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Dissertation

Determinants of Public Charging Infrastructure for Plug-in Electric Vehicles in the European Union - using Fuzzy-Set Qualitative Comparative Analysis (fsQCA)

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GLOSSARY

EU - European Union

EV - Electric Vehicles

PEV - Plug-in Electric Vehicles

BEV - Battery Electric Vehicles

ICE - Internal Combustion Engine

PHEV - Plug-in hybrid Electric Vehicles

DC - Direct-current

CCS - Combined Charging System

GDP - Gross Domestic Product

PCI_PC - Public Charging Infrastructure per capita

PEV_PC - PEV per capita

PEV_SS - PEV Sales Share

GDP_PC - Gross Domestic Product per capita

PD - Population Density

PCII - Public Charging Infrastructure Incentive

Abstract, Keywords and JEL Codes

Electric vehicles are considered a critical answer for decarbonisation of the transportation sector. The European Green Deal calls for a carbon-neutral Europe by 2050. In 2021, more than four million EVs were active in the EU fleet. For this purpose, a robust public charging infrastructure allied with policies to incentivize home charging is necessary for meeting these objectives. We propose a model using fuzzy set Quality Comparative Analysis to better understand the necessary conditions and successful pathways for the development of public charging infrastructure in the European Union. The results show two equifinal solutions, the first one, nations with a higher population density and no incentives for public charging infrastructure, and the second, nations with presumably a lower population density and governmental incentives for the development of the public charging infrastructure; additionally, both groups present high levels of EVs per capita, sales share of EVs and GDP per capita. It is also possible to observe geographic and geopolitical similarities between the nations representing each solution. Thus, other political and sociocultural characteristics could be related to the deployment of public charging infrastructure. However, this merits further investigation by future research. This research could represent an insight to stakeholders, namely industry players and governments, on what are some of the characteristics that enable the development of the public infrastructure and which nations can serve as an example for policy implementation.

Keywords: Public Charging Infrastructure; Diffusion; Plug-in Electric Vehicles; Innovation; Public Incentives.

JEL Codes: O31; O38; O44; O52; O57.

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MFW AT ISEG

By Tiago Pessotti

1. Introduction

A big transition in the automotive industry is happening and the race for the next alternative fuel, for now, is being won by electricity (Hardman et al., 2016; Poullikkas, 2015; Sierzchula et al., 2014). Signed in 2019, the European Green Deal was crafted with the main goal of addressing Climate Change, making it the top priority with the proposal of a carbon neutral Europe by 2050. To reach the present EU decarbonisation ambitions, transportation would need to be totally decarbonised by 2050 (*A European Green Deal*, 2018). Electric Vehicles (EV) are widely seen as a critical answer for decarbonisation of the transportation sector, which has emerged as the primary impediment to achieving the EU's objective of a climate-neutral Europe by 2050 (*A European Green Deal*, 2018). Road transportation accounts for almost three-quarters of the EU transport sector's emissions (Fredriksson et al., 2018). Meaning that the EU has a huge potential market and it can become an industry leader. In 2021, more than four million EVs were active in the EU's fleet, and had 84,28% growth in sales when compared with the previous year (*European Alternative Fuels Observatory*, 2022). To support the fast growth of the technology, a robust and connected infrastructure is necessary, pondering the question: "What are the necessary conditions and successful pathways for the development of the public charging infrastructure in the European Union?"

To this end, we present a fsQCA model to better understand which conditional variables are necessary and what characteristics are shared between European nations with developed public charging infrastructure. In the literature review, we present an overview of studies on EVs, their charging infrastructure and related consumer preferences and public policies.

2. LITERATURE REVIEW

2.1. PLUG-IN ELECTRIC VEHICLES

Plug-in Electric Vehicles (PEV) can be divided into two classifications, Battery Electric Vehicles (BEV), which only operate through the energy stored in the electric battery and Plug-in hybrid Electric Vehicles (PHEV), which can source its energy from battery, a Internal Combustion Engine (ICE) or both. There are also conventional hybrid EVs that use only the ICE to generate energy for the electric motor, present in some of the early literature, but will not be in the scope of this dissertation. Most studies take into account both PHEVs and BEVs, with others focusing solely on BEVs or PHEVs. According to Fredriksson et al., 2018 some studies look at PEVs in general, rather than discriminating between BEVs and PHEVs. BEVs rely only on a big battery pack (17-100 kWh). These vehicles normally have a driving range of 70 to 120 miles, with some currently having ranges of 200-300 miles. When the battery in a BEV runs out, the vehicle must be recharged using a charge station or an electrical outlet. PHEVs feature a smaller battery pack (4-17kWh) with an internal combustion engine, and their electric driving range typically ranges between 10 and 50 miles. When a PHEV's battery is low, the car can continue to drive using its ICE. A charging point or an electrical outlet can be used to recharge the battery. The ICE can also be used to charge the battery or to maintain the charge level in the pack. Because of the variations between PHEVs and BEVs, people drive and charge the vehicles differently. BEVs with shorter driving ranges have fewer average vehicle miles travelled than ICE vehicles, although PHEVs have similar miles travelled (Hardman et al., 2018; Tal et al., 2014).

Vehicle electrification has emerged as a prominent trend in the automotive industry, spurred by concerns about clean energy and climate change, as well as regulatory interventions aimed at reducing greenhouse gas emissions, such as support for zero-emission vehicles and carbon taxes (Fredriksson et al., 2018). A patent analysis of power-train technologies (*EPO Annual Report*, 2018) shows that a transition toward cleaner power-train technologies has begun, with a significant decrease in ICE patents, while the last two decades show a steady increase in EV technology .

As EV technology has developed, technical advancements have lowered EV manufacturing costs, particularly battery prices, fostering the growth of the industry

(*Global EV Outlook 2018 – Analysis*, 2018). Lithium-ion (Li-ion) is the preferred technology for EV batteries and is predicted to maintain its dominance over the next decade (*Global EV Outlook 2018 – Analysis*, 2018). Prices for Li-ion batteries have dropped dramatically since their inception in the 1990s, whether for electronics, household and utility storage, or EV-related applications. Along with dropping Li-ion technology costs, scaling up battery production capabilities in recent years has been a primary driver for reductions in battery cost. EVs are expected to continuously increase their market share in the future. To meet commitments under the Paris Agreement, more governments will expand their support for zero-emission cars, introduce banishment for polluting vehicles, and encourage the deployment of EVs and charging infrastructure. At the same time, as production grows, EV technology and manufacturing costs are expected to continue to reduce. According to the International Energy Agency, the key driver of battery cost reduction will be increased production capacity (*Global EV Outlook 2018 – Analysis*, 2018). Further cost reductions and technological advancements will accelerate the growth of EV markets.

According to Transport & Environment (2020), while analysing carbon emissions, EVs outperform diesels and gasoline ICE vehicles in all scenarios, even on carbon-intensive power grids like Poland, where they outperform conventional vehicles by roughly 30%. EVs are already around five times cleaner than traditional counterparts in the best-case scenario (an EV running on clean power with a battery created with clean electricity). Crucially, the research conducted by Transport & Environment, (2020) reveals that electric cars powered by average energy pay off their "carbon debt" from battery manufacture after slightly more than a year and save more than 30 tons of CO_2 over their lifetime when compared to a conventional counterpart and EVs that travel long distances (such as shared vehicles, taxis, or Uber-like services) can save up to 85 tons of CO_2 throughout their lifespan (compared to diesel).

Consumer knowledge is critical for any industrial sector, specially related to technology and innovation driven industry, so an element to address is public awareness and acceptance, as EVs and EV Charging Stations have transformed customers' travel habits and home energy consumption structures. Consumer adoption of an EV is bound to go through a process similar to that of a car with a completely different powertrain such as ICE vehicles and hybrid EVs. This is due to the fact that EVs' fuelling technique (charging), driving range, braking performance, maintenance expenses, and brand recognition differ from regular ICE vehicles.

