Building main paths of patent citations: article 1

One of the problems of patent data is that most inventions do not have a significant economic value, and only few of them have great value, being used in successful innovations (OECD, 2009). By analyzing patent citations, it is possible to get insights on their relative value and on the knowledge spillovers — along with their geographical scope — that contribute to the emergence of different technologies (Jaffe and Trajtenberg, 2002). Yet simple citation counts can be misleading. Differences in citation practices across jurisdictions make it problematic to assign the same value to their citations. Also, some patents might be very cited in a particular moment, but their technology might be quickly replaced by an alternative option. Conversely, other patents might not be very cited but constitute an important improvement on which later, highly cited patents could build.

Considering this debate, in the first article I adopted the methodology of "main path analysis" to identify the main flow of ideas between cited and citing patents (Hummon and Doreian, 1989; Verspagen, 2007; Barberá-Tomas et al., 2011). This approach is based on reconstructing the network constituted by patent citations, and then finding the links with a strategic position, *i.e.,* those that serve to connect the highest number of alternative paths between sources (recent patents that are not cited) with sinks (older patents that do not cite). By isolating the main path connecting recent inventions to older ones, it is possible to identify the most significant knowledge flows in the network, and the patents related to them.

To build a citation network, I extracted the first three CPC codes[5] from the database on patent families, which includes patents that are considered particularly relevant for having been submitted to the world's leading patent jurisdictions (Dernis and Khan, 2004). Then, I recursively followed their citations, building three large networks that I filtered according to the presence of keywords in the patent's titles or abstracts. Finally, I applied the Search Path

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[5] The fourth one, related to Internal Combustion Engine technologies, was used only in the second article.

Count algorithm (SPC), to extract the main path of patent citations from each network (de Nooy et al., 2018). Each path comprised around 50 inventions that contributed to the creation of knowledge in the electric vehicle, battery, and smart grid technologies in the past century. After identifying the main paths and attributing each invention to 70 urban regions, I constructed a patent-city-applicant network in which applicants are also connected to the city of inventors. Since applicants participate in the development of man patents, I could use this information to understand how city networks were connected through the activities of major innovating firms.

The methodological approach adopted in this paper has some limitations. A main shortcoming of this study is that I only considered patents from the US patent office. This choice was motivated by the fact that the patent citations analyzed needed to have the same relative value. While US citation practices imply that many citations are attached to each patent, this is not the case in the European or Japanese patent offices, so the relative value of one citation differs from one jurisdiction to the other. Hence, I decided to consider only US patents, where citations are widely used and as such could provide deeper insights on the evolution of EV related knowledge. This choice inevitably implies that patents created in the US are more represented, even though European and Japanese inventions also appear frequently. On the other hand, Chinese patents are less represented, likely because Chinese firms became globally innovative only recently, and as such they didn't file many US patents before. Finally, the fact that large networks of citations were filtered using keywords related to each technology inevitably limited the diversity of patents that we could find with this method. This implied that the presence of key connecting inventions in unexpected technologies could not be accounted for.

### 5.1.5 Technological coevolution, colocation, and specialization: article 2

In the second article, I investigated the geography of invention with co-authors, by widening the analytical lens from a sample of strategic patents located in few cities to all patents across all many urban regions. In the first article, I provided an overview of coevolution dynamics between electric vehicle, battery, and smart grid inventions, and I explored which cities emerge as important coevolutionary locations thanks to the activities of applicants. Instead, in the second one we considered global patenting in these three technologies, adding combustion engine inventions to compare patent trends in opposing technologies. This allowed to provide a global vision of technological and geographical relatedness and of specialization trends in four technologies across more than 100 urban regions.

Relatedness, or proximity between technologies, has been often measured by constructing a “technology space” using patent data (Yan and Luo, 2017). In this article we used co-classification (two codes appearing in the same patent) to indicate technological relatedness, and colocation (two codes appearing in the same city) to indicate geographical relatedness. We constructed two square matrices of 656 CPC codes for each of these measures, and we compared the evolution in time of the most related technologies to EV. We attributed cities to four different groups according to their scores in the four technologies object of investigation, using correspondence analysis. We calculated the specialization of urban areas in each of the four technologies using the location coefficient or RTA: Revealed Technological Advantage (Balassa, 1965). This index shows to what extent a region is specialized in a technology compared to other regions. Using this index, we checked if the four groups of cities identified previously are specialized in specific combinations of technologies that support EVs. Finally, we evaluated using multiple regressions the extent to which colocation of patents in battery, smart grid, and combustion engine, is a factor that promotes EV patents. Taken together, these methods allow to comprehend the evolution of technological and geographical proximity between EV other technologies, which cities are specializing in EV-related technologies, and if this gives them an edge to patent more EV inventions.

This article suffers from some limitations. In general, the use of patents to measure innovation has many well-known drawbacks (Griliches, 1990). Unlike in article 1, here we considered many patent jurisdictions at the same time, and all patents in the technology codes selected. This provided a more general perspective on invention dynamics in these technology fields, but it also posed challenges in the geolocation of inventions, as developing countries such as China and India featured fewer regional units than Europe or Japan. This means that cities in these countries have been considered as being at the center of very wide urban regions so that the scores of cities like Bangalore and Shanghai are somewhat overestimated compared to New York or Madrid. Another limitation of this article is in the quantitative models that estimate the effect of related technologies on developing or losing EV specialization. Because only few cities are specialized (or lost a specialization) in EV, these models feature only few dozens of observations, so their results must be interpreted with caution.

## 5.2 Geographies of production: article 3

Recent studies have shown that automotive firms increasingly participate to the EV value chain by producing batteries and electric motors (Alochet et al., 2022). The type of control they exert on these tasks can differ: car makers can make them internally, enter into joint ventures, or even buy firms to acquire control over production skills and resources. By obtaining insights on the evolution of ownership networks, we can know to what extent previously unrelated productive sectors — such as battery, automotive, and electric ones — have become increasingly connected through reciprocal participations, and which firms and sectors drove this process.

### 5.2.1 Orbis database and NACE codes

To get insights on the geography of production, we use the ORBIS database from Bureau van Dijk (BvD; 2013, 2016, 2019, 2022). ORBIS includes detailed information about the top 3,000 multinational companies in the world by turnover, along with their direct and indirect subsidiaries. It includes the geographical location of establishments and the NACE production category in which each firm operates. This database allows to create ownership network in which owners are connected to the firms they own, then to other firms that these own, and so on creating chains of ownership that are quasi-trees. ORBIS includes subsidiaries, or direct emanations of a mother company in different locations, but also ownership links in which one company may participate another one only for a limited amount (even 5% or less). It is not infrequent that two firms might have reciprocal ownership shares: this can respond to a logic of diversifying investments, even by participating financially to the activities of competitors. In all cases, information about ownership provides an indication that two firms are connected, along with the sectors they belong to and the cities where they are located.

NACE is an acronym that stands for the European classification of economic activities[6]. NACE codes are comparable at the world level through correspondence with ISIC codes that are maintained by the United Nations. As with patent codes, the classification of economic activities has two main features: first, it is hierarchical, so narrower categories are contained in larger groups, which requires a choice of the level at which to consider codes. Second, even precise codes do not perfectly match the technologies that I am interested in. As a result, I chose to identify them at the four-digit level (the most precise), by selecting the four following codes (Eurostat, 2008):

- Code 2910: “*Manufacture of motor vehicles*”.
- Code 2720: “*Manufacture of batteries and accumulators*”

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[6] NACE corresponds to the French : « Nomenclature générale des Activités économiques dans les communautés Européennes » .

- Code 2711: “*Manufacture of electric motors, generators and transformers*”
- Code 2712: “*Manufacture of electricity distribution and control apparatus*”

As it can be noticed, EVs do not have a dedicated code, but they are contained within the automotive category. Code 2711 refers to manufacturing electric motors because, as mentioned above, it is a key activity that is required to construct EVs, but also one that is typically conducted by firms in the electric sector and not by automotive producers. Code 2712 is the closest productive activity that is related to the production of smart grid devices.

Besides selecting these specific codes at the four-digit level, two-digit codes were also considered, that correspond to the 88 main NACE divisions. These codes relate to aggregate categories that contain many different technologies, but they are interesting to categorize the general domain of activity to which firms in the four specific classifications may be connected. Two-digit NACE codes were used to identify the domains that are most related to automotive, to account for their evolution in time, and to filter ownership networks. The 15 most related domains of activities are reported in table 2:

| NACE Code | Description |
|---|---|
| 22 | Manufacture of rubber and plastic products |
| 24 | Manufacture of basic metals |
| 25 | Manufacture of fabricated metal products, except machinery and equipment |
| 26 | Manufacture of computer, electronic and optical products |
| 27 | Manufacture of electrical equipment |
| 28 | Manufacture of machinery and equipment not elsewhere classified |
| 30 | Manufacture of other transport equipment |
| 45 | Wholesale and retail trade and repair of motor vehicles and motorcycles |
| 46 | Wholesale trade, except of motor vehicles and motorcycles |
| 64 | Financial service activities, except insurance and pension funding |
| 65 | Insurance, reinsurance and pension funding, except compulsory social security |
| 66 | Activities auxiliary to financial services and insurance activities |
| 70 | Activities of head offices; management consultancy activities |
| 71 | Architectural and engineering activities; technical testing and analysis |
| 72 | Scientific research and development |

***Table 2*** *: The 15 NACE codes most related to automotive (which is NACE code 29)*

### 5.2.2 Key companies

Besides selecting firms with technology codes, we also identified several key companies that are leader in automotive in general (including EV), in EV only, and in manufacturing batteries, electric motors, and smart grid devices. Some of them participate to more than one code: Tesla, for example, participates to all four codes, Siemens to both electric motors and smart grid ones, and BYD to automotive and battery. These firms are the global leaders in these sectors, and they are the head of very extensive networks of subsidiaries all over the world. It is important to identify them and to understand their role in connecting different sectors and geographical locations together.

| | **Automotive** | **EV only** | **Battery** | **Electric motors** | **Smart grid** |
|---|---|---|---|---|---|
| 1 | Toyota | Tesla | CATL | Siemens | Itron inc. |
| 2 | Volkswagen | BYD | LG Chem | Toshiba | Ibm |
| 3 | Hyundai | NIO | Panasonic | Abb inc | Cisco Systems inc. |
| 4 | GM | Rivian | SK Innovation | Nidec corp. | Enphase Energy, inc. |
| 5 | Ford | | Samsung | Rockwell Automation | Schneider Electric |
| 6 | Nissan | | EVE Energy | Ametek inc. | Alstom Grid |
| 7 | Honda | | | Regal Beloit | General Electric |
| 8 | FCA | | | Johnson Electric | Landis + Gyr |
| 9 | Renault | | | Franklin Electric | Aclara Technologies |
| 10 | PSA | | | Allied Motion | Eaton corp. |
| 11 | Suzuki | | | Danahaer | Hitachi |
| 12 | Daimler | | | Emerson Electric | |
| 13 | BMW | | | | |

***Table 3 :** Key companies producing automotive, EV, battery, electric motor, and smart grid technologies*

### 5.2.3 Ownership networks and urban locations

The main methodological tool for this article was to construct an ownership network for each of the year in which we had data and use this relational information to make sense of linkages between technologies and urban regions. To build the network, we started from a general analysis of the co-presence of NACE codes at the two-digit level. Two codes were considered as connected when they appear in an ownership link between a parent firm and subsidiary. At an aggregate level, this shows two things: the relative share of different categories in the ownership portfolio of automotive firms, and the share of categories to which belong the firms that own automotive companies. This analysis involved all links featuring NACE information for the four years for which we had reliable information (2013, 2016, 2019 and 2022) and it served to identify the most related technologies to automotive. The evolution of ownership relatedness between categories provides an indication of the participation of different activity sectors to automotive.

After representing activity relations, we selected in the ORBIS database all companies that were tagged with the four technology codes listed above (four-digit NACE), together with the key firms in table 3. From all company linkages in a selected year, we extracted the ego-networks for this group of companies. Ego-networks contain the connections of a given node, and the links between them (Wasserman and Faust, 1994). In this case, ego-networks contain all owners — or owned — entities of a given firm, plus the links between them. The four resulting networks (one per every year) were filtered by selecting only the firms participating to the activities most related to automotive (see table 2). This allows to represent the evolution of interfirm ownership networks in time, to elaborate on the role of different technology categories in them, and to identify firms that occupy a strategic position in this relational structure.

We used this relational information to construct a network of Large Urban Regions (LURs), in which two regions are connected when they are linked by ownership ties. This geographic network includes both connections within cities (intra-urban) and between cities (inter-urban). This allows to account for both “local buzz”, or those denser knowledge exchanges that involve geographical proximity, and “global pipelines”, or the farther-reaching connections that stretch globally (Bathelt et al., 2004). These networks were interpreted considering how cities enable connections between different activities that are related to EVs and which cities have a position of centrality in them.

This research has some limitations. First, the ORBIS database included limited information on the relative strength of ties, so that we don’t know if each ownership participation is closer to a full ownership and control, or to a marginal sharing. Second, companies are attributed to a primary NACE classification but also a secondary one, which can contain many different categories. It is difficult to know to what extent secondary codes are also representative of the firm’s production activities. In this article I used both primary and secondary to identify the four specific four-digit codes we were interested in, but I used only primary codes to attribute firms to the larger two-digit domains. Third, and related to this point, NACE codes do not match the technologies that we were interested in, but they offer instead a wider container: this is true at the four-digit level, and even more so at the two-digit one, where the breadth of the classification makes it difficult to make sense of its meaning. Finally, the network methodology applied to ownership ties resulted in the construction of very dense, tree-like structures, that are controlled by some main firms and their extended ownership chains. The fact that the network is dominated by the hierarchical structure of few major companies implies that the network cannot be easily analyzed with overall quantitative indicators of centrality, degree, and modularity since these would simply mirror the high centralization of this structure.

# 6- Results

This thesis set out to answer a general question: to what extent are the technological complementarities that emerge in transitions accompanied by urban colocation of inventors and producers? The overall aim was to propose a coevolutionary approach where the new multi-sectoral configurations that emerge during socio-technical transitions are embedded into regional economic and institutional networks, but also participate to global exchanges. To answer this question, I provided evidence on the urban emergence of inventions in four technologies: EV, battery, smart grid, and combustion engine, and on the production networks that sustain their production.

The empirical findings suggest that urban colocation matters, but also that cities differ in the extent to which they support technological recombinations. Conceptually, the coevolutionary approach presented has shown its merits in framing technological relatedness dynamics within a wider transitionary perspective, allowing to integrate insights from economic geography and transition studies. Taken together, these results only allow to scratch the surface of the general question that informed this research, but they do provide valuable empirical clues, and the contours of a coevolutionary framework that can drive new investigations on this topic.

## 6.1 Empirical contributions

This research investigated how increasing technological proximity between EV-supportive technologies such as battery, smart grid, and electric motor, translated into increased geographical colocation of patents and productive establishments. It also explored the extent to which path dependence with traditional automotive technologies played a role in EV. This has produced three main empirical results: first, the development of EVs has been accompanied by the establishment of new technological connections between automotive, battery, smart grid, and electric motor innovations. Second, it has revealed that cities where EV patenting is growing the most are those where related technologies are also growing, and not traditional automotive cities where ICE patents are more important. Third, this thesis has exposed patent and ownership networks, and disclosed the strategic role of applicant firms and multinational producers in connecting different technologies and urban regions through their activities.

### 6.1.1 Paper 1: main results

In the first article, I found out that the focus of invention in the EV, battery and smart grid main paths of patent citations became increasingly similar in time. Starting from 2010, the battery main path featured several inventions related to EVs, of which one was the most central patent in the whole path (patent #1 in Fig.5). In the smart grid trajectory, EV inventions also appeared in the past 10 years, concerning EV recharge and vehicle-to-grid capabilities, but their position is less central than for battery patents. I also analyzed the network connecting cities and applicants, finding that Tokyo, Nagoya, and San Francisco exhibited high diversity of applicants and technologies that could favor coevolution. In particular, the firms Toyota, Honda and IBM appeared very central in this network, linking different cities through their activities. This analysis also permitted to point at the role of universities and other research institutions, such as the public-private German consortium GES (Electric Road Transport Society) involving local institutions, utilities, car makers and battery companies.

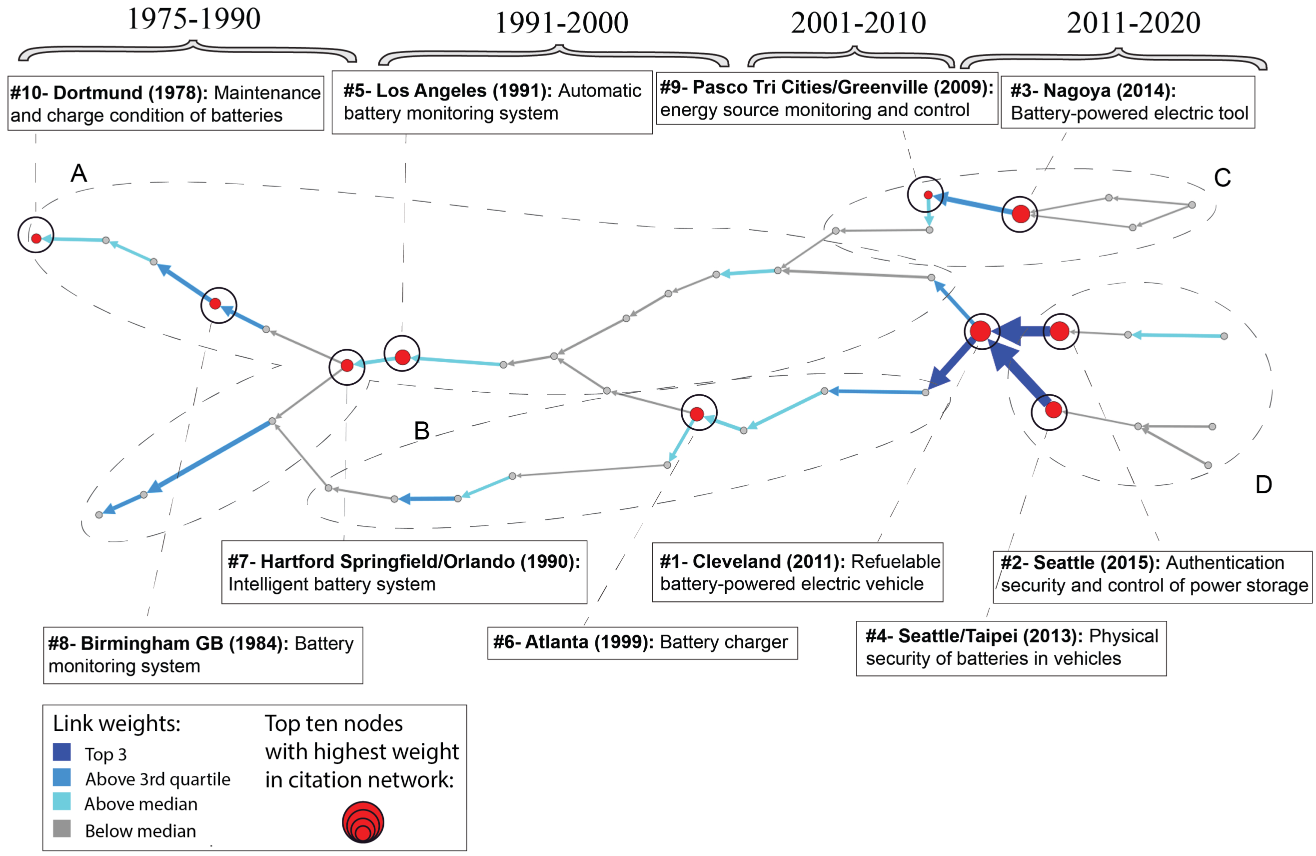

***Figure 5:** The main path of battery inventions*

### 6.1.2 Paper 2: main results

In the second article we confirmed our coevolutionary hypothesis, discovering that EV patents became more technologically related to battery and smart grid, but less to combustion engine. Yet, when geographical relatedness was analyzed, we found increased geographical proximity of EVs with combustion engine patents, which might mean that automotive producers retain a key role in EV innovation. When evaluating the trajectories of cities in these technologies (Fig. 6) we found a generalized distancing from combustion engine towards EV, smart grid and battery patents. These differences became more apparent when considering specialization: in fact, cities in group 4 (e.g., Nagoya, Stuttgart, Detroit) were by large the most specialized in combustion engine, but also in EV. However, cities in group 1 (e.g., Tokyo, Seoul, Shanghai), displayed higher growth rates in EV and smart grid, with declining combustion engine specialization. This suggested that, over time, emerging innovation hubs might find it easier to produce EV-related technologies than traditional automotive locations if the latter remain anchored to combustion inventions. Quantitative models confirmed an increased effect of battery and smart grid on EV patent scores, and a decreasing effect of combustion engine one.

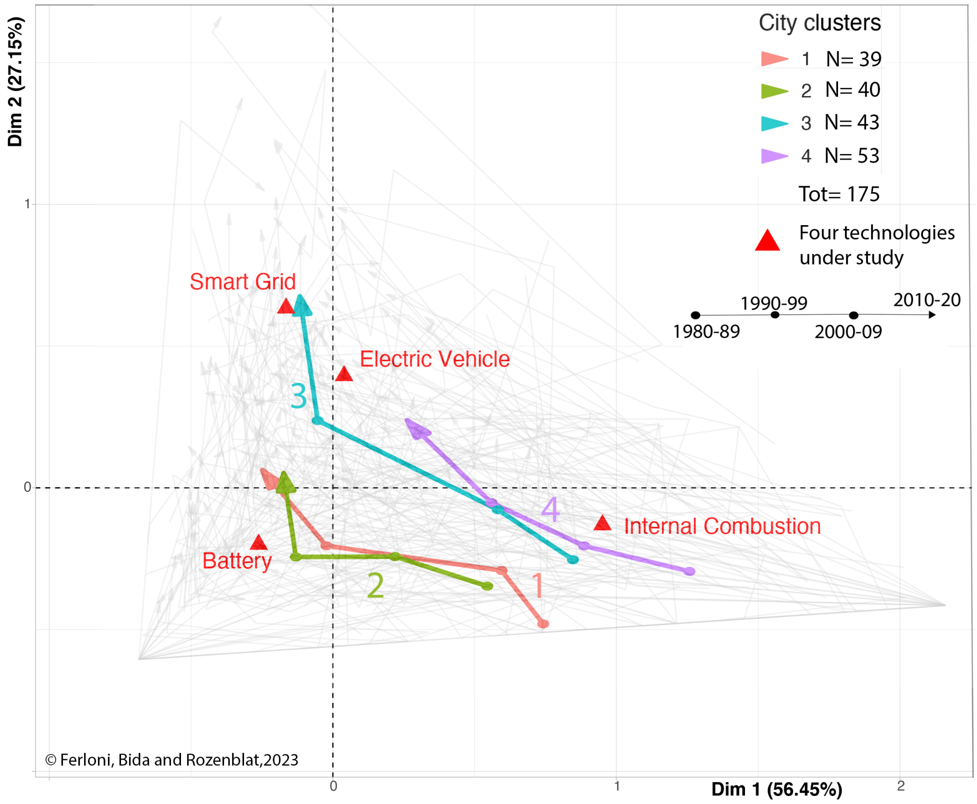

***Figure 6:*** *Trajectories of city clusters with respect to EV, battery, smart grid and combustion engine technologies. Each line is a group of cities, and the evolution of the trajectories reflect the proximity of the inventions produced in each group to the four technologies.*

### 6.1.3 Paper 3: main results

In the third article, the analysis of NACE classifications and inter-firm ownership networks provided support to the hypothesis that coevolution between EV, battery, electric motor, and smart grid might be reflected by increased ownership ties between firms in these categories. In fact, we found that the finance sector greatly reduced its participation to automotive ownership, and that the computer and electric categories became more important, both in general classifications and in the specific networks of selected automotive firms such as Tesla and Toyota. The analysis of geographical networks revealed a decreasing proportion of intra-city ties between electric and automotive categories in time, which could suggest that inter-city connections became more important or that, after a phase where geographical proximity was required for innovation, productive capabilities became more widespread. Still, the analysis of differences between a city where intra-city ties are few (Detroit) and one where they are many (Tianjin) shows that while the former is dominated by automotive companies, the latter features a high diversity of firms related to electric motor, smart grid, and battery (Fig. 7). This suggests that intra-city ties might still be crucial to enable coevolution between EV-related sectors.

