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Types of Policies for the Joint Diffusion of Electric Vehicles with Renewable Energies and Their Use Worldwide

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Abstract: A large reduction in greenhouse gas (GHG) emissions will be needed in the coming decades to keep global warming well below 2 °C. Together, energy and transport sectors are responsible for around $\frac{3}{4}$ of carbon dioxide (CO_2) emissions worldwide. The transition to a low-carbon economy involves an increase in the share of renewable energies in power grid and the electrification of the transports thus demanding policies focused on the joint diffusion of the two technologies This study adopted a hybrid methodology to examine several types of policies and their implications in the use and diffusion of the electric vehicles charged with renewables. We argue that it is not enough to have policies to expand electric mobility with renewable sources. The results reveal that production and technology represent $^1/_3$ of electric vehicles and renewables policies. Broad coverage of policies does not translate into market gains since 20% of the countries that encourage electric vehicles have a low market share. Policies need to be broad, consistent, reach more countries and promote synergies between renewables and electric mobility to provide the conjoint diffusion of both technologies and allow the CO_2 emission mitigation targets for 2030 to be achieved. This study contributes to research on sustainable policies and innovations to decarbonizing the energy and transport sectors.

Keywords: policy; sustainability transition; renewable energy; electric vehicle; power system

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1. Introduction

Carbon dioxide (CO_2) and other greenhouse gases (GHG) emissions present one of the world's most pressing challenges to keep global warming well below 2 °C and avoid dangerous climate change effects. For the first time, since accurate measurements began 63 years ago, a monthly average peak level of 419 parts per million (ppm)—an increase around of 30% in the period—was registered in May 2021 [1]. The energy and transport sectors are responsible for nearly $\frac{3}{4}$ of CO_2 emissions worldwide, and only 3.4% of transport is powered by renewable energy (3.1% biofuels and 0.3% renewable electricity) [2].

Therefore, planning and formulating policies to decarbonize transports have become crucial, namely by promoting the diffusion of electric vehicles (EVs) [3]. Policies to promote the diffusion of EVs have been justified by the need to achieve decarbonization targets, but also by their positive effects on the reduction in air and noise pollution, and oil dependency [4–7]. These become particularly pressing in the face of events with unpredictable results and threatening energy security, such as the current armed conflict in Eastern Europe and pandemics (e.g., COVID-19). Accordingly, countries around the world have been using several instruments to promote the adoption of EVs [8,9]. In 2021, nearly 10% of global car sales were electric, four times the market share in 2019 [10]. However, the pace of the diffusion of EV technologies needs to be further accelerated to comply with the Paris Agreement targets. Moreover, the environmental benefits associated with the increased penetration of EVs can only be realized if the electricity used to charge the vehicles is being generated from renewable energy sources (RES) [11].

The concept of socio-technical systems suggests that technologies, such as RES and EVs, should be understood in their social context in which the different values expressed by different stakeholders shape technological innovation and its applicability in their own way [12]. Policymakers, aware of the synergistic potential of technologies, have sought to promote the integration of RES in the electrical network, the adoption of EVs, and the inherent peripheral technologies, such as renewable-based microgrids [12], smart homes considering distribution feeder reconfiguration [13] and energy management [14], to boost the penetration of both technologies and achieve the expected environmental, energy and social benefits [15–17].

Extant research has already identified types of policies to promote EV diffusion and types of policies to increase the share of RES in the power grid, as presented in Section 2. However, the categorization of policies that jointly promote both technologies has been overlooked and needs to be better understood. To the best of our knowledge, no previous study has tried to identify the types of policies that address the promotion of EVs charged with renewables and to assess their use around the world.

Therefore, the motivation of this investigation is to address this gap and to identify and understand which type of policies have contributed most to the joint development of EV and RES in countries worldwide. The paper fills an important gap in science and society left by the scarcity of studies focused on the joint expansion of EVs with renewables in the power grid at the country level. For that, it targets the following research questions (i) What are the main types of policies to promote the joint development of EVs and RES? (ii) In which countries are these policies being implemented? (iii) Are these policies being adopted in the countries that have a higher share of EVs charged with RES?

By answering to these questions, the paper provides relevant contributions and insights for academics, policymakers, and other stakeholders. It reveals that the achieving the joint expansion of both RES and EVs technologies depends on consistent public policies to encourage the increase in the market penetration of the two technologies. It suggests that policies need to be broad, well-calibrated and reach more countries willing to support the joint expansion of the two technologies so that the 2030 climate mitigation targets are achieved.

This paper consists of five sections. The next section presents the background, covering the main issues of policies to promote RES and EVs. The third section is dedicated to the methodology, detailing how the data were collected and analyzed. The fourth section presents the findings of the study. The fifth and last section refers to the discussion and conclusions, considering the most relevant aspects of the study, addresses the limitations of the research and points out recommendations for future studies.

2. Conceptual Background

RES are an important pillar for energy transition. Power sector and electric mobility (EM) have been undergoing profound transformations. The changes in the electricity sector comprise processes of deregulation, decentralization, privatization, digitalization, and an increasing share of renewable power generation technologies, such as offshore RES, solar energy improvement and emerging ocean energy technologies [18]. EM, on the other hand, is changing the automotive sector, enabling the introduction of low emission technologies. In this context, innovation is occurring at the level of EVs and charging infrastructure, as well as on improvements in affluent technologies and innovative products, services, and business models like cars-as-a-service (CaaS) system (that is a differentiated energy service provider (focus on consumer service) that combines energy storage system, energy management system and service contract to increase the reliability of the energy supply more economically). Together, RES and EVs play an important role in the public policies being adopted to promote the transition to low-carbon systems [19].

2.1. Policies to Increase EV Adoption in Low-Carbon Technology Transitions

The vehicle industry operating system has been anchored in the socio-technical regime of automobiles [20], characterized by the production in large, centralized manufacturing facilities and revenues based on the continuous sale of new cars and associated financial services, through an integrated distribution network of dealerships franchisees [21]. This operating system is being questioned by the growing demand for EVs, high-tech connected and autonomous vehicles, along with smart mobility services (which refers to many modes of transport that includes public transport with real-time timetabling and route optimization, car sharing schemes, Cars-as-a-service (CaaS), Mobility on Demand (MOD), and autonomous transport systems). Together, they are the main drivers of the transformation of the automotive sector that requires innovative governance policies capable of providing the sustainable development of the sector [3,22].

