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Essays on the economics of the energy mix diversification in the Transport Sector

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Resumo

A presente tese foca-se em analisar as consequências da diversificação do *mix* de energia no sector dos transportes. Este sector é intensivo no consumo de combustíveis fósseis e consequentemente, é responsável por elevados níveis de emissões de gases com efeito de estufa. De forma a mitigar o seu impacto ambiental, o uso de fontes de energia alternativas, tais como eletricidade e combustíveis renováveis deve ser incentivado. Contudo, existem inúmeros desafios associados à utilização destas fontes. Com o intuito de abordar alguns dos desafios enfrentados, a presente tese realiza quatro ensaios, organizados em três partes. Na parte inicial, são estudadas as interações entre o consumo de fontes de energia convencionais e alternativas no sector dos transportes, bem como a sua relação com o crescimento económico e com as emissões de dióxido de carbono. De forma a analisar essas interações, foram realizados dois ensaios. Neles, foram aplicadas duas metodologias recentes de análise de dados em painel: Vetor Autorregressivo em Painel (*Panel Vector Autoregressive - PVAR*) e o Modelo Autorregressivo com Desfasamento Distribuído (*Autoregressive Distributed Lag - ARDL).* Os principais resultados sugerem que o consumo de eletricidade no setor dos transportes será benéfico para o ambiente, se essa eletricidade for gerada a partir de fontes de energia renováveis. Enquanto isso, as fontes alternativas poderão estar a comprometer o crescimento económico, enfatizando que o custo-benefício dessas fontes deve ser melhorado.

A introdução de eletricidade no *mix* energético do setor dos transportes poderá ter um grande potencial em, por exemplo, possibilitar o armazenamento de eletricidade renovável aumentando assim a sua utilização. Para isso, as políticas devem promover o carregamento dos veículos quando existe excesso de geração de eletricidade renovável. Para que seja possível capturar esses benefícios, é necessária a implementação de eletricidade no transporte rodoviário. Definitivamente, estas evidências motivaram a segunda e terceira parte desta tese. As mesmas incidem nos principais desafios que a mobilidade elétrica rodoviária enfrenta: a penetração de veículos elétricos no mercado automóvel e o impacto dos veículos elétricos, quer na gestão do sistema elétrico quer na integração de energias renováveis. Assim, a segunda parte pretende analisar os fatores que suportam a adoção de veículos elétricos, abordando o seu papel individualmente tanto nos veículos 100% elétricos como nos híbridos *plug-in*. Fatores políticos, sociais, económicos, ambientais e técnicos foram incluídos e analisados. A Regressão Linear com Erros Padrão Corrigidos para Painel (*Panel Corrected Standard Errors - PCSE*) foi aplicada para analisar países da União Europeia e a robustez dos resultados foi comprovada mediante a aplicação de modelos de Regressão Aparentemente não Relacionada (*Seemingly Unrelated Regression - SUR*). A análise mostrou que o progresso tecnológico das baterias tem se revelado como um dos principais desafios para a implementação dos veículos 100% elétricos e dos híbridos *plug-in*. Além disso, este ensaio realça que as políticas devem ser focadas em cada tipo de veículo individualmente em vez de concentradas na mobilidade elétrica como um todo. Tendo em conta os resultados obtidos na primeira parte desta tese, países com elevado potencial em energias renováveis devem promover mais os veículos 100% elétricos do que os veículos híbridos *plug-in*, de forma a conseguir tirar maior vantagem da utilização intensiva de eletricidade renovável. Pelo contrário, países com baixo potencial em renováveis devem promover mais a utilização de híbridos *plug-in*.