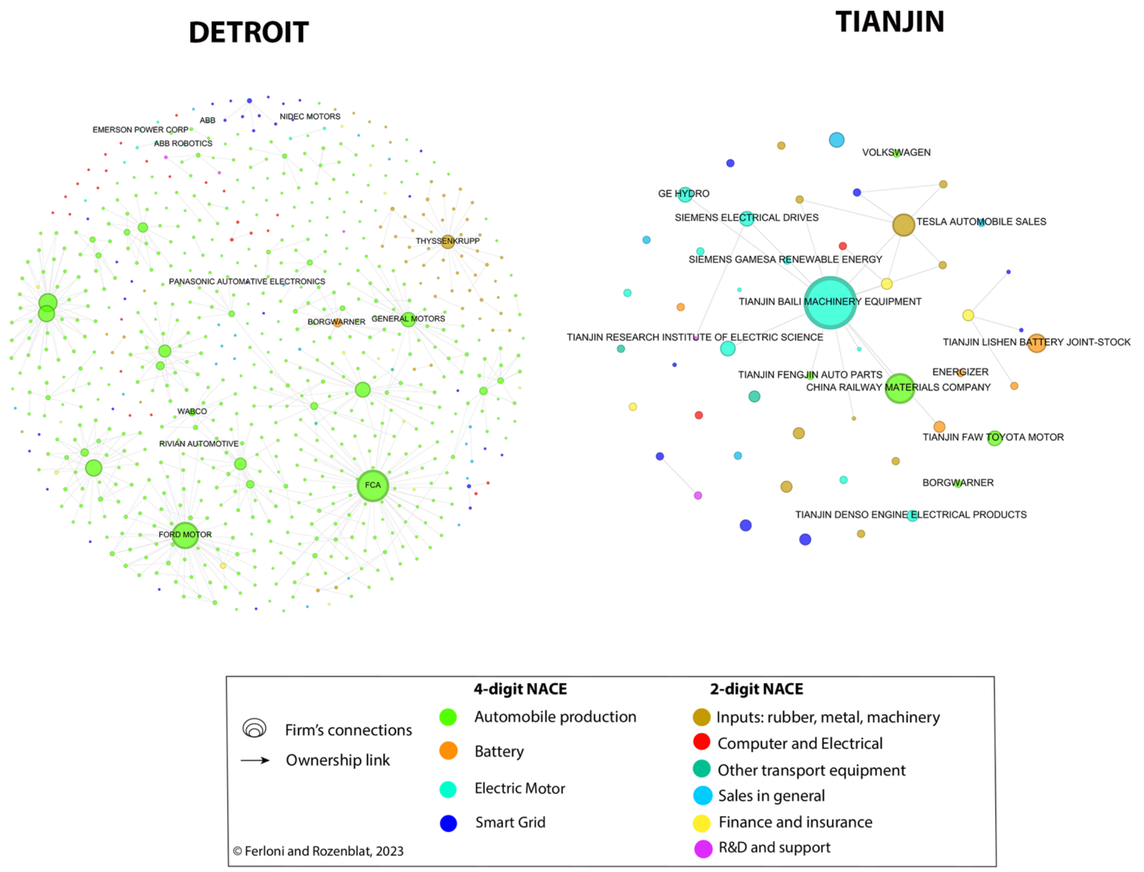

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***Figure 7:*** *Ownership networks in Detroit and Tianjin for the year 2022*

## 6.2 Synthesis of the empirical results

| Research questions | Key contributions |
|---|---|
| Article 1: Transitions as a coevolutionary process: the urban emergence of electric vehicle inventions. | |
| - Are the main trajectories of EV, battery, and smart-grid patents increasingly similar in time?<br>- In which urban regions do patents from these technologies emerge from?<br>- What role do applicants play in facilitating intersectoral and interurban connections?<br>- How can coevolution connect multi-sectoral interactions to their spatial embeddedness? | - Contemporary transitions can be seen as a process of distinct technologies and sectors becoming more related in time. While EV, battery and smart grid have become increasingly connected, the emergence of new centralities in the EV value chain can lead to changes in power relations.<br>- Traditional automotive regions retain a role in main EV patents, but new regions might soon surpass them.<br>- The networks that support invention connect many urban regions together, and include private firms, universities, and public agencies. |
| Article 2: The emergence of Electric Vehicle transition in cities: technological coevolution and spatial colocation. | |
| - Is technological coevolution between EV, battery, smart grid, and combustion engine technologies matched by geographical coevolution?<br>- What different groups of cities can be distinguished in the presence of EV and related technologies?<br>- Does patenting in related technologies play a role in EV patenting? | - Growing relatedness between EV, battery, and smart grid implies that these patents are increasingly co-located. ICE inventions are increasingly co-located despite being less technologically related.<br>- Traditional automotive cities retain a key role in EV patenting, but cities that are growing EV patents the most are those with battery and smart grid specializations.<br>- The econometric analysis shows an increasing effect of battery and smart grid patenting on EV patenting, and an important but decreasing effect of ICE ones. |
| Article 3: Relatedness and colocation in Electric Vehicle production networks: a coevolutionary network approach | |
| - Are battery, electric motors and smart grid technologies increasingly connected to automotive through ownership networks?<br>- Does production in these technologies increasingly concentrate in the same cities? | - The computer and electric activities are more connected to automotive ones, while financial ones are less related.<br>- The importance of intra-city ties for ownership links between electric and automotive is decreasing overall, but it is growing in some cities. |

***Table 4 :*** *Summary of the thesis's articles with questions and main results.*

## 6.3 Conceptual contributions of a coevolutionary approach

The coevolutionary approach presented in this research has provided three main contributions. First, to contextualize innovation into a wider perspective on transitions, focusing on the coevolution of the specific technologies that are at the core of socio-technical change. Second, to link emerging multi-sectoral connections to geographical path interdependence, as innovative actors are embedded in regional socio-economic structures. Third, to focus on networks as the key articulating mechanism that permits to visualize and make sense of technological and geographical interconnections.

This thesis contributed to both economic geography and transition studies by combining them. Economic geographers have shown that countries and regions can innovate and diversify their economic base when the skills and competences required by new activities are related to those that are already present. Transition studies have shown that innovations are transformative forces that can reconfigure many societal domains and help address social and environmental problems. Picking up recent contributions in this direction (Boschma et al., 2017; Chlebna et al., 2023), this thesis suggests that these perspectives are complementary, and their integration is needed.

### 6.3.1 Transitions: a coevolutionary background to innovation

A transitions perspective provides a coevolutionary background to interpret innovation dynamics in light of the opportunities that emerge in time around specific technologies. In fact, transitions selectively enable the growth of some industrial sectors over others. The EV transition, for example, provides a window of opportunity that rewards diversification in technologies such as battery, renewable energy, or smart grid. At the same time, diversifying towards hybrid combustion engines or fuel cell cars, might be a less promising strategy for regional development in the present context. A transitions approach provides a comprehensive framework to study issues of (green) innovation, relatedness, and complexity that are concentrating research efforts in economic geography (Boschma, 2017; Balland et al., 2022).

Research on complexity has found that more complex activities are better valued and geographically concentrated. Thus, if nations and regions wish to retain more value-added and be globally competitive, they should pursue related diversification into more complex activities, but also similar to their productive base (Balland et al., 2019). Scholars are also increasingly considering “green” sectors and innovation, or the social and environmental desirability of different activities. Mealy and Teytelboym (2022), studied the role of economic complexity to in the transition towards new green technologies, while Napolitano et al. (2022) found that the capability to produce green innovations is related to lower levels of income inequality. Understanding how economic activities are connected to each other, and measuring their degree of complexity, is key to improve our understanding of the geographical dynamics that drive invention and production. Yet a wider perspective on transitions can help to better frame relatedness, complexity, and the green side of innovation.

During transitions, as this thesis demonstrated, relatedness changes dynamically. A coevolutionary perspective shows that the technological combinations that were possible and *desirable* 40 years ago have been replaced by others. A dynamic approach shows that, for example, the emergence of hybrid capabilities is tightly connected to EV inventions, but that today full electric capabilities related to battery chemistry and recharge have become more important. Focusing on coevolution between and around the technologies that are important for a specific transition, allows making a general focus on innovation, complexity, or wider aggregations of "green" sectors much more precise. In other words, the transitions framework has the advantage to show innovation as a generalized phenomenon, because socio-technical change has a global reach and impact, but also a selective one, because it involves only some specific technologies and emerges in different ways in geographical space.

### 6.3.2 Spaces of transition and path interdependence

This thesis shows that urban regions are very different in the *combinations of technologies* they are capable to generate. If we considered technologies in isolation, we could observe that, as shown in paper 2, traditional automotive regions such as Nagoya, Stuttgart, or Detroit, are very specialized in EV patents, but also in combustion engine ones. On the other hand, cities such as Seoul, Shanghai, or Grenoble are also specialized in EV, but also increasingly in battery and smart grid. A coevolutionary approach considers interactions between technologies and sectors and as such it is better suited to identify dynamics of path interdependence.

During transitions, some regions can benefit of path dependence if the emerging solutions are related with the incumbent capabilities that are already present. In the case of EV, automotive capabilities are clearly important to innovate, as the analysis of patents and production networks shows. However, traditional automotive regions might lose their competitive advantage if other technologies became more central to EV innovation. Thus, new path creation can take place in regions whose traditional capabilities are unrelated with incumbent technologies but related to emerging ones. In our case, regions with battery and smart grid capabilities are well positioned to innovate in EVs. A coevolutionary approach can show us how regional capabilities in different sectors are interrelated, bringing local innovation networks into focus.

In transition studies, research on multi-sectoral interactions is focusing on the creation of complementarities between different sectors (Andersen et al., 2020), while the geography of transitions approach offers a general framework to make sense of how "local buzz and global pipelines" support both dense knowledge exchanges and global networking (Binz et al., 2020). These two perspectives are very related, and this thesis proposes to integrate them further in a dialogue with economic geographic insights. In fact, invention and production dynamics in transitions have been relatively underexplored. We need to know more about how local economic capabilities, networks, and institutions support multi-sectoral configurations. The literature on relatedness and regional diversification trajectories can help us comprehend better the advantages of colocation and contextualize them within inter-urban innovation networks.

### 6.3.3 Networks as articulating mechanisms

In this thesis, relations between technologies are represented as a network that evolves in time. Individual nodes are inventions, technology codes, or firms. Links are patent citations, co-presence of patent codes in inventions and cities, or inter-firm ownership ties. The key advantage of a network approach is that networks constitute a scaffold of relations that tells us that two entities are connected. Onto this structure, we can articulate many different analytical dimensions and investigate how applicant firms, urban regions, or larger technology classifications are connected.

Networks are central to a coevolutionary approach, because we need to identify some form of bidirectional influence between groups of actors to prove coevolution. In this thesis, I adopted a high level of aggregation, and coevolution was conceptualized simply as technological or geographical copresence. However, after analyzing millions of patent documents, I provide examples in article 1 of how we can zoom in to identify the role of specific applicant firms. Thus, networks allow to study coevolution at very different levels, a highly aggregate or a much more precise one. Also, they permit to solve the contrast between local and global, by acknowledging that cities participate of multilevel and multiscale relations (Rozenblat, 2021).

To sum up, the third main contribution of this thesis is to set the analysis of transitions within a complex system perspective that acknowledges the importance of distributed and open systems, non-linear dynamics, path-(inter) dependence, emergence, and adaptive behavior

(Martin and Sunley, 2007). While transition scholars have used ideas from complex systems theory, they have not contextualized them within a wider framework (Kohler et al., 2019). Contributions from evolutionary economic geography can help to go in this direction (Safarzyńska et al., 2012). Yet, the use of formal modeling should not be seen as an obstacle to engage with a systemic approach, nor it betrays an inadequate reductionist stance. Rather, it is one instrument more that we can employ to make sense of the complex web of interdependencies, feedback and unforeseeable consequences that characterize contemporary transitions. As this thesis has shown, a network approach can help combine quantitative and qualitative tools around a shared relational structure based on coevolution.

## 6.4 Conceptual limitations of this research

This research suffers from some general conceptual limitations, beyond the specific ones that have been already identified for each article. First, I have operationalized coevolution as simple copresence of technologies in patent documents or in cities. The idea behind this, is that increased copresence is a proxy for coevolution because it indicates that there might be growing probability of interaction and complementarity formation between sectors. While copresence is an important clue that different technological actors might be interacting, it is certainly very different from the actual identification of a relation.

Second, in article 2 we asked to what extent technological coevolution implied colocation. In this research we could not address issues of causality, so this formulation does not rule out the possibility that it might be colocation that facilitates technological coevolution and not the other way around. The aim of distinguishing technological and geographical relatedness was not to decide which came first, but whether they change at the same time. That being said, the automotive, battery and smart grid, cannot be considered as radically new technologies, whose initial colocation with other industries in specific regions might be decisive. Instead, they are mostly mature technologies that are globally diffused: thus, it is unlikely that colocation might be the driver behind general technological relatedness. A different research design centered on a few regional case studies would be more appropriate than the one pursued here, to find if and where colocation might have triggered technological coevolution.

Third, the findings of this thesis are not easily transferable to other technologies and sectors. The drivers behind colocation and coevolution are technology and sector-specific, so if we had investigated the IT sector, biotech or nanotech sectors we would likely have reached different conclusions. However, a key takeout of this thesis is that the coevolutionary approach proposed here could be transferred to study the emergence of different transitions using a network approach and showing how technological interactions are related to geographical ones.

# 7. Future research and policy perspectives

This research leaves many questions unanswered, but it also provides useful reflections for elaborating policies. Future endeavors to account for coevolution in the EV transition could focus on the diffusion phase, and how it relates to invention and production. Besides, they could further account for geographical differences, and the role of incumbent sectors. The main policy results of this study are to interrogate the extent to which incumbent automotive regions will be able to retain a competitive advantage in the future, and in providing a framework to specify smart specialization by studying multi-sectoral coevolution along the whole value chain.

## 7.1 EV adoption, regional capabilities, and the role of incumbents

This research explored invention and production, but could not address adoption, even though coevolution is crucial at this stage where new interfaces and user environments create interdependencies between users, automotive firms, battery producers and utilities. The adoption of innovations is connected to invention and production, so a coevolutionary framework should consider not only these phases separately, but also the interactions between them. As shown by Malhotra et al. (2021), developments in EV adoption can feed back to influence the focus of invention. Meelen et al. (2019) showed that user communities can contribute to the uptake of EVs by circulating and debating information on technical problems, recharge practices, and driving patterns. Organized groups of consumers are likely to influence productive decisions by carmakers, so future research should try to understand how different phases of transitions — from invention to adoption — are connected, and which feedback and interactions characterize them.

The geographical diffusion of EVs is uneven across countries and regions. A key aspect of EV adoption is the necessity to develop public recharge infrastructures, to allow people without a private car space to quickly recharge their vehicle (IEA, 2022). The regions that also possess invention and production capabilities in related sectors might be better at promoting EV uptake and the participation of local socio-economic actors to setting up recharge points. Conversely, regions that lack related innovative skills might leave the economic benefits of this process to automotive companies or electric utilities. These dynamics call for further research to make sense of the drivers behind the uneven geographical inclusion of cities and territories in all phases of the EV transition from invention to adoption.

Another possible direction of research is in better understanding the role of incumbent industries in transitions. On the one hand, we know that existing automotive firms are key actors in the EV transition, but to what extent does their presence support the emergence of an articulated ecosystem of EV-related firms, as compared to regions where are located fully EV producers such as Tesla or NIO? Furthermore, does the fact that the EV transition is largely producer-driven imply that it will “fit and conform” with mainstream paradigms rather than “stretching and transforming” them (Smith and Raven, 2012)? In fact, the present moment resembles a “stretch and transform” phase for the extent, depth and radicalness of the changes involved in a widespread car electrification. Yet, even though the emergence of EVs is being accompanied by new mobility paradigms such as car sharing, car renting schemes, or remote working, the model of individual private car is still at the center of a resource-intensive automotive paradigm (Urry, 2004). This, and the fact that automotive companies are retaining the key competences and value chain functions that are necessary to produce EVs, can allow us to wonder to what extent the transition to EV will represent a positive systemic change or if it will provide marginal environmental benefits while leaving other social issues unchanged.

## 7.2 Policy implications

The results of this thesis point to three major policy contributions. First, technological relatedness changes dynamically, so innovation policies should acknowledge how wider societal transitions have shaped technological coevolution and imagine how they might develop in the future. As this research shows, EV inventions are tightly linked to combustion engine ones, so that traditional automotive regions such as Detroit or Nagoya appear capable to continue innovating in EVs. Yet we also see that regions with battery and smart grid capabilities are those where EV specialization is growing most, and that some emerging Asian cities appear as much more diversified center of EV innovation than traditional car cities. As a result, policies in support of regional EV innovation should try to retain automotive assembly capabilities, since this is likely to remain a key phase to maintain a systemic control on the whole manufacturing process. However, they should also try to acquire other capabilities along all the value chain, in different domains such as battery assembly and recycling, software and recharge interfaces, smart grid management. In fact, these competences are becoming increasingly central to EV innovation, with battery packs and control systems grabbing a substantial proportion of a vehicle's value, and this trend will likely continue with the increasing role of driver assistance systems and autonomous cars.

The second main contribution is that, more generally, smart specialization strategies should be based on a systemic understanding of how different value chain phases and sectors are dynamically connected. Intersectoral connections can emerge at different steps along the value chain. Thus, related diversification policies should not only focus on design, marketing, R&D, and high knowledge intensive phases, even though these will continue to be crucial. Rather, they should acknowledge that strategic innovations can occur anywhere along the value chain, and that controlling other steps as raw material sourcing, assembly, or recycling, can permit to innovate further around each of them. As a result, diversification policies should be directed at supporting several value chain steps and nurturing multisectoral interconnections.

The third contribution is that institutional involvement is key not only to support invention and production but also adoption. This should happen not through direct subsidies, as EVs are already competitive with conventional cars, but rather by supporting the roll-out of public infrastructures such as recharge stations, promoting installations in real estate projects, and supporting partnerships with utilities and local firms to set up renewable energy schemes and make recharge cheaper for citizens.

As the EV transition accelerates, we must be aware that it runs the risk of being an exclusive process, leaving out some social categories and creating spatial inequalities across regions and within cities. There can be important backlashes to phasing out existing technologies because workers in incumbent sectors are likely to resist change (Egli et al., 2022). If incumbent automotive regions fail to adapt their production base, increasing unemployment coupled with demographic decline or emigration could have serious social effects in many regions. This could fuel a geography of discontent where the population of declining industrial cities turns towards populist political forces that capitalize on the resentment of the "places that don't matter" (Rodríguez-Pose, 2018). This could in turn contribute slowing down and questioning the desirability of a transition to EVs. We must therefore find ways to account for the multi-sectoral relatedness of transitions, to better comprehend regional economic dynamics and devise improved policies to support diversification. This thesis hopes to make a step in this direction.

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Research article

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

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Patent networks

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

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[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 spillovers—along with their geographical scope—that contribute to their emergence (Jaffe and Trajtenberg, 2002; Jaffe and de Rassenfosse, 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 inventors 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

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[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<br>Links: 13.9 million | Nodes: 3.1 million<br>Links: 17.7 million | Nodes: 2.9 million<br>Links: 14.4 million |
| Filter networks by keywords | Nodes: 20′446<br>Links: 47′350 | Nodes: 142′960<br>Links: 469′263 | Nodes: 5′820<br>Links: 9′295 |
| Main paths of patent citations | Nodes: 54<br>Links: 55 | Nodes: 42<br>Links: 44 | Nodes: 50<br>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

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[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.

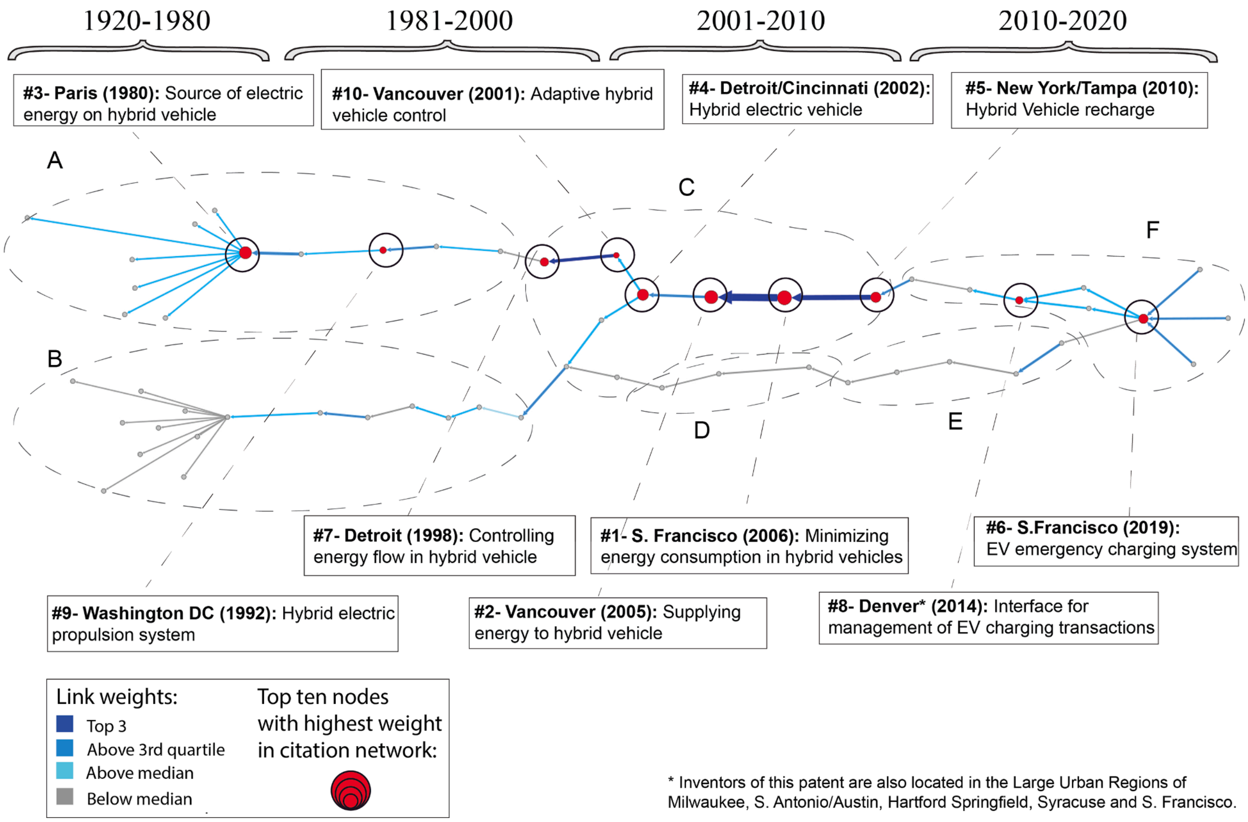

**Fig. 1.** Electric Vehicle main path in time with the ten most central patents in the citation network and six key technology fields.

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.

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[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.

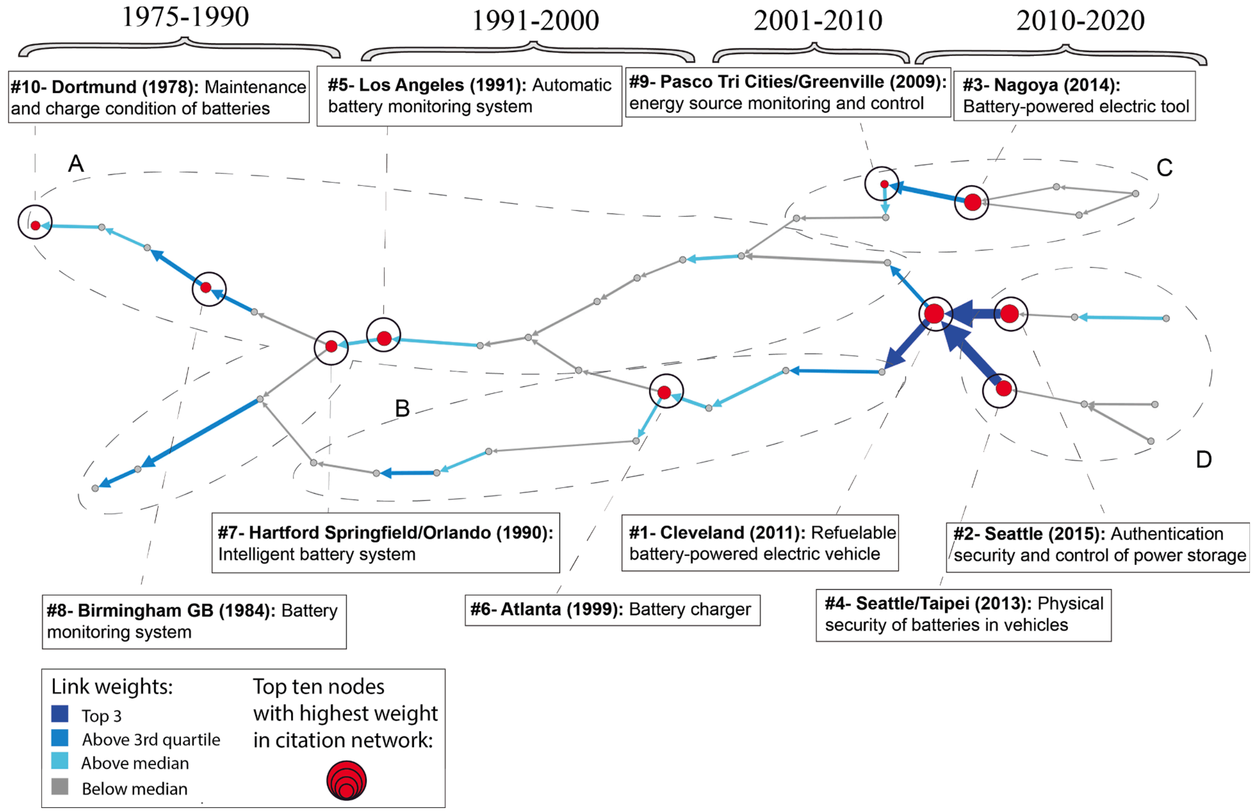

**Fig. 2.** Battery main path in time with the ten most central patents in the citation network and five key technology fields.