The share of EVs has been consistently increasing over the last decade. However, in 2021, the global electric car stock only represented around 2% of the world stock, reaching around 16 million units [10]. Electric car sales share in worldwide market rose 70% to a market-share record of around 10% in 2021 [10]. However, achieving the Sustainable Development Scenario (SDS) target between 2020 and 2030 will require an average annual growth of 36% in the EV stock.

The expansion of EM depends on the adhesion of countries that do not yet promote EV and on the growth of EVs penetration in the markets where it has already started to diffuse [10]. China, Europe, and the United States account for around 95% of the sales in 2021. EV sales are small in other emerging and developing economies. For example, in Brazil, India and Indonesia, fewer than 0.5% of car sales are electric. In fact, only a few countries have a significant share in electric car sales in 2021: Norway reached a record high sales share of 86%; sales shares exceeded 70% in Iceland, and 43% in Sweden [10].

Although EVs are perceived as a key technology for a transition to a decarbonized society, increasing their penetration requires bypassing business practices, political interests, and social and cultural values [23]. Public policy is decisive for this transition [24], namely in a context of restrictions on GHG emissions.

EVs diffusion incentive policies must address consumer knowledge and behavior, as well as overcome highly interconnected technical and economic barriers such as high purchase price, limited range, long charging time and lack of charging infrastructure that continue to persist [4,17]. Therefore, governments need to adopt a policy mix, mobilizing different instruments, addressing both internal and external factors that affect the adoption decision [5,8,25].

According to Åhman [26], EV diffusion policies can be grouped into three categories: R&D for vehicles and components, market support and support for infrastructure.

R&D instruments (e.g., subsidies to R&D investment) aim to spur technological innovation that enhances the EVs characteristics and performance [27], namely of batteries, which influence cost, driving range and charging time [28]. Previous research has shown that the increase in EVs adoption is greatly contingent on technological progress in batteries [29].

In terms of market support, scholars stress the use of financial and non-financial instruments to increase EV adoption [8]. Among financial incentives to consumer's adoption, governments are using tax incentives or subsidies on EV purchase, reduced registration fees, exemptions from road prices, free parking, that is, instruments that enable to reduce the price gap between EVs and conventional vehicles [30,31]. Non-financial incentives involve favorable traffic regulations like access to high occupancy vehicle lanes and preferred parking [24]. Moreover, governments develop policies to increase consumer awareness of the environmental benefits of EVs, namely information campaigns and education programs that lead to increase the willingness to adopt EVs [5,32,33].

The build-up of the charging infrastructure also needs to be supported by public policies, both in terms of the number of charging stations [31], of its spread in the territory [34], and of the standards adopted in the infrastructure [27,35].

2.2. Policies to Improve RES Share in Low-Carbon Energy Transitions

From the decarbonization perspective, policies are pushing to increase the production of low-carbon energy, with support for the expansion of RES such as solar and wind sources. It is expected that, in 2050, over 90% of the energy solutions will involve RES [18]. Their share in global power generation has been growing consistently, e.g., it jumped to 29% in 2020 from 18% in 2000, especially solar and wind energy [36]. Policies for the transition to low-carbon energy will play an increasingly important role for the future generations, contributing to a change in the consumption profile with greater share of RES, as well as the reduction in energy consumption itself through increased efficiency and technological innovations. Driven by environmental issues, to ensure the below 2 °C scenario, policies should prioritize the electrification of end-use sectors using RES, to provide mitigation of more than 90% of CO_2 emissions up to 2050 [18].

The most recent policies seek to support the events with the greatest impact on the transformation of the energy sector, especially power sector. These policies involve deregulation, decentralization, and digitalization and a greater presence of RES in the global energy mix [37,38]. Deregulation policies in energy sources provide an increased competition in the power sector requiring a new stance from dominant companies. Among the main impacts caused by deregulation of the sector is the reduction in wind and solar power generation costs, as well as the empowerment of the different types of policies to improve the share of RES sources in energy mix and to the reduction in the price of electricity for consumer [39,40]. From the perspective of decentralization, scholars, e.g., [37,41] highlight that policies related to the integration of consumers in consumption, production and distribution of energy need to contemplate the change from the centralized model, where network operators are organized around large fossil fuel plants and transmission networks, operating under a single national market structure, for a decentralized model and with greater user presence, including energy generation and consumption away from traditional networks and jurisdictions. Digitalization policies, characterized by the exploitation of urban spaces, allow the expansion of innovative products and services, e.g., smart grids, smart meters, internet of things (IoT), virtual power plants (VPP) [39,41].

From a technological perspective, policies for the development of RES in the power sector aim to include innovative mechanisms, such as the transition to VPP, that is cloud-based distributed power plants that aggregate heterogeneous distributed energy resource capabilities to harness RES and enhance power management. VPPs require the connection of several types of flexible generation and consumption units via an energy management system involving decentralized generation, collective computerized intelligence, and extensive use of online technology.

Policies to promote VPP assume that adding several small and medium scale virtually integrated generation facilities, consuming, or producing electricity through the generation distribution system, energy storage system and detachable loads, can increase electricity supply [42,43]. They should focus on competitive and optimized traders' requirements capable of providing balance, quality of controls and perfect coordination between generation and demand. So, VPP policies aim to provide integration of RES into the power network, with the purpose of balancing supply and demand using 'smart' grids revealing a new dynamic in energy consumption using 'smart' meters that optimize electricity losses and providing reliable power to consumers. Thus, VPP policies need to overcome important operational challenges and enhance the strengths of the system to optimize benefits for consumers and other stakeholders [42].

2.3. Policies to Promote EV with RES in the Low-Carbon Energy Transition

RES and the EV sectors complement each other in the transition to a low-cardon economy, and a higher penetration of EVs powered by RES is a desirable solution to promote energy transition.

In fact, extant literature recognizes strong interdependencies between EV charging and electric power distribution system. Integrating a larger EV fleet into the power grid raises challenges and benefits. Challenges are related to planning, operation, and control of the power grid infrastructure [44], namely regarding the dynamic loads which are difficult to schedule, potentially leading to situations where the system is unable to deal with the additional energy demand instigated by the EV charging. Benefits are related to the fact that EVs can deliver ancillary services to the electric utilities such as peak power shaving, acting as a potential back up for the power grid [45].