2.2. CHARGING INFRASTRUCTURE

The development of the charging infrastructure, besides being moving quickly, is still in its relatively early stages, and many studies on the subject are from macro and planning views. First, the impact of EV charging infrastructure on carbon emissions reduction, the promise of vehicle-to-grid technology that connects charging stations to the electrical grid, and renewable energy charging stations are all promising. The amount of charging stations required for future EV use has also been looked at. According to the findings of Ma & Fan, (2020), 10 fast chargers may be adequate for 1000 EVs, and the number of EV charging stations does not have to expand exponentially (Gnann et al., 2018; Liu et al., 2020). In terms of the influence of the charging infrastructure's power consumption on the electric grid, most studies indicate that it has a minor impact on the power system at the moment, but large-scale EV charging in the future may have an impact on the local power grid (Hardman et al., 2018). Although EV users anticipate free charging (Huang et al., 2019), there are possible negative side effects, such as a significant number of charging stations being occupied needlessly and charging station congestion (Hardman et al., 2018). Azadfar et al. (2015) suggests that the majority of drivers were able to finish their travels without the use of public charging infrastructure, yet a sizable number of drivers remain persuaded that public charging stations are necessary. Dong et al., 2016 conducted research using a game model and discovered that the quantity and density of EV charging stations developed by profit-seeking investors cannot accomplish the objective of increasing societal welfare, therefore public sector investments or incentives could be required for proper coverage in the near future (Ma & Fan, 2020).

Until more technological advances in energy storage and high-power charging are developed, building a major charging infrastructure may be the most effective approach to boost EV adoption. Residential buildings, urban public areas, and regions along intercity roadways are the three most common locations for EV charging stations (Lee et al., 2020). Public charging stations have been marketed internationally as an essential off-home charging method, even though authors like Hardman et al. (2018) say that home charging has the least social and individual costs. Furthermore, high-power direct-current (DC) charging piles, which are not suited for household installation, may enable significantly faster EV charging, making them perfect for metropolitan regions with high parking charges, such as Madrid and Manhattan (Faria et al., 2014).

Europe and China are gradually transitioning to the Combined Charging System (CCS) standard, which uses the Type 2 plug plus an extra DC connection. CCS connections are the standard charge point type in the European Union and must be fitted at all charge point sites pursuant to an EU mandate. In addition to CCS, other connections such as CHAdeMO and Tesla connectors can be fitted. CCS permits charging rates of up to 40 kW, while current charge rates range from 40-150 kW. These chargers are frequently provided in areas where customers need to recharge their PEV rapidly, such as along highways. Chargers in North America are classed based on their charge level. Level 1 chargers charge the slowest. These charge PEVs with 100 miles of range in roughly 24 hours using ordinary plug outlets and are usually used for overnight charging at home. Level 2 charging (208-240 V) provides a broad variety of charging speeds depending on the charging equipment utilised and the vehicle capabilities. Level 2 infrastructure can charge a PEV with a range of 100 miles in 4-12 hours. In the United States, dedicated charge stations are often required for level 2 chargers. Level 2 charging is the normal level from residential plug outlets in Europe, Australia, much of Asia, and most of South America. Level 2 chargers are often placed in homes, offices, and public spaces. DC rapid chargers charge PEVs as rapidly as feasible. They're also a lot more costly than level 2 chargers. Because of the large kW power outputs of the charging stations, they have very high-power needs.

The travel habits of PEV owners determine charging options. Charging takes place in four main locations: at or near home (usually overnight), at workplaces or commute locations (e.g., a transit hub), at publicly accessible locations other than work (e.g., grocery stores, shopping malls), and on travel corridors where drivers stop between the trip origin and destination during long-distance travel (M. Nicholas et al., 2017; M. Nicholas & Tal, 2015). According to the average number of charging events for BEVs and PHEVs, around 50-80 percent of all events for BEVs and PHEVs occur at home (*California Air Resources Board*, 2017).

According to Nicholas et al., (2017), the intended placement of DC fast chargers, as defined by proximity from PEV drivers' homes, might vary depending on the data analysed. The study examined data from GPS-tracked ICEVs and PEV buyer surveys. According to the study, desired sites based on survey data are the furthest away from home, ideal locations based on GPS data are marginally closer to home, and actual usage data from DC fast chargers reveals charging happens much closer to home than is optimal or wanted. This shows that customers expect to charge further away from home than they really do.

Whilst ordinary plug sockets may be used to recharge PEVs, these outlets charge PEVs slowly and are not always easily accessible by automobiles. The deployment of the EV charging infrastructure must be carefully considered in order to maximise the benefits of infrastructure investment. Policymakers, Original Equipment Manufacturers, utilities, workplaces, housing developers, charging infrastructure firms, municipalities, parking companies, retail centres, gasoline stations, and any other stakeholders may drive the development of PEV charging infrastructure. Infrastructure must be created to meet the demands and usage patterns of customers while also taking into account the impact of PEVs on local and regional power networks. Policymakers have some control over ensuring that the proper infrastructure is in place and can regulate how infrastructure is delivered.

Previous research has demonstrated that decreased running expenses compared to ICE vehicles are a popular purchasing reason and advantage of owning a PEV (Hardman et al., 2016; Hardman & Tal, 2016). To maintain this advantage, the cost of charging a PEV or the cost per mile driven by a PEV should be less than that of an ICE vehicle. Time of use and smart charging tariffs can be utilised to reduce the cost of charging a PEV even more. In many circumstances, users are provided free charging; while this might be an incentive to acquire the vehicles (Hardman et al., 2017), it can also have negative repercussions, such as charge station congestion (Nicholas & Tal, 2015). Typically, the only BEV and PHEV drivers who exploit this free infrastructure are those who can drive all day without recharging (Nicholas et al., 2013; Nicholas & Tal, 2015). BEV owners who need to charge to complete their daily commute may avoid driving their PEV if they believe charge point congestion is an issue or that charge points may be inoperable. Charging stations are frequently available in high-income residential areas. Previous research has shown that EVs are frequently the "second" car in households, with long-distance journeys made by a traditional "first" automobile and the EV functioning as a cost-effective form of transportation for everyday commutes (Jakobsson et al., 2016; Plötz et al., 2014). Commuting journeys and the ability to charge the automobile at home are advantages for suburban residents (Westin et al., 2018).

According to some studies, the majority of occurrences of low dependability are caused by congestion at the chargers (Hardman et al., 2018; Jarvis & Moses, 2019; M. Nicholas & Tal, 2015), rather than a lack of infrastructure or a lack of technological reliability. Investing in extra infrastructure to alleviate charge point congestion can be costly and inconvenient, particularly with level 2 or DC fast chargers. Pricing and legislation that limit the transition of home charging to public charging, according to the authors, might be part of the answer. Free DC fast charging, according to Nicholas et al., (2017), may induce users to charge when they do not need to. During high power demand periods, consumers may replace overnight home charging with free DC fast charging. This can also be an issue for PEV drivers that need to utilise rapid chargers because they won't be able to charge when they need it the most.

In Norway, the majority of users have home charging, with 61 chargers per 1000 PEVs. The United States has a comparable number of users, as well as 72 chargers per 1000 PEVs. Most users in China and the Netherlands do not have access to home charging. There are 217 charge points per 1000 PEVs in China, and 239 charge points per 1000 PEVs in the Netherlands. Few studies have been conducted to determine the number of charging stations required to enable PEV deployment. The appropriate number of public charging stations may be determined by factors such as the number of workplace chargers, access to home charging (which is frequently determined by housing type), travel habits, and the market share of PHEVs and BEVs. Three German studies have proposed the number of charging stations that are required. Jochem et al., (2015) modelled traffic data in different regions in Germany, to predict charging station requirements for the region's autobahn network. They discovered that 77 adequately placed chargers could cover the 3569 km of highways in that region for BEVs with a range of 100 miles. Gnann et al. (2016) created a model to evaluate public charging infrastructure needs in Germany, and based on their findings, 10 chargers may be enough for every 1000 PEVs. Finally, Funke & Plötz, (2017) calculated the number of DC fast chargers required in Germany using data from 6339 trip diaries. According to their findings, 500 chargers could support 500,000 PEVs.

2.3. CONSUMERS AND POLICIES

According to questionnaire surveys and interviews, mainstream automobile purchasers currently have little understanding and awareness of PEV recharging facilities (Kurani et al., 2016). Consumers who have purchased a PEV or are interested in acquiring one are the only ones who are well-versed on charging infrastructure. Individuals who have not acquired a PEV are less educated about their prospective charging alternatives. Only 18% of mainstream automobile purchasers have seen a public EV charger, according to Bailey et al., (2015). According to studies, a lack of knowledge is associated with a lack of intent to purchase a PEV. However, it is uncertain if increasing awareness of charging infrastructure would enhance the likelihood of purchasing a PEV - statistical data suggests a poor or non-existent association (Bailey et al., 2015). In other research, boosting PEV users' understanding of infrastructure led to higher usage of charge stations, which increased the overall electric kilometres travelled by the cars (Kurani et al., 2016).