Poderão os veículos 100% elétricos contribuir para o aumento da eficiência do sistema elétrico e para a integração de renováveis? Esta curiosidade constitui-se como a essencial motivação para a terceira parte. O seu principal objetivo é analisar os impulsionadores do pico de consumo de eletricidade e de integração de renováveis, dando especial foco ao papel que os veículos 100% elétricos desempenham nesse equilíbrio. A Regressão Linear com Erros Padrão Corrigidos para Painel (*Panel Corrected Standard Errors - PCSE*) e a Regressão com Erros Padrão de *Driscoll-Kraay* (*Regression with Driscoll-Kraay standard errors*) foram os modelos aplicados para analisar países da União Europeia. Foram testadas diferentes especificações nos modelos, confirmando assim a robustez dos resultados. Esta parte salienta que o aumento da quota de mercado de veículos elétricos gera um decréscimo do pico de consumo de eletricidade, o que é, na verdade, um efeito desejável num sistema electroprodutor. Este efeito deve, no entanto, merecer atenção dos decisores de políticas, uma vez que, a implementação de um elevado número de veículos 100% elétricos, poderá alterar este efeito colocando picos de consumo em outros períodos. Importa salientar também que os resultados sugerem que as políticas aplicadas para a gestão ativa da procura (*Demand Side Management - DSM*) de eletricidade têm sido efetivas na integração de renováveis, mas não têm contribuído para reduzir o pico de consumo. Os decisores de políticas devem delinear políticas de DSM eficientes, promovendo, por exemplo, medidas de resposta da procura, tais como tarifas de eletricidade com preços diferenciados entre períodos de pico e períodos fora de pico.

Palavras-chave

Sector dos Transportes, Fontes de Energia Convencionais, Fontes de Energia Alternativas, Crescimento Económico, Emissões de Dioxido de Carbono, Veículos Elétricos a Bateria, Veículos Híbridos P*lug-in*, Pico de Consumo de Electricidade, Fontes de Energia Renováveis

Resumo Alargado

O sector dos transportes é altamente intensivo no consumo de combustíveis fósseis, sendo responsável não apenas por elevados níveis de emissões de gases com efeito de estufa, como também por manter as economias dependentes de combustíveis fósseis. Deste modo, esta tese pretende analisar as consequências da diversificação do *mix* de energia do sector dos transportes. De facto, analisando os dados históricos, pode verificar-se que, mesmo com o elevado desenvolvimento e penetração de energias renováveis no *mix* de energia dos países, em geral observa-se que a sua dependência em relação ao uso de combustíveis fósseis mantém-se. Deste modo, poder-se-á afirmar que os transportes têm atuado como uma barreira a diversificação do *mix* de energia das economias.

Para ultrapassar essa barreira, a dependência dos transportes em combustíveis fósseis deve ser reduzida, promovendo a utilização de fontes alternativas como eletricidade e combustíveis renováveis. É importante realçar que, este não é apenas mais um sector que necessita de mudar o seu paradigma de energia. De facto, os transportes têm um enorme potencial que deve ser aproveitado, nomeadamente no armazenamento de eletricidade e na acomodação de fontes renováveis. Esta é, na verdade, a principal motivação para o desenvolvimento desta pesquisa que pretende providenciar evidência empírica sobre os efeitos que têm resultado da diversificação do *mix* de energia do sector dos transportes no crescimento económico e no ambiente. Posteriormente, este documento aborda os principais desafios da eletrificação, a saber: a penetração de veículos elétricos e o seu consequente impacto na gestão do sistema elétrico e também na acomodação de renováveis. Para abordar esses desafios, primeiramente foram analisados os fatores que suportam adoção de veículos elétricos. Em segundo, analisaram-se os impulsionadores do pico de consumo de eletricidade dando especial foco ao papel desempenhado pelos veículos 100% elétricos. Para alcançar estes objetivos, esta tese é composta por três partes que acomodam quatro ensaios.

Na primeira parte, analisam-se as interações entre crescimento económico, emissões de dióxido de carbono e o consumo de energia nos transportes subdividindo-o em fontes convencionais e alternativas. Para um melhor entendimento da complexidade da diversificação do mix de energia no sector dos transportes e os seus impactos, dois ensaios foram realizados. Para tal, utilizaram-se modelos autorregressivos, nomeadamente Vetor Autorregressivo em Painel (*Panel Vector Autoregressive - PVAR*) e modelos Autorregressivos com Desfasamento Distribuído (*Autoregressive Distributed Lag - ARDL*). No geral, os resultados sugerem que, a redução de consumo de combustíveis fósseis pode ser alcançada através da promoção de investimento em transporte ferroviário e também de promoção do uso de eletricidade. No entanto, encontra-se evidência empírica para que a utilização de combustíveis renováveis esteja a deprimir o

crescimento económico. Esta parte evidencia também que os benefícios ambientais da utilização de eletricidade poderão só ser alcançados caso essa eletricidade seja gerada a partir de fontes renováveis. Esta suspeita é suportada porque, por um lado, o consumo de eletricidade nos transportes não tem relação com as emissões nos países de alto rendimento. Por outro lado, para 15 países da Organização para a Cooperação e Desenvolvimento Económico (OCDE), o consumo de eletricidade impulsiona as emissões de dióxido de carbono.