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

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

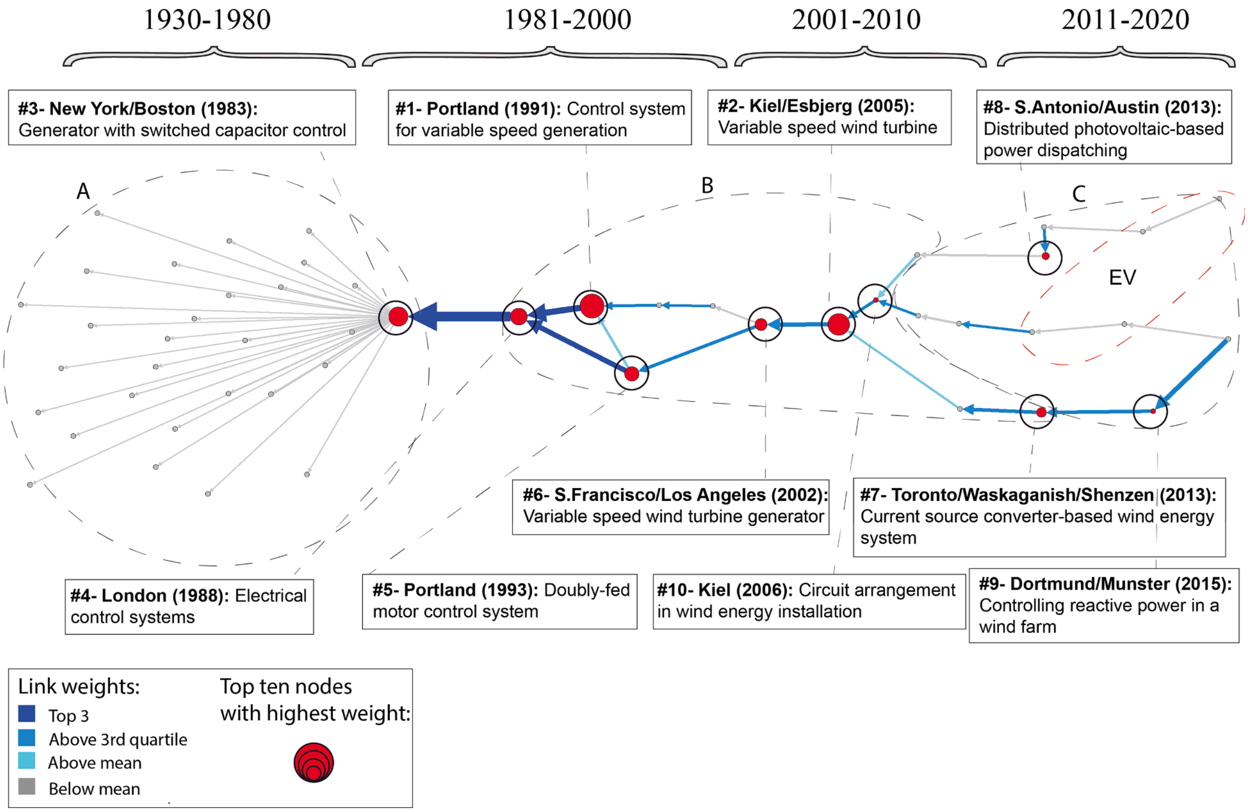

**Fig. 3.** Smart Grid main path in time with the ten most central patents in the citation network and three key technology fields.

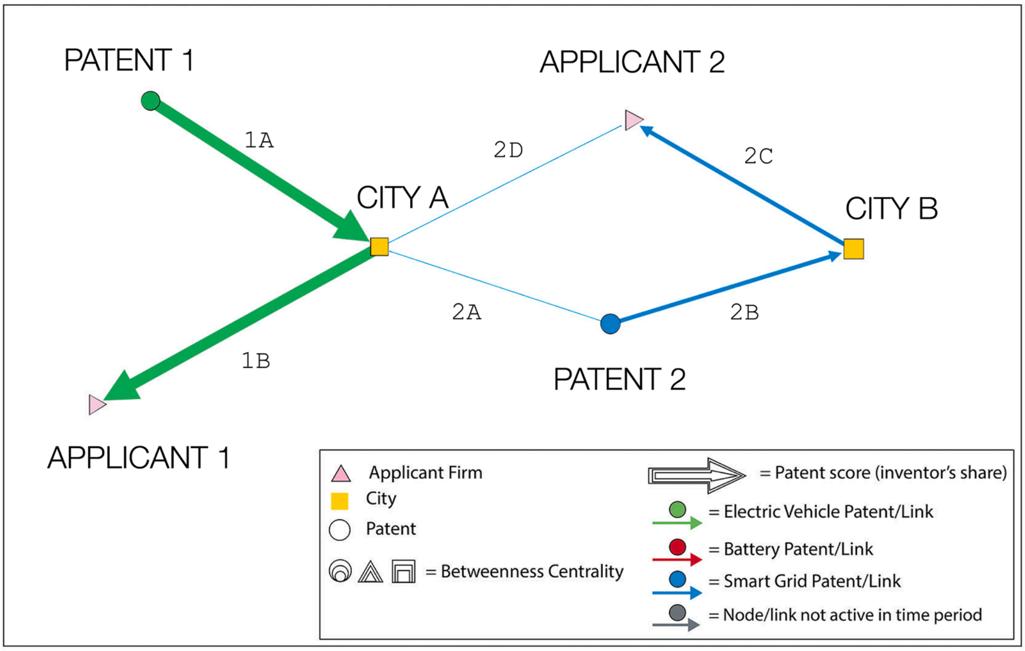

**Fig. 4.** Link weights in the patent-city-applicant network.

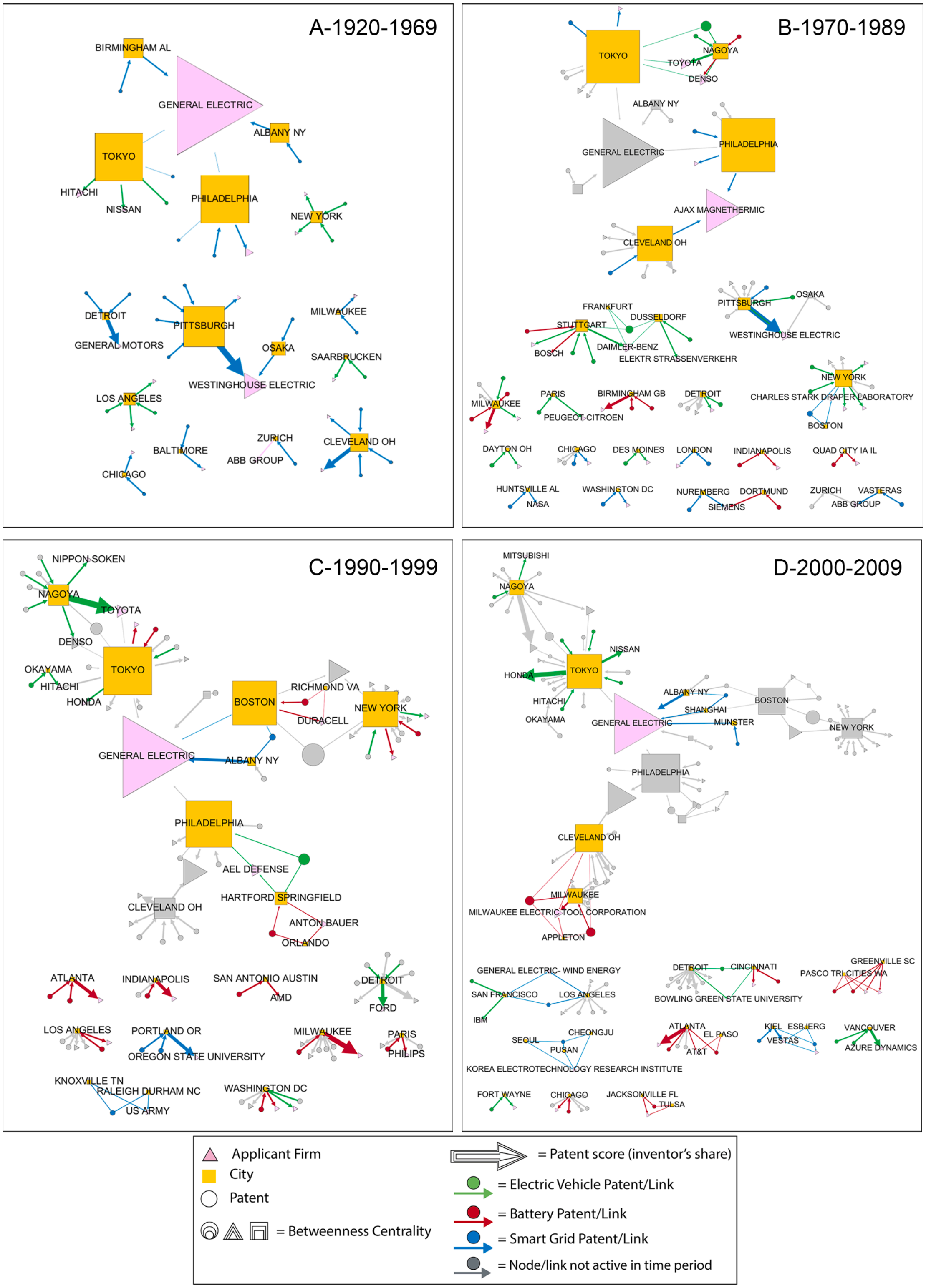

**Fig. 5.** ***(A-D)***: the patent-city-applicant network from 1920 to 2009.

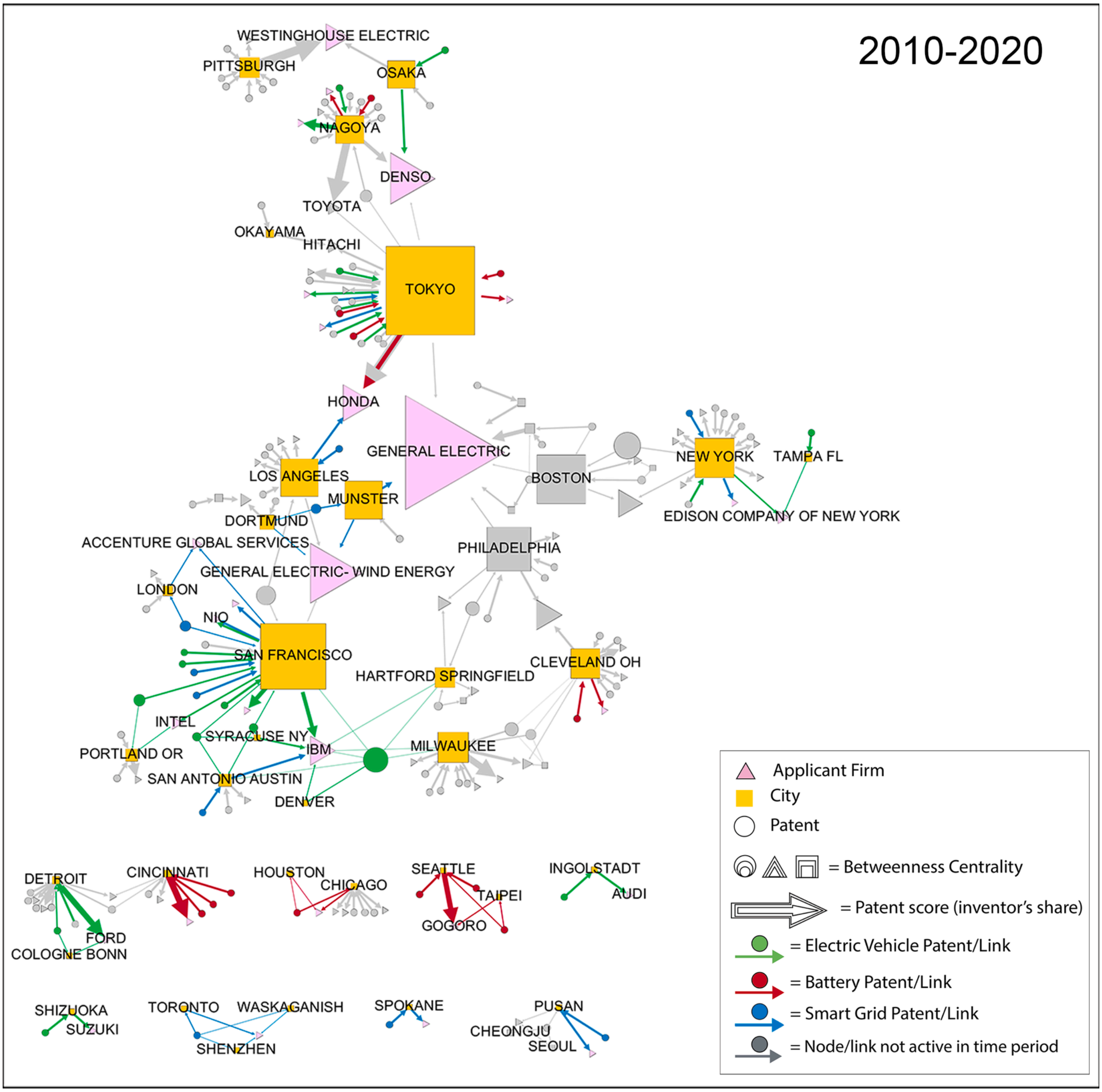

**Fig. 6.** The patent-city-applicant network from 2010 to 2020.

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

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[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<br>Tokyo | Toyota<br>Denso |
| 17 | 4,153,128 | 1979 | Drive aggregate for electric vehicles | Frankfurt<br>Stuttgart<br>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<br>Springfield<br>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<br>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<br>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<br>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<br>San Antonio-Austin<br>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<br>San Antonio-Austin<br>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<br>Milwaukee<br>San Francisco<br>San Antonio<br>Austin<br>Syracuse NY<br>Hartford<br>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<br>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<br>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<br>Springfield<br>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<br>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<br>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<br>Tulsa | Eveready Battery Company |
| 25 | 6,624,616 | 2003 | Portable battery recharge station | Atlanta<br>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<br>Greenville SC | Techtronic Power Tools Technology |
| 28 | 7,508,167 | 2009 | Method and system for charging multi-cell lithium-based batteries | Milwaukee<br>Appleton<br>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<br>Appleton<br>Cleveland OH | Milwaukee Electric Tool Corporation |
| 30 | 7,496,460 | 2009 | Energy source monitoring and control system for power tools | Pasco Tri Cities WA<br>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<br>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<br>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 |

(*continued on next page*)

**Table 5** (*continued*)

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|---|---|---|---|---|---|
| 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<br>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<br>Raleigh Durham NC | US. Army |
| 34 | 5,907,192 | 1999 | Method and system for wind turbine braking | Albany<br>Boston | General Electric |
| 35 | 6,420,795 | 2002 | Variable speed wind turbine generator | Los Angeles<br>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<br>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<br>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<br>Seoul<br>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<br>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<br>Waskaganish<br>Shenzhen | Rockwell Automation Technologies |
| 46 | 9,046,077 | 2015 | Reactive power controller for controlling reactive power in a wind farm | Munster<br>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<br>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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# The emergence of Electric Vehicle transition in cities: technological coevolution and spatial colocation

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## Abstract

The transition towards Electric Vehicles (EVs) is connecting previously unrelated technologies. We combine a transition approach with economic geography, to explore how colocation can support the emergence of coevolution between EV-related sectors. We study technological and geographical relatedness between electric vehicle, battery, smart grid, and combustion engine inventions between 1980 and 2020. Geographical colocation of related technologies can signal coevolution between firms and inventors, that is specifically visible in some classes of cities that we identify. Finally, we fit a multiple regression to estimate the impact of patenting in related technologies on EV patents. Results show increased relatedness and colocation in time between electric vehicle, battery, and smart grid patents, demonstrating that relatedness is dynamically evolving during transitions. We also find that combustion engine capabilities are still relevant to support this transition, suggesting path interdependence between regional innovative sectors.

## Keywords:

Transition, Electric Vehicle, cities, coevolution, innovation, relatedness.

## 1. Introduction

Contemporary transitions such as the one towards Electric Vehicles (EVs), involve interactions and complementarities among different technologies, including renewable energy generation, grid management, and vehicle recharge (Markard, 2018). Such complementarities are evident at the diffusion phase but also exist in invention and production (Malhotra et al., 2021). The creation and exchange of knowledge to invent and produce EVs is likely favored by geographical proximity between inventors and firms (Boschma, 2005), so the EV transition can be accompanied by new geographical centralities of invention: cities and regions that are better endowed with EV-related knowledge, or more capable to acquire it, might lead the way while those where incumbent technologies are prevalent could experience job losses and the challenge of converting their production base (Skjølsvold and Coenen, 2021). Revealing the multi-sectoral and spatial interdependencies of transitions can help evaluate their social consequences and design improved multi-level policies to support them (Tödtling et al., 2022).

Evolutionary economic geographers and transition scholars have asked for more integration between both literatures in the investigation of regional diversification (Boschma et al., 2017). We pick up this invitation and propose an original coevolutionary perspective on transitions, which explores how the colocation of EV-related technologies in cities evolves in time as different sectors become increasingly connected. We integrate insights from the multi-sectoral perspective (Andersen et al., 2020), and the geography of transitions (Binz et al., 2020), to frame transitions as geographically emergent processes that involve interactions between many sectors. In this perspective, we consider how localized networks and their dynamic interactions can support technological recombination during transitions.

In this article we provide empirical evidence at the world scale from 1980 to 2020 on the co-evolution of EV patents with battery, smart grid, and combustion engine technologies, in the concerned cities that are defined in a comparable way. We examine technological and geographical relatedness between these patent codes, before classifying cities in four different groups according to their patent scores. Finally, we build a multiple regression model to estimate the impact of related technologies on EV patenting. We finally discuss the uneven sectorial relatedness processes in the innovation transitions appearing in the cities of the world.

## 2. Theoretical framework

The main theoretical issues when we seek to develop a coevolutionary perspective of innovation transitions, consist in combining the literature on multi-sectoral interactions and on the geography of transitions (2.1) and how the concept of relatedness from economic geography can be used as an empirical tool to infer coevolution (2.2). Then, we elaborate on technological and geographical forms of relatedness and apply the reasoning to Electric Vehicle technologies in 2.3. Finally, we summarize the argument and raise three research questions in section 2.4.

### 2.1 Multi-sectoral interactions, coevolution and the geography of transitions

Research on transitions has shown that the process of innovation generation and diffusion can deeply transform many societal domains (Geels, 2002; Köhler et al., 2019). Traditionally, transition scholars have mostly focused on single technologies and regimes (Rosenbloom, 2020), but recent studies propose a multi-sectoral perspective to identify mechanisms of complementarity formation across technologies and domains of applications (Andersen and Markard, 2020; Mäkitie et al., 2022). These contributions unpack the plurality of sectors and value chains that interact around a focal technology, showing that transitions involve interactions between many sectors and nuancing the contrast between incumbent and emerging sectors: in fact, while some technologies might be overall unrelated or competing (*e.g.,* oil and hydrogen) some parts of their value chains might have similarities (*e.g.,* pipeline construction). That is why sectoral boundaries fall short of explaining transitions, and a precise identification of intersectoral complementarities might support improved policies of industrial diversification (Andersen and Gulbrandsen, 2020).

Parallel to these developments, a literature on the geography of transitions has emerged (Binz and Truffer, 2017; Binz et al., 2020; Miorner and Binz, 2021). Not only it focuses on the specificity of transitions in cities and developing countries (Kohler et al., 2019), but it calls for a systematic investigation of the role of local resources, production systems and institutions in enabling transitions, and of the involvement of different geographical scales in this process. This approach can complement a multi-sectoral one by stressing how the interplay between "local buzz and global pipelines" (Bathelt et al., 2004) can support the establishment of complementarities across sectors. Geographical proximity along with the associated cognitive and institutional forms of proximity (Boschma, 2005), can foster knowledge exchanges and the creation of linkages across sectors.

These two literatures can complement each other: while the multi-sectoral approach doesn't usually address the spatial dimension of complementarities, literature on the geography of transitions doesn't include multi-sectoral interactions. Therefore, we propose to combine these literatures using the concept of coevolution (Ferloni, 2022). Coevolution can be used in two main ways: to indicate specific interactions between technologies, economic actors, or other entities, or to designate wider system-level influences (Schamp, 2010; Gong and Hassink, 2018). Here, we see coevolution as a process of "coupled, deforming landscapes where the adaptive moves of each entity alter the landscape of its neighbors in the ecology or technological economy" (Kauffmann and Mc Ready, 1995:27). This definition states that for coevolution to occur we need distinct populations of actors whose independent actions affect each other, but it remains agnostic as to what research objects it should be applied to, and at which level of aggregation.

We propose to apply coevolution to indicate two different dynamics: an increasing complementarity between specific technologies, and the geographical colocalization of these technologies in the same urban regions. Taken together, these two ways to consider coevolution can account both for the mutual interdependencies that emerge among different inventions in the technology space, and for the extent to which these are upheld by geographical proximity with its associated advantages in terms of local networking, knowledge exchange and institutional support.

By applying a coevolutionary perspective, we integrate some key ideas of evolutionary economic geography (EEG) into a transition framework. We use the concepts of relatedness (Jaffe, 1986) to measure coevolution through the proximity of different patent classes in technological or geographical space, and path dependence to explore the persistence of inventive specialization in urban regions.

## 2.2 The dynamics of relatedness and path dependence

The concept of relatedness refers to the observation that products, economic sectors, or technologies can have varying degrees of complementarity with each other, or of similarity in the inputs that are required to generate them (Hidalgo et al., 2018; Farinha et al., 2019). Inputs can be tangible (raw materials, machinery) or intangible (knowledge, skills), and they are typically not available everywhere. Despite scientific and policy agreement on the importance of relatedness, several issues about its definition and measurement remain unresolved (Boschma, 2017). Among them, we focus here on how relatedness is dynamically evolving, so we should explain how unrelated technologies and sectors can become related over time (Castaldi et al., 2015; Juhász et al., 2021). Particularly, the dynamic nature of relatedness has not been investigated in the context of socio-technical transitions.

This paper frames relatedness as dynamic, by interpreting socio-technical transitions as a process of unrelated technologies becoming related over time. Besides, we explore the geographical evolution of technology location and specialization, to uncover regularities and growth patterns in the location of coevolving inventions. We consider emerging inventions (Electric Vehicle, battery, and smart grid) alongside established ones (combustion engine) to investigate how technological *path dependence*, in the form of a long-lasting leadership of traditional combustion engines, evolves in time, and whether this implies that cities specialized in incumbent technologies might retain a key position also in emergent ones. By considering coevolution between several technologies, we open a window on *path interdependence*, or the situation in which regional path-dependent trajectories in different technologies might interact and reinforce mutually (MacKinnon et al., 2019; Chlebna et al., 2022).

### 2.3 Relatedness, coevolution, and the transition to electric vehicles

Innovation involves combining existing technologies in new ways (Arthur, 2009) and during transitions the combinatorial process that leads to regime-changing innovations can be facilitated by landscape developments such as an environmental or economic crisis. Changed conditions make some technological solutions become more likely or desirable, and others less so, making technologies grow related or unrelated. If we apply this reasoning to EVs we see that at the end of the 19th century, electric cars were more diffused than fuel ones in many European and US cities (Larminie and Lowry, 2012). Back then, electric engines and batteries were more related to cars than combustion engines. However, when oil allowed vehicles to travel long distances, cars became more related to combustion engines and less to batteries and electric motors. During the 20th century, alternatives to fuel cars were developed, including hybrid, fuel cell and battery-powered vehicles. Following cycles of hype and disillusion (Dijk et al., 2016), relatedness between vehicle technologies and various types of propulsion systems has also evolved in time following the ups and downs of different acceptable solutions.

Nowadays, EV adoption rates and European policy decisions to ban fuel car sales by 2035, suggest that a transition to EVs is underway (IEA, 2022). This implies not only replacing fuel cars but also deploying extensive recharge infrastructures, generating more renewable electricity, and adapting the grid through “smart grid” systems and stationary storage (Richardson, 2013). Many technologies must be combined, creating complementarities among various sectors including automotive, chemical, digital and electronics (Golembiewski et al., 2015; Markard, 2018). Increased relatedness between different technologies can result in the emergence of a shared body of knowledge, so that integration of different technology fields and their competences becomes increasingly necessary to innovate. For example, recent studies have shown that increased complementarities between EV and batteries at the diffusion phase, influenced the focus of battery inventions (Malhotra et al., 2021). This means that battery inventions became more tailored to EV necessities, but also that EV inventions need to integrate gradually more knowledge of battery, smart grid, recharge, and other technologies.

Following this reasoning, growing technological relatedness is likely to be accompanied by increased geographical relatedness. In fact, as technologies become more complementary, the creation of new knowledge is likely to involve some degree of geographical proximity of inventors and firms. The advantages of localization economies and knowledge spillovers provide positive feedback to co-located agents, that coevolve in space as their growing technological interdependencies become embedded within local networks and institutions. By combining technological and geographical coevolution, it is possible to reflect on the extent to which wide-ranging technological transitions, that connect previously unrelated technologies, are accompanied by spatial concentration of the agents that create them.

## 2.4 Conceptualization and research questions

We apply this coevolutionary approach to four domains: Electric Vehicle, battery, smart grid, and Internal Combustion Engine (ICE) technologies. These technologies are interdependent, so that EVs require batteries, and smart grid systems can use EVs for vehicle-to-grid arrangements to stabilize loads. Yet they are also independent, because batteries are used for many other applications (e.g., e-bicycles, laptops, toothbrushes) and smart grid devices can be used to integrate renewable energy sources. Thus, these four technologies can be considered as developing along separate trajectories and becoming increasingly related in time. A coevolutionary dynamic between them is apparent at the diffusion phase, where interfaces such as recharge stations involve EVs along with many different artifacts including chargers, plugs, transformers, grid connections, and photovoltaic panels among others. In this study, we do not investigate how diffusion dynamics can feed back to invention (Malhotra et al., 2021), but we assume that increased complementarities between EV, battery and smart grid, can be mirrored by increased coevolution between patents in these three technologies.

To recognize coevolution, it is necessary to identify distinct populations of actors and the processes of reciprocal influence through which they change together (Murmann, 2013). In this article, coevolution is inferred by measuring the evolution of technological and geographical relatedness using patent data:

- Patent co-classification, or the presence of two patent codes in the same document provides a measure of technological relatedness
- Patent colocation, or the presence of two patent codes in the same urban region, indicates geographical relatedness.

Increased technological and geographical relatedness are taken as proxies for the existence of technological and spatial coevolution between technologies. The goal of this paper is to gain insights on the dynamics of coevolution of EV-related technologies and their geographical emergence. Accordingly, we formulate the following research questions:

1- To what extent is technological coevolution between EV, battery, smart grid, and ICE technologies, accompanied by geographical coevolution?
2- What do technology colocation patterns across different groups of cities suggest about EV coevolution?
3- Does patenting in battery, smart grid, or ICE influence EV patenting, and does path-dependence play a role?

We expect to find increased technological and spatial relatedness between these technologies. Even though hybrid technologies constitute a key building block of EVs, we expect ICE patents to become less related to EV ones, as fully electric capabilities became more important. We also anticipate that these technologies are not evenly localized, but that some urban regions — particularly those with long-lasting automotive capabilities — will display relevant EV patenting skills. As a result, we expect path dependence, particularly with respect to ICE capabilities, to play a significant role in EV patenting. Furthermore, we expect battery, smart grid and ICE patenting to positively influence EV invention.