From the technological perspective, several solutions are being developed for smart charging, advanced metering and advanced communication and control network infrastructures. Policies targeting the integration of RES in the power grid have stood out by promoting intermittent wind and solar sources to encourage EVs charging (namely in parking spaces), as well as integrated applications such as smarter metering, smart grid and EVs battery as a backup system. Policies targeting EM have stood out by promoting the smart EVs charging infrastructure and connect them with intermittent RES. Besides that, the EV itself as an energy storage instrument and management mechanism for the power network, as well as the use of EVs charging infrastructure technology, and other resources like vehicle-to-grid (V2G), vehicle-to-home (V2H), vehicle-to-street (VTS) and vehicle-to-everything (V2X) has been the target of policies that provide benefits for all stakeholders, mainly for the consumers [3,22,40].

3. Materials and Methods

For the purposes of studying the types of policies to charging EVs with RES, light duty vehicles such as battery electric vehicles (BEVs), fuel cell electric vehicles (FCEVs), and plug-in hybrid electric vehicles (PHEVs) were considered as EVs.

To study the types of policies adopted by countries as well as their potential implications on the diffusion of EVs powered by RES, a secondary data methodology analysis was adopted [46,47]. In this context, the paper combines three approaches: a systematic literature review (SLR), bibliometrics and analysis of secondary data on EVs and RES penetration and actual adoption of policies in several regions and countries.

SLR and bibliometrics are complementary approaches that enable an understanding of the structure of a field of study [48]. SLR is considered to provide methodological rigor to literature reviews [49], since it compels researchers to specify explicit and rigorous criteria for searching, filtering, and synthesizing the literature, leaving an audit trail that guarantees its replicability and transparency [50]. It enables to summarize existing evidence, identify gaps, and suggest some directions for future research by "comprehensively identify, appraise and synthesize all relevant studies on a given topic" [51] (pp. 19). Bibliometrics consists of a quantitative analysis of the bibliographic references of a body of literature [52], enabling to detect patterns of authorship and publication strategies [53], as well as the development of scientific fields [54].

Both SLR and bibliometrics resort on a search of the literature conducted on the two most relevant bibliographic databases: SCOPUS and Web of Science (WoS) on 30th December 2020. The article selection process is represented in Figure 1. The search query used in the study identification was: "polic*" AND "renewable*" AND ("electric vehicle" or "electric mobility"). All electric vehicle such as BEV, PHEV, FCEL, and all RES were considered. Three inclusion criteria were considered in the search: (i) the study identifies policies to promote EVs charged with RES; (ii) the study was published after 1999; (iii) the study is an academic journal article published in English. The process was performed by using the State of the Art through Systematic Review (StArt) tool.

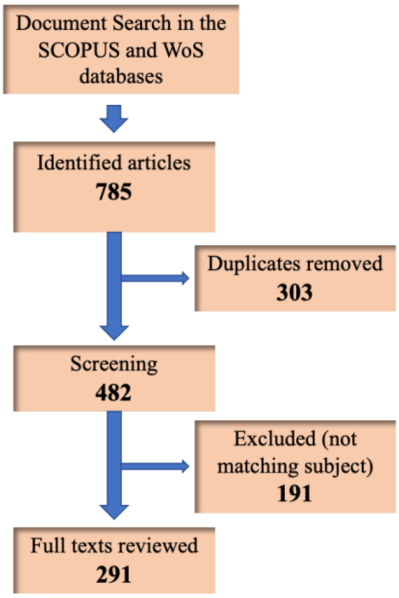

Figure 1. Search process. Source: Authors' own elaboration.

After the removal of duplicates (i.e., documents present in both bibliographic databases), all abstracts have been read, and 191 articles were removed because they were not focusing on the subject, that is, they were not contributing to the understanding of policies that promote both the adoption of EVs and their charging with RES. The remaining 291 were downloaded and fully read. These papers constitute the corpus analyzed through bibliometrics (year of publication, journal, citations, author, and author' affiliation country) using the Bibliometrix package and content analysis (for SLR). Content analysis was performed manually by using spreadsheet resources, considering the following dimensions for coding:

1. Paper methodology: two main categories were considered, subsequently decomposed in sub-categories:
   a. Theoretical article: a conceptual paper or a paper providing a literature review
   b. Empirical study: a paper with empirical research adopting a:
      i. Quantitative approach
      ii. Qualitative approach
      iii. Mix method approach
2. Type of policy considered in the study: considering the insights from the previous section, the following categories were considered:
   a. Infrastructure
   b. Technology
   c. Production/Supply
   d. Market/Demand
   e. Other types of policies (e.g., environmental, urban planning, etc.)

As explained in Section 2, countries that encourage the adoption of EVs use different mechanisms to do so. Since no previous study presents a typology for the policies that jointly promote RES and EVs, the categories used for coding resorted to the principles of treatment of public policies adopted by Åhman [26] and the international energy agency [10]. This classifies the policies into three categories: (i) aimed at the dissemination of products (DOP) through support to production (supply) and consumption (marketing/demand) of the EVs [8]; (ii) aimed at the development of technologies (TDE) that aim to support the expansion of EM [27,29]; and (iii) aimed at the expansion of the infrastructure to support EVs, called the infrastructure initiative (INI) [27].

To assess the actual use of policies for expanding the use of EVs with renewable sources, a selection of countries with strong support for EVs was made, which together represent more than 90% of the EV market share in 2021. Then, the EV penetration was compared with the share of RES in the generation of the power system, in the selected countries, using secondary data publicly available.

3. Geographical reach of the study, considering both the continent and the country.

The coding was performed by the two authors. To assess the robustness of the coding, an inter-coder reliability analysis was conducted. A subset of 25 papers was randomly selected from the corpus and independently coded by the authors. Inter-coder reliability was assessed by using the percentage agreement, i.e., the share of papers coded in the same way by the two authors. Table 1 shows that in all categories, the value was above the standard acceptable rate of percentage agreement of 80% [55]. The cases that were classified differently by the two coders were analyzed and a consensus was reached.

Table 1. Inter-coder reliability of the coding dimensions (percentage agreement, %).

Paper Methodology	Type of Policy	Geographical Reach
100	91	100

Source: Authors' own elaboration.