Os resultados alcançados por estes dois ensaios revelaram-se cruciais para motivar e essencialmente guiar o desenvolvimento da segunda e da terceira partes desta tese. Nelas são abordados os principais desafios com que a eletrificação dos transportes está confrontada, nomeadamente, a implementação de veículos elétricos no mercado automóvel, e o seu impacto na gestão do sistema elétrico e na acomodação de fontes renováveis.

A implementação de veículos elétricos é essencial para que seja possível capturar o potencial dos transportes quer na gestão do sistema elétrico, quer na integração de renováveis. Esta é, na verdade, a principal motivação para a segunda parte, que é constituída por um ensaio. Nele, pretende-se analisar o papel que vários fatores, nomeadamente políticos, sociais, económicos, ambientais e técnicos, desempenham na adoção de veículos elétricos, considerando individualmente os veículos 100% elétricos e os híbridos *plug-in*. Importa realçar que neste ensaio se inova também pela proposta de construção de uma variável que visa medir a evolução do progresso tecnológico das baterias. Para isso, recorreu-se à Análise da Componente Principal (*Principal Component Analysis - PCA*) para capturar a principal informação da evolução do custo, do alcance e da capacidade da bateria. Tomou-se como referência o veículo 100% elétrico *Nissan Leaf* porque este venceu vários prémios, nomeadamente , *2010 Green Car Vision Award, 2011 World Car of the Year and European Car of the Year, and 2011-2012 Car of Year Japan* e pode ser aceite como referência no mercado de veículos elétricos (Nhamo, 2015).

Empiricamente, foram utilizados dados anuais desde 2010 até 2016 para 20 países da União Europeia. Desenvolveram-se modelos utilizando a Regressão Linear com Erros Padrão Corrigidos para Painel (*Panel Corrected Standard Errors - PCSE*) e a robustez dos resultados foi comprovada pela aplicação de uma Regressão Aparentemente não Relacionada (*Seemingly Unrelated Regression - SUR*). Os resultados sugerem que um dos principais desafios para o desenvolvimento do mercado de veículos elétricos é tecnológico. A variável utilizada como *proxy* do progresso tecnológico das baterias dos veículos provou ser um significante impulsionador da sua quota de mercado. Este capítulo salienta também que os decisores de políticas devem focar-se em cada tipo de veículos, ao invés de na mobilidade elétrica como um todo. Por exemplo, e em linha com a primeira parte, países com grande potencial em renováveis devem promover mais veículos 100% elétricos em vez de híbridos *plug-in*. Pelo contrário, países com baixo potencial em renováveis devem promover mais híbridos *plug-in* em vez de 100%

elétricos. Entende-se que estes resultados podem ser de grande utilidade para que os decisores de políticas promovam a penetração de veículos elétricos no mercado automóvel.

O potencial dos veículos elétricos deve ser adequadamente explorado. De outra forma, a adoção de veículos elétricos em grande escala, poderá comprometer o normal funcionamento do sistema elétrico, caso esse elevado número de veículos efetuem o seu carregamento em horários semelhantes. Neste caso, poderá existir até a necessidade de aumentar a capacidade instalada de fontes flexíveis, como o carvão, para satisfazer a procura de eletricidade principalmente em períodos de pico, aumentando a ineficiência do sistema como um todo. Com um apropriado apoio político, nomeadamente em desenvolvimento tecnológico, os veículos 100% elétricos poderão contribuir para aumentar a eficiência do sistema elétrico e a integração de renováveis. Na verdade, estes têm um enorme potencial para poderem armazenar eletricidade renovável nas suas baterias e repô-las no sistema, para satisfazer, por exemplo picos de consumo (*Vehicle-to-Grid - V2G*). Esta tecnologia permite movimento bidirecionais de eletricidade entre o veículo e a rede elétrica, podendo ser carregado quando existe produção renovável e repor essa eletricidade na rede quando a produção de renováveis é baixa. Assim contribuirão não apenas para aumentar a eficiência do sistema, mas também para acomodar as renováveis.