## 3. Methods

Despite their notorious limitations, patents are well-established indicators to measure innovation (Griliches, 1990). Patent codes can disclose relevant information to identify technological capabilities and track their evolution and recombination in time (Strumsky et al., 2012). We studied all patents classes, but among them, we specifically focused on four Cooperative Patent Classification (CPC) codes, at the four-digit level, to identify the technologies of Electric Vehicle (EV), battery, smart grid, and Internal Combustion Engine (ICE) that were revealed of higher interest, both in the literature (Golembiewski et al., 2015; Borgstedt et al., 2017) and with our first results. These technology codes are (EPO, 2022):

- For EV, Code B60L: "*Propulsion of electrically propelled vehicles*".
- For battery, code H01M: "*Processes or means,* e.g.*, batteries, for the direct conversion of chemical energy into electrical energy*".
- For Smart Grid, the tag Y04S was considered, that refers to "*Systems integrating technologies related to power network operation, communication or information technologies [...],* i.e., *smart grids*".
- For Internal Combustion Engine (ICE), code F02B: "*Internal-Combustion piston engines; combustion engines in general.*"

These codes are at a rather aggregate level of the CPC classification (the subclass, which comprises 656 codes that appear across all our periods) and as such they can include more inventions than those we are interested in. Renouncing to more detailed levels of classification is motivated by the need to strike a balance between precisely delimiting technologies and keeping the number of combinations between codes at a manageable level. This choice is backed by similar studies in which the analysis of IPC/CPC knowledge networks is often conducted at the four or even three-digit level (Kogler et al., 2013; Leydesdorff et al., 2017; Yan and Luo, 2017; Song et al., 2019; Li and Rigby, 2022;).

### 3.1 Patents and geo-localization

We use the REGPAT patent database (OECD, 2022; Maraut et al., 2008), that includes information about the geographical location of inventors and applicants at the regional level, for patents submitted to the European Patent Office (EPO) and internationally via the Patent Co-operation Treaty (PCT-WIPO), from 1980 to 2020. The address of inventors is used to geolocate patents, as it is usually considered the most reliable indicator to this end (OECD, 2009). While data for European regions are precise at the NUTS 3 level, and US data are identified at the County level, the OECD defines regions in other countries such as China and India at a higher level of aggregation[1]. To mitigate this uneven delineation, we account for the fact that inventors gravitate around major metropolitan areas by aggregating smaller urban locations into LURs or Large Urban Regions (Rozenblat, 2020). LURs are defined all over the world on the notion of Mega-city region (Hall & Pain, 2009), and describe the fact that economic dynamics transcend municipal administrative boundaries forming large regional systems of workers and firms around urban agglomerations.

OECD regional codes have been matched to LURs in different ways. European and US data have been matched by NUTS and County, using a correspondence table with LURs (Rozenblat, 2020). In some cases, multiple NUTS or counties have been aggregated into LURs, which are usually larger units. Conversely, for countries such as China, India or Japan, several LURs

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[1] As a comparison, EU countries such as Italy or France have each 111 and 102 regional units identified, while China has 36 and India 37.

could be present for one OECD code. In these cases, we attributed manually patents to the most representative LUR[2]. Finally, few patents (less than 2%) were not regionalized in the REGPAT database, which explains why some patents could not be attributed to LURs (Tab. 1).

| | **NUTS (EU+EFTA)** | **USA** | **Japan** | **South Korea** | **China** | **India** | **Hong Kong** | **Taiwan** | **Total** |
|---|---|---|---|---|---|---|---|---|---|
| Tot. patents (EPO + WIPO) | 2,297,426 | 1,680,753 | 1,033,510 | 251,283 | 413,028 | 66,271 | 12,763 | 35,066 | 5,790,100 |
| Patents matched to LURs | 2,256,249 | 1,646,715 | 1,014,356 | 250,187 | 410,660 | 65,284 | 12,763 | 35,066 | 5,691,280 |
| % Of patents matched to LURs | 98.2 | 98.0 | 98.1 | 99.6 | 99.4 | 98.5 | 100 | 100 | 98.3 |
| Distinct LURs | 329 | 113 | 29 | 9 | 31 | 28 | 1 | 1 | 541 |

*Table 1: Patent locations in Large Urban Regions (LURs), (1980–2020)*

### 3.2 Relatedness and specialization

We use patents to construct a technology space, or network of technological relatedness between any two codes *i* and *j*, which measures the strength of the connection, or the proximity between technologies. There are different ways to measure technological proximity (Engelsman and Van Raan, 1994; Yan and Luo, 2017): co-classification measures how often two codes appear together in a patent, while citation indicators measure when codes cite each other or are cited together (co-citations). Furthermore, colocation measures consider that two codes are related if they appear together in the same spatial unit (here LURs). Studies on technological relatedness have applied alternatively measures of co-classification (Balland et al., 2019; Balland and Boschma, 2021), colocation (Boschma et al., 2015) or citation (Rigby, 2015).

In this paper, we calculate and compare measures of co-classification and colocation, conceptualizing them as *technological relatedness* and *geographical relatedness* respectively. The comparison between these two forms of relatedness is the background against which we contextualize technology coevolution and urban specialization. Accordingly, we construct two

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[2] These are usually the capital cities of states or provinces. For example, for the OECD region of Rajasthan (India), patents were attributed to Jaipur, which is the capital and largest city of the state. Other LURs are present in Rajasthan such as Jodhpur, Udaipur, or Kota, but address data from REGPAT were not precise enough to attribute patents to these LURs in the absence of a sub-regional code.

square matrices of 656 CPC codes, across four non-overlapping periods of 10 years from 1980 to 2020, and we calculate the frequency of two patent codes $i$ and $j$ appearing together in the same patent, or of two patent codes being located in the same LUR. Then, we normalize these scores using the well-established cosine similarity index (Yan and Luo, 2017). The cosine formula equals the ratio between the number of times when codes $i$ and $j$ appear together and the geometric mean of the number of times each code is observed, and it takes values between 0 (two technologies are never together) and 1 (they are always together):

$$cos(i,j) = \frac{\sum_{p\in P} \mathbf{1}_i(p)\mathbf{1}_j(p)}{\sqrt{\left(\sum_{p\in P} \mathbf{1}_i(p)\right)\left(\sum_{p\in P} \mathbf{1}_j(p)\right)}}, \qquad (1)$$

where $P$ is the set of all patents, and $\mathbf{1}_i(p)$ is equal to 1 if patent $p$ has code $i$ and 0 otherwise. Following Balland and Boschma (2021), we calculated the concentration of patent codes in LURs, to check the extent to which a city's inventive activity is specialized. Hence, we calculate patent counts, and we measured the RTA or Revealed Technological Advantage (Soete and Wyatt, 1983) for each technology $i$, in region $r$, at time $t$ ($r$=1, …, $n$; $i$=1, …, $k$). $RTA^t_{r,i}$ is expressed as the ratio between the share of technology $i$ in the patent production of region $r$, and the share of technology $i$ in the patent production of all regions (patent jurisdictions in table 1). If a region has $RTA^t_{r,i} > 1$ it can be considered as specialized in $i$ at time $t$:

$$RTA^t_{r,i} = \frac{N^t_{r,i}/\Sigma_{j\in T}\, N^t_{r,j}}{\Sigma_{r\in R} N^t_{r,i}/\Sigma_{r\in R}\Sigma_{j\in T}\, N^t_{r,j}} \qquad (2)$$

where $N^t_{r,i}$ is the number of patents of technology $i$, produced in region $r$ at time $t$, $T$ is the set of all technologies and $R$ the set of all regions. Given the RTA, we also calculate a diversity index to measure the extent to which a region is capable to invent in several different technology fields. The diversity of region $r$ is measured as the sum of technologies $i$ in which $r$ is specialized ($RTA^t_{r,i}$>1):

$$Diversity_r^t = \left|\left\{i \in T \mid RTA_{r,i}^t > 1\right\}\right| \qquad (3)$$

### 3.3 City classifications and the role of related technologies

To analyze patent trends and differences across cities, we applied correspondence analysis (Sanders, 1989), that allows to simplify variability and identify similarities across observations. Applied on temporal data, it allows to cluster trajectories (Pumain et al., 2015). LURs are grouped into different clusters according to similarities in the trajectories of their absolute patents scores in EV, battery, smart grid, and combustion engine technologies patents. Correspondence analysis allows to appreciate the extent to which each group of cities produce inventions in a specific technology or a combination of them. City groups are also used to account for average specialization paths by group and technology.

After classifying cities, we construct two regression models to estimate the effect of patenting in battery, smart grid, or combustion engine on EV patents. We include data for 175 urban regions across four ten-year periods, for a total of 700 observations. We remove cities with a score of 0 in all technologies, and we add 1 to technology scores to avoid issues when calculating logarithms, ending up with a total of 655 observations (Tab.2). We add patent counts to control for the effect of big cities' diverse environments and sheer patenting size.

| Statistic | N | Mean | St. Dev. | Min | Max |
|---|---|---|---|---|---|
| EV score | 655 | 50.6 | 209 | 1 | 3,791 |
| Battery score | 655 | 146.6 | 611.4 | 1 | 10,930 |
| Smart grid score | 655 | 21.7 | 67.3 | 1 | 1,222 |
| ICE score | 655 | 43.3 | 113.4 | 1 | 1,678 |
| Diversity | 655 | 196.0 | 59.2 | 5 | 381 |
| Tot. patents LUR | 655 | 18,895.144 | 44,487.2 | 7 | 748,291 |

*Table 2: Summary statistics for regression models*

Then, we fit the following model using OLS:

$$\log(N_{t,r,EV}+1)=\alpha_t+\beta_{BA,t}\log(N_{t,r,BA}+1)+\beta_{SG,t}\log(N_{t,r,SG}+1)+\beta_{ICE,t}\log(N_{t,r,ICE}+1)+\beta_{Div,t}\log(Diversity_{t,r})+\beta_{t,r,ALL}\log(N_{t,r,ALL})+\varepsilon_{t,r} \quad (4)$$

For the second model, we use a quasi-Poisson specification, to control for possible heteroskedasticity in the OLS model (Silva and Tenreyro, 2006). Thus, we have:

$$\mathbb{E}[N_{t,r,EV}]=\exp\left(A_t+\beta_{BA,t}\log(N_{t,r,BA}+1)+\beta_{SG,t}\log(N_{t,r,SG}+1)+\beta_{ICE,t}\log(N_{t,r,ICE}+1)+\beta_{Div,t}\log(Diversity_{t,r})+\beta_{t,r,ALL}\log(N_{t,r,ALL})\right) \quad (5)$$

where $N_{t,r,EV}, N_{t,r,BA}, N_{t,r,SG}, N_{t,r,ICE}, N_{t,r,ALL}$ are the number of patents in EV, battery, smart grid, combustion engine and total patents produced by each LUR at each time period *t*.

Furthermore, we estimate a second model in which we calculate the effect of battery, smart grid and ICE patents at period *t*, on EV specialization at period *t+1*. We fit a logistic regression to estimate the probability of a certain LUR to specialize (entry model) or lose its specialization (exit model) in EV in period *t+1* given its patent scores in battery and smart grid in period *t*. We add again diversity and regional size in terms of patents. The entry model writes:

$$\log\left(\frac{P(RTA_{EV,(t+1)}>1|RTA_{EV,t}\leq 1)}{1-P(RTA_{EV,(t+1)}>1|RTA_{EV,t}\leq 1)}\right)=\alpha_t+\beta_{BA,t}\log(N_{t,r,BA}+1)+\beta_{SG,t}\log(N_{t,r,SG}+1)+\beta_{ICE,t}\log(N_{t,r,ICE}+1)+\beta_{Div,t}\log(Diversity_{t,r})+\beta_{t,r,ALL}\log(N_{t,r,ALL})+\varepsilon_{t,r} \quad (6)$$

The exit model writes:

$$\log\left(\frac{P(RTA_{EV,(t+1)}\leq 1|RTA_{EV,t}>1)}{1-P(RTA_{EV,(t+1)}\leq 1|RTA_{EV,t}>1)}\right)=-\alpha_t-\beta_{BA,t}\log(N_{t,r,BA}+1)-\beta_{SG,t}\log(N_{t,r,SG}+1)-\beta_{ICE,t}\log(N_{t,r,ICE}+1)-\beta_{Div,t}\log(Diversity_{t,r})-\beta_{t,r,ALL}\log(N_{t,r,ALL})-\varepsilon_{t,r} \quad (7)$$

We adopt the sign convention in equation (7) to have a consistent way of interpreting the sign of the coefficients across the different equations. Using this convention, positive coefficients in (7) are associated with a higher probability of preserving their specialization in EV. By estimating the contemporaneous and the lagged models, we can make sense of two dynamics:

models 4 and 5 show *simultaneous* technological coevolution, as the effects of related technologies operate within each 10-year period. Instead, models 6 and 7 show *path dependence*, or the effect of previous patent scores on subsequent EV specialization. By combining them we can have insights about coevolution in different periods and as a path-dependent process.

# 4. Results

## 4.1 The evolution of technological and geographical relatedness to EVs

The first question we asked was to what extent technological coevolution between EV, smart grid, battery, and ICE was accompanied by geographical coevolution. We examine here relatedness to EVs, and we assess the evolution of both measures separately, before comparing their dynamics.

### 4.1.1 Technological relatedness

Figure 1 shows the evolution of technological relatedness in the past four decades through the ego-networks[3] constructed around EV technology within the whole space of all technologies. The red-encircled nodes represent the four studied technologies, while other colors indicate the general patent sections to which codes belong. Nodes' sizes are proportional to the share of a code on total patents, while link size denotes the intensity of technological relatedness.

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[3] The ego-networks for technological relatedness are built by selecting from the whole knowledge space, the top 25% most (technologically) related technologies to EVs, and the links between them. For the sake of clarity, only links involving EV, battery, smart grid or ICE codes have been included.

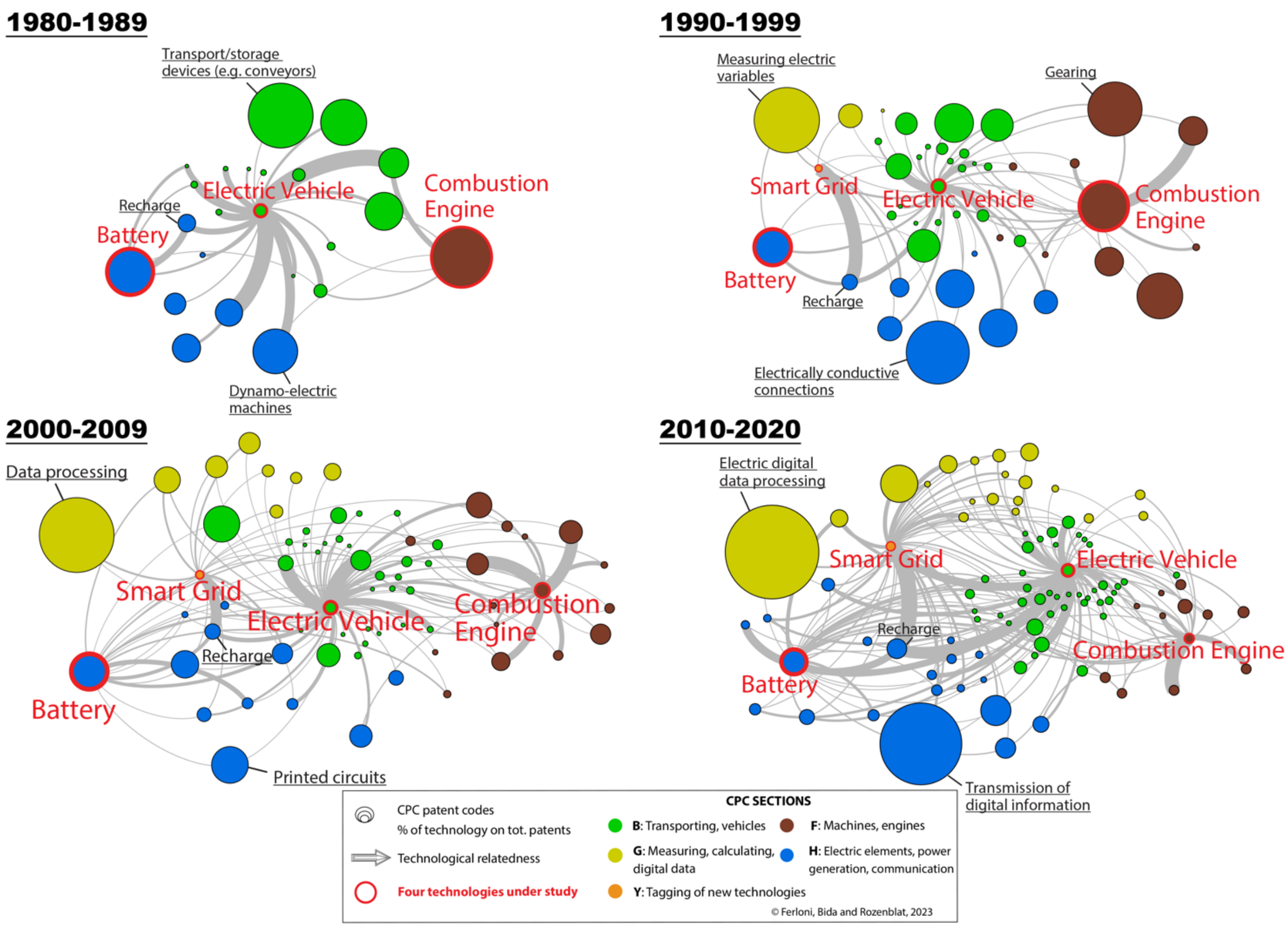

*Figure 1: the evolution of technological relatedness to EVs*

This figure shows that the relative weight of machine and engine-related patents drops constantly in time, as smaller node sizes indicate a decreasing proportion on total patents. Besides, this group of codes is becoming increasingly peripheral, as shown by weaker tie strength and fewer connections to sections other than the F one (machines, engines). Conversely, battery and smart grid codes become connected to many other technology codes from the B (transporting vehicles), H (electric elements) and G (measuring/digital data). The growing importance of these sections, particularly the electric elements and digital technologies ones, is apparent in the growing number of different codes and their size in terms of patents[4]. In the evolution of this knowledge space, it is interesting to note the role of recharge technologies[5]. This category

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[4] A general description of patent codes and their rankings in terms of node size (code counts on total counts) can be found in the supplementary material, for both technological and geographic relatedness.

[5] This code is H02J and is defined as: “Circuit arrangements or systems for supplying or distributing electric power” (EPO, 2022).

of technologies is very related to smart grid and battery since the first periods, and in the last period it becomes the most related technology to EVs. Recharge technologies arguably play a strategic role of interfaces that enable complementarities between technologies and infrastructure (electric grid, local energy generation, batteries, appliances).

#### 4.1.2 Geographical relatedness

Figure 2 shows the evolution of the EV ego-network for geographic relatedness, or the extent to which two technologies appear in the same cities[6]. Smart grid patents are absent from this graph because they are not enough related to EV, and battery patents appear only in the third period. Contrary to figure 1, we don't see a clear growth of the G (measuring/digital data) and H (electric elements), but they are stable or decreasing in time (particularly the former). Engine and machine-related patents of the F section increase in relative importance (size) and connections, instead of declining as in figure 1. Overall, geographical relatedness is more evenly distributed than technological one, so that tie strength is more homogeneous than the technological relatedness. Also, the network of geographical relatedness is more stable because the technological capabilities that are located in some urban areas in the activities of firms and inventors, have a certain degree of geographical stickiness and inertia. Considering this, the presence of engine-related patents until the final period suggests that the cities that invent motor-related patents are also able to create EV-related inventions.

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[6] The ego-networks for geographic relatedness are built by selecting the top 5% most geographically related codes to EV. Unlikely technological relatedness, geographical one is much more evenly distributed. Therefore, we had to proceed to an extra filtering: we used the top 5% most related codes to select links that contained them in the whole network. For each code, we selected the top 5% of their most related links. Finally, we select from the resulting network only the ego-network of EV patents, which includes the connections of EV and their links. Only links to EV, battery, smart grid, or combustion engine codes have been included.

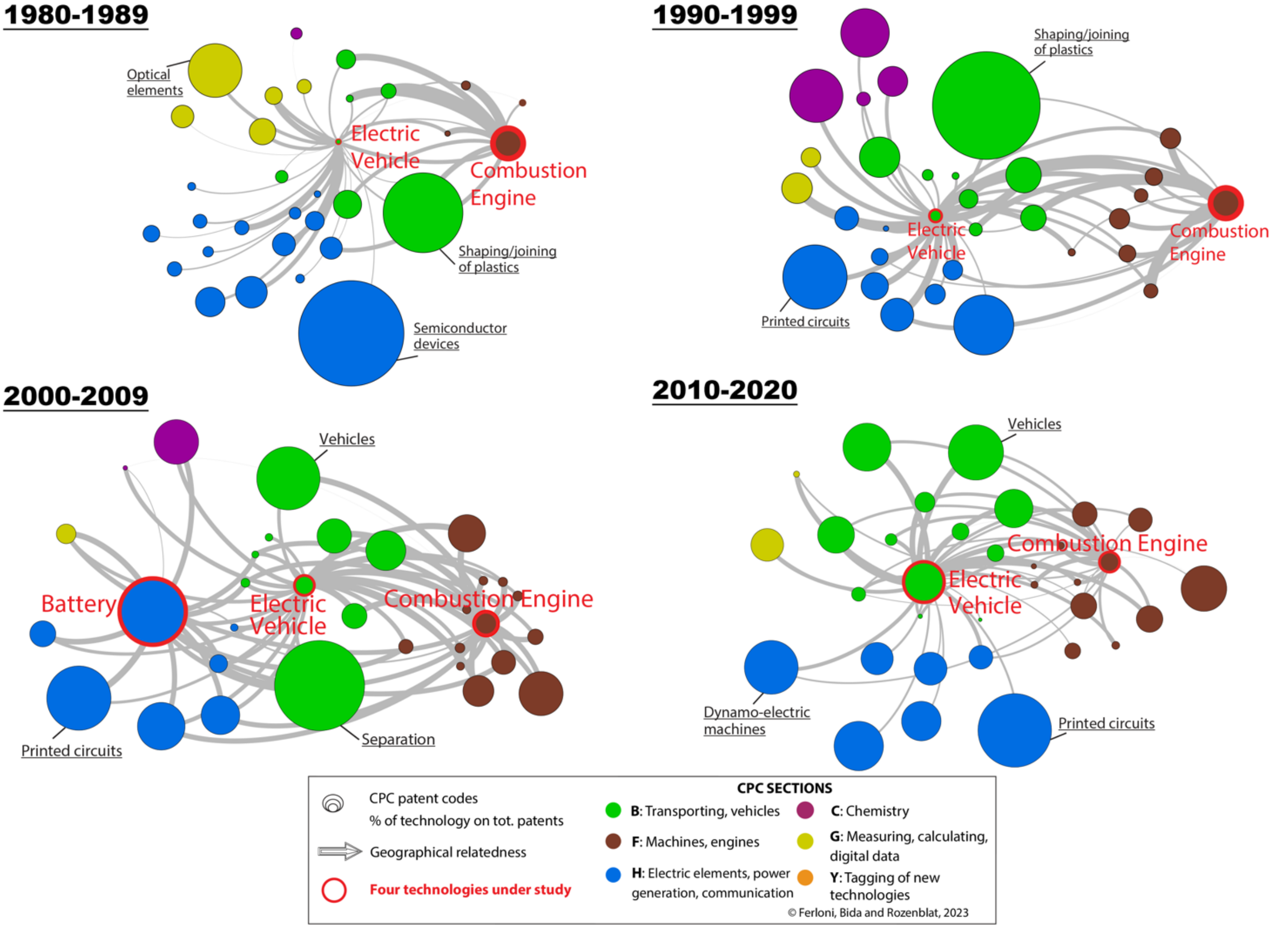

*Figure 2: the evolution of geographical relatedness to EVs (1980–2020)*

### 4.1.3 Does geographical relatedness reflect technological one?

We can now combine the evolution of technological and geographic relatedness for 152 technology codes that are the most related to EVs (Fig. 3). Codes have been clustered into five groups that display similar trends, using a k-means algorithm, to provide a clearer visualization, and table 3 summarizes their composition and main technology codes. Then, we compared the average relatedness to EVs of these five groups of technologies with that of battery, smart grid, and combustion engine technologies.

While clusters 1, 2 and 3 feature very diverse patent codes and technologies, the most related clusters to EV technology are 4 and 5. Cluster 4 includes codes that have to do with electricity distribution/recharge, and cluster 5 comprises technologies related to vehicle propulsion/assembly. Smart grid and battery patents are among the most related technologies to EVs, both in technological and geographical terms, and this trend increases in time. Most other patent codes are much less related to EVs, particularly technologically, and only patents in groups 4 and 5 score equally high. On the other hand, combustion engine patents become less related to EVs technologically, but more related geographically.