A demand-driven model has as its main objective the construction of charging piles to encourage EV adoption, however focusing solely on the one-way impact of EV charging infrastructure on EVs will result in a one-sided view of this issue. The placement of EV charging stations in select public facilities or strategic locations where use is expected (e.g., government buildings, retail malls, leisure venues) can be a valid strategy in the early stages of EV marketing in order to attract customers to the EV market. As a result, given that the technical and financial barriers to investment in the EV charging infrastructure sector are not large, the dissemination of charging stations are also expected to be influenced by the growth in EVs (Zhu et al., 2017). In conclusion, research evaluating the link between EVs and EV charging infrastructure should include methods for detecting not just one-way effects but also interactions.

In order to incentivise the consumers to change their behaviour, PEVs are subsidised by governments in numerous nations. PEV refunds range from $3450 to $8500 in France, Sweden, the United Kingdom, China, and different Canadian provinces (Sheldon & Dua, 2019). Norway, the Netherlands, France, Denmark, the United Kingdom, and China all provide significant tax incentives for PEV purchases and registrations (Sheldon & Dua, 2019). The United States offers a federal income tax credit for PEV purchases, with a minimum credit of $2500 for electric propulsion vehicles, increasing by $417 for the first 5 kWh of battery capacity and an additional $417 for each additional kWh of battery capacity in excess of 5 kWh, up to a maximum credit of $7500 (Sheldon & Dua, 2019).

According to Yang et al., (2016), the leading PEV markets, such as California, Norway, and the Netherlands, offer the most generous PEV purchasing incentives. Sierzchula et al., (2014) employ regression methods to investigate the link between consumer financial incentives and national PEV market share in 30 countries, discovering a positive association between incentives and PEV adoption. Tal & Nicholas, (2016) use a stated preference survey of PEV customers in 11 different states in the United States. According to their findings, the federal tax credit accounts for more than 30% of PEV sales.

Data on EV registrations illustrates two major trends: the worldwide EV industry is still a small proportion of the entire automobile market, but it is fast rising. In 2017, EVs accounted for less than 5% of total car registrations in all major nations. Only in Norway did the percentage significantly reach 5% (Fredriksson et al., 2018). A wide, time-consistent policy strategy explains Norway's high proportion of registrations. Norway has implemented a successful policy mix through a succession of minor policy measures, encompassing a wide variety of interventions: regulations, direct investment, and fiscal benefits. Such a wide and long-term commitment has proven beneficial in influencing customer behaviour. The end product is stunning. Since 2010, the Norwegian EV fleet's proportion of total vehicle fleet has increased dramatically, from nearly nil in 2010 to 25,42% in 2022 ('Elbilbestand', 2022). Schulz & Rode, 2022 use an event study method applied for Norwegian regions and show evidence on the influence of public charging infrastructure installation on PEV sales, discovering that it enhances growth in electric car ownership in the given municipality.

PEV sales in the United States for 2013 were shown to be substantially connected with charging infrastructure, environmentalism, energy costs, education levels, vehicles miles travelled per capita, high-occupancy vehicle lane accessibility, and purchasing incentives by Vergis & Chen (2015). This study also found that consumer attribute variables (education, EV's awareness), geographic variables (average winter temperature, population density), energy cost variables (gasoline and electricity costs), and ability to access charging infrastructure away from home are all correlated with BEV market shares. Market characteristics (the number of PHEV models available for sale in the state), incentives (the presence of a direct purchase incentive, as well as the cumulative number of other supportive incentives/policies in the state directed towards PEVs), and average winter temperatures are the variables that are correlated with PHEV market shares. Only average winter temperatures were shown to be connected with both BEV and PHEV market shares, albeit in different directions. The discrepancies in final model composition and significant factors between the BEV and PHEV models established in their study imply that the variables contributing to the BEV markets may differ from those contributing to the PHEV markets. While this is unsurprising given the variations in range and refuelling/charging between a BEV and a PHEV, the study's findings suggest that policies targeted at boosting plug-in electric cars in general may not be equally beneficial in aiding both the BEV and PHEV markets. Education level, income (although income is generally connected with education level), age, and green lifestyle (defined as substantial changes in lifestyle and buying habits in the previous five years) have all been found to be positively correlated with the desire to purchase an EV (Hanke et al., 2014; Hidrue et al., 2011). Although, when other explanatory variables are included in the model, socio-demographic attributes can decrease or even disappear (Jansson et al., 2017).

Zubaryeva et al., (2012) polled European Union experts to determine the variables most likely to boost PHEV and BEV markets, and found that while the parameters mainly overlapped across the two technologies, the experts assessed them slightly differently for the two markets. Charging infrastructure, GDP per capita, population density, fuel cost reductions, and governmental incentives were listed as the most significant factors in BEV markets. In contrast, access to dedicated lanes or parking, fuel savings, GDP per capita, and infrastructure were ranked top in PHEV markets. Many different studies, using both surveys or statistical models, shows that the charging infrastructure is positively correlated with EV adoption (Jia & Chen, 2021;

Vergis & Chen, 2014; Zubaryeva et al., 2012), but often these studies do not show the diffusion of the infrastructure itself and the difference between the charging methods, which may exert different effects (Jia et al., 2019). Also surveys may express misconception and low awareness by the consumers (Krause et al., 2013; Long et al., 2019). The heterogeneity in the EU deployment of EV charging stations can help us better understand different factors that lead to a better infrastructure and how it impacts the consumers.

Endogeneity due to simultaneity bias and omitted variables is a key problem with regression estimations for the influence of charging infrastructure. While more charging options are likely to encourage local adoption, charging points are also being installed to meet the region's expanding demand for EVs, allowing impacts to operate in both directions. If this uncertainty could be statistically resolved, an ideal way for governments to choose between subsidising charging infrastructure and actively stimulating EV sales may be established. In Germany, for example, this decision has frequently come down to image politics and isolated, symbolic measures (Zink et al., 2020). Studying the Public charging infrastructure in Norway, Schulz & Rode (2022) showed that there is no statistically significant difference in BEV ownership rates between treatment and control groups prior to the installation of the first charging point.

As previously stated, the purchase of EVs and the development of EV charging infrastructure are significantly correlated, thus we can utilise similar condition variables for the model. It is also important to understand the consumer behaviour and government policies that could explain the outcome variable. Therefore, we decided to study the main contributors for a successful EV charging infrastructure diffusion, and propose as conditions for causality, a region's social-economical variables (GDP per capita, population density) allied to the sales share of PEVs, the number of PEVs per capita (Schulz & Rode, 2022) and governmental incentives for public charging infrastructure.

3. METHODOLOGY

3.1. SAMPLES AND PROCEDURES

All of the EV and EV charging infrastructure information were downloaded from the platform developed by the European Alternative Fuels Observatory. Eurostat provided the macroeconomic statistics. We can see the raw data used for the creation of the conditions and outcome variables in more detail in the Table I below.

TABLE I

BASELINE VARIABLES

Description	Variable	Source
Public Charging Infrastructure	PCI	*European Alternative Fuels Observatory* (2022)
PEV total fleet	PEV_TF	
PEV market share of new registrations (%)	PEV_SS	
Public Charging Infrastructure Incentive	PCII	
Population	POP	*Database - Population and Demography - Eurostat* (2022)
GDP per capita in PPS	GDP_PC	*Database - GDP per Capita, Consumption per Capita and Price Level Indices - Eurostat* (2022)
Area (km^2)	AREA	*Database - Population and Demography - Eurosta*t (2022)

The variables in the fsQCA model were produced by treating the aforementioned data in excel into the correspondent outcome and conditions variables presented in the Table II. In this study, we converted the raw data of four conditions: PEV per 1000 habitants (PEV_PC), PEV Sales Share (PEV_SS), GDP per capita (GDP_PC), Population Density (PD), Public Charging Infrastructure Incentive (PCII) and one outcome set, Public Charging Infrastructure per 1000 habitants (PCI_PC).