Todas estas evidências, em particular o potencial deste sector em aumentar a eficiência do sistema elétrico, constituem a principal motivação da terceira parte. Assim, pretende-se analisar os impulsionadores do pico de consumo e da integração de renováveis. Neste ensaio, conferiu-se especial atenção ao papel que os veículos 100% elétricos desempenham neste equilíbrio. Para tal, analisaram-se países da União Europeia aplicando modelos de Regressão Linear com Erros Padrão Corrigidos para Painel (*Panel Corrected Standard Errors - PCSE*) e Regressão com Erros Padrão de *Driscoll-Kraay* (*Regression with Driscoll-Kraay standard errors*). Diferentes especificações foram testadas nos modelos para garantir a robustez dos resultados. Estes mostram que, por um lado, a penetração de veículos 100% elétricos têm contribuído para reduzir o pico de consumo de eletricidade. Este é, na verdade um resultado desejável, mas que deve continuar a merecer a atenção dos fazedores de política económica e de energia, uma vez que a quota de mercado destes veículos permanece baixa. Por outro lado, os veículos 100% elétricos estão a dificultar a integração de renováveis. Deste modo, são necessárias políticas de gestão ativa da procura (*Demand Side Management - DSM*) que promovam o carregamento de veículos quando existe excesso de eletricidade renovável. As medidas de gestão ativa da procura devem também ser delineadas com vista a reduzir o pico de consumo, uma vez que esta pesquisa verificou que essas políticas não têm sido eficientes na redução de picos de consumo. Incentivos para a utilização de tarifas de eletricidade diferenciadas entre horários de pico e horários fora de pico podem ser uma boa forma de alcançá-lo.

No geral, esta tese fornece evidências empíricas que devem ser consideradas pelos decisores de políticas. Elas, na verdade, refletem o que tem ocorrido até ao presente. De facto, esse conhecimento é essencial para a formulação de políticas eficientes. Contudo, o sector dos transportes está em mudança, em muito devido ao progresso tecnológico. No futuro, os resultados menos desejáveis encontrados poderão ser alterados mediante a aplicação de políticas adequadas e mais eficientes e também em resultado dos progressos tecnológicos que se irão verificar. De qualquer forma, os transportes e a eletricidade devem ser tidos em consideração conjuntamente na elaboração de políticas. Esse enquadramento poderá permitir que o sistema elétrico seja mais eficiente, aproveitando o potencial fornecido pelos transportes, nomeadamente da sua capacidade não só de armazenamento, mas também de entrega à rede. Para isso, os transportes devem tornar-se mais flexíveis, não apenas nos horários de carregamento dos veículos, mas também permitindo movimentos bidirecionais de eletricidade entre o veículo e a rede. Um novo mundo nos transportes está a ser construído. Está-se ainda a tempo de tomar decisões acerca dos modelos de construção e dos materiais a aplicar nessa construção. Se este documento ajudar na definição dessas opções, o objetivo maior estará atingido.

Abstract

The analysis of the consequences of the diversification of the Transport Sector energy mix is the main focus of this thesis. As a sector highly powered by fossil fuels, the promotion of alternative energy sources such as electricity and renewable fuels has to be pursued to reduce the use of oil, and consequently cut greenhouse gases emissions. However, currently, the alternative sources are faced with several challenges. To address some of these challenges, this thesis performs four analyses organized into three main parts. In the first one, the interactions between both conventional and alternative transports' energy sources, economic growth and carbon dioxide emissions have been examined. Two essays have been carried out in the first part, to achieve these objectives. The recent methods of Panel-Vector Autoregressive and the Autoregressive Distributed lag models have been applied. The main findings suggest that the electricity use in the transport sector only contributes to reducing GHG emissions if this electricity is coming from renewable sources. At the same time, the alternative energy sources could compromise the economic growth highlighting that their cost-effectiveness must be enlarged.