4. Results

4.1. General Characteristics of the Reviewed Studies

Figure 2 shows the evolution of the number of papers published. The oldest publication dates to 2005. Subsequently, the number of studies has been increasing, notably since 2017, and reveals that the expansion of interest on global electrical mobility has occurred steadily. This may have been driven by multiple factors such as environmental drivers that have mobilized civil society and governments to fight carbon emissions, mitigate climate change and support the sustainability transition pathways. In addition, the toxic gases emitted by traditional vehicles or fuel-powered vehicles are causing an increase in air pollution and causing diseases, deaths, and the deterioration of the quality of life in large urban centers, which has led governments to from various regions to enact stringent regulations against carbon emissions. As a result, the number of countries interested in eliminating combustion engines or create ambitious transport electrification targets. In addition, there are other issues like energy security that governments pursue. Together these facts result in policies to subsidies and incentives for EVs and are contributing to the growth of the global EM market.

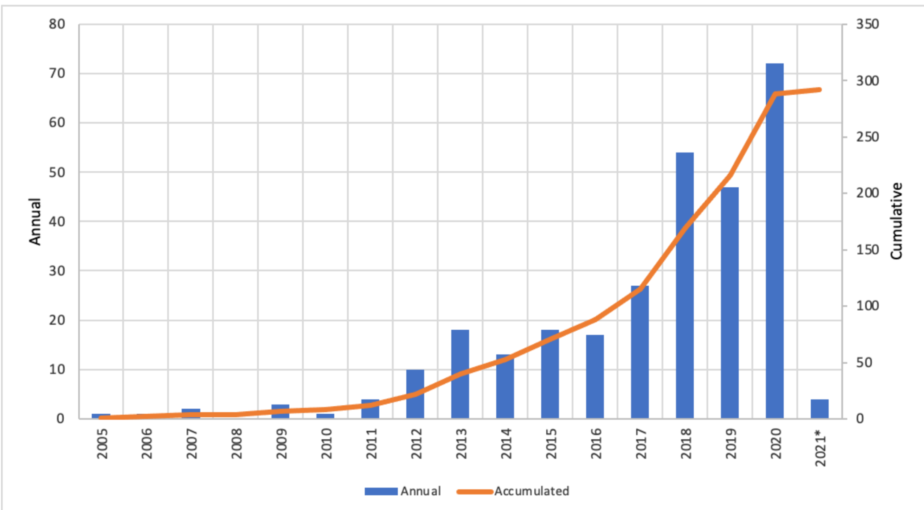

Figure 2. Reviewed studies by year (annual and cumulative). Source: Authors' own elaboration. * forthcoming studies.

The papers were published in 116 different journals, but a large share (40%) is found in five high-impact journals (Table 2), while 85 journals have only published one paper on the topic. The most frequent subject areas of the most relevant journals are Energy, Engineering and Environmental Sciences. Journals focused on transportation appear in lower ranking positions (e.g., Transportation Research Part A and Part D, each with four papers).

Table 2. Most relevant journals *.

	N	Quartile **	Citations per Document (4 Years) ***	Subject Area ***
Energy Policy	33	Q1	6.696	Energy Environmental Science
Applied Energy	28	Q1	10.812	Energy Engineering Environmental Science
Applied Energy	28	Q1	10.812	Energy Engineering Environmental Science Mathematics
Energy	20	Q1	7.477	Energy Engineering Environmental Science Mathematics
Journal of Cleaner Production	18	Q1	9.791	Business, Management and Accounting Energy Engineering Environmental Science
Energies	16	Q2	3.354	Energy Engineering Mathematics

Source: Authors' own elaboration. * Selected according to the Bradford Law; ** higher quartile according to the 2020 Scimago Journal Rank. Quartiles reflect the journal's prestige through the impact in terms of citations. Journals in the first quartile (Q1) are the most prestigious; *** According to the SRJ—Scimago Journal Rank.

The most cited papers are presented in Table 3. These papers were published between 2006 and 2016 and have more than 10 citations per year. Seven of these papers were published in the most relevant journals.

Table 3. Most cited papers *.

Paper	Total Citations	Citations per Year
Sovacool BK, 2009, Energy Policy	350	26.9
Yong JY, 2015, Renewable Sustainable Energy Rev	257	36.7
Ball M, 2015, Int J Hydrogen Energy	222	31.7
Romm J, 2006, Energy Policy	203	12.7
Mathiesen BV, 2009, IET Renew Power Gener	190	14.7
Mathiesen BV, 2009, IET Renew Power Gener	175	21.9
Liserre M, 2016, IEEE Ind Electron Mag	174	29.0
Bauer C, 2015, Appl Energy	167	23.9
Andersen PH, 2009, Energy Policy	165	12.7
Zhang T, 2014, IEEE Trans Veh Technol	138	17.3
Tulpule PJ, 2013, Appl Energy	138	15.3
Zeng X, 2015, Renewable Sustainable Energy Rev	121	17.3
Shafiei E, 2012, Technol Forecast Soc Change	112	11.2
Budde Christensen T, 2012, Energy Policy	103	10.3
Iversen EB, 2014, Appl Energy	101	12.6

Source: Authors' own elaboration. * Only papers with more than 100 citations are listed.

The growing interest in the topic is evident in the number of authors involved in the analyzed publications, which amounts to 973. However, 90% of these authors have only been involved in one publication. Table 4 presents the authors who stand out as more prolific in the area.

Table 4. Most prolific authors *.

Author	Number of Papers
Li, J.	6
Sovacool, B.K.	6
Li, Y.	5
Noel, L.	5
Thiel, C.	5
Cipcigan, L.	4
Kester, J.	4
Shafiei, E.	4
Zhang, L.	4

Source: Authors' own elaboration. * Only authors with more than 3 papers are listed.

The authors are affiliated in organizations from 44 different countries from all continents, thus forming a global community. The countries that stand out in terms of the number of articles and total citations are presented in Figure 3.