3.2. METHOD

A fuzzy set qualitative comparative analysis (fsQCA) methodology was applied in order to develop a new viewpoint on the subject and better understand the diffusion of the EV charging infrastructure. First introduced by Ragin (2000), Qualitative Comparative Analysis (QCA) is a hybrid between both qualitative (case-oriented research) and quantitative analysis (variable-oriented research) and it perceives the situation as a whole rather than breaking it down into variable components, emphasising the equifinality that several causes and routes might lead to the same conclusion (Yong & Park, 2017). With a reduced number of observations, this set-theoretic paradigm examines conjectural causality and condition combinations. In other words, this technique examines the causal relationship of many factors rather than testing individual independent effects. Unlike the traditional regression model, QCA allows for multicollinearity.

The causal relationship is explained as a series of relationships between the conditional variables in the fuzzy set analysis. If a causal condition X is present in the outcome Y ($X \subseteq Y$), then the causal condition X is a sufficient condition for the outcome Y. When the causal condition is always present when the outcome exists ($X \supseteq Y$), it becomes a necessary condition. Consistency can be used to determine the causal link between the conditions. The suitability of the link between the causal set and the outcome is referred to as consistency. The consistency value ranges between 0 and 1, and if it is more than 0.75, the causal condition becomes a sufficient requirement for the outcome (Ragin, 2008).

The most significant distinction between fsQCA and QCA is that although QCA uses the traditional aggregation principle of only 0 and 1, fsQCA may be represented by different degrees between 0 and 1, decreasing information loss in the analysis (Lai et al., 2015). Rather than the independent impacts of specific variables, the fsQCA can discover an integrated causal relationship established by numerous causal conditions. Furthermore, fsQCA provides benefits when there are few or no cases, and is actively utilised when performing comparison studies between nations.

As previously stated, numerous factors impact the adoption of EV charging infrastructure, with varied penetration rates per nation depending on how these factors are combined. As a consequence, qualitative comparative analysis is used, which is considered ideal for analysing distinct findings based on the combined causal relationship of causal circumstances. Furthermore, QCA has been proven appropriate for a medium-sized cross-country comparative study (Sehring et al., 2013).

Given the structure of the truth table, which not only helps researchers to think in terms of configurations but also displays exactly how much (or how little) actual data exist in the property space, this feature of limited diversity is adequately addressed in the QCA methodology (Ragin, 2008). Unlike quantitative methods, which cover areas devoid of empirical evidence with an estimated underlying distribution, QCA employs only the available evidence to map the property space and explicitly reveal all unknown configurations.

The standard scientific approach for dealing with a lack of evidence (non-existence or incomplete data) is to conduct experiments and generate the data required to construct theories. Curiosity drives science, and when such experiments are feasible, researchers participate in an active process of discovery by adjusting various input factors and observing whether (and how much) the output changes. However, the social sciences are not experimental, as researchers are unable to change input factors. They undertake thought experiments, including a counterfactual analysis, after being given the observed empirical data (Brady & Collier, 2004; Ragin, 2000).

The conditions used for this study are summarised in Table II. Starting with the outcome condition, it is reasonable to consider if the public charging infrastructure in each situation is sufficiently developed. Naturally, this examination will be in a state of continuous shift. A favourable outcome does not indicate that a said infrastructure is completely developed, nor does an unfavourable outcome at this point imply a completely unsuccessful endeavour to promote EV charging infrastructure in the long term. In other words, it portrays a specific moment in time.

TABLE II

CAUSAL CONDITIONS AND OUTCOME

Variables	Description
Outcome	
PCI_PC	Public Charging Infrastructure per 1000 habitants
Conditions	
PEV_PC	PEV per 1000 habitants
PEV_SS	PEV Sales Share (2021)
GDP_PC	GDP per capita (2021)
PD	Population Density (2021)
PCII	Public Charging Infrastructure Incentive

Using fsQCA, we will investigate the combinations for each condition using boolean algebra method (the logic of two binary alternatives; 0 and 1) and recommend optimal routes for a successful regional model for the diffusion of EV charging stations. The methodology highlights more cases than the variable. During the pooling process, the traditional variable-oriented analysis overlooks the individual features of each variable. fsQCA, on the other hand, treats each case as a whole, and each case retains its original characteristics with a membership score. The calibration process reflects these original characteristics, and the raw data is converted into fuzzy membership scores. The fuzzy membership score is the original data's standardised value using the maximum, average and minimum values.

First, the calibration thresholds were set using the minimum, average, and maximum values for a standardised middle point, suitable for the Boolean algebra application. Each raw data was converted into a value between 0,05 and 0,95 (default calibration method in *QCA* library for R) based on the concept of a continuous fuzzy set, using the function presented in the code (Appendix III - DATABASE CALIBRATION). The specific values of the raw data and the converted fuzzy scored data are listed in the Appendix I.

With this data, Necessity Analysis, Truth Table and Complex and Parsimonious Solutions were calculated as shown in the following (Appendix III - FSQCA MODEL). All the parameters for the calculations were set based on the literature (Sehring et al., 2013; Yong & Park, 2017) and/or default settings provided by the *QCA* library in R software.

4. RESULTS

We used basic descriptive statistics for both the baseline data and converted fuzzy scored data before conducting the Necessity Analysis, as shown in Table III and IV - each database can be seen in the Appendix I.

TABLE III

DATABASE DESCRIPTIVE STATISTICS

	Variable	N	Mean	Std. Dev.	Min	Pctl. 25	Pctl. 75	Max
1	PCI_PC	27	0.759	1.121	0.048	0.197	0.85	5.166
2	PEV_PC	27	8.394	9.395	0.49	1.006	14.135	32.234
3	PEV_SS	27	11.498	10.614	1.61	3.16	16.77	40.91
4	GDP_PC	27	104.296	47.643	55	75	120	277
5	PD	27	186.394	305.247	18.194	71.949	142.179	1610.412
6	PCII	27	0.407	0.501	0	0	1	1

TABLE IV

CALIBRATED DATABASE DESCRIPTIVE STATISTICS

	Variable	N	Mean	Std. Dev.	Min	Pctl. 25	Pctl. 75	Max
1	PCI_PC	27	0.282	0.269	0.05	0.089	0.496	0.95
2	PEV_PC	27	0.349	0.335	0.05	0.06	0.669	0.95
3	PEV_SS	27	0.36	0.319	0.05	0.077	0.629	0.95
4	GDP_PC	27	0.366	0.245	0.05	0.148	0.567	0.95
5	PD	27	0.271	0.222	0.05	0.119	0.316	0.95
6	PCII	27	0.417	0.451	0.05	0.05	0.95	0.95

To better illustrate, six maps containing each of the outcome and condition variables, using the baseline database, were created with the help of the tmap library for R, and are presented in the appendices. These maps and descriptive statistics (Table III and IV) can help us understand some of the outputs of the truth table, complex and parsimonious solutions when compared with the baseline data and will be discussed in due course.

Assume that, if a certain outcome Y occurs, a specific cause X must exist. This particular cause X is defined as a required condition. In other words, Y implies that X and Y are subsets of X (Thomann & Maggetti, 2020). To establish that a certain condition is necessary, the consistency level (inclN) should be greater than 0.9 (Hirschhorn et al., 2019; Vis & Dul, 2018). With the rigorous standard of 0.9 for inclusion (inclN) and 0.6 for relevance (RoN), we have 4 solutions for the Necessity Analysis, PEV_PC, and combinations of PEV_SS + GDP_PC, PEV_SS + PD and GDP_PC + PD. Each of these results presented on Table V could be explained - as previously discussed during the literature review, the development of the EV public charging infrastructure is generally strongly correlated with the sales of PEVs, this can be explained by the consistency of 0.912, the coverage of 0.737 and relevance level of 0.876. We can also observe that the permutations of the sales share of PEVs in 2020, GDP per capita, and population density are necessary, although they have slightly less coverage; they all have relevance superior to 0.75.

TABLE V

NECESSITY ANALYSIS

	inclN	RoN	covN
PEV_PC	0.912	0.876	0.737
PEV_SS + GDP_PC	0.959	0.760	0.607
PEV_SS + PD	0.934	0.752	0.591
GDP_PC + PD	0.925	0.786	0.623

With 5 causal conditions, there are 32 rows in the truth table (Table VI), out of which 3 positive output, 5 negative output configurations, and 24 remainders. The truth table is sorted first by the values of the OUT column (in descending order), then by the values of the frequency column n. The consistency scores are unsorted, but this choice of structure emulates Schneider & Wagemann (2013).