With adequate policy supporting, the penetration of the electricity in transport sector could have a great potential in, for instance, storing renewable electricity, improving renewable electricity utilisation. For that, the deployment of electricity on the road transportation is required. These evidences have definitively motivated the second and third main parts of this thesis. They are focused on the main challenges that the electric mobility on road transportation is faced: the penetration of electric vehicles in the automotive market and the impact of these vehicles on the electricity system management and renewables integration. Thus, the second part of this thesis aims to analyse the driving factors of electric vehicles adoption. This analysis goes further by distinguishing the adoption drivers of 100% electric vehicles, also known as battery electric vehicles, and plug-in electric vehicles. The factors analysed include: political, social, economic, environmental, and technical. A Panel-Corrected Standard Errors (PCSE) estimator is used for European Union countries and the robustness of the results has been confirmed by employing a Seemingly Unrelated Regression (SUR) method. Actually, the main challenge for both 100% electric vehicles and plug-in electric vehicles adoption is the technological progress of the batteries. Furthermore, this analysis highlights that the policymaking should be focused on each type of vehicle technology instead of electric vehicles as a whole. In line with the findings of the first part of this thesis, countries with high endogenous potential should promote more 100% electric vehicles than plug-in electric vehicles to take advantage of the renewable electricity. While countries with low renewable potential should promote more plug-in electric vehicles. The policies supporting electric mobility have been effective in the 100% electric vehicles market share enlargement, but not for plug-in electric vehicles.

With an appropriated policy support and technological development, the 100% electric vehicles could contribute to increasing the efficiency of the electricity system and renewables integration. These evidences constitute the main motivation for the third part of this thesis. Therefore, the main objective of the third part is to analyse the drivers of both peak electricity demand and renewables integration, providing special attention to the role played by battery electric vehicles to this equilibrium. Both Panel-Corrected Standard Errors and Driscoll-Kraay estimators have been applied for European Union countries. Different models' specifications have been used to confirm the robustness of the results found. This part highlights that the deployment of the 100% electric vehicles has led to a decrease of the peak electricity demand, which is indeed a desirable effect. Still, it should deserve further attention since the deployment of the large amounts of battery electric vehicles could modify this effect. At the same time, the 100% electric vehicles have not contributed to renewables integration. The policies focused on demand side management have been effective in integrating renewables in contrast to their lack of success in reducing peak electricity demand. The policymakers should design demand side management efficient policies to reduce the peak load demand. The promotion of Demand Response measures, such as differentiated electricity tariffs in peak periods and out-off peak periods could be an efficient way to achieve it.

Keywords

Transport sector, Conventional Energy Sources, Alternative Energy Sources, Economic Growth, Carbon Dioxide Emissions, Electric Vehicles, Battery Electric Vehicles, Plug-in Electric Vehicles, Peak Electricity Consumption, Renewable Energy Sources

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Acronyms list

BEV	Battery Electric Vehicles
CO_2	Carbon Dioxide
DSM	Demand Side Management
DK	Driscoll-Kraay
EV	Electric Vehicles
EAFO	European Alternative Fuels Observatory
EU	European Union
ESS	Energy Storage Systems
EV	Electric Vehicles
FEVD	Forecast Error Variance Decomposition
FRED	Federal Reserve Economic Data
GCF	Gross Capital Formation
GDP	Gross Domestic Product
GHG	Greenhouse Gases
HEV	Hybrid Electric Vehicles
ICE	Internal Combustion Engine
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
IRF	Impulse Response Functions
LCU	Local Currency Unit
OECD	Organisation for Economic Co-operation and Development
Solar PV	Solar Photovoltaic
SUR	Seemingly Unrelated Regression
PCSE	Panel-Corrected Standard Errors
PCA	Principal Component Analysis
RES	Renewable Energy Sources
R&D	Research and Development
TOU	Time of Use
TPES	Total Primary Energy Supply
TSO	Transmission System Operator
TS	Transport Sector
UNFCCC	United Nations Framework Convention on Climate Change
V2G	Vehicle to Grid
VIF	Variance Inflation Factor
WIPO	World Intellectual Property Organization
WDI	World Development Indicators