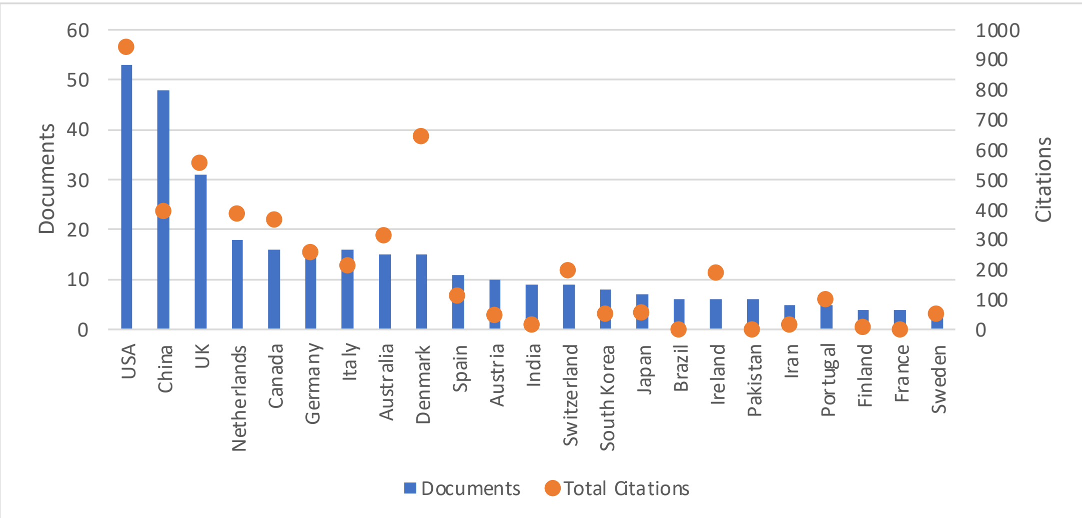

Figure 3. Country * scientific production and citation. * Only countries with more than 3 papers are listed. Source: Authors' own elaboration.

4.2. Analysis of Papers' Content

4.2.1. Methodologies Adopted

From the analysis of Figure 4 becomes visible that most of the analyzed papers have an empirical approach. Two thirds of the studies have a quantitative approach, resorting to several estimation, modeling, and simulation techniques.

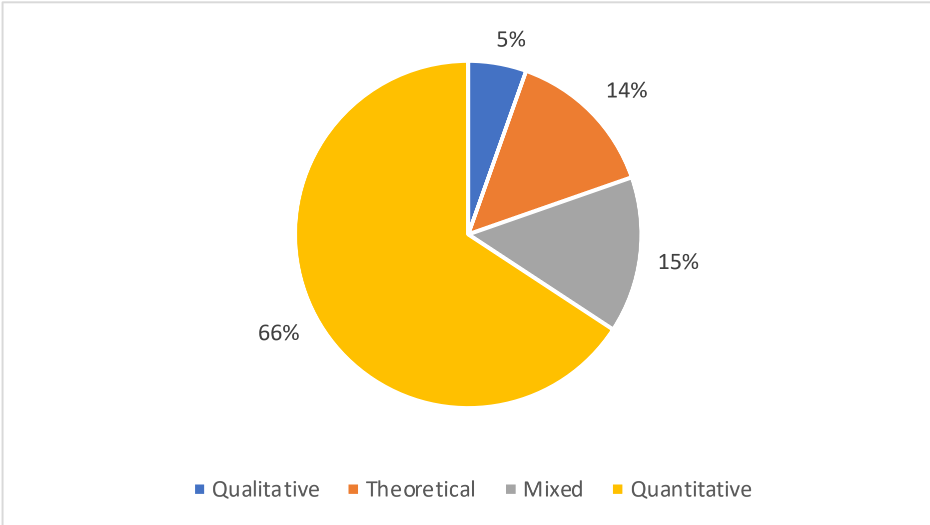

Figure 4. Paper's methodology. Source: Authors' own elaboration.

4.2.2. Type of Policies Addressed by the Studies

Most studies are addressing policies related to production and technology, while demand and infrastructure earn a slightly lower attention (Figure 5). It is worthy to mention that most of the papers cover more than one policy recognizing the need for a policy-mix that tackles the several dimensions that influence the adoption of EVs, as stressed by the literature [5,8,9]. In fact, only 16% of the papers are focusing on a single policy type (Figure 6), studies focused on technology being the most frequent.

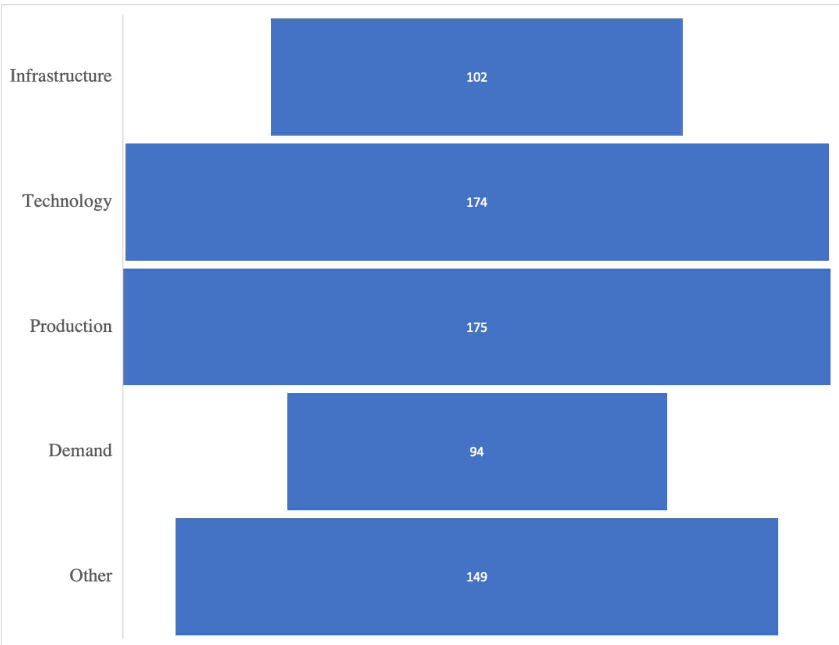

Figure 5. Type of policy considered in the study. Source: Authors' own elaboration.

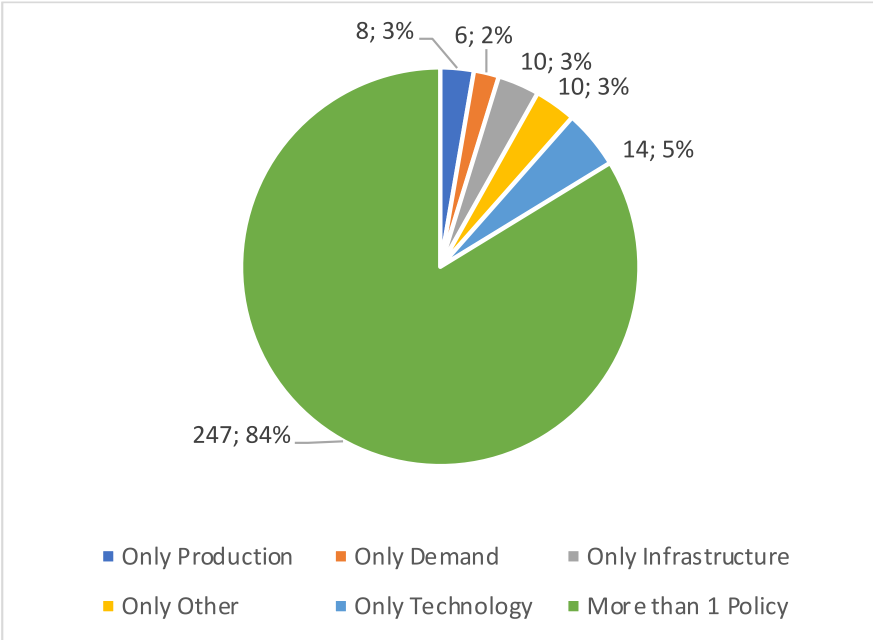

Figure 6. Studies focusing on a single policy type. Source: Authors' own elaboration.