TABLE VI

TRUTH TABLE

PEV_PC	PEV_SS	GDP_PC	PD	PCII	OUT	n	incl	PRI	cases
1	1	1	1	0	1	3	0,999	0,996	BEL,LUX,NLD
1	1	1	0	1	1	4	0,956	0,790	AUT,DNK,FIN,SWE
1	1	1	1	1	1	1	0,932	0,000	DEU
1	1	0	0	0	0	2	0,828	0,340	FRA,PRT
0	1	1	0	0	0	1	0,780	0,129	IRL
0	0	0	1	0	0	2	0,607	0,058	ITA,MLT
0	0	0	0	1	0	6	0,364	0,000	HRV,GRC,LTU,ROU,SVK,ESP
0	0	0	0	0	0	8	0,329	0,017	BGR,CYP,CZE,EST,HUN,LVA, POL,SVN

After outputting the truth table for better visualisation, we implement both, Complex and Parsimonious in order to determine the possible pathways for a successful public charging infrastructure implementation, based on the five condition variables. For the Complex, or conservative solution, unless a configuration's output value is altered to a positive value, it plays no function in the minimising process and hence does not contribute to the final outcome. It is for this reason that the solution is referred to as "conservative," since it makes no assumptions about any alternative configurations (most notably the remainders) other than those with a favourable outcome. It is conservative when compared to the parsimonious solution, which includes the remainders, therefore making counterfactual assumptions for which there is little or no empirical evidence. It is often referred to as "complex" because, while the solution is a simpler expression than the original configurations, the parsimonious solution is even simpler (contains fewer literals). Conservative solutions are more complex than parsimonious solutions and vice versa, but both are comparable to (and simpler than) the initial configurations. Explaining the negative output makes no sense: it is not the same as negating the outcome, and explaining configurations with consistencies below the inclusion cutoff is pointless.

The complex solution , outputted was the following:

M1: PEV_PC*PEV_SS*GDP_PC*PD + PEV_PC*PEV_SS*GDP_PC*PCII -> PCI_PC

TABLE VII

COMPLEX SOLUTION

		inclS	PRI	covS	covU	cases
1	PEV_PC*PEV_SS*GDP_PC*PD	0.965	0.871	0.554	0.284	BEL,LUX,NLD; DEU
2	PEV_PC*PEV_SS*GDP_PC*PCII	0.935	0.715	0.506	0.236	AUT,DNK,FIN,SWE; DEU
	M1	0.957	0.863	0.790		

The above solution can indicate two different cases: the first one, where there is a higher population density and no incentives for public charging infrastructure, and the second with presumably a lower population density and governmental incentives for the development of the public charging infrastructure, as observed on the maps on Appendix III.

The two pathways proposed by the complex solution are: PEV_PC*PEV_SS*GDP_PC*PD and PEV_PC*PEV_SS*GDP_PC*PCII, both with high levels of consistency as in Ragin's theory (Ragin, 2008), respectively 0.965 and 0.935.

In comparison to a complex solution, a parsimonious solution is a simpler yet equivalent expression. It is achieved by taking a less conservative approach to the empirical evidence and including remainders into the minimisation process. For the pure parsimonious solution, we include the specific output values "?" in the minimization process, better illustrated in Figure 1. Since remainders are not basic expressions, the Quine-McCluskey method (Ragin, 2004) regards them as having the same output value as the explained configurations.

The parsimonious solution , outputted was the following:

M1: PEV_PC*GDP_PC -> PCI_PC

TABLE VIII

PARSIMONIOUS SOLUTION

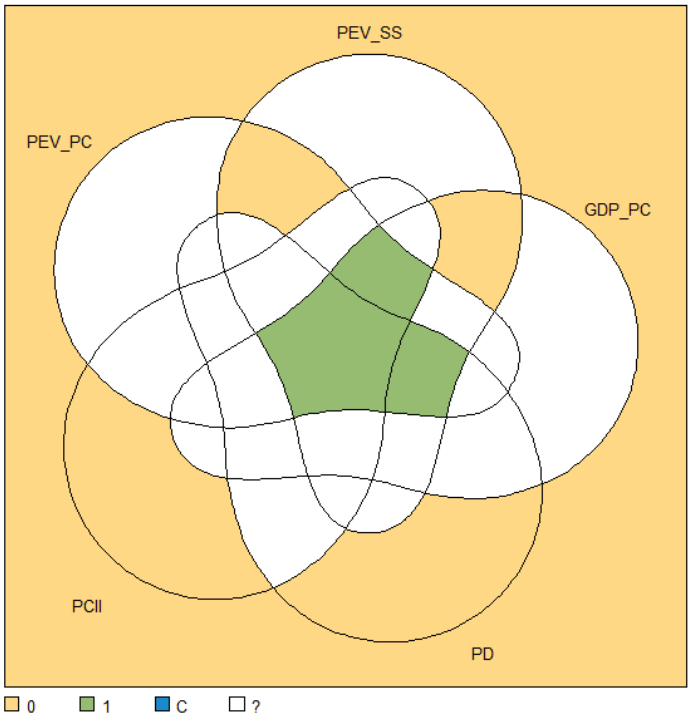
	inclS	PRI	covS	covU	cases
1 PEV_PC*GDP_PC	0.855	0.643	0.846	-	AUT,DNK,FIN,SWE; BEL,LUX,NLD; DEU
M1	0.855	0.643	0.846		

This minimum configuration reduction set should provide a straightforward and simple approach to the successful deployment of public charging stations in member states. Although recent literature indicates that the parsimonious solution can be more accurate in the social sciences (Baumgartner & Thiem, 2017, 2020), we could argue that the present model can benefit from the analysis of both solutions in parallel. The parsimonious solution had a coverage of 0.846, which means 84,6% of the explanatory power for all cases, and a total consistency of 0.855, which can be considered a high level of consistency based on Ragin’s theory (Ragin, 2008). This means that we can say that the clear pathway to the developed public charging infrastructure is a high number of PEVs and a high GDP per capita. This outcome was expected, although the complex solution can better illustrate the different characteristics between the two groups of countries.

The following venn diagram (Figure I) illustrates the results of the truth table (Table VI).

FIGURE I

VENN DIAGRAM



5. DISCUSSION

This study explored the combination of five conditional variables into the successful development of public charging infrastructure in a European Union case study. The Parsimonious solution confirms the proposed correlation between the market share of EVs and the implementation of the public charging infrastructure by different studies, using both surveys or statistical models, showing this positively correlation (Jia & Chen, 2021; Vergis & Chen, 2014; Zubaryeva et al., 2012), allied with the high levels of GDP per capita, also present in the literature (Zubaryeva et al., 2012). The complex solution displays an interesting fact: we observed that Belgium, the Netherlands, and Luxembourg are three of the countries in which the model indicates a high level of infrastructure development by the first pathway in the complex solution. These three countries mentioned above do not have monetary incentives for the implementation of public EV charging infrastructure at the present time of this study. Two hypotheses can be proposed to explain the reasons behind it. The first is that such incentives were present in the past, but are no longer necessary because the current level of infrastructure is already satisfactory. It is also important to clarify that countries have different charging needs and EV charging infrastructure policies. A country's public charging requirements can be greatly influenced by housing characteristics. For instance, Belgium has most of its houses prepared for slow-charging infrastructure compared with the Netherlands, which most are not, and the need for public charging stations is diminished. The second hypothesis is that because of the intrinsic characteristics of each country, policymakers thought that such incentives were not necessary and that the diffusion of public chargers was already adequate.

According to Zubaryeva et al. (2012), it is possible to deduce that the majority of regions are focused on large densely populated urban centres with apparent infrastructure and market size advantages. Some countries, such as Germany, Portugal, Sweden, Finland, Italy, Austria, the Netherlands, and Belgium, have an evenly distributed potential for lead for PEV markets, and consequently a opportunity for deployment of public charging stations whereas selected regions in Eastern Europe, such as the Polish region around Warsaw and the Hungarian region around Budapest, become viable lead markets for PEVs only in the 2030 accelerated scenario.

For the second successful pathway proposed by the complex solution, Austria, Denmark, Sweden, and Finland, the outsider, culturally, would be the central European, while the other three countries can behave very similarly and are heavily influenced by their neighbour and industry leader Norway. It is also possible to observe geographic and geopolitical similarities between the nations representing each solution. As a consequence, other political and sociocultural characteristics could be related to the deployment of public charging infrastructure. Germany is the only country that scored highly in all causal variables and can be explained by both successful pathways.