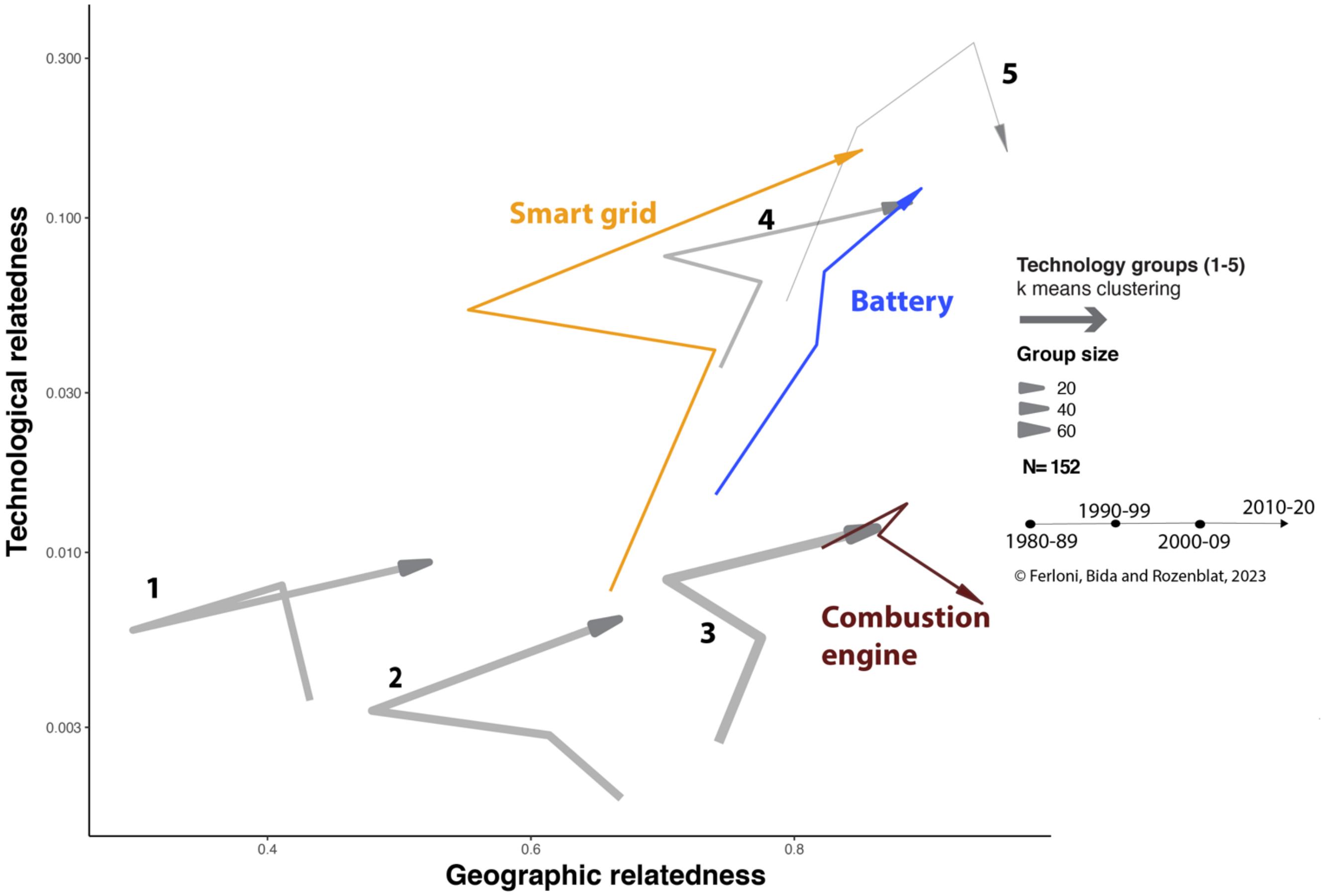

*Figure 3: The evolution of technological and geographic relatedness to EVs (1980–2020)*

The trajectory of battery and smart grid patents is coherent with our coevolutionary hypothesis that increased technological proximity might be reflected by growing colocation. In contrast, combustion engine technologies become increasingly co-located with EVs despite their decreasing technological relatedness, and this could be explained by path dependence: traditional automotive producers, which are mostly responsible for innovating in ICE, participate more and more in EV innovation so even though patent documents show decreasing proximity between EV and ICE, they continue to be invented in the same urban regions.

| Cluster | Number of codes | Main technologies |
|---|---|---|
| 1 | 32 | Vehicles, railway, aircraft, domestic cleaning. |
| 2 | 42 | Digital data, transmission of information, medical preparations. |
| 3 | 64 | Semiconductor devices, measuring variables, vehicle components. |
| 4 | 8 | Distributing electric power, dynamos, converters. |
| 5 | 2 | Mounting propulsion units in vehicles. Control of vehicle subunits. |

*Table 3: Size of technology clusters and their main technologies*

Finally, it should be noted that fig. 3 features a significant reduction of geographical relatedness from the second period to the third (from 2000 to 2009). This reduction involves all patent codes, but it's particularly strong for EV technologies. To gain insights on this dynamic, we analyzed the geographical distribution of patenting for each technology. In particular, we measured the evolution of the geographic concentration of patenting for each technology with the commonly used Hirschman-Herfindahl index (HHI) (e.g., Fornahl & Brenner, 2009):

$$\mathrm{HHI} = \frac{\sum_{r \in R} s_{ri}^2 - 1/n}{1 - 1/n}, \qquad (8)$$

where $R$ is the set of all regions and $s_{ri}$ is the share of region $r$ in the total patent production in technology $i$. The HHI takes values between 0 (all regions produce the same number of patents) and 1 (all patents are produced in one region), with higher values corresponding to more geographic concentration.

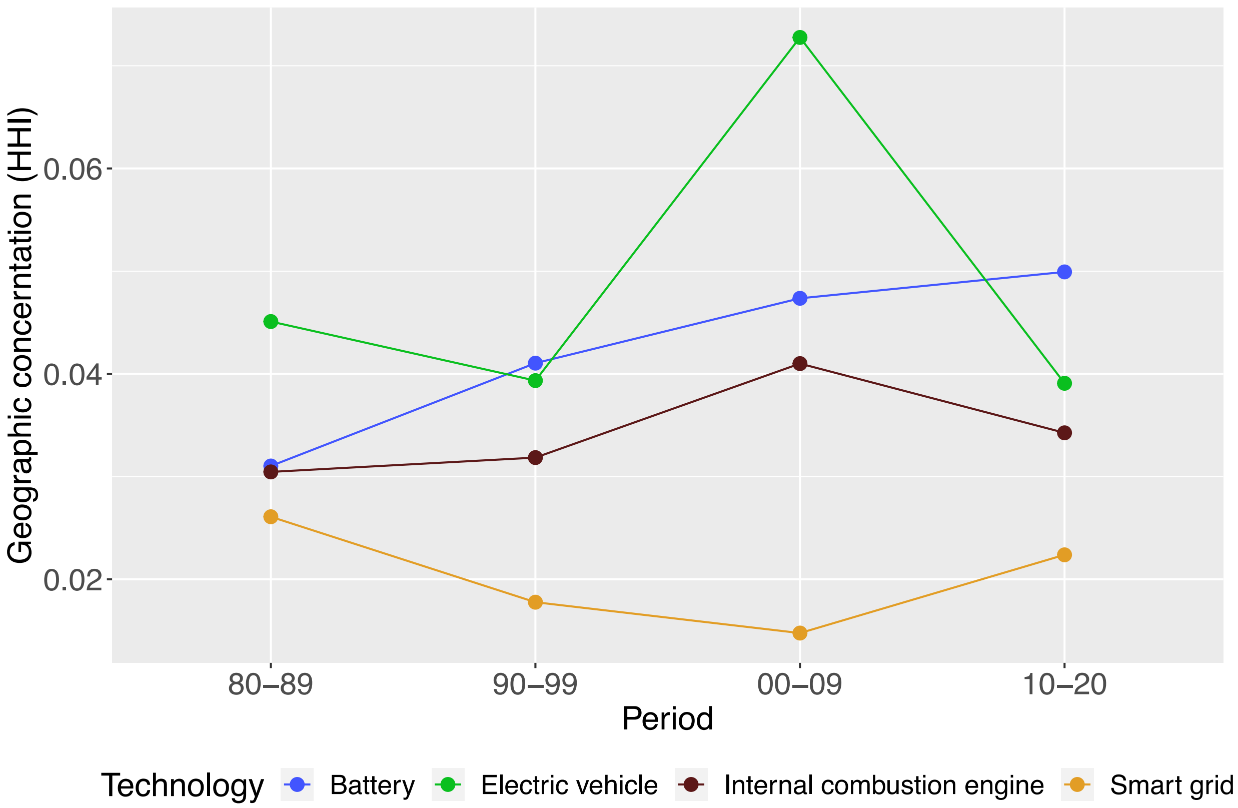

*Figure 4: Evolution of the geographic concentration of patenting activities for the four considered technologies*

The HHI (Fig. 4) shows a peak in the geographic concentration of patenting for electric vehicles for the period 2000–2009, that is not observed for the other technologies. The concomitance of this peak in geographical concentration with the decrease of geographical relatedness of EV with the other technologies suggests that EV patents concentrated in fewer urban centers that will be identified below.

To sum up, the evolution of technological relatedness to EVs has indicated that combustion engine technologies have lost importance while electric and digital technologies have taken center stage, particularly those related to recharge. The comparison of technological and geographical relatedness has nuanced these findings by showing that ICE patents are less related technologically but more co-located with EV ones. We can answer the first research question saying that for battery and smart grid, these two forms of relatedness grow together, but not for

ICE. This suggests that by distinguishing these two forms of relatedness we can disclose insightful exceptions, despite a general common trend.

### 4.2 City specialization clusters: technological trajectories and spatial proximities

After providing a general context on relatedness dynamics, we now want to know if the analysis of patent locations can suggest the existence of different coevolution patterns across groups of cities. We performed a correspondence analysis on cities according to their specialization in the four technologies during the four periods. It yielded four groups of cities according to their relative proximity to each technology in time. Based on this, we could map the trajectories with respect to the four technologies in figure 5, one for each city (gray arrows) and the average trajectory by group (colored arrows). Red triangles show the position of the four technologies, or the average of cities' specialization during the whole period. Thus, the proximity of each group trajectory to the red triangles indicates how much their patent output is specialized in the four technologies under study.

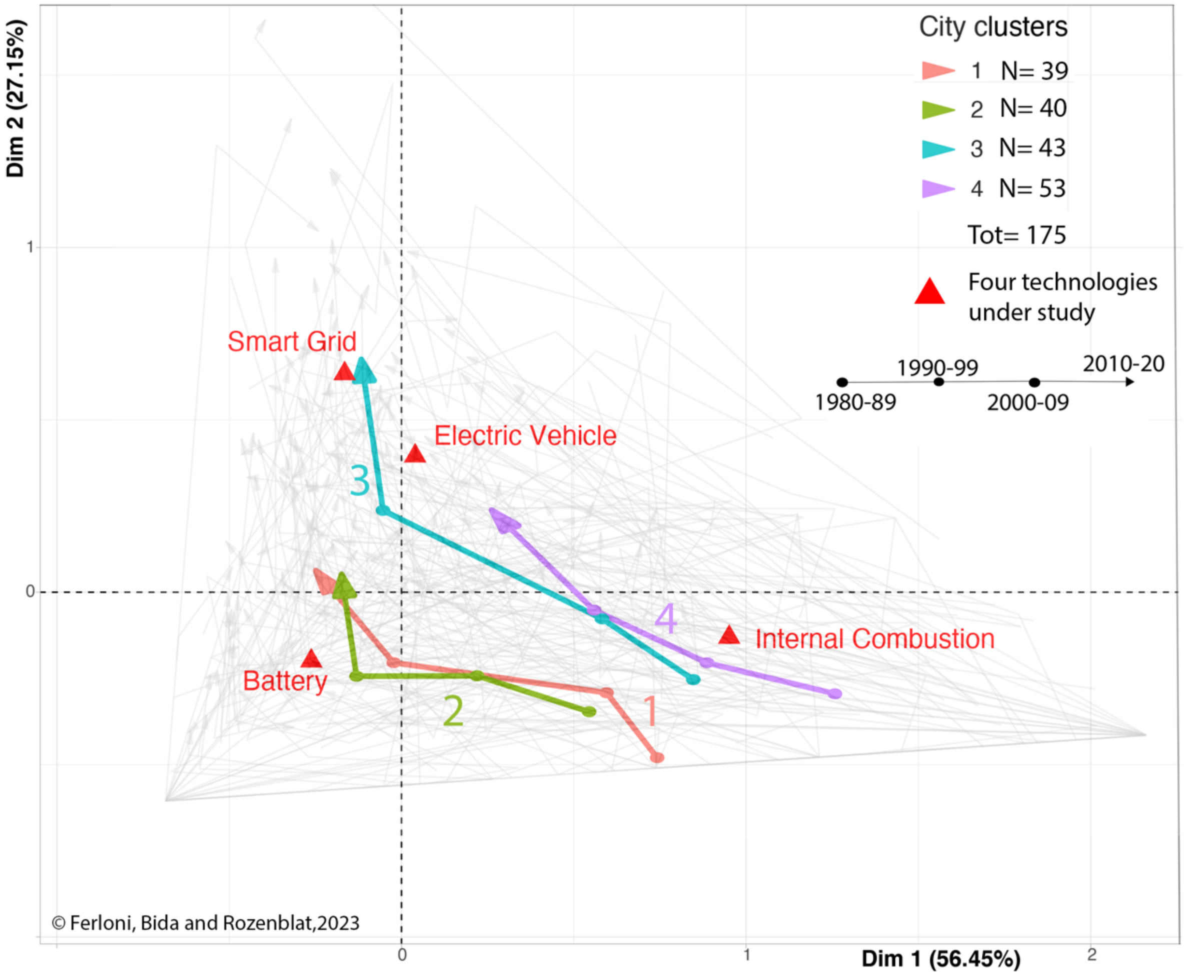

*Figure 5: the trajectories of city clusters with respect to technologies (1980–2020)*

Cities' trajectories show a generalized distancing from internal combustion patents, towards EV, battery, and smart grid ones. Groups 1 and 2 are close to battery inventions and group 3 to smart grid ones, while group 4 is the closest to ICE patents. This figure permits to visualize the overall patent trajectories of city clusters and to situate them with respect to technologies. Before analyzing the composition of these cities' groups more in detail in table 4, we can already announce their general characteristics: cluster 1 is composed of emerging innovation hubs, most of them located in Asian countries. Cluster 2 includes major global cities, while cluster 3 reunites several leaders in new technologies. Finally, cluster 4 contains established automotive cities. We now analyze the specialization patterns of these groups of cities more in detail.

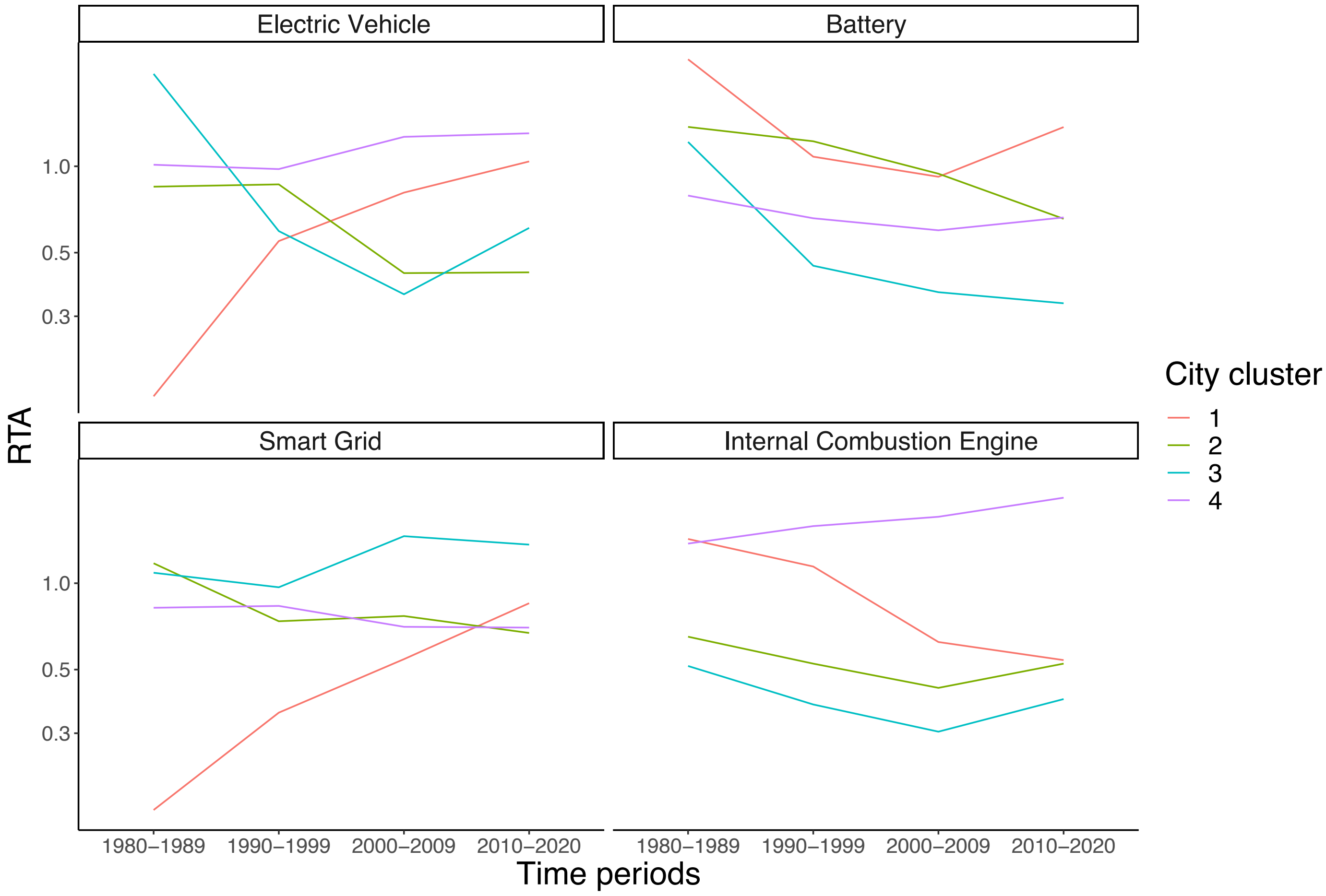

*Figure 6: The evolution of specializations of city clusters by technology*

In figure 6 we see the evolution of group specialization in EV, battery, smart grid, and ICE. While we used absolute patent scores in our four technologies to build figure 5, here we use RTA scores. Thus, these trajectories are relativized according not only to the four technology groups of patents, but to the overall patents' production of each city (averaged by cluster) and by global patent outputs for each technology (see equation 2). The most specialized groups in EV are numbers 1 and 4. However, group 1 displays a dramatic growth of specialization in time, while the latter remains stable. About ICE specialization, cities in group 4 are the only ones to be set on an increasing path while all others decrease. Besides, cities in group 1 are rather specialized in battery and smart grid, while those in group 4 are not, and they do not grow in these technologies. Group 3 appears particularly specialized in smart grid, while group 2 mostly shows an unspecialized dynamic across technologies.

Table 4 shows the most relevant cities, in terms of patent numbers, for each cluster. Group 1 features several Asian cities, some of which experienced strong economic growth in recent decades (Shenzhen, Shanghai, Taipei). Apart from Tokyo, all of them including to some extent European cities such as Brussels and Grenoble, can be considered as emerging innovation hubs. Conversely, cities in group 4 such as Paris, Nagoya, Stuttgart, or Detroit are established automotive centers. This suggests that automotive cities have a significant specialization in EVs because of their experience in traditional automotive production, and this is confirmed by the fact that their specialization in ICE patents grows more than that in EVs. Conversely, cities in cluster 1 are not at all specialized in ICE, their specialization in EVs is growing and this dynamic is accompanied by growth in the related sectors of battery and smart grid. Cities in cluster 2 are major global centers that do not display significant specialization trends, while cities in cluster 3 are technological leaders such as S. Francisco, S. Diego, Seattle or Dallas and their increasing specialization in smart grid is matched by growing EV specialization in the most recent period.

| **Cluster 1** | **Cluster 2** | **Cluster 3** | **Cluster 4** |
|---|---|---|---|
| Tokyo | Osaka | S. Francisco | Paris |
| Seoul | New York | S. Diego | Nagoya |
| Shenzhen | Boston | Eindhoven | Stuttgart |
| Guangzhou | Frankfurt | Nuremberg | Munich |
| Shanghai | Los Angeles | Seattle | London |
| Cincinnati | Philadelphia | Basel | Chicago |
| Taipei | Houston | Washington | Düsseldorf |
| Brussels | Milano | Berlin | Zurich |
| Grenoble | Copenhagen | Dallas | Detroit |
| Münster | Geneva | Helsinki | Stockholm |
| **N= 39** | **N= 40** | **N= 43** | **N= 53** |

*Table 4: Most patenting cities by cluster*

Accordingly, we answer the second question by saying that EV coevolution is most likely in emerging innovation hub cities of cluster 1 that, despite not having a strong automotive heritage, are those where the related technologies of battery and smart grid are growing the most. Automotive cities are likely to retain their innovative capabilities for some time, but the fact that their specialization in related technologies is stagnating puts their capability to maintain an innovative edge into question. Global and unspecialized urban areas such as New York or Frankfurt are not expected to be significant coevolutionary *milieus*, but rather global platforms in support of technological diversity and financial networking. Finally, technological leaders such as San Francisco could become important hubs of EV innovation and coevolution, but that will depend on the relative importance of digital technologies in general, and smart grid ones in particular, to EV innovation.

### 4.3 The effect of related technologies on EV patenting

The third question asked if being inventive in battery, smart grid or ICE impacted EV invention, and whether path dependence played a role in this. To answer, we show the results of multiple regressions where we consider the effect of battery, smart grid, and internal combustion engine patenting on EV invention. We add a measure of the total number of inventions and a measure of diversity, to account for the role of large cities and of possessing diversified innovative capabilities. The models show the results of multiple cross-sectional regressions calculated for every time period. The first model is a simple OLS regression, while the second one uses a quasi-Poisson distribution which provides an heteroskedasticity-robust fitting (Silva and Tenreyro, 2006).

| **Dependent variable: EV patent scores** | | |
|---|---|---|
| **Independent Variables** | **OLS** | **PPML** |
| Period 1 (1980–1989) | -0.054 | -0.33667 |
| | (0.493) | (0.84518) |
| Period 2 (1990–1999) | -1.202 | **-2.34812**$^{*}$ |
| | (0.778) | (1.34857) |
| Period 3 (2000–2009) | -1.444 | **0.454422**$^{***}$ |
| | (1.157) | (1.67489) |

|  |  |  |
|---|---|---|
| Period 4 (2010–2020) | -1.840<br>(1.678) | **2.34922**$^{*}$<br>(1.38330) |
| Battery scores (1980–1989) | **0.131**$^{**}$<br>(0.066) | **0.15885** $^{**}$<br>(0.07452) |
| Battery scores (1990–1999) | **0.225**$^{***}$<br>(0.067) | **0.25127**$^{***}$<br>(0.09914) |
| Battery scores (2000–2009) | **0.306**$^{***}$<br>(0.064) | **0.63961**$^{***}$<br>(0.08054) |
| Battery scores (2010–2020) | **0.413**$^{***}$<br>(0.071) | **0.47060**$^{***}$<br>(0.05397) |
| Smart Grid scores (1980–1989) | **0.285**$^{***}$<br>(0.097) | **0.23965**$^{***}$<br>(0.08841) |
| Smart Grid scores (1990–1999) | **0.253**$^{***}$<br>(0.090) | **0.22877**$^{**}$<br>(0.09914) |
| Smart Grid scores (2000–2009) | 0.055<br>(0.070) | **0.18594**$^{**}$<br>(0.08852) |
| Smart Grid scores (2010–2020) | **0.188**$^{**}$<br>(0.081) | **0.20542**$^{**}$<br>(0.08045) |
| ICE scores (1980–1989) | **0.238**$^{***}$<br>(0.069) | **0.39600**$^{***}$<br>(0.07241) |
| ICE scores (1990–1999) | **0.361**$^{***}$<br>(0.064) | **0.44124**$^{***}$<br>(0.06816) |
| ICE scores (2000–2009) | **0.366**$^{***}$<br>(0.057) | **0.67242**$^{***}$<br>(0.05986) |
| ICE scores (2010–2020) | **0.328**$^{***}$<br>(0.059) | **0.45228**$^{***}$<br>(0.04568) |
| Diversity (1980–1989) | -0.179<br>(0.163) | -0.16161<br>(0.17832) |
| Diversity (1990–1999) | 0.265<br>(0.166) | 0.30469<br>(0.20155) |
| Diversity (2000–2009) | 0.058<br>(0.173) | -0.32794<br>(0.23951) |
| Diversity (2010–2020) | 0.326<br>(0.200) | -0.14750<br>(0.16455) |
| Tot. patents (1980–1989) | 0.097<br>(0.099) | 0.08838<br>(0.10663) |
| Tot. patents (1990–1999) | -0.044<br>(0.088) | 0.04682<br>(0.11538) |
| Tot. patents (2000–2009) | 0.144<br>(0.097) | **-0.53518*****<br>(0.13276) |
| Tot. patents (2010–2020) | 0.049<br>(0.133) | -0.18198<br>(0.11261) |
| $R^2$ | 0.851 |  |
| *Adj.* $R^2$ | 0.845 |  |
| *Observations* | 655 | 655 |

*p <0.1; **p <0.05; ***p <0.01

Standard Errors in parentheses (Robust estimation for PPML model)

All dependent variables are log-transformed.

The independent variable is also log-transformed in the OLS model.

*Table 5: Ordinary Least Squared and Poisson Pseudo Maximum Likelihood models for estimating the effects of the independent variables on EV patent scores of cities (1980–2020).*

*Green color indicates significant and positive effect. Blue indicates significant and negative effect.*

Results indicate that:

- In the PPML model, coefficients for each period are significant and increasing, starting from period 2, and show a trend of increasing specialization in EVs in time.
- Battery patents are significant and increasing across periods, suggesting increased co-evolution between battery and EV technologies.
- Smart grid patents are important in periods 1 and 2, their effect decreases in period 3 before recovering in period 4. This suggests that smart grid played a role in the first generations of EV patenting and that this role is again important in recent years.
- The effect of ICE patents is increasing until period 3 for both models, before decreasing its effect in period 4. This suggests that specializing in combustion engine technologies is important to EV patenting, but that its effect is decreasing.
- Diversity appears to have no effect on EV patents.
- LUR size is not significant. Only in period 3 for the PPML model, it has a significant negative effect on EV patents.