Overall, studies that address infrastructure-related policies recognize that lacking charging infrastructure or inadequate infrastructure for EVs is critical for the expansion of EM and outline policies for structured expansion of the charging network (e.g., [56]) There is a set of factors that relate to the electric vehicle supply equipment (EVSE) network, such as the possibility of linking it to the RES network, keeping the consumer up to date about the location of the EVSEs, inform the user of the EVs about prices, fees, connector types, loading speed, queues, waiting time, payment methods, etc.

One of the common problems is the lack of alignment in the criteria in the development of the public EV charging network. Sometimes, the development of EVSE prioritizes the number of stations over the quality of charging stations. To solve the problem, new ways of evaluating public charging infrastructure performance need to be developed, avoiding the oversizing of public charging infrastructure without addressing the important charging needs required by EV owners. For example, Zhang et al. [57] consider that proper public policies can help to solve important issues such as optimizing the location of fast charging stations, reducing charging wait times, connecting charging equipment to public platforms (to facilitate payment methods), inform the consumer in advance of billing amounts.

Studies that address the technology-related policies stress not only the development of technologies, but also dynamics that leverage those technologies by revealing opportunities for the several stakeholders. For example, new business models can offer new sources of value to prosumers and power grid managers (generating new sources of revenue). For Liu and Zhong [58] the perfect coordination between taxed renewable energy (DRE) contemplating EVs, battery storage system, solar photovoltaics, supporting infrastructure technology and advanced V2G systems can provide EV owners with a cost lower energy supply from the photovoltaic source than the supply from the traditional power network, revealing an important technological benefit for the better use of EM. Kester et al. [32] reveal that the V2G system promises inexpensive energy storage and flexibility for EV owners but points out that there are doubts about the degradation of batteries using V2G systems, leaving EV users insecure. The authors warn of the lack of understanding about the functioning of the technologies that involve the EV and the electrical system, as they consider that the consultancies are focused on the power sector, not the automotive sector.

In studies that address the production-related policies, the prevailing arguments are based on the benefits of EV. They stress that BEVs are more environmentally friendly than internal combustion engine (ICE) competitors, that the price of electricity (electrification is developing a new and better technology) is lower than other combustion options to be used in ICE, that the EV has more benefits for users, society, and the environment than other mobility options (available for use on a large scale) (e.g [59,60]). To support the arguments, most studies adopt Life Cycle Assessment (LCA) analysis to reveal that EVs can pave the way for a sustainable transition since they are more efficient than ICE and help to solve the problem of intermittency in renewables. For example, Onat et al. [59], adopting a study of LCA in the USA, defend the use of federal resources to strengthen the penetration of EV in the most favorable regions for this type of technology (due to the greater participation of RES in the power generation mix and the cost factor of EVs ownership being favorable to the consumer).

Studies that address the demand-side of policies tend to stress the preferences of consumers and the barriers to diffusion of the EVs (e.g., [15,61–63]. Among the main barriers is technology, such as V2G system, that requires complementary and sophisticated technological and operational resources to run efficiently. Some barriers to the transition process towards RES can be overcome with local energy communities. For example, increasing self-consumption through of the implementation and combination of new technology such as smart metering, smart charging, and the aggregators via a cloud database [39]. In a study on transport demand and high energy dependence with tariff deficit (a reduction in gasoline consumption will reduce government revenues) in Spain, based on a sustainable transport model, Colmenar-Santos [64] advocates for the adoption of EM (electric cars, e-buses and e-taxis and smart grids) as a solution. He argues that, with adequate policies, it is possible to overcome the deficit problem (recover tax losses due to reduced gasoline consumption) with the adoption of EV by the government, aggregators, and power companies. In addition to mitigating GHG emissions, and preventing the government's deficit, the country will have greater protection against oil price fluctuations and greater energy security.

Most hot topics classified under "other policies" support different types of policies and adoption of several technologies and procedures aimed at the decarbonization process with diffusion of EM and improvement of electrification with RES. The central arguments focus that the adoption of a set of incentive and restriction policies for emissions are necessary to mitigate CO_2 emissions and meet on efficiency standards (invisible measures) policies that can be met through an international assignment of CO_2 specific standards, as with the 95 gCO_2/km mandate, of 80 gCO_2/km in 2040 and 75 gCO_2/km in 2050. For example, Mulholland et al. [65], in a study on Ireland, argues that the 2% annual reduction in intangible costs provides a 70% increase in EVs share (considering 70% PHEV, 30% BEV) in 2050.

4.2.3. Countries Addressed by the Studies and the Policies They Are Adopting

Although many papers (54) have a global nature, that is they study the promotion of EV powered by RES without addressing a specific country, it was possible to identify studies on 57 countries from all over the world. Several countries are attracting more attention from scholars, namely from the North America (the USA and Canada), China and European Countries as shown in Figure 7.