6. CONCLUSION

Over four million EVs were active in the EU fleet in 2021, and there is a significant increase in sales each year since 2010. To support the rapid expansion of technology, a solid and interconnected public charging infrastructure is required. In the introduction, we proposed to answer the question "What are the necessary conditions and successful pathways for the development of the public charging infrastructure in the European Union?" For that, the necessity analysis produced four different necessary conditions: PEV per 1000 habitants, and combinations of PEV sales share and GDP per capita; PEV sales share and population density; GDP per capita and population density . And, to answer the second part of the question, we employed two different tools present in the fsQCA methodology, Complex and Parsimonious solutions in order to establish the possible pathways for a successful public charging infrastructure implementation. The complex solution can indicate two different cases: the first one, where there is a higher population density and no incentives for public charging infrastructure, and the second with presumably a lower population density and governmental incentives for the development of the public charging infrastructure. The Parsimonious outputted the more simple and expected pathway, which is, simultaneously, a high number of PEVs and a high GDP per capita. Even though this outcome was foreseen, the complex solution can better illustrate the different characteristics between the two groups of nations.

There is currently no other publication in the literature that suggests a similar investigation. We could find others using the same methodology in a comparable application, such as the paper regarding the deployment of recharging infrastructure for hydrogen fuel in South Korea published by Yong & Park (2017), but none regarding the deployment of public EV charging infrastructure.

It was interesting to observe that the model output is clustering countries with similar cultural backgrounds, which could be a focal point for future studies in the area. A limitation of the model and another possible subject of interest would be the intrinsic characteristics of each country that can contribute to the development of EV public charging infrastructure versus home charging. It is also important to remember that this study retracts a snapshot of the variables in time, and that a model with temporal variation could result in different outcomes.

This research could represent an insight to stakeholders, namely industry players and governments, in what are some of the characteristics that enable the development of the public infrastructure and which nations can serve as an example for policy implementation.

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Appendix I - Database

	PCI_PC	PEV_PC	PEV_SS	GDP_PC	PD	PCII
AUT	1,468	12,546	16,810	121,000	108,057	1
BEL	1,185	15,724	15,640	122,000	381,250	0
BGR	0,077	0,490	2,660	55,000	63,873	0
HRV	0,429	0,864	3,530	70,000	138,573	1
CYP	0,064	0,903	1,610	88,000	145,785	0
CZE	0,205	1,483	2,910	92,000	130,667	0
DNK	0,985	21,589	30,930	133,000	71,526	1
EST	0,289	2,040	2,470	87,000	30,584	0
FIN	0,993	18,229	27,380	113,000	18,194	1
FRA	0,549	11,606	15,080	104,000	123,056	0
DEU	0,714	15,755	23,890	119,000	238,024	1
GRC	0,048	0,949	6,310	65,000	83,014	1
HUN	0,261	2,074	5,950	76,000	106,839	0
IRL	0,308	7,844	12,960	221,000	72,372	0
ITA	0,397	4,173	8,610	95,000	199,676	0
LVA	0,222	0,933	3,640	71,000	30,608	0
LTU	0,074	1,596	3,490	88,000	44,625	1
LUX	2,807	28,874	19,370	277,000	259,432	0
MLT	0,190	5,607	1,750	98,000	1610,413	0
NLD	5,166	22,342	25,200	132,000	518,013	0
POL	0,074	0,781	3,150	77,000	123,784	0
PRT	0,400	9,310	16,730	74,000	112,407	0
ROU	0,060	0,877	6,800	73,000	83,699	1
SVK	0,250	1,063	2,610	68,000	113,536	1
SVN	0,621	3,159	3,170	90,000	104,409	0
ESP	0,221	3,581	6,890	84,000	94,802	1
SWE	2,428	32,234	40,910	123,000	25,419	1

Appendix II - Calibrated Database

	PCI_PC	PEV_PC	PEV_SS	GDP_PC	PD	PCII
AUT	0,616	0,625	0,630	0,571	0,202	0,950
BEL	0,571	0,712	0,602	0,575	0,599	0,050
BGR	0,056	0,050	0,067	0,050	0,105	0,050
HRV	0,203	0,057	0,085	0,114	0,302	0,950
CYP	0,053	0,058	0,050	0,274	0,329	0,050
CZE	0,091	0,071	0,072	0,324	0,274	0,050
DNK	0,538	0,836	0,875	0,620	0,118	0,950
EST	0,125	0,086	0,064	0,262	0,061	0,050
FIN	0,539	0,771	0,831	0,537	0,050	0,950
FRA	0,295	0,598	0,589	0,496	0,248	0,050
DEU	0,454	0,713	0,776	0,562	0,527	0,950
GRC	0,050	0,059	0,176	0,087	0,141	0,950
HUN	0,113	0,087	0,161	0,156	0,199	0,050
IRL	0,134	0,449	0,537	0,880	0,120	0,050
ITA	0,183	0,172	0,297	0,365	0,507	0,050
LVA	0,098	0,058	0,088	0,120	0,061	0,050
LTU	0,055	0,074	0,084	0,274	0,077	0,950
LUX	0,797	0,926	0,687	0,950	0,538	0,050
MLT	0,087	0,262	0,052	0,407	0,950	0,050
NLD	0,950	0,848	0,798	0,616	0,665	0,050
POL	0,055	0,055	0,077	0,164	0,250	0,050
PRT	0,185	0,528	0,628	0,141	0,215	0,050
ROU	0,052	0,057	0,198	0,134	0,142	0,950
SVK	0,108	0,061	0,066	0,103	0,218	0,950
SVN	0,361	0,125	0,077	0,299	0,192	0,050
ESP	0,097	0,143	0,202	0,229	0,168	0,950
SWE	0,753	0,950	0,950	0,579	0,056	0,950