Chapter 1

Introduction

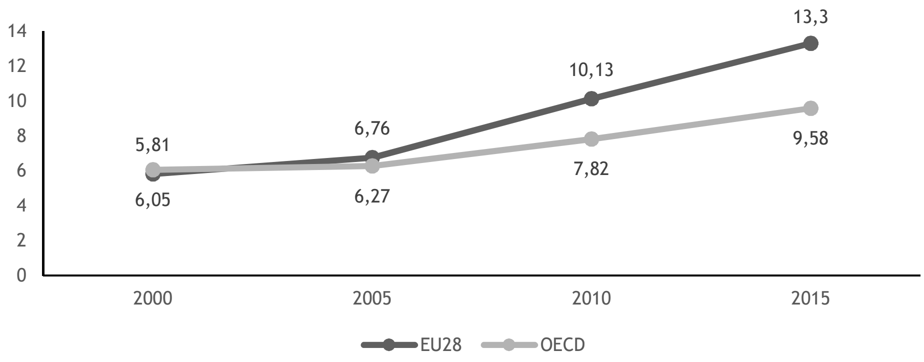
This thesis is focused on Transport Sector (TS) energy mix diversification. This is indeed a relevant focal point that has concerned not only the researchers but also policymakers worldwide. There are two relevant effects caused by the TS that deserve the focused attention of policymakers. On the one hand, the TS is responsible for high levels of Greenhouse Gases (GHG) emissions resulting from the combustion of fossil fuels. On the other hand, given that this sector is highly intensive in fossil fuels use, it acts as a barrier for both electricity and Renewable Energy Sources (RES) penetration. Thus, the shift of the energy paradigm in the economies remains quite dependent on the diversification of the TS' energy mix. The penetration of the electricity in the TS could be an efficient solution in decarbonising the TS, since it allows for capturing RES potential. These facts constitute the basis of the motivation for the development of this thesis. As well as the need of the transport sector to contribute to the reduction of GHG emissions, how the energy mix diversification impacts the transport sector is the main and transversal research question of this thesis.

Our main objective is to provide evidence, mainly empirical, about the effects that have resulted from the alternative TS energy sources use in both the economic growth and carbon dioxide (CO_2) emissions. Additionally, it also addresses the main challenges with which the transition to electric mobility has been faced, namely the social acceptance and the impact on electricity system management. Therefore, it is composed of three main sequential parts accommodating four analyses. Overall, it starts with the general framework of the TS' energy use, analysing individually both conventional and alternative energy sources. Following that, it addresses challenges that electric mobility has faced, namely the factors supporting their penetration into the automotive market and the Electric Vehicle (EV) impact on peak load demand and RES integration.

The empirical evidence of this thesis is based mainly on the Organization for Economic Co-operation and Development (OECD) countries and the European Union (EU) countries. The choice of these specific countries analysed has been described in each chapter. Overall, these countries seem to us of particular relevance and interest because they are in general leaders in the diversification of the energy mix, not only regarding the electricity produced, but also in the diversification of the TS energy sources. This main reason allied with data availability determines the main selection criteria of the specific countries studied followed throughout this thesis.

To furnish this empirical evidence, different recent econometric techniques have been employed in accordance with both the research objectives as well as with the data features. Moreover, various techniques are used to prove the robustness of the results. In particular, taking into account the contemporaneity of the study the available data is scarce. At times the nature of our study obligated us to operationalise econometrically models with a short-time span. For these reasons, the panel data techniques have been used because it allows us to obtain a reasonable number of observations, which makes the econometric operationalization viable. Moreover, by fusing the cross-sectional with the time-series data, it enables the precise parameters estimation (Hsiao, 2007).

In order to understand the motivation for this thesis development, some facts and statistics have been shown as follows: For the purpose of the reduction of the GHG emissions from energy, the promotion of the RES, namely on the electricity generation has been pursued. Figure 1.1 reveals the evolution of the contribution of the RES for the Total Primary Energy Supply (TPES) for 28 EU countries and OECD countries.