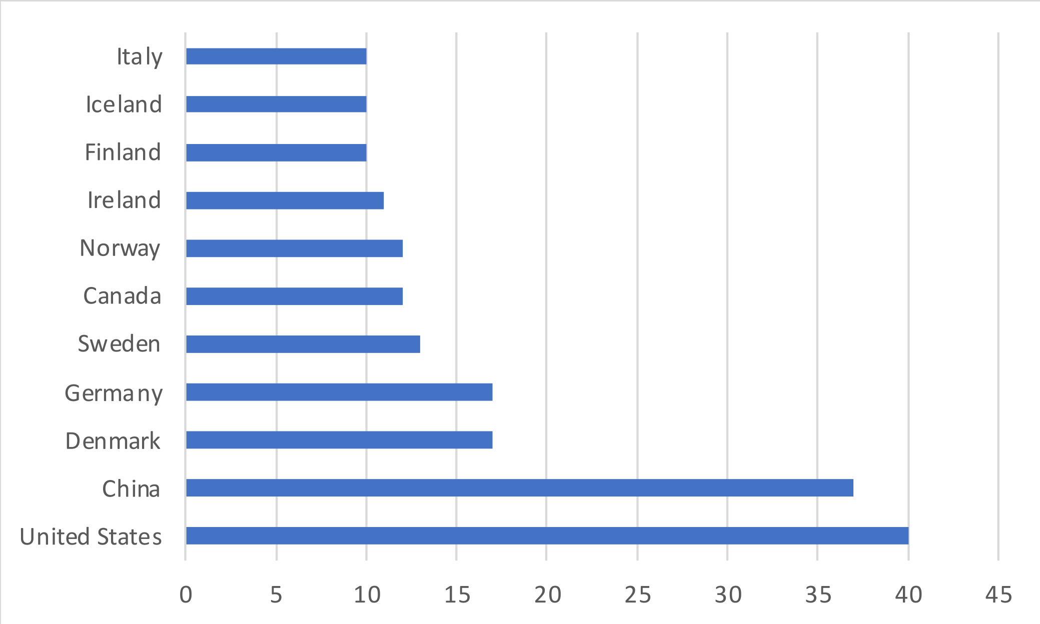

Figure 7. More studied countries *. * Only countries with 10 or more studies are included. Source: Authors' own elaboration.

The analysis of the policies adopted, in 2020, by a selection of countries that encourage the expansion of EVs, and RES is revealed by Table 5. It is possible to observe that most country are not yet combining the several policy types in their Policy making, and that many are still concentrating on DOP instruments. However, it is also possible to identify countries that are already adopting a policy mix that combines all type of policies—China, the USA, and a set of European countries (France, Germany, Italy, the Netherlands, Norway, Portugal, Spain, and Sweden). The analysis suggests that policies to encourage and subsidize the production and purchase of EVs are dominant. On the other hand, policies for the diffusion of technology to support the EV, as well as policies for the expansion of the charging infrastructure, are less intense. This may help explain why electric car sales doubled in 2021, and charging infrastructure grew by less than 40%, both compared to 2020.

Table 5. Policies adopted by countries to promote EV powered by RES (2020).

Country	DOP *	TDE **	INI ***
Austria	✔	✔	
Belgium	✔		
Bulgaria	✔		
China	✔	✔	✔
Croatia	✔		
Cyprus	✔		
Czech Republic	✔		
Denmark	✔		✔
Finland	✔		✔
France	✔	✔	✔
Germany	✔	✔	✔
Greece	✔		
Hungary	✔		
Iceland	✔		✔
Ireland	✔		✔

Table 5. *Cont.*

Country	DOP *	TDE **	INI ***
Italy	✔	✔	✔
Latvia	✔		
Liechtenstein			
Lithuania	✔		
Luxembourg	✔	✔	
Malta	✔		✔
Netherlands	✔	✔	✔
Norway	✔	✔	✔
Poland			✔
Portugal	✔	✔	✔
Romania	✔		✔
Slovakia	✔		
Slovenia	✔		
Spain	✔	✔	✔
Sweden	✔	✔	✔
Switzerland	✔	✔	
Turkey	✔		
United Kingdom	✔		✔
United States	✔	✔	✔
Ukraine	✔	✔	

Source: Authors' own elaboration using data from [10]. * For the dissemination of products (DOP), in this case the EVs. ** for the development of technologies (TDE) that aim to support the expansion of EM such as EV battery production, smarter metering solution, etc. *** initiatives for the expansion of the support infrastructure for EVs, called infrastructure initiative (INI). ✔ represents the presence of the policy in the country.

Another relevant dimension of the analysis was trying to understand the potential effect of the policies adopted to promote EM together with RES. Figure 8 reveals the results that include the countries that exercise leadership in the promotion of both technologies (those identified previously as adopter of all types of policies) and allows a holistic view of the behavior of policies in the joint expansion of them.

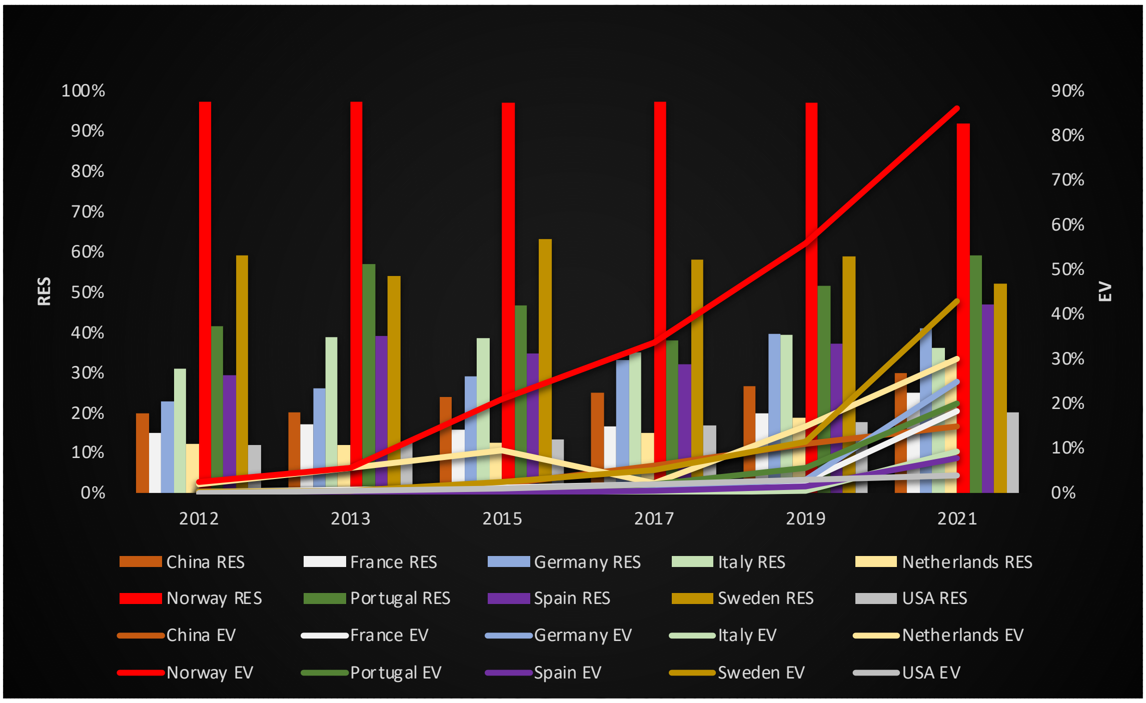

Figure 8. Top market share countries in renewable energy and EV. Source: Authors' own elaboration using data from [66–72].