Appendix III - R Scripts

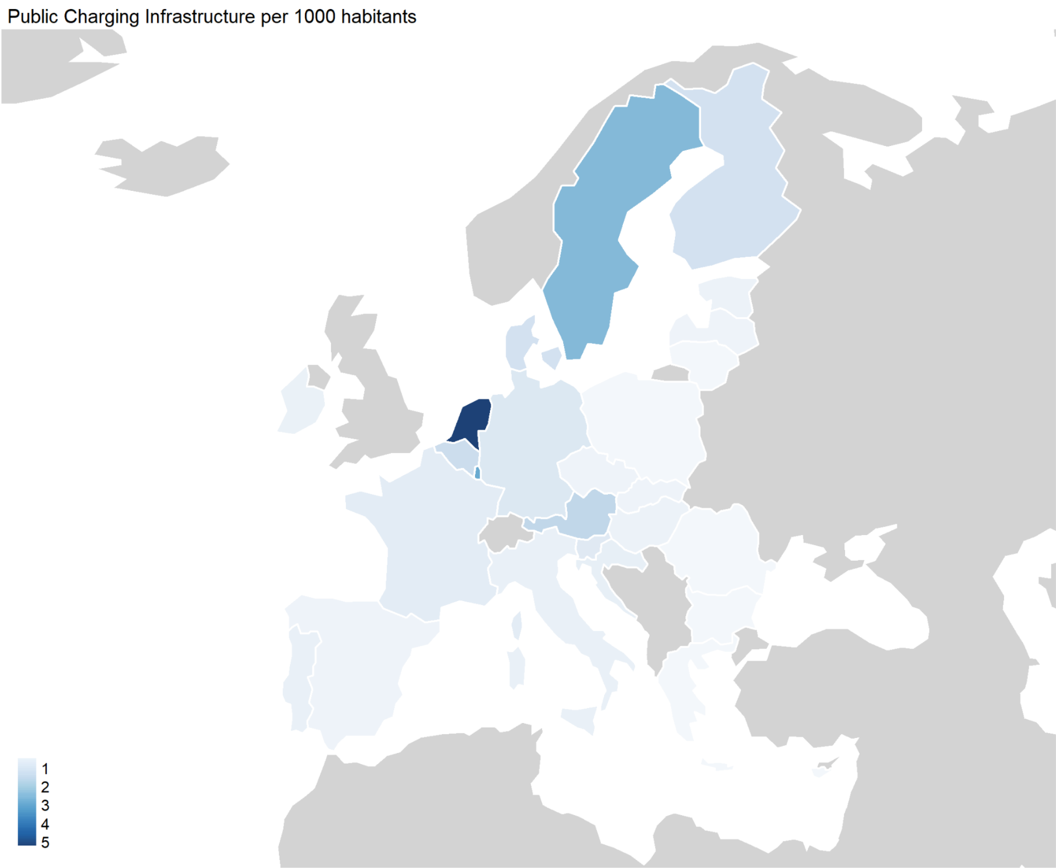
DATABASE CALIBRATION

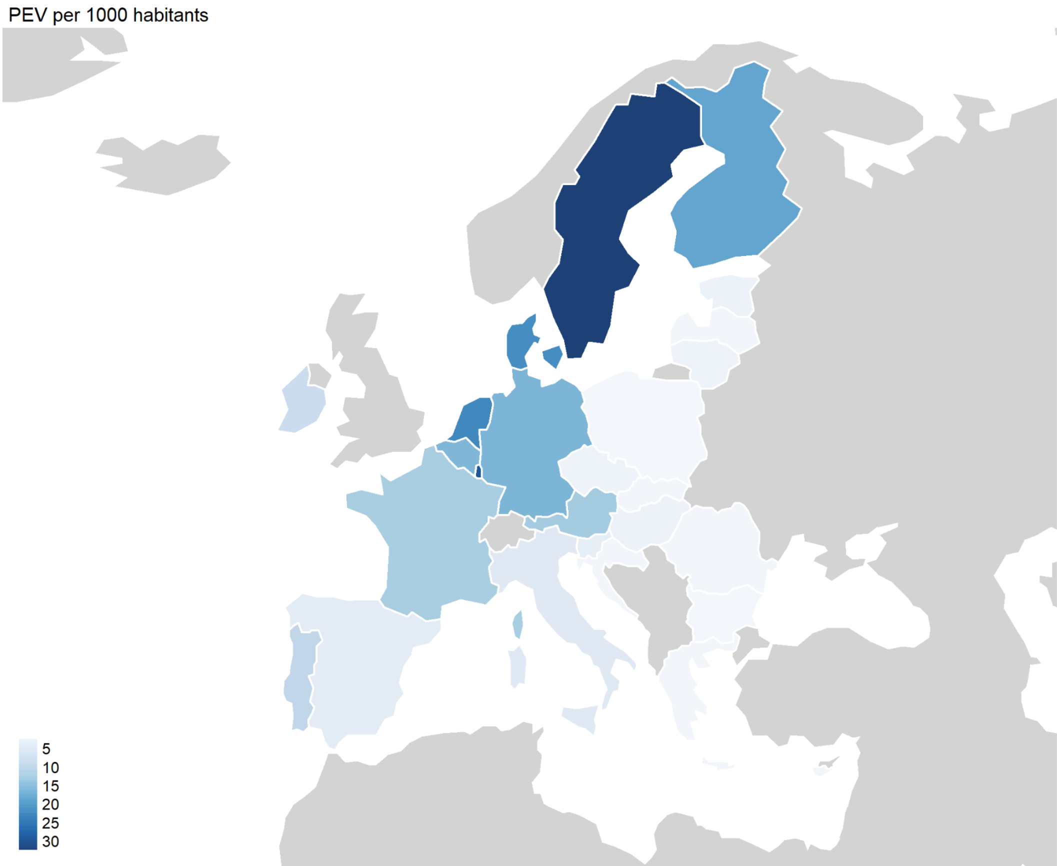
```
#Calibrated database
cal_database <- database

for(j in 1:(ncol(database))){

  # Calibration thresholds
    e <- min(database[,j])
    c <- mean(database[,j])
    i <- max(database[,j])
    th <- c(e, c, i)
  #Database Calibration
    x <- as.numeric(unlist(database[j]))
    cal_database[j] <- calibrate(x, thresholds = th)

}
```