### 4.3.2 Acquiring or losing EV specialization: an exploration

After estimating the effect of related technologies on EV within each period, we explore the effect of patenting in battery, smart grid, or ICE in period *t*, on developing a specialization in EV in period *t+1*. Thus, we keep only three time periods because we check for effects of independent variables on subsequent periods. We then fit a logit and probit model for each period, and we do this exercise for entry (acquiring a specialization that is new to the region) and exit (losing a specialization that was once present). For entry and exit, the dependent variable is 0 when regions do not develop EV specialization or lose it respectively. It is 1, when regions become specialized in EV, or they maintain EV specialization respectively.

**Dependent variable: entry in or exit from EV specialization (binary)**

| | **Logit** | | | **Probit** | | |
|---|---|---|---|---|---|---|
| | Period 1 (1980–1989) | Period 2 (1990–1999) | Period 3 (2000–2009) | Period 1 (1980–1989) | Period 2 (1990–1999) | Period 3 (2000–2009) |
| | | | **Entry Models** | | | |
| (Intercept) | **-7.585**$^{*}$<br>(4.450) | -1,477<br>(2.794) | -3.181<br>(5.409) | **-4.097**$^{*}$<br>(2.290) | -1.022<br>(1.553) | -1.489<br>(2.940) |
| Battery | 0.476<br>(0.305) | 0.490<br>(0.393) | 0.396<br>(0.340) | 0.286<br>(0.177) | 0.243<br>(0.210) | 0.216<br>(0.183) |
| Smart grid | -0.038<br>(0.469) | **-1.094**$^{*}$<br>(0.616) | 0.391<br>(0.359) | -0.031<br>(0.275) | **-0.657**$^{*}$<br>(0.340) | 0.192<br>(0.197) |
| ICE | **0.586**$^{*}$<br>(0.316) | **0.864**$^{**}$<br>(0.374) | 0.164<br>(0.325) | **0.352**$^{*}$<br>(0.183) | **0.445**$^{**}$<br>(0.205) | 0.073<br>(0.181) |
| Diversity | **1.929**$^{**}$<br>(0.981) | 0.773<br>(1.006) | **2.239**$^{**}$<br>(1.086) | **1.074**$^{**}$<br>(0.531) | 0.409<br>(0.537) | **1.118**$^{**}$<br>(0.557) |
| All patents | -0.716<br>(0.439) | -0.819<br>(0.531) | **-1.422**$^{***}$<br>(0.547) | **-0.431**$^{*}$<br>(0.250) | -0.400<br>(0.281) | **-0.741**$^{**}$<br>(0.292) |
| *AIC* | *112.719* | *88.375* | *116.601* | *112.892* | *88.514* | *116.969* |
| *BIC* | *128.410* | *104.299* | *134.033* | *128.583* | *104.438* | *134.400* |
| *Log Likelihood* | *-50,359* | *-38.188* | *-52.300* | *-50.446* | *-38.257* | *-52.484* |
| *Deviance* | *100.719* | *76.375* | *104.601* | *100.892* | *76.514* | *104.969* |
| *Num. obs.* | *101* | *105* | *135* | *101* | *105* | *135* |
| | | | **Exit Models** | | | |
| (Intercept) | 8.882<br>(7.202) | -0.289<br>(7.449) | 9.757<br>(10.195) | 5.447<br>(4.039) | -0.681<br>(4.099) | 5.609<br>(5.908) |
| Battery | -0.341<br>(0.384) | -0.456<br>(0.518) | 0.954<br>(0.736) | -0.223<br>(0.233) | -0.293<br>(0.296) | 0.577<br>(0.425) |
| Smart grid | 0.491<br>(0.495) | -0.304<br>(0.518) | -0.105<br>(0.554) | 0.313<br>(0.297) | -0.136<br>(0.302) | -0.028<br>(0.323) |
| ICE | **0.895**$^{*}$<br>(0.458) | **2.179**$^{***}$<br>(0.720) | **1.581**$^{***}$<br>(0.555) | **0.552**$^{**}$<br>(0.273) | **1.238**$^{***}$<br>(0.372) | **0.938**$^{***}$<br>(0.302) |
| Diversity | -1.548<br>(1.467) | 0.857<br>(1.360) | -0.106<br>(2.207) | -0.956<br>(0.852) | 0.552<br>(0.762) | 0.042<br>(1.257) |
| All patents | -0.311<br>(0.735) | -1.128<br>(0.798) | -1.873<br>(1.168) | -0.185<br>(0.444) | -0.616<br>(0.437) | **-1.164**$^{*}$<br>(0.661) |
| *AIC* | *65.159* | *64.758* | *45.872* | *65.008* | *64.864* | *45.611* |
| *BIC* | *75.999* | *76.802* | *55.853* | *75.848* | *76.908* | *55.592* |
| *Log Likelihood* | *-26.579* | *-26.379* | *-16.936* | *-26.504* | *-26.432* | *-16.485* |
| *Deviance* | *53.159* | *52.758* | *33.872* | *53.008* | *52.864* | *33.611* |
| *Num. obs.* | *45* | *55* | *39* | *45* | *55* | *39* |

$^{***}$p <0.01; $^{**}$p <0.05; $^{*}$p <0.1

*Table 6: Logit and probit models for estimating the effect of independent variables, in period t, on entry or exit of cities in or from EV specialization in period t+1 (1980–2020). Coefficients in each period influence entry or exit in the following one. All dependent variables are log-transformed. Green color indicates significant and positive effect. Blue indicates significant and negative effect.*

The results of the entry model suggest that ICE patents have a positive effect on developing a specialization in EV, for the first two periods, while in the third period this is no longer the case. On the other hand, battery patents are not significant, while smart grid ones have a significant and negative effect in the second period. Contrary to the previous models, diversity appears to have a positive effect on developing a specialization in EVs, and this effect grows in the latest period. Interestingly, this effect appears unrelated to city size, because the overall patent output affects EV specialization negatively, especially in the last period.

For the exit models, we find that ICE patenting across periods has a positive effect on retaining an existing specialization in EV. In the last period, however, this effect decreases. This could mean that as EV innovation became more diffused and important, regions with automotive competences were finding it easier to retain it. Some form of path dependence with ICE patents could provide an advantage in EV patenting to automotive regions, but the coefficient declines in the last period, which suggests that in the future this might not be the case anymore[7].

To answer the third research question, we can say that the quantitative models support our coevolutionary hypothesis by showing that battery, smart grid, and combustion engine patents have a strong effect on EV patent scores, when they are considered within the same 10-year periods. However, when the effects of patenting in these technologies are assessed on the development of EV specializations in the following 10 years, we found no role for battery and a negative role for smart grid. Instead, we found that diversity played an increasingly relevant role in the emergence of EV technology. Besides, being specialized in ICE patents can help to develop a new EV specialization or not to lose an existing one, even though the effect is decreasing in the last period.

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[7] This result should be interpreted with caution given the small number of observations for the exit model, compared to the entry one, resulting from the limited number of EV-specialized regions.

## 5 Discussion: increased EV coevolution, but not everywhere

The analysis of technological relatedness has confirmed that battery and smart grid patents are some of the most related codes to EV technologies, while ICE and machine-related patents constantly decrease their importance. When geographical relatedness is analyzed, the network appears stable in the 40-year period under study, with low relatedness of battery and smart grid (resulting in absence from the network) and a central role of ICE and machine-related patents. Combining these two measures confirms that growing technological relatedness among battery, smart grid and EV technologies is accompanied by geographical one, but also that the spatial localization of EV patents involves growing proximity with ICE inventions, despite being less related technologically. Finally, geographic relatedness to EV patents sharply dropped for most technologies in the period 2000–2009 before growing again, which might be explained by a temporary concentration of EV patents in fewer urban areas.

In line with previous studies, these findings contribute to understanding relatedness as dynamically changing in time, and to investigate the link between technological relatedness and colocation (Juhász et al., 2021). Yet in our article we didn’t pursue a generalizable explanation of technological proximity in terms of spatial proximity, but we rather took them as two different measures of relatedness that can help interpreting coevolution between some specific technologies in the transition to EVs. Accordingly, the analysis has revealed that, amidst a general similarity in the trajectories of the two measures, relevant exceptions existed. These discrepancies can disclose relevant insights and therefore justify this comparative analysis and the refinement of relatedness measures and their application (Farinha et al., 2019).

When analyzing city groups and their specializations, we found that traditional automotive cities such as Munich, Nagoya or Detroit are highly specialized in EV and ICE patents, but not in battery and smart grid ones. Conversely, emerging cities such as Seoul, Shanghai or

Grenoble turn out as highly specialized in EV but also increasingly so in battery and smart grid while at the same time considerably reducing their ICE patent specialization. This suggests that path dependence, in this case the experience of urban inventors and firms in ICE technologies, is an important factor in producing EV patents, but only for traditional automotive cities that were already specialized in both ICE and EV patents. Indeed, the cities that have more recently acquired a specialization in EV patents, have done so while increasing or stabilizing their smart grid and battery specializations and decreasing ICE one.

This observation confirms the interest of a coevolutionary framework because it can address not only path-dependence dynamics but also *path interdependence* (MacKinnon et al., 2019). If we had only considered EV patent scores, we would have observed that the most specialized cities are traditional automotive centers. Yet we would have overlooked the sustained growth in EV patents and smart grid experimented by another group of cities, coupled with a high specialization in battery and a disengagement from ICE inventions. This dynamic, coevolutionary perspective allows us to question whether automotive firms will be capable of retaining their path-dependent leadership on EV inventions, or if firms with competences in digital technologies, electronics or other sectors will become the main innovators in EVs, relegating automakers to a role of assemblers (Alochet et al., 2022; Ferloni, 2022). The acceleration of the EV transition implies phasing out some technologies and sectors that sustain the economies of many urban regions, which can have heavy social consequences, heighten competition between territories and fuel discontent (Skjølsvold and Coenen, 2021). A multi-sectoral perspective can help address these issues by unpacking value chains and allowing to trace the relatedness potential between incumbent and emergent sectors (Andersen and Gulbrandsen, 2020).

The econometric analysis has mostly confirmed the coevolutionary hypothesis by showing an increased effect of battery and smart grid patents on EV invention, especially within each 10-year period. This suggests that battery, smart grid, and EV patents are indeed coevolving in the sense that they are increasingly found in the same urban regions at the same time. However, in the lagged models these two technologies do not appear to support the development of a new EV specialization, or the conservation of an existing one. On the other hand, ICE patents have a significant effect on EV ones: in the contemporary models, this effect grows until period 3, before decreasing in period 4. A similar trend was detected in the lagged entry model, where patenting in combustion engine is associated to an increased probability to develop a specialization in EV. In the exit model the effect of ICE patents in not losing an EV specialization is particularly evident across all time periods, albeit decreasing in the last one. Finally, the economic diversity of cities was found to have a significant positive effect in promoting EV specialization, particularly in the last period.

Overall, our coevolutionary hypothesis is supported by the fact that coevolution between emerging technologies can be clearly observed, but mostly in the same-period models. When the issue of path-dependence is addressed, the prominence of ICE technologies suggests that EV patents are still very dependent on traditional automotive capabilities. The effect of battery and smart grid sectors on developing an EV specialization could become more apparent in the future, if coevolutionary interactions among these technologies grow stronger.

## 6. Conclusion

This article has shown that a coevolutionary perspective combining a transition approach with EEG can prove useful to both research fields. EEG is greatly advancing our understanding of relatedness and its role in processes of regional diversification and smart specialization towards more complex sectors (Balland et al., 2019; Rigby et al., 2022). Economic geographers are also providing evidence on the drivers of green tech specialization and diversification (Perruchas et al., 2020; Losacker et al., 2022). These insights are fundamental to study the geography of transitions, as they illuminate the spatial interdependencies that uphold the emergence of new sectors with robust methodological tools such as measures of relatedness and complexity.

The increased attention on smart specialization and green technologies responds to the need to overcome the idea of innovation as growth engine and account for its role in addressing social and environmental imbalances. EEG, in turn, could benefit from a transition-based perspective because it allows pointing at the specific technologies and sectors that are involved into a co-evolutionary, interdependent trajectory. A transition framework provides a systemic back-ground against which the dynamic evolution of relatedness and specializations can be more meaningfully interpreted. This article hopes to contribute to furthering the engagement between both literatures (Boschma et al., 2017).

This research has several limitations. First, we have used patent data to infer coevolution at an aggregate level, but we could not trace and delimit specific interactions between groups of agents. Future research may study interdependencies of innovative actors at the micro level to confirm our findings. Second, we only addressed the phase of invention, but coevolution takes place also in production and diffusion, with feedback operating across these phases. The analysis of coevolution could be widened to other phases and account for these interactions. Finally, even though the transition to EV is underway, a full-scale replacement of conventional cars is still far. New developments — e.g., the hydrogen car, or new battery technologies — might radically change technological equilibria, which would require considering different sectors and coevolutionary relations. In times of climate urgency and uncertainty, more studies will be needed to understand coevolution across the quickly evolving sectors of energy, digital technologies, and mobility, to promote public debates and better-informed innovation policies.

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# Relatedness and colocation in Electric Vehicle production networks: a coevolutionary network approach

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## Abstract

The transition to Electric Vehicles (EVs) is underway, and it implies a radical configuration of production networks across many sectors including automotive, electric motor, battery, and smart grid production. The consequences of productive reorganization are profound, as regions need to abandon incumbent jobs and activities and create new ones in relation with EVs. It is urgent to improve our understanding of the geographic impact of this transitional process. To do so we connect a coevolutionary understanding of transitions with economic geography, because this allows to explore the extent to which urban colocation supports recombination between different sectors. Empirically, we explore inter-firm ownership networks through ownership data from 2013 to 2022, to understand if coevolution between sectors appears through increased joint ventures between firms from different sectors, and if these companies locate in the same urban regions.

## 1. Introduction

EV sales are increasing and today they represent 9% of new registrations (IEA, 2022). The automotive industry is traditionally capital-intensive and producer-driven because major car firms exert a strong power on all the value chain and influence over suppliers (Sturgeon et al., 2009). Yet today, some high value-added parts in the EV value chain are located outside automotive firms, particularly those related to batteries, electric engines, and software for autonomous drive. While in the long run, this could mean increased modularity and less centralization in the automotive industry (Ferloni, 2022), car makers are increasingly integrating battery assembly, the development of battery management systems (BMS) and electric motor manufacturing into their core competences (Alochet et al., 2022). Instead of simply relying on market exchanges, automotive firms integrate new competences by buying, participating, or developing alliances with other firms which often develop related sectors.

Policy initiatives such as the ban of fuel motors by 2035 across the European Union, or the Green Deals in both the US and the EU, signal the will of public authorities to accelerate the transition and foster EV and battery production. The global reorganization of automotive production will likely be geographically uneven, so that regions will have to cope with job losses and try to acquire new innovative competences to stay in the game (Skjølsvold and Coenen, 2021). It is therefore crucial to gain insights on the geographical drivers of EV production, and to understand to what extent competences in related sectors are important to the location of new EV production plants.

Contemporary transition towards Electric Vehicles (EVs), involves complex interactions between the automotive, electric, and battery technologies among others (Markard, 2018). Multisectoral transitions are more the norm than the exception, and scholars of transitions are increasingly considering complementarities between multiple sectors (Andersen et al., 2020). However, these approaches need to be connected to an understanding of the geography of transitions (Binz et al., 2020) because intersectoral exchanges are embedded within global innovation networks that exploit the advantages that regional agglomerations and global connectivity can provide to innovation. Following Boschma et al. (2017), we propose to combine insights from transition studies and economic geography, to understand how local agglomerations can support the recombination of knowledge and resources that is needed to innovate in EVs, and to what extent sectors become related or unrelated.

This paper investigates this dynamic by considering data on ownership networks between 2013 and 2022 to evaluate this recombination between sectors becoming more related by their financial linkages and/or by their geographic locations. In particular, we seek *to understand how multinational companies in the production of vehicles, batteries, electric motors, and smart grid equipment are becoming increasingly connected and co-located in the same urban regions*. If automakers integrate new competences by buying or developing alliances with firms in different sectors, ownership networks should mirror this increased interrelation between sectors by becoming more connected in time. Furthermore, these connections are likely to be particularly strong in some urban areas because spatial proximity is known to favor knowledge exchanges, and innovation is very concentrated geographically (Maskell and Malmberg, 1999; Balland et al., 2020). As a result, we hypothesize that multi-sectoral interactions are particularly concentrated in specific urban regions.

This article is organized as follows: in section 2 we combine the literature on transitions and economic geography, reviewing their main contribution and open questions. Then, we introduce the empirical case and the research questions. In section 3 we address the methodology. Finally, we present results in section 4 and their discussion in section 5.

## 2. Theoretical framework

The transition to EVs involves interactions among different technologies and sectors (Golembiewski et al., 2015). Transition studies are devoting growing attention to multi-sectoral dynamics (Andersen et al., 2020), but we argue that it is increasingly necessary to connect this literature to the one on the geography of transitions (Binz et al., 2020) and to economic geography, because complementarities are organized within global networks that involve a mix of spatial proximity within large urban regions, and distant networking between these regions. A coevolutionary perspective can help find common ground between these approaches to investigate the emergence of transitions in cities.

### 2.1 Transitions as a coevolutionary process: multi-sectoral dynamics in space

Transition research has usually focused on the replacement of one technology or regime with another (Rosenbloom, 2020). Some studies have expanded on this by including interactions between two regimes such as, for example, waste and electric ones (Raven, 2007), or functional foods and pharmaceutics (Papachristos et al., 2013). Only recently, however, a coherent multi-sectoral approach has emerged which has proposed enlarging the scope of analysis to include many more technological interactions (Andersen et al., 2020). These can include not only complementarities between different sectors at the same level of the value chain (*e.g.,* between electric cars, personal computers, and solar panels) but also across different value chains steps such as *e.g.,* raw material sourcing, components, R&D, sales and marketing. For example, Andersen and Guldbrandsen (2020) have studied the offshore oil sector in Norway finding that complementarities between sectors as diverse as oil, wind energy and aquaculture are rooted on the skills needed to construct and maintain offshore platforms. Mäkitie et al. (2022) studied positive and negative complementarities around the coastal shipping sector in developing alternative boat motorizations based on hydrogen, biogas, or electric power.

These studies contribute to the literature on transitions in three main ways. First, transitions studies have mostly dealt with technology adoption, but they have seldom addressed invention and production: a multi-sectoral approach enables a wider view on value chain interactions. Second, they show that relatedness and complementarities can exist between incumbent and emerging sectors. This means that transitions do not always imply radical discontinuities, which can help in the elaboration of policies to mitigate the economic and social impact of industrial restructuring. Third, even though the multi-sectoral perspective does not explicitly account for spatial interactions, it provides an entry point to unpack proximity dynamics in the context of localized networks and exchanges. The lack of a spatial dimension in these contributions can be remedied by connecting them to the literature that accounts for the spaces, places, and scales of transitions.

The literature on the geography of transitions has emerged from the need to account for the role of spatial differences in the emergence and diffusion of socio-technical change across cities, regions, and nations (Coenen et al., 2012). Empirical studies have brought evidence on place specificities, but general theory building has been lacking (Hansen and Coenen, 2015). To move beyond "topical concerns", Binz et al. (2020) have called for a better conceptualization of issues of scale, place, and space. A multi-scalar understanding of transitions has several advantages. First, similarly to the multi-sectoral approach, it brings issues of invention and production into focus, by acknowledging that the innovation networks that produce emerging technologies involve a "strategic coupling" between global assets and local specificities (Binz et al., 2014). Second, it shows that while incumbent regimes are often globally prevalent, emerging alternatives are not necessarily local, but they can also be connected across scales (Funfschilling and Binz, 2018; Sengers and Raven, 2015). Third, it centers on a relational perspective that overcomes pre-defined boundaries, to acknowledge interconnections across cities and regions. On the other hand, a geographical approach to transitions could give increased attention to multi-sectoral dynamics and engage further with the literature on economic geography, which has investigated the drivers of spatial agglomeration, innovation, and diversification.

## 2.2 The economic geography of transitions

Socio-technical transitions have important consequences for local economic development because the decline of incumbent sectors has to be matched by growth in emerging ones, to maintain employment and activities (Skjølsvod and Coenen, 2021). Yet the literature on economic geography has shown that restructuring the economic base of regions is not straightforward, as economic activities become embedded within institutional structures and social networks, which can lead to lock-in and an inability to adapt (Grabher, 1993). As a result, the key issue surrounding transitions is how *path dependence*, or the legacy or existing economic activities, relates to *path creation*, or the capability to create new connections and competences (MacKinnon et al., 2019). Not only the ever-changing nature of contemporary globalization demands the capability to continuously innovate and diversify, or "smartly specialize" local economies (McCann and Ortega-Argilés, 2013). But also, the urgency of climate change, and societal challenges such as conflicts and migrations, call for policies that might promote economic development while addressing these problems (Tödtling et al., 2022).

The main teaching of recent economic geographic research is that it is easier to renew and diversify local economies if new technologies and sectors are *related* to existing ones. Relatedness means that there is some degree of complementarity or similarity in the inputs (including knowledge, skills, capital) that are required to generate products (Hidalgo et al., 2018; Farinha et al., 2019). Contributions have shown that relatedness positively influence economic growth and makes it easier to acquire new capabilities (Whittle and Kogler, 2018). Focusing on relatedness also brings attention to the fact that path dependence should be seen as path interdependence, because co-located economic sectors coevolve together (MacKinnon et al., 2019).

Despite its success as a conceptual and policy instrument, the literature on relatedness has two limitations that this research could contribute to address. First, existing contributions have mostly portrayed relatedness as static whereas it dynamically evolves (Castaldi et al., 2015; Juhász et al., 2020). During transitions, the emergence of new socio-technical relations approaches or sets apart technologies, so that relatedness changes (Ferloni et al., 2023). The second drawback of this literature is that in considering relatedness as geographically bounded it sheds light on local capabilities, but it fails to recognize the role of external networks and connections as sources of unrelated resources (Binz and Anadon, 2018; Neffke et al., 2018). In this article we adopt a dynamic perspective that explores the evolution of relatedness between firms in different technologies. Furthermore, by analyzing inter-firm networks explicitly we show how different cities and regions are connected by similar or different activities.

### 2.3 Firm strategies and the localization of EV production networks

The transition to EVs is in full swing, and governments are assuming the support of the whole EV value chain, including battery production and raw material sourcing, as a strategic priority. The European Union, for example, has approved a Green Deal to curb CO2 emissions, which includes a ban on new combustion vehicles by 2035. This has been accompanied by measures to support EV and battery production, and mining across EU regions. There is little doubt that EVs are the future, and their increased adoption in recent years is likely to grow even further soon (IEA, 2022). This implies that the whole automotive industry will need to transform.

Globalization in the 1990s has implied the "integration of trade and disintegration of production" (Feenstra, 1998). The automotive industry made no exception to this, but it has several specific features (Sturgeon et al., 2009): automotive production is organized globally, but it is highly regionalized. Major car makers play a key role in organizing production networks that are mostly characterized by hierarchical or captive governance relations with suppliers (Gereffi et al., 2005). In fact, specifications must be tightly followed, and the low degree of modularity between different brands prevents the establishment of purely market relations. As a result, car firms maintain a tight control over vertically integrated networks that are global in reach but also region and market specific.

The literature on corporate coherence tells us that firms tend to diversify their activities along related lines of business that imply technological or market commonalities with existing production (Teece et al., 1994). In fact, technological advances such as the emergence of improved and cheaper battery chemistries for EVs, and changed market conditions, such as the preference for non-polluting vehicles, create constraints and opportunities for firms to adapt and diversify production. Changed conditions can imply that the knowledge base of industries can converge (or diverge), making it more economically feasible to diversify in related fields. In particular, the advent of EVs (and, in perspective, of autonomous cars) has shifted a significant part of the vehicle value — the battery, the battery control system and the software — outside of carmakers' traditional competences. Since automotive producers need to reduce their production of fuel vehicles (ending it altogether by 2035 in the EU), they have an incentive to redeploy existing productive assets to grab part of the value generated in these adjacent fields.

Studies have already shown that automotive firms are adapting production lines to flexibly produce EVs alongside conventional cars, and that they are internalizing the competences they lack in related fields by buying, participating, or creating joint ventures with other companies (Alochet et al., 2022). Thus, while observers have speculated that car making might turn in the future into a modular activity, where most of the value is generated outside of car assembly (Ferloni, 2022), this isn't happening for the moment. An example of vertical integration is Tesla, who concentrated most manufacturing operations on-site, producing their own electric engines and battery packs (Cooke, 2020). Other examples are the joint ventures between General Motors and LG Chem, or Toyota and Panasonic, to produce car batteries (*ibid.*). These industrial movements of alliances and acquisitions bring the focus of attention to the inter-firm ownership networks that are being established around EV production, because they are likely to be increasingly participated by firms that were not previously linked to automotive production.

The acknowledgment that automotive firms are internalizing EV-related functions brings the question of: where is this happening? Do automotive firms add battery-making or software development functions close to existing plants or they control their production through global networks? Alcácer and Delgado (2016) have shown that firms benefit not only from *external agglomeration* advantages that stem from co-locating with different firms, but also of *internal agglomeration* advantages that derive from geographical proximity with same-firm units. By co-locating units that participate to different value chain functions, firms can improve information exchange, economies of scale and scope in internal labor markets, the access to intermediate inputs, coordination, and control. It is important to know more about the role of geographical proximity in supporting the participation of automotive firms to related value chain functions because if proximity plays a role, regional policies in support of battery, smart grid, and software technologies could help retaining automotive jobs or attracting new ones.