The cross-analysis of policies for the dissemination of EVs and RES—especially in the period from 2012 to 2019—a period not influenced by the effects of the COVID-19 pandemic—reveals that the expansion of EM is dependent on public policies to promote an increase in its market share (Figure 8). The greatest penetration of EVs occurs in countries that most support, with expansionist policies, the diffusion of EVs.

However, the results suggest that there is no direct relation between the adoption of policies and the diffusion of EVs. Thus, a broad coverage of policies is not a sufficient condition for accomplishing a high diffusion of EVs. For example, countries such as Spain, Italy, France, China, and the USA have a wide range of policies for the expansion of EM but have a low market share of EVs, below 20% in 2021. Therefore, it is not enough, for example, to have a policy to encourage the purchase of EVs. For the policy to translate into an expansion of EM, it is necessary that the value of the incentive is significant to the point of balancing total cost of ownership (TCO), accessible, and capable of reaching a high number of consumers. Another important aspect is that policies to support EM have contributed to the increase in the supply of electric car models. At the end of 2021, there were more than 450 models available on the market, around five times more than in 2015. Policies began to reveal more significant results in the expansion of EVs from 2017 onwards, when a greater number of automakers began to show interest in increasing the electrification of their fleets.

On the other hand, there is also no direct relation between the penetration of RES in the power grid and the diffusion of EVs. In other words, countries that have a high share of RES in the power generation do not always have a significant share of EVs, as the cases of Portugal, Spain and Sweden show. These countries are not fully exploiting the decarbonization potential of RES, due to the low use of EM.

The results also show that the countries that have adopted broad, lasting, and consistent policies to support the diffusion of EVs and RES are also those that register the most expressive growth in the market share of EVs, e.g., Norway and the Netherlands.

Among the countries that show a balance between the diffusion of EVs, and RES is the Netherlands (in 2019, it registered 19% of penetration of RES and 15% of EVs market share) and Norway (in 2019, it registered 92% of RES and 86% of EVs market share). Another aspect observed is that countries that lead vehicle sales volumes have low EVs market share, as is the case of the USA (in 2019, it registered 18% of RES and 3% of EVs market share) and China (in 2019, it registered 27% RES and 11% EVs market share).

Although not the purpose of this study, the military crisis involving two Eastern European countries with restriction and even interruption of energy supply to Europe associated with unprecedented economic restrictions and political interventions are relevant additional components for policymakers. The energy and economic crisis that has set in, and which may worsen, causes the increase in commodity prices and exacerbates the issue of energy insecurity, becoming additional ingredients that require urgent attention from policymakers in order to guarantee mass expansion of RES and other low carbon technologies such as EM.

5. Discussion and Conclusions

To understand which policies have contributed most to the joint development of EVs and RES and answer the research questions as well as provide relevant insights for academics and policymakers, this study examined the literature and mapped the different types of public policies to promote jointly promote the diffusion of EVs and RES and investigated the actual penetration of RES in the power system and the diffusion of EVs at the country level.

Although the EV market share has been growing rapidly in recent years, much more needs to be done if the transport mitigation target is to be achieved. Climate policies assume that EVs will account for around 30% of vehicles sold by 2030, globally. This is well below the 60% share required by 2030 to achieve zero net CO_2 emissions [10] and most of the countries are far below these values, even those that implement a broad set of policies to jointly promote diffusion of EVs charged with RES.

Therefore, it will be necessary to create innovative and consistent policies to stimulate increased market share of EVs powered by RES and ensure the joint diffusion of both technologies. In this sense, it is desirable to encourage other countries—in addition to those that we found that are jointly supporting EM and RES—to adopt EM. For example, EV sales have a lot of room to grow in emerging and developing economies such as Brazil, India and Indonesia, where EV market share is less than 1%.

More policy support will be needed to ensure scaling up EVs infrastructure as well as the adoption of targeted policies to encourage smart charging system to plug the EVs straight into RES. In addition, policies should broaden their scope to cover the electrification of other transport segments. In 2021, global sales of electric heavy trucks accounted for just 0.3%. This share would need to increase to around 10% by 2030 and 25% by 2050 to achieve established climate targets [9]. Besides that, policymakers must not forget that policies need to move forward to encourage the electrification of other modes of transport, such as ships and aircraft.

To effectively contribute to GHG emissions mitigation goals, policies must favor the transfer of freight transport from road to rail and passenger transport from cars to buses, as both have a lower ecological footprint. In addition, it must stimulate the production chain to ensure the availability of essential minerals: including lithium, nickel, and cobalt at competitive prices and through more sustainable battery manufacturing processes.

The policies for restricting the use of vehicles powered by ICE should be highlighted for the diffusion of EM. In addition, it is recognized that the COVID-19 pandemic issues and the effects of the armed conflict in Eastern Europe, associated with restrictive policies on the use of ICE helped to accelerate the EVs market share. For example, registrations for gasoline and diesel cars saw double-digit drops in the European Union in 2021 compared to 2019, and diesel cars decline more strongly from around 32% in 2019 to around 20% in 2021 [73]. Naturally, the space left by the fall in the market share of cars powered by fossil fuels was taken over by electric cars. However, policymakers need to be vigilant and support R&D to ensure that the diffusion of EVs and RES takes place regardless of unforeseeable external factors favorable or contrary.

This study presents the general context of countries using secondary data, but it has the limitation of not studying in detail the policymaking processes nor its impacts, which would demand the collection of primary data. In this sense, future research could further explore issues involving policies to support innovation and technology diffusion and sustainable business models involving multiple actors interested in adjacent businesses and in transition processes [74] as well as trying to understand the reasons that lead certain countries not to support EM even with a favorable mix of RES in the electric network thus allowing expand the structures, and processes explored in this article. Moreover, it would be relevant to explore the social impacts in the diffusion of EM with RES and to ways to promote the paths for sustainable transitions.

Finally, this study aims to contribute to the field of research and practice as it offers unprecedented information to support stakeholders such as policymakers and industry in arranging new, innovative, and sustainable products and services.

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