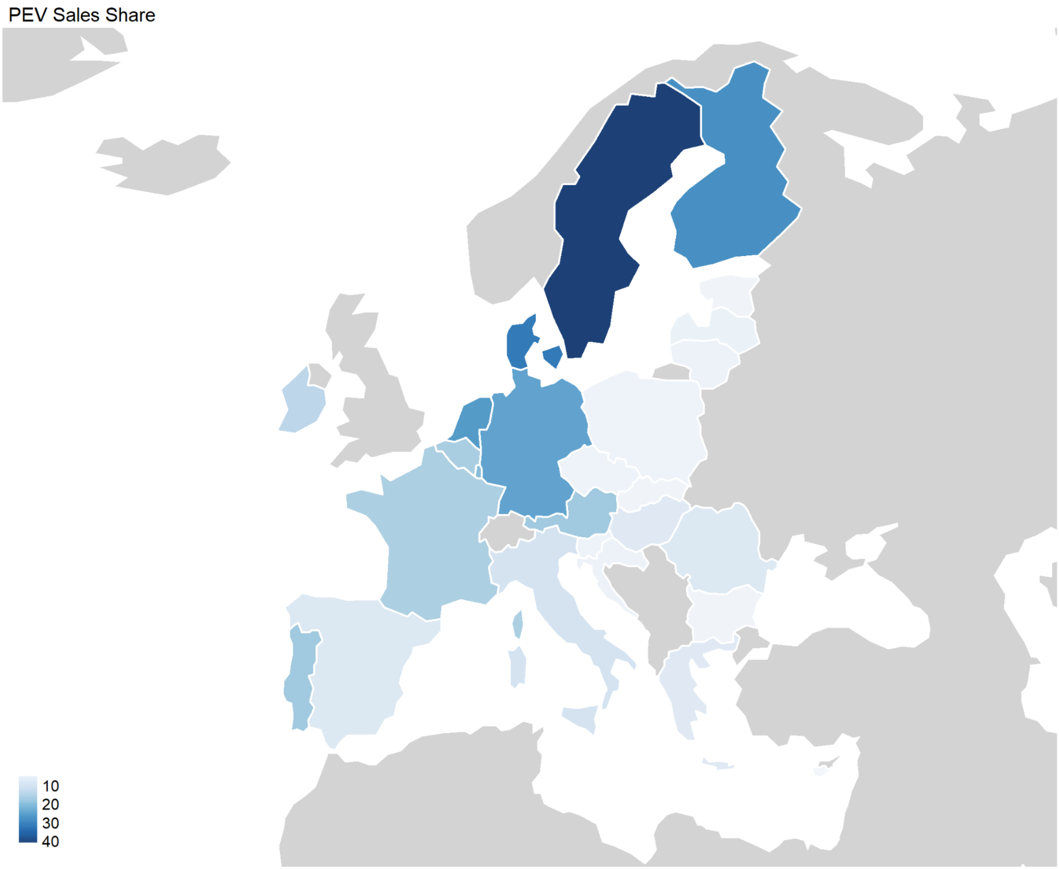
fsQCA MODEL

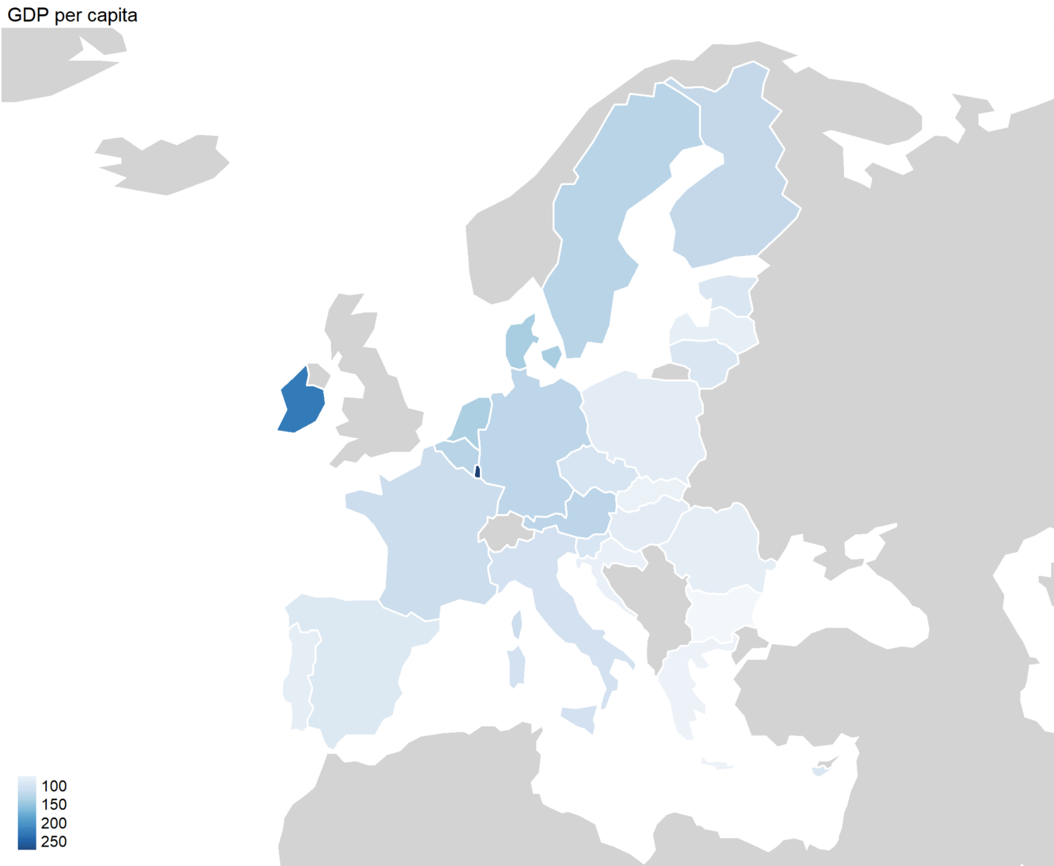
```
#Select conditions variable
cond <- names(cal_database)[2:ncol(cal_database)]

#Outcome = Public Charges
out <- names(cal_database[1])

  #Necessity Analysis
  necessity <- superSubset(cal_database, outcome = out, conditions = cond,
                           incl.cut = 0.9, ron.cut = 0.6)
  necessity
  #Truth table
  tt <- truthTable(cal_database, outcome = out, conditions = cond, incl.cut = 0.9,
                   n.cut = 1, complete = FALSE, show.cases = TRUE, sort.by = "incl, n",
dcc = FALSE)
  tt
  #Complex Solution
  complex <- minimize(tt, details = TRUE)
  complex
  #Parsimonious Solution
  parsimonious <- minimize(tt, include = "?", details = TRUE, show.cases = TRUE)
  parsimonious
```

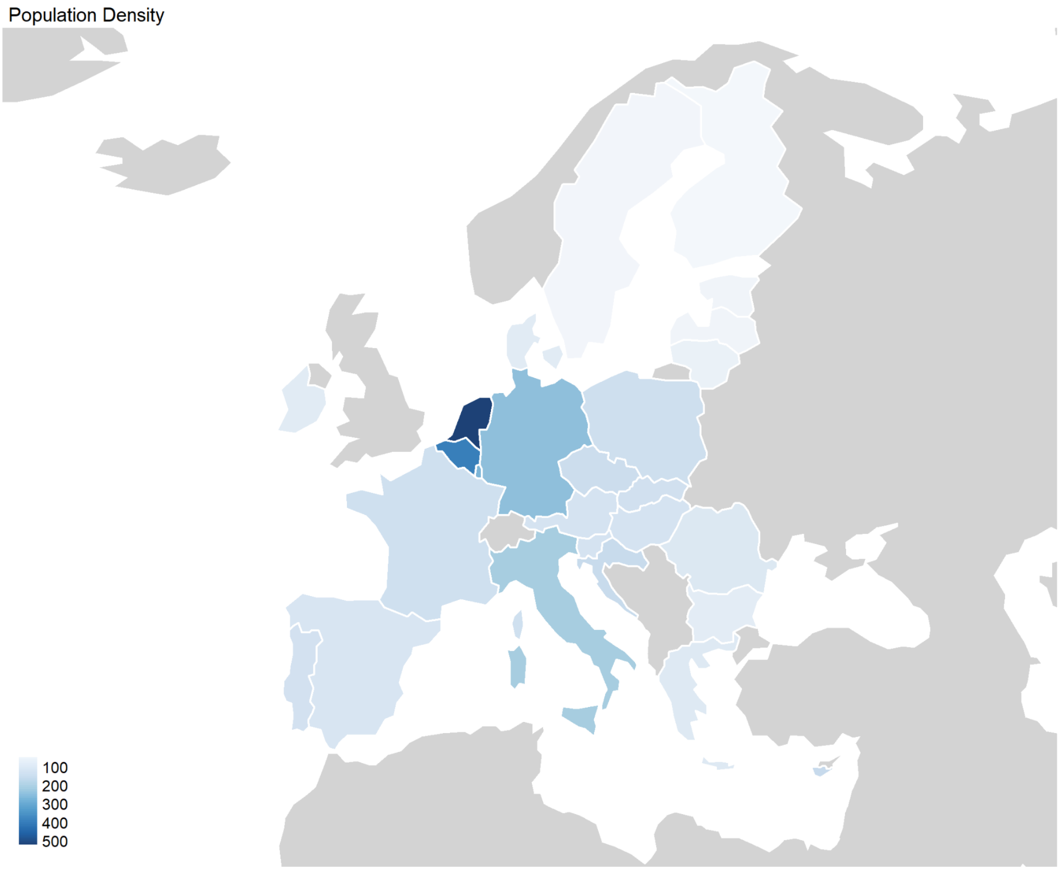
Appendix IV - Descriptive statistical maps

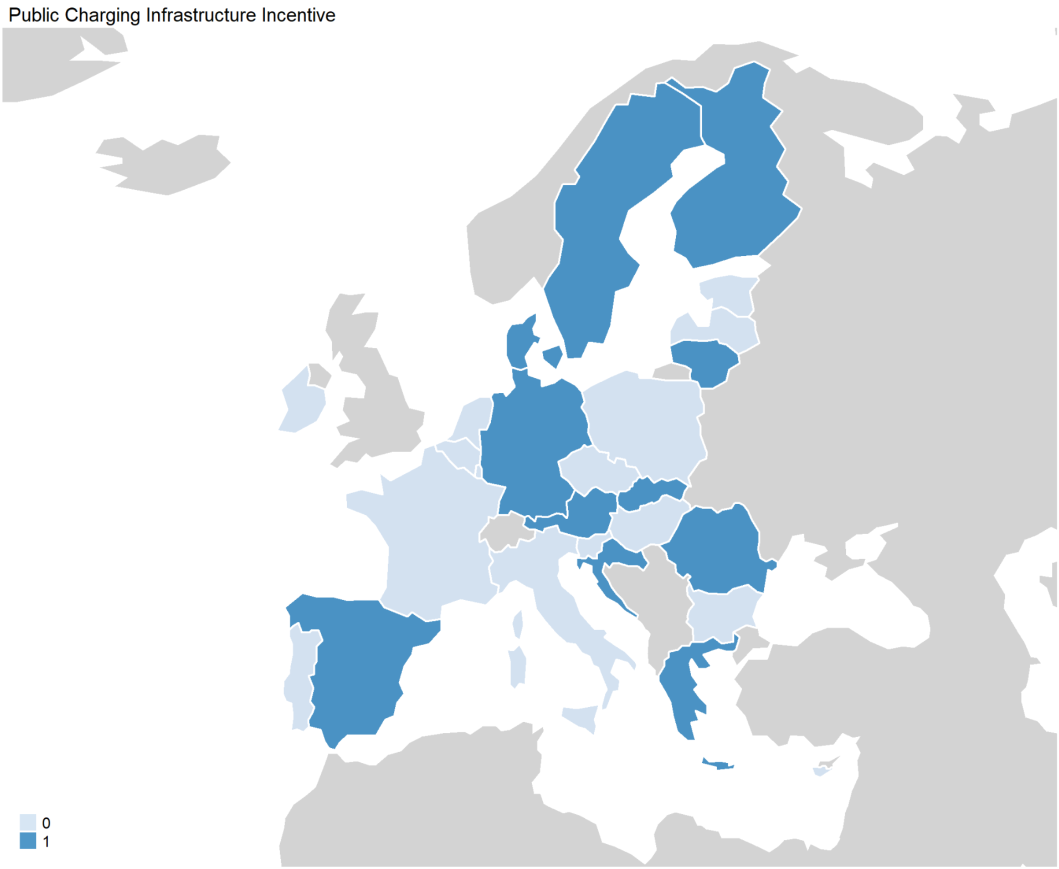



PEV per 1000 habitants
5
10
15
20
25
30


PEV Sales Share
10
20
30
40


GDP per capita
100
150
200
250


Population Density
100
200
300
400
500


Public Charging Infrastructure Incentive
0
1