Notes: Own elaboration. Data source: OECD (2018),
Renewable energy (indicator). doi: 10.1787/aac7c3f1-en (Accessed on 23 October 2018)

Figure 1.1 - Share of renewable in Total Primary Energy Supply

Despite the enlargement of RES penetration in the electricity mixes, and their growing contribution to the TPES (see Figure 1.1), it has not yet resulted in a reduction of the GHG from energy. In fact, following the data from the United Nations Framework Convention on Climate Change (UNFCCC) in the OECD countries this energy contributed 80.2% of the GHG emissions in 1990, and 81.2% in 2016[1]. This is a quite interesting question and even more interesting would

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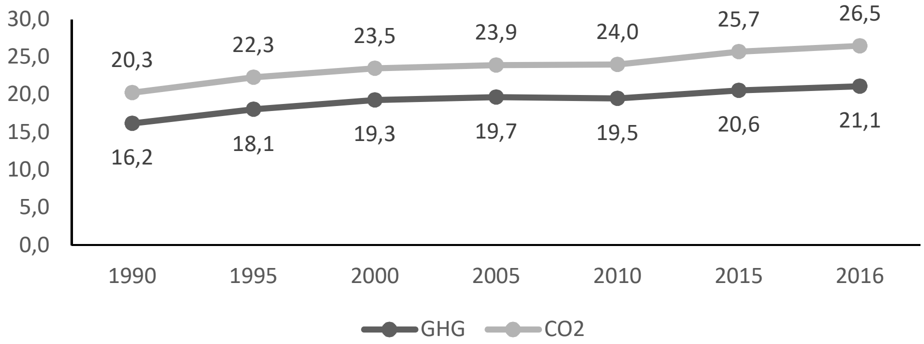
[1] The countries that compose Annex-I from UNFCCC are: Australia, Austria, Belarus, Belgium, Bulgaria, Canada, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary,

be to understand the reasons behind this fact. Definitively, this unexpected evidence has caught our attention.

This means that sectors highly powered by fossil fuels, such as TS has made the diversification of the energy mix more difficult. In other words, the economies remain dependent on fossil fuels to satisfy the TS energy demand. As a consequence, the RES penetration has not been reflected in a reduction of the GHG emissions because this sector is responsible for high levels of emissions. Figure 1.2 shows the contribution of the TS for both GHG and CO_2 emissions in OECD countries contained in Annex-I from the UNFCCC.



Notes: Own elaboration. Data source: UNFCCC Data Interface.

Figure 1.2 - Contribution of the TS for total GHG and CO_2 emissions in OECD countries (%)

As can be seen in Figure 1.2, the contribution of the TS for the total GHG and CO_2 emissions is still growing. The stabilization verified from 2005 to 2010 could be a consequence of the economic crisis verified in the OECD countries, namely the sovereign debt crisis. This contribution could even still be growing once it is expected that world demand for energy by the TS will increase in the next years as well as the demand of this sector for petroleum products (U.S. Energy Information Administration, 2017)[2]. Therefore, changes are required in this sector in order to reduce the negative externalities caused by TS, such as pollution, which compromise both public health and climate protection (Gössling, Cohen, Higham, Peeters, & Eijgelaar, 2018).

In this sense, the improvements in terms of energy efficiency have been pursued. In the EU, the energy efficiency in TS has improved 1.2% per year, reducing TS energy consumption (Gössling et al., 2018). Despite the energy efficiency progress verified, the effects remain

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Iceland, Ireland, Italy, Japan, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Monaco, the Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russia Federation, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine, the United kingdom of Great Britain and Norther Ireland, and the United States of America.

[2] The citation style APA 6th edition (American Psychological Association, 2010) been used throughout this thesis.

insufficient to accomplish the environmental goals. There is a broad consensus wherein the shift in the TS energy paradigm is mandatory to decarbonise not only the sector but also the entire economy. The promotion of alternative TS energy sources (electricity and renewable fuels) ought to be followed. However, this shift in the TS energy paradigm is more challenging than in other sectors less intensive in fossil fuels, such as the services sector.

All together these facts have definitely inspired the motivation for this thesis. The first part of this thesis is composed by two analyses (chapters 2 and 3) focused on the analysis of the effects that result from the simultaneous use of both conventional and alternative TS' energy sources on economic growth and CO_2 emissions. Although the relationship between TS' energy consumption, economic growth and CO_2 emissions are amply documented in the literature (see e.g. Chandran & Tang, 2013; Saboori, Sapri, & bin Baba, 2014), the analysis of the effects that result from the simultaneous use of both conventional and alternative TS energy sources is a quite unexplored topic. Therefore, chapter 2 of this thesis aims to fill this gap, by analysing the consequences of