## 2.4 Research questions

As EVs become strategic, automotive firms — that were previously disconnected from battery or electric motor production — have become increasingly involved in direct participation to these fields. Recharge systems are key to EVs, so the production of electricity distribution systems for grid control and metering are also expected to become more connected to automotive production in time, albeit to a lesser extent. Increased connectivity between different sectors should be apparent in the evolution of inter-firm ownership networks in time, which are expected to involve a growing number of ties between automotive firms, battery, and electric ones. The first question is:

**RQ 1:** *Have the networks of multinational firms in the battery, electric motor and smart grid sectors become increasingly connected to those of automotive firms?*

Increased network connections between firms in these sectors are also expected to be reflected in increased geographical proximity. To verify, we aggregated networks based on the urban regions where firms are located, and we ask:

**RQ 2:** *Does the production of automotive, battery, electric motor, and smart grid increasingly concentrate in the same cities?*

The main hypothesis is that automotive firms are increasingly co-located with firms in these coevolving sectors. However, not all locations where automotive activities take place are producing EVs. Thus, we investigate if the locations where EVs are produced are involved in this colocation dynamic more than those where conventional cars are produced. By answering these questions, we can assess if there is a tendency of growing colocation of production sectors that are related to EVs in the same cities, which could suggest that coevolutionary interactions are one of the reasons for it.

## 3. Data and Methods

In this paper we use a network methodology to account for inter-firm relations through ownership networks. The network of ownership links is the main scaffold through which we interpret relations between different technologies and cities. Here we describe the data we use, and the methodological choices we take.

### 3.1 The ORBIS database: multinational firms in Large Urban Regions

To analyze and represent the network of inter-firm relations we used the ORBIS database from Bureau van Dijk (BvD; 2010, 2013, 2016, 2019, 2022). The extraction from ORBIS includes detailed information about the top 3,000 multinational companies in the world by turnover, along with their direct and indirect subsidiaries. Links in the ORBIS database represent ownership relations which can involve different degrees of ownership. In some cases, the owned firm can be the branch of a mother company, while in other cases ownership can mean simple financial participation which can amount to as little as 5%. Firms can also have ties of reciprocal ownership, which can respond to a logic of diversifying investments even by participating to the ownership of competitors. The information about ownership creates a relational structure in which the connection between two firms shows the links between two (or more) technologies and between cities. Besides, each firm is located at its headquarters (primary establishment), but can also have secondary establishments belonging to the same legal entity inside the same country. In this case, we also considered the links between primary and secondary establishments as a total ownership linkage. It should be noted that data on secondary establishments became available starting from 2016. The data for the year 2013 do not include secondary establishments and this should be remembered when interpreting results.

All firms are attributed to a LUR or Large Urban Region following the database and methodology developed by Rozenblat (2020). LURs are defined globally on the concept of mega-city region (Hall and Pain, 2009) which reflects the idea that economic activities do not match administrative urban boundaries, but they form larger regional systems around major agglomerations. LURs represent the gateway to global flows, so their geographical centers are the main international airports of each region. ORBIS information was attributed to LURs with a long process of cleaning and correction of addresses, so it is possible to know how different large urban regions are connected through the activities of the firms that are located there.

### 3.2 NACE classifications and key firms

Each company is described by the different activities they develop by NACE 4-digit codes. The acronym NACE stands for the European classification of economic activities, which is comparable globally through correspondence with ISIC codes (maintained by the United Nations). The classification of economic activities is hierarchical, so narrower categories are contained in larger groups, which requires a choice of the level at which to consider codes. Second, even precise codes do not fully correspond to the technologies that we investigate in this paper. Based on desk research, we identified these technologies at the 4-digit level (the most precise), by selecting the four following codes (Eurostat, 2008):

- Code 2910: "Manufacture of motor vehicles"
- Code 2720: "Manufacture of batteries and accumulators"
- Code 2711: "Manufacture of electric motors, generators and transformers"
- Code 2712: "Manufacture of electricity distribution and control apparatus"

EVs are not included in a specific code but within the category of "Manufacture of motor vehicles". In this study we also consider two-digit codes, that correspond to the 88 main NACE divisions and relate to aggregate categories, to consider also all the other activities. For example, the four codes identified above relate to the two-digit codes 29 (manufacture of motor vehicles, trailers and semi-trailers) and 27 (manufacture of electrical equipment). Beyond these, other codes could be relevant to our argument for example those related to trade (45: wholesale and retail trade and repair of motor vehicles and motorcycles), those related to information technologies (26: manufacture of computers, electronic and optical products) or those related to finance, legal, or R&D activities (64: Financial service activities, except insurance and pension funding; 72: Scientific research and development). The linkages between the four main codes and other fields of activity can disclose relevant information about the embeddedness of these sectors into wider sets of relations[1].

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[1] When selecting companies based on these four codes, we performed a search in the ORBIS fields "primary NACE" and "secondary NACE". Since the database can attribute more than one NACE to a firm, companies can participate to many technologies. For two-digit NACE, however, only primary NACE were used, so firms were univocally tagged with a code. This created sometimes conflicts between the primary two-digit categorization (e.g. automotive) and the four digit one (e.g. electricity distribution). Cases of multiple categorization were solved

Besides selecting companies based on technology codes, we identify several key companies that are leader in automotive in general (including EV), in EV only, and in manufacturing batteries, electric motors, and smart grid devices. These firms are the global leaders in these sectors, and they are the head of very extensive networks of subsidiaries all over the world. It is important to identify them and to understand their role in connecting different sectors and geographical locations together.

*Table 1 — Key companies producing automotive, EV, battery, electric motor, and smart grid technologies*

| | **Automotive** | **EV only** | **Battery** | **Electric motors** | **Smart grid** |
|---|---|---|---|---|---|
| 1 | Toyota | Tesla | CATL | Siemens | Itron inc. |
| 2 | Volkswagen | BYD | LG Chem | Toshiba | Ibm |
| 3 | Hyundai | NIO | Panasonic | Abb inc | Cisco Systems inc. |
| 4 | GM | Rivian | SK Innovation | Nidec corp. | Enphase Energy, inc. |
| 5 | Ford | | Samsung | Rockwell Automation | Schneider Electric |
| 6 | Nissan | | EVE Energy | Ametek inc. | Alstom Grid |
| 7 | Honda | | | Regal Beloit | General Electric |
| 8 | FCA | | | Johnson Electric | Landis + Gyr |
| 9 | Renault | | | Franklin Electric | Aclara Technologies |
| 10 | PSA | | | Allied Motion | Eaton corp. |
| 11 | Suzuki | | | Danahaer | Hitachi |
| 12 | Daimler | | | Emerson Electric | |

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by prioritizing two-digit NACE codes, except for key firms (table 1) where we chose the category that we considered – based on secondary sources – as closer to the core activity of the firm.

| | |
|---|---|
| 13 | BMW |

### 3.3 Methodological choices and procedure

Inter-firm ownership networks are very large, and we had to find a way delimit the relations that constituted our key concern. As a first step, we explored the evolution of technological relations between the couples of two-digit NACE codes formed by all interfirm links. Based on this general overview, we selected the codes that were most related to automotive: in other words, we selected the two-digit codes that were mostly present in ownership links that included automotive. Based on this we selected 15 codes that were most related to automotive.

As a second step, we constructed the interfirm ownership network, our main relational structure, by selecting from all companies those that are tagged with one of our four technology codes, plus the key firms in table 1. Then, we separated ownership links by four different years (2013, 2016, 2019, 2022) and we extracted the ego-networks for these companies and for each year. Ego-networks contain the connections of a given node, and the links between them (Wasserman and Faust, 1994). In this case, ego-networks contain all owners — or owned — entities of a given firm, plus the links (owner-subsidiaries) between them. To further filter these networks, we selected only firms that were categorized in one of the 15 codes identified above plus automotive. The advantage of constructing ego-networks is that it permits to clearly delimit the focus of our network (firms that participate of our technology fields) while maintaining an overview on firms that are connected to them but do not necessarily participate of the same codes/sectors. It resulted in a selection of:

- 9,600 companies linked by 19,600 ownership linkages in 2013
- 26,300 companies linked by 37,400 ownership linkages in 2016
- 43,800 companies linked by 64,200 ownership linkages in 2019
- 59,900 companies linked by 71,350 ownership linkages in 2022

To represent the ego-networks, we simplified them by removing firms with degree 1, that are connected only to one other firm, and we iterated the process removing the isolated firms that can appear in the process. Then, we constructed a geographic network where each node represents a location, to understand which cities have a strategic position within inter-firm exchanges. These networks represent inter-LUR linkages, and we also analyzed their complements, that are the intra-LUR linkages. We can thus compare intra and inter-LUR linkages, analyzing how the relatedness varies in time between sectors and to what extent intra-LUR networks differ from inter-LUR ones.

## 4. Results

The empirical results focus first on the relatedness between activities by the frequency of their ownership linkages (4.1 to 4.3). According to these relatedness intensities, we explore their uneven distribution between cities of the world and inside them.

### 4.1 Technological classifications

We begin by analyzing the evolution of technological relatedness between automotive and other technologies. By doing so, we provide a general snapshot from which we can identify the most related technologies to automotive, to guide the exploration of ownership networks. Thus, we proceed by considering all NACE codes at the 2-digit level: two codes are connected when they share an ownership links. We construct a square matrix to show these linkages, and we take away the diagonal because links between the same codes are expected, and they would constitute an unnecessary noise. Owners are shown in lines and subsidiaries in columns: in other words, rows indicate which activities are held by firms that are categorized in a specific code. Columns indicate the activity to which the owners of a specific code are categorized.

It should be noted that NACE categories are very different in terms of average number of owners and owned firms. For example, firms in the finance and wholesale categories have many more ties than firms in other categories. Thus, we had to find a way to relativize these values, and we did so by scaling values by row (by owner). This means that for each line, darker squares represent activities that are most related to owners in that category. While we could also have relativized data by owned firms, we chose to focus on owners to highlight their active role in the constitution of new linkages between activities.

Figure 1 shows the differences in technological relatedness between two-digit NACE codes from 2013 to 2022. The highlighted columns feature very dense connections between most categories and codes related to wholesale trade, finance, and management. This means that the trade, finance and management sectors represent a significant share of the firms owned by many other categories. This makes sense, because most categories need to relate with these sectors to sell their products and manage their assets.

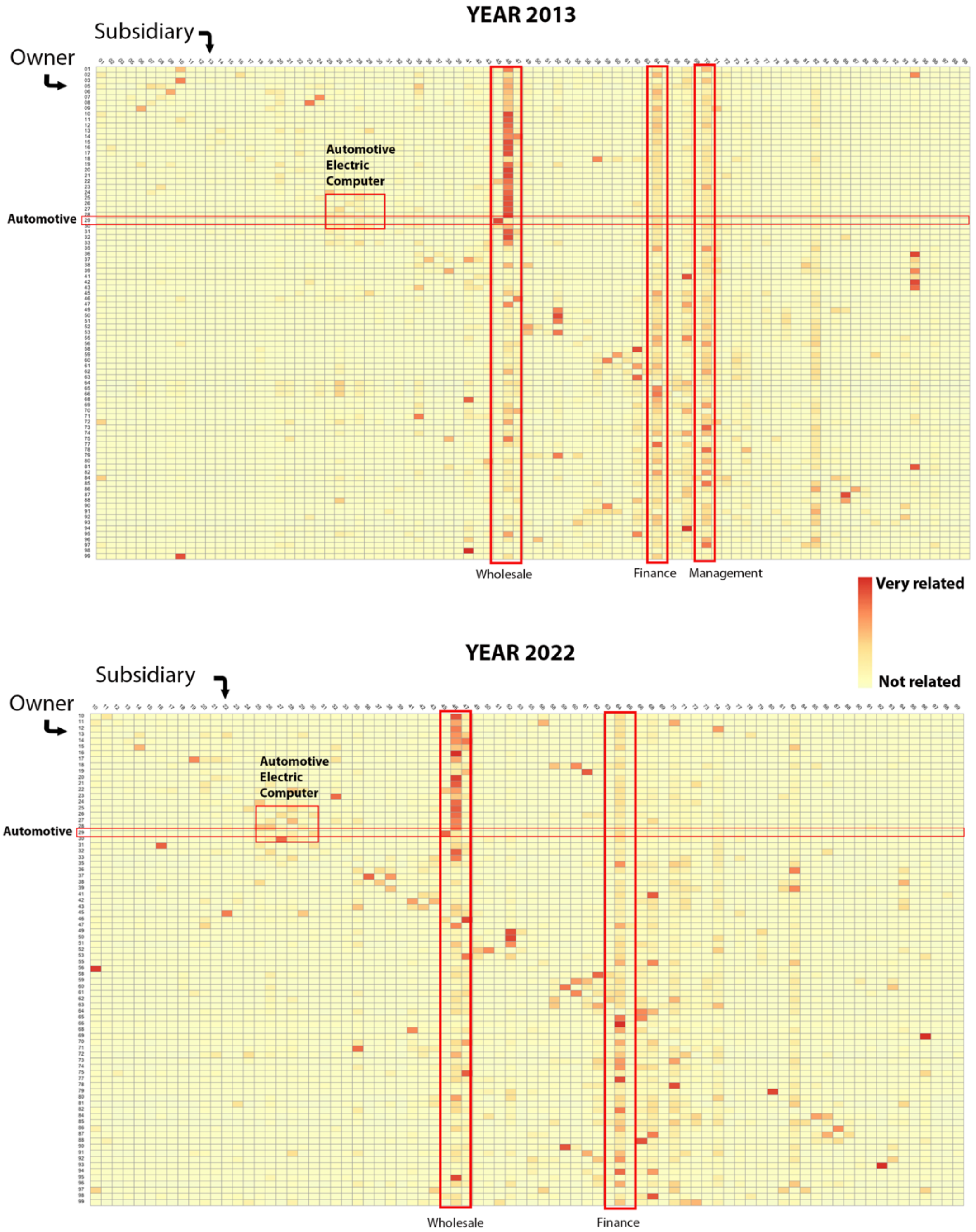

*Figure 1: The most connected NACE activities by ownership linkages in 2013 and 2022 (% per activity owners (rows)*

The highlighted rectangles at the top left delimit some sectors that appear as increasingly related with each other, and these include automotive owners (the highlighted row). These rectangles include connections between the codes 25 through 30, which comprise the categories of fabricated metal (25), computer (26), electrical (27) machineries (28), automotive (29) and other transport (30). The matrix shows that links between these codes become stronger from 2013 to 2022, and it provides a general overview of relatedness dynamics between all NACE codes.

### 4.2 Most related categories to automotive

Based on this general overview of technological relatedness, we refine the analysis by zooming on the specific codes that are most related to automotive. We consider all technologies for which an ownership link exists with automotive, and we measure what is the share of other activities in the portfolio of automotive companies (Fig. 2), and to what categories belong the firms that have shares in automotive companies (Fig. 3). We color codes by attributing them to some general categories — from inputs to R&D — for the sake of clarity.

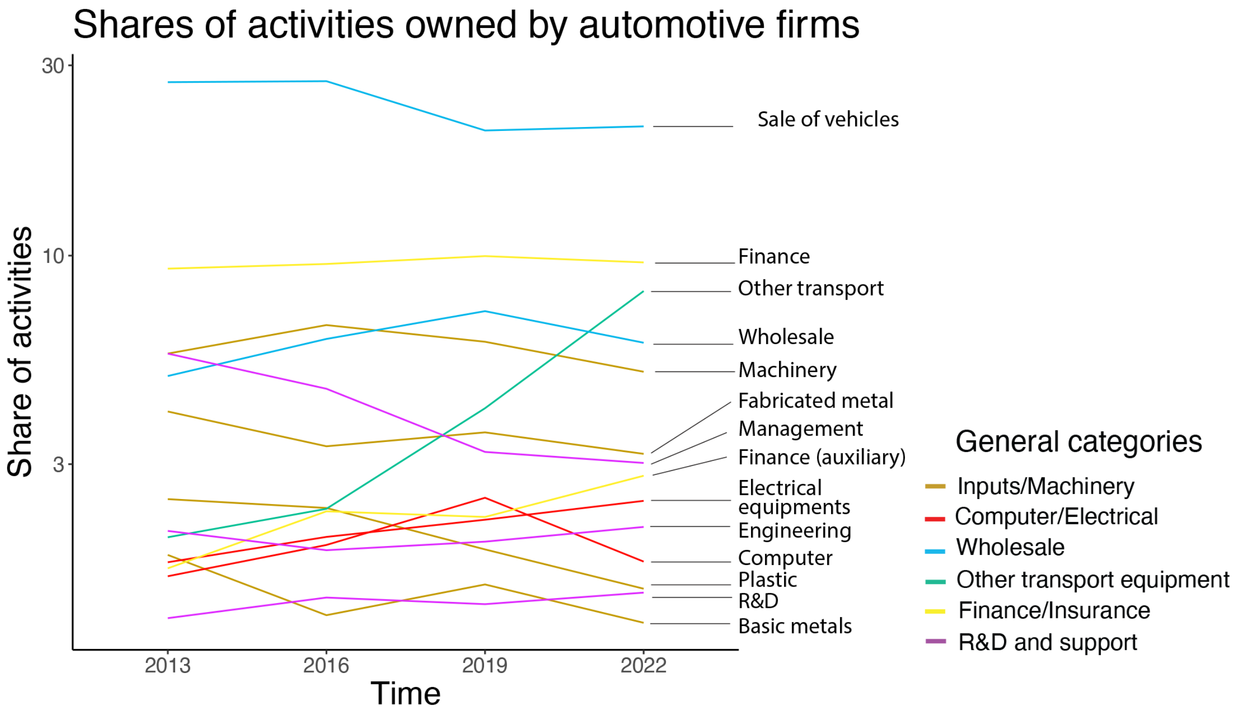

*Figure 2: Shares of NACE activities in the firms owned by automotive firms (percentage in automotive ownership)*

These figures suggest that, between 2013 and 2022, the automotive sector became more related with other transport technologies, sales, and inputs such as plastic, metal, and machinery. They also show that computer and electrical equipment became more related to automotive: Figure 2 shows a moderate increase in the percentage of electric firms owned by automotive companies, while Figure 3 shows a stronger trend in that computer and electric firms increasingly participate to automotive ownership. On the other hand, categories such as R&D, management and engineering remained stable, while the sector of finance and insurance strongly disinvested from automotive activities (Fig. 3).

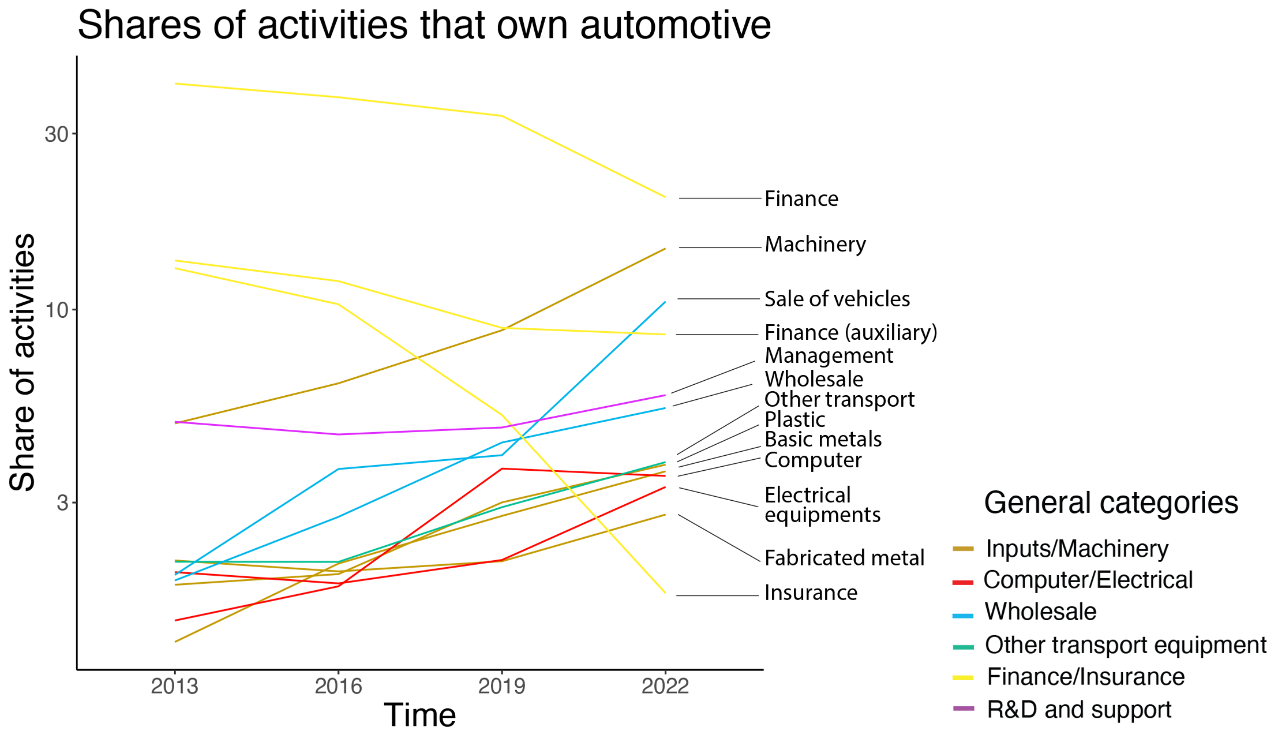

*Figure 3: Shares of NACE activities in the firms that own automotive companies (percentage in the owners of automotive)*

These observations serve to delimit more precisely the field around which coevolution between automotive and other technologies could be taking place. Accordingly, the most related codes to automotive (Tab.2) permitted the selection of activity sectors for which we delimited ego-networks and analyzed their evolution.

*Table 2: Fifteen most related codes to automotive (NACE code 29).*

| **NACE codes** | | |
|---|---|---|
| Code | Description | General category |
| 22 | Manufacture of rubber and plastic products | Inputs |
| 24 | Manufacture of basic metals | Inputs |
| 25 | Manufacture of fabricated metal products, except machinery and equipment | Inputs |
| 26 | Manufacture of computer, electronic and optical products | Computer and electric |
| 27 | Manufacture of electrical equipment | Computer and electric |
| 28 | Manufacture of machinery and equipment not elsewhere classified | Inputs |
| 30 | Manufacture of other transport equipment | Other transport |
| 45 | Wholesale and retail trade and repair of motor vehicles and motorcycles | Sales in general |
| 46 | Wholesale trade, except of motor vehicles and motorcycles | Sales in general |
| 64 | Financial service activities, except insurance and pension funding | Finance and insurance |
| 65 | Insurance, reinsurance and pension funding, except compulsory social security | Finance and insurance |
| 66 | Activities auxiliary to financial services and insurance activities | Finance and insurance |

| | | |
|---|---|---|
| 70 | Activities of head offices; management consultancy activities | R&D and support |
| 71 | Architectural and engineering activities; technical testing and analysis | R&D and support |
| 72 | Scientific research and development | R&D and support |

## 4.3 The inter-firm ownership network around automotive and electric production

The analysis of the inter-firm ownership networks provides a general overview that suggests that several changes occurred in the period from 2013 to 2022. Figure 4 shows the network of ownership linkages, which was filtered by removing isolated firms with only one connection. Labeled firms are the key actors in the network, as identified in table 1. The evolution of the network from 2013 to 2022 shows that:

- Financial firms, drawn in yellow, had a very prominent position in 2013, where many global firms such as Blackrock or JP Morgan had a high degree of connectivity within the network. In 2022, financial firms are no longer central, and they are barely visible.
- Automotive firms decreased their linkages whereas other technologies increased their connectivity such as smart grid firms (blue nodes).
- EV-only producers such as TESLA, BYD, NIO, and Rivian, which were absent in 2013 are present in 2022, but they are not very connected to other parts of the network.
- Smart grid firms became much more present and also firms related to computer and electric sectors (in red) increased in number.

After showing the general structure of the inter-firm ownership network, we can analyze more in detail the evolution of the ego-network of some representative firms and explore the geographical emergence of these networks.

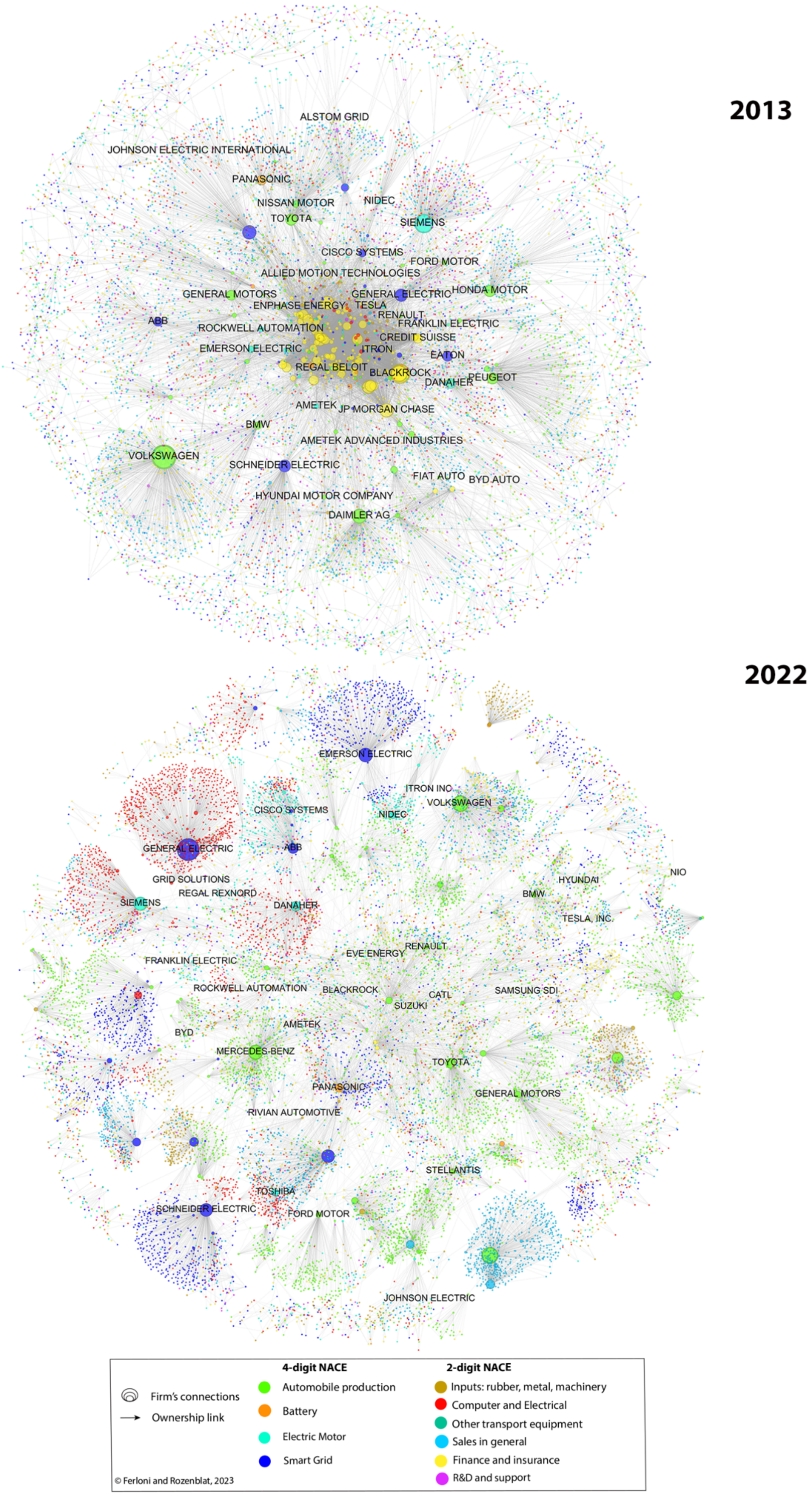

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*Figure 4: The interfirm ownership networks in 2013 and 2022*

### 4.4 Ego-network comparison

To better understand the evolution of the whole network, we can take the example of two very different companies: Tesla and Toyota. These two companies are very representative because Tesla is the leading all-EV car maker, and Toyota is, together with VW, the leading manufacturer of conventional cars in the world. By comparing their ego-networks we can explore more in detail how interfirm ownership network are organized, and how different technologies became connected to automotive. Figure 5 represents the evolution of the ego-networks of the firms Tesla and Toyota, from 2013 to 2022.

We can observe that in 2013 Tesla was connected to Daimler, a major conventional car producer, and to Panasonic, a battery maker. However, these connections were abandoned in 2022, and Tesla became connected to several companies operating in the renewable energy sector, including Solarcity, Silevo and Iliosson. Furthermore, Tesla connected to Siilion, a battery startup, and to Maxwell Technologies, a smart grid company and battery producer. The network of Tesla became less dependent on financial connections and possibly more self-sufficient with respect to batteries, by producing their own supply, and turning towards the sector of renewable energies (Cooke, 2020).

The network of Toyota, on the other hand, also displays a decrease in the importance of financial firms, which can be related to the overall disengagement of financial firms from the automotive sector, observed in fig. 3 and in the interfirm network in fig. 4. Since 2013, it is clear that the network of Toyota is more complex and articulated that the one of Tesla, involving — besides the connections with financial companies — links with many different companies including a large network of retailers (light blue), and providers of inputs and services (brown and purple). In 2013, Toyota is connected to Toyota Turbine and Systems, operating in the electric motor category, and to GS Yuasa Corporation, producing batteries. In 2022 Toyota is connected to two more battery producers (Sinogy Toyota, and Panasonic).

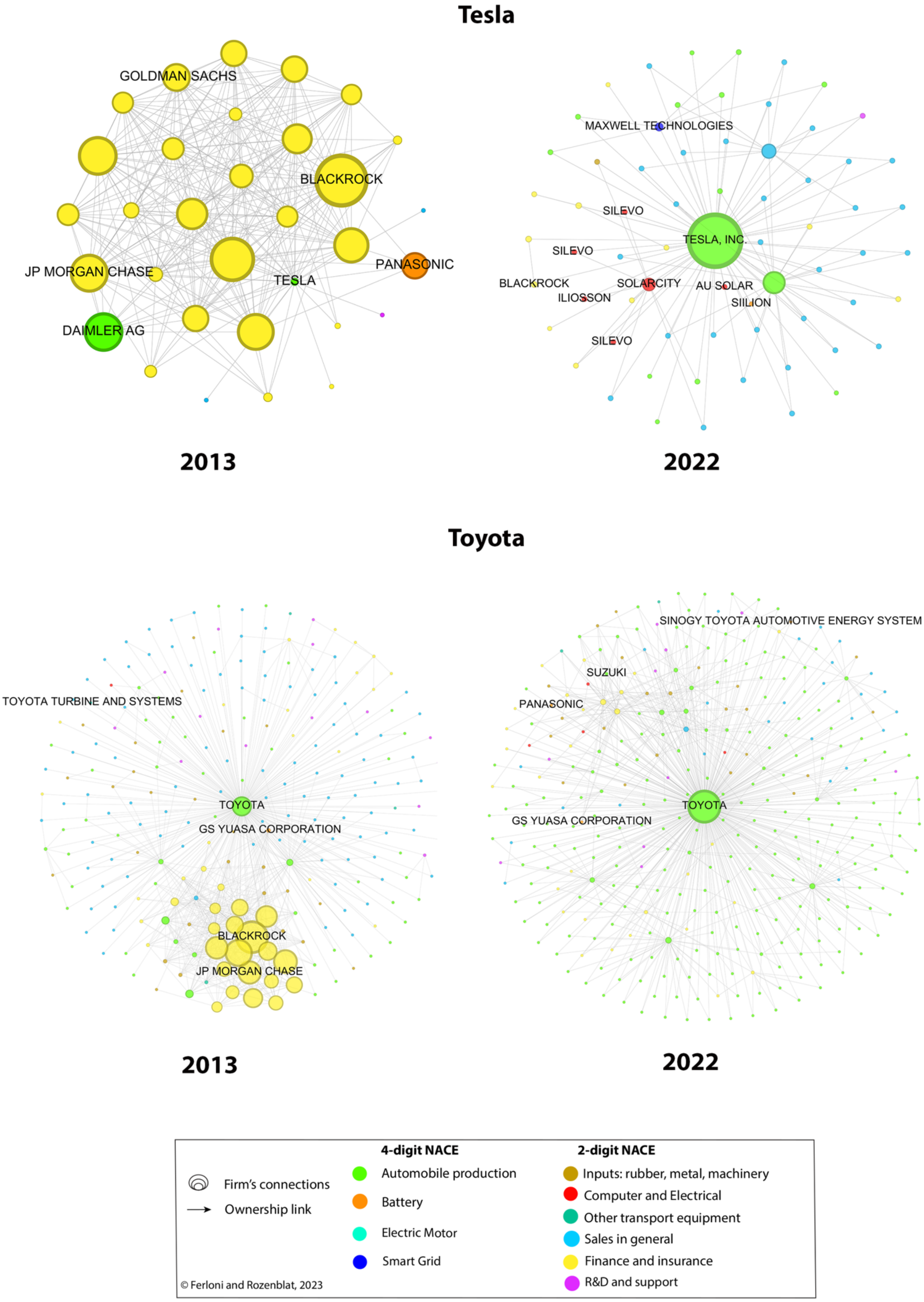


*Figure 5: The ego-networks of Tesla and Toyota in 2013 and 2022*

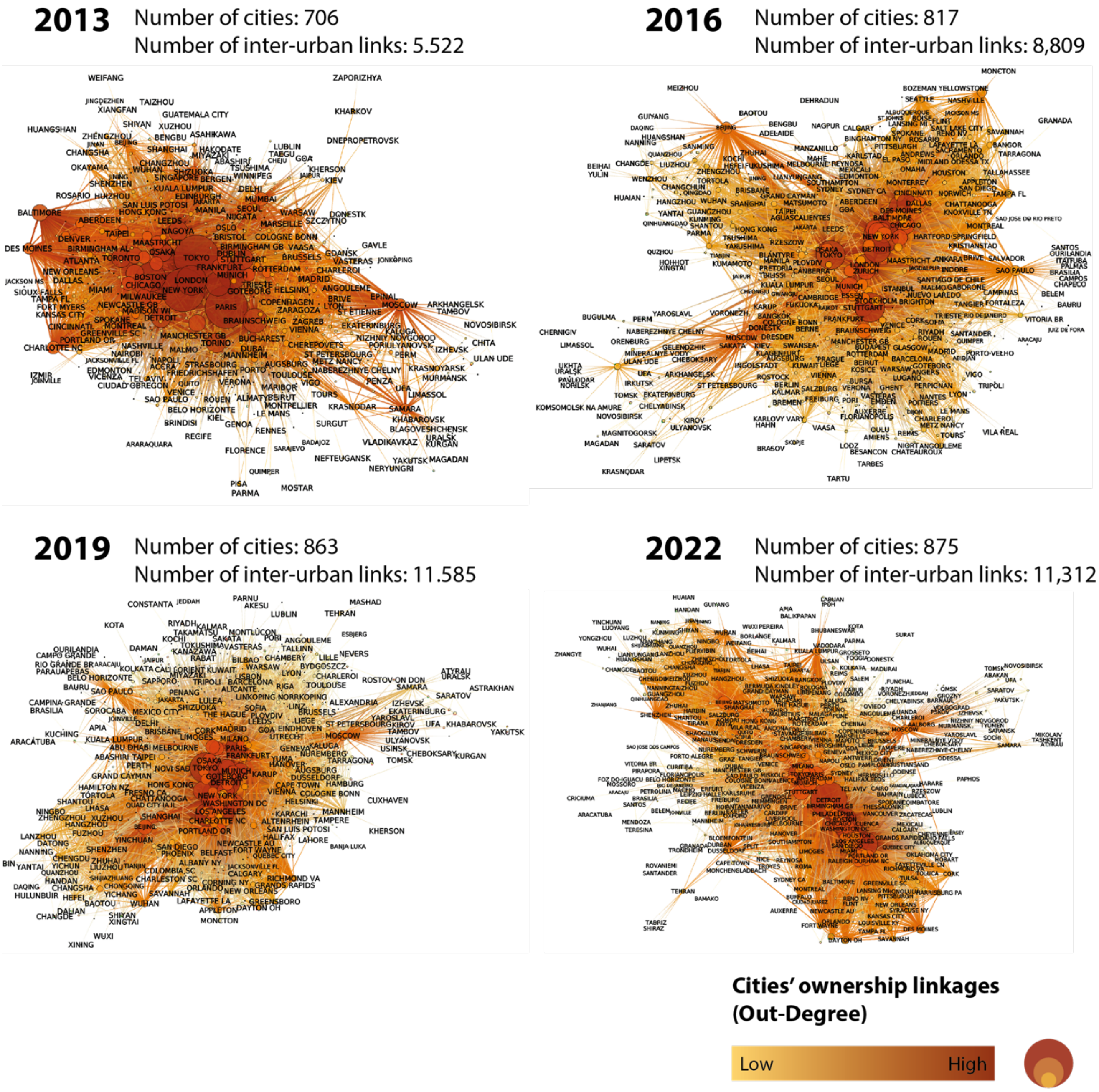
The comparison of different ego-networks allows to explore more in detail how coevolution between different sectors might be taking place. A further step in the analysis of ownership networks is to make sense of their geographical location, to understand the role played by geographical proximity in promoting technological recombination.

## 4.5 The inter-urban configuration of inter-firm networks and coevolution

In this paper we hypothesize that as the EV transition unfolds, it is increasingly likely that automotive firms become connected through ownership links to firms that operate in the battery, electric motor, and smart grid domains. We explored first the worldwide network of cities that these sectors represent all together by their ownership linkages. We summed up the linkages between two cities to obtain the inter-urban linkages for the four years (Fig.6).

While the total of companies in time grew exponentially except in the last period (9,600, 43,800 in 2019), the increase of the number of cities has slowed down over time until decreasing in the last period. This means a higher concentration in some main cities.

Regarding the major cities, Tokyo, New York, Paris, London and Boston dominated in 2013 regarding their ownership power in the network. In 2022, it changed a lot because of Detroit, Los Angeles, and Atlanta surpassing Tokyo, which is now the fourth city, followed by Boston. The rise of Detroit is mainly due to Ford and General Motors who caught up the integration of electric companies inside the automotive production only the last years, strongly supported by the US Federal government. Besides, the company with the highest power in 2022 (owning the highest number of firms) is the Genuine Parts Company, with its headquarters in Atlanta. Toyota motors (based in Los Angeles), Ford and General Motors (in Detroit) follow.



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Source: Orbis BvD, CITADYNE -UNIL, 2023

*Figure 6: Networks of cities according to their ownership links between all technologies most related to automotive (2013–2022)*

### 4.6 The intra-urban configuration of interfirm networks and coevolution

Beside the inter-urban linkages, the intra-urban ones reveal better the concentration of activities in the same cities and the interrelations that are consolidated locally by mutual ownership linkages. We want to verify to what extent geographical proximity between these technologies can play a role by enabling knowledge exchanges and networking. To get insights on this dynamic we turn to the contributions on urban scaling, which suggest that as the size of cities increase, their capability to support innovation increases more than linearly (Bettencourt et al., 2007). Applied to our case, we want to know if the cities that host many ties between automotive and electric technologies also display many intra-urban connections between owner and owned companies, which could suggest local coevolution.

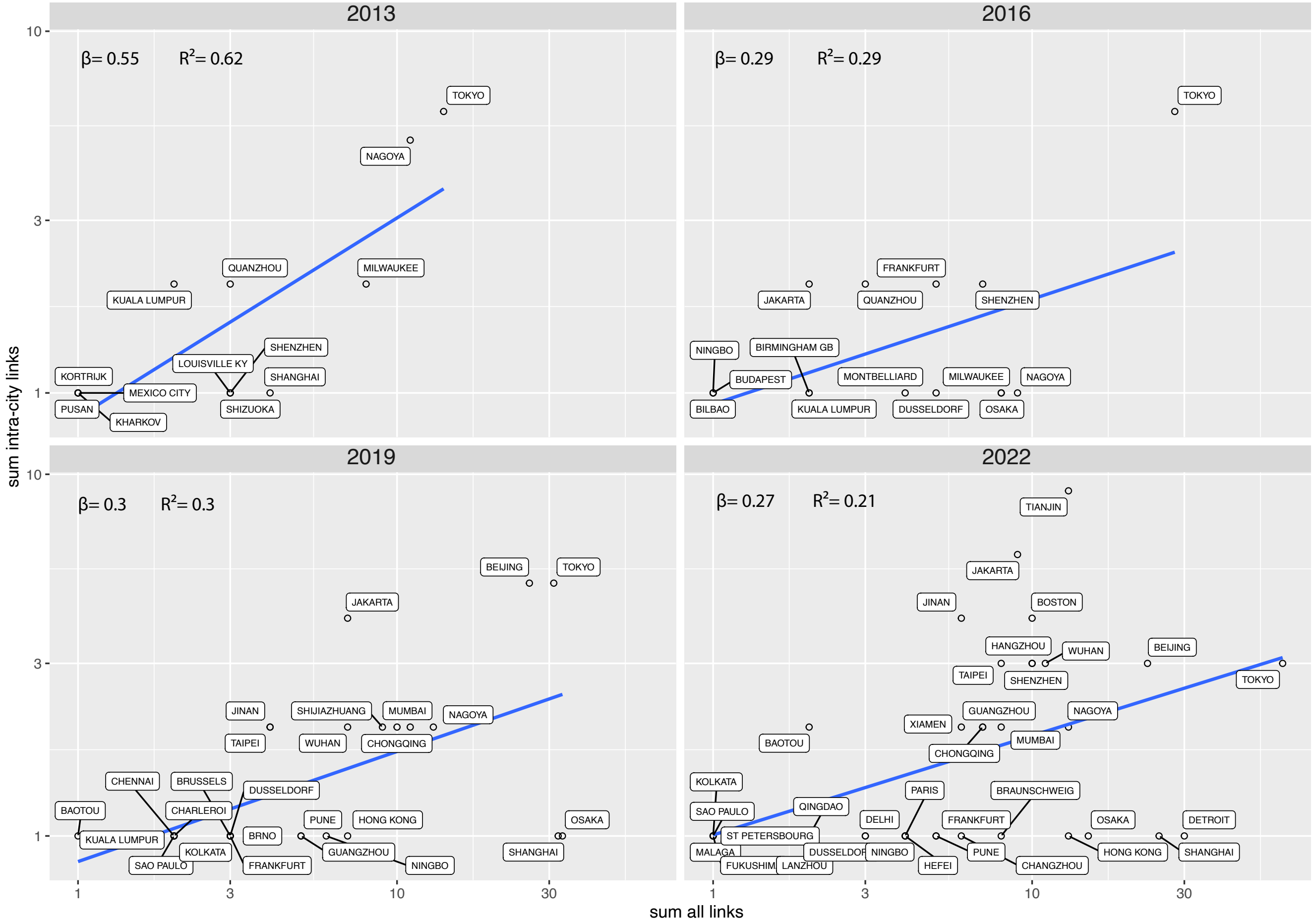

*Figure 7: Evolution of cities according to their ownership links between electric and automotive technologies (2013–2022). Intercity and intra-city links (X-axis), against intra-city only (Y-axis). Cities with values 0 for either X or Y have been filtered out.*

We proceed by selecting all connections between automotive and electric codes (two-digit NACE codes 29 and 27 respectively), and we attribute a score of 1 to every connection linking the two activities inside a city or between two cities. Then, we count how many of these links happen within the same city (intra-urban) or across cities (inter-urban). In Figure 7, we plot the total number of linkages on the X axis against the number of intra-urban linkages only (on Y), and we do so for the four years for which we have data.

Results show that the slope of the scaling generally decreased on time (from 0.55 to 0.27). It means that while the intra-urban linkages were very high compared to the total linkages in the first period revealing high economies of agglomeration, this effect decrease with the development of the process.

Cities change their relative position in time, in particular it seems that the high concentration of intra-urban linkages accompanies the general growth of the participation of the city to this connection between automobile and electric activities. For example, intra-urban linkages in Tokyo appear to grow more than linearly in the first three periods, but in the last one intra-urban linkages of the city reduce to the average proportion close to the regression line. More generally, results show that in many Asian cities intra-urban linkages are particularly high with respect to their overall linkages. We use these findings to select cities where intra-urban linkages are very high and compare them to those where they are low.

In figure 8 we compare the ownership linkages in the cities of Detroit and Tianjin which score respectively very low and high on intra-urban linkages between electric sector and automotive. We can see that Detroit features many companies from the automotive sector, some of which are major multinationals (Ford, General Motors, FCA). They are linked mostly to other automotive firms, and while Detroit hosts battery, smart grid and electric motor firms, and firms in the electric and computer sectors, they do not appear central in comparison with large automotive firms that grab a large share of linkages. On the contrary, Tianjin features a much more diverse sectoral distribution, with companies related to electric motors, battery and smart grid sectors.

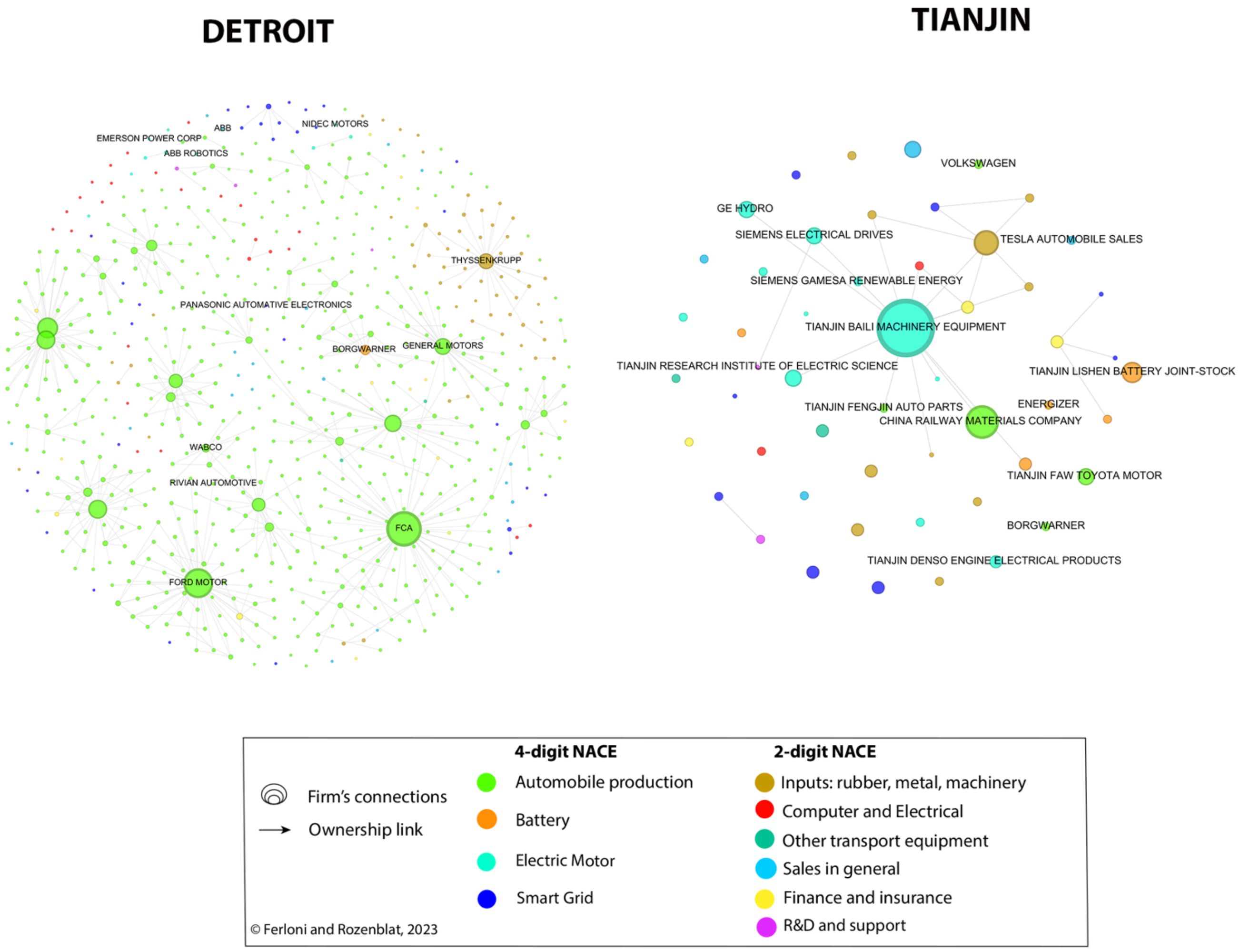

*Figure 8: Ownership linkages in Detroit and Tianjin for the year 2022*

## 5. Discussion

We set out to verify if the automotive sector is involved in a coevolutionary dynamic with battery, electric motor, and smart grid production, and to what extent coevolution is apparent in colocation. The evolution of technological classifications has shown that the computer and electrical categories are increasingly connected to automotive through ownership ties, answering to RQ1. The exploration of ownership networks has also shown that automotive firms appear increasingly connected to smart grid and electric firms, while financial companies are less prominent. Comparing the ego-networks of an EV producer (Tesla) and a conventional automotive firm (Toyota), reveals — saving the obvious difference in manufacturing size — that the former oriented their activities much more clearly towards the battery and electric sector, particularly by engaging in the sector of renewable energies. On the other hand, the network of Toyota remains anchored mostly to automotive firms. This first exploration provides some support to our hypothesis that EV development requires coevolution, reflected in increased network connections between firms from different sectors.

The evolutions of the micro-level of firms' networks and the macro-level of cities reveal a quite classical process of diffusion of innovations (Pumain, 2004, 2018). First, the growth of firms is high, but their geographic selection is strong leading to a concentration of firms in the largest cities that are very diversified. In a second stage, the number of firms continues to grow, and it diffuses to other cities. In a third stage the number of cities decreases, and firms concentrate in more specialized cities, answering to RQ2. The proportion of intra-urban linkages also seems to follow this cycle by being higher in the first periods when the process of production necessitates numerous tacit information, and then decrease as the production becomes more generic.

In terms of activities, we demonstrated the important role of the financial sector in the first periods for implementing the prototypes of production, but this role decreased over time as the production becomes generic. Rather, sectors related to electric motors, battery and smart grid sectors are more and more present around the automotive industry, confirming the co-evolutionary process that we hypothesize in this article. New cities entering in the production like Tianjin specifically demonstrate this tendency by displaying a higher proportion of intra-city linkages between the electric and automotive sectors, and much higher diversity than traditional motor cities like Detroit, still very dominated by automotive companies. Automotive cities like Detroit have been found to retain innovative capabilities in studies that have analyzed patent output (Hanigan et al., 2015). Yet this might not be enough to reverse a long-lasting decline of manufacturing capabilities, as in the case of Detroit, and attract growth in sectors related to the EV transition.

The limit of the approach presented in this paper is that the NACE activity classification is not fully appropriate to study Electric Vehicle production, but we tried to approach this category by all the closest activities. In future steps, we will be able to classify cities according to their trajectories of the activity sectors profiles of their intra-urban linkages to EV. It will help to better clarify their respective stage in the process cycle of the new production of electric vehicles and understand how the inter-urban competition evolved during this diffusion.

## 6. Conclusion

This paper has studied inter-firm ownership networks to understand if increased technological interdependencies between firms producing automotive, battery, electric motors and smart grid systems translated into increased network interconnections. We have found that indeed there is evidence of increased relatedness between the automotive, electric and computer production categories. In particular, while the role of financial firms was prominent in the first periods of time, they have partly reduced their influence and automotive companies have diversified their connections to include links with battery making and the electric sector in general.

Our explorations on coevolution and the geography of EV-related production permitted to demonstrate the increase of the co-presence of automobile industry with other related sectors like electricity and smart grid and the decrease of the concentration of these activities in some cities over the 9 studied years, following stages of diffusion. However, depending on whether they had some previous specialization in automotive or not, cities take advantage of different profiles of activities that are more or less diversified, and with the proportion of intra-urban linkages decreasing with time. It highlights that these intersectoral collaborations are more and more scaled up in global networks than local ones as the EV production becomes more common. This suggests that the emergence of intra-city and inter-city linkages between different sectors might be crucial to enable knowledge diffusion when new complementarities must be created between novel technological solutions. The depth of the changes that will be induced by the EV transition call for an improved understanding of how multiple industrial paths interact and recombine locally, to devise appropriate policies and accompany the changes that will ensue (Chlebna et al., 2022). This article provided a step in this direction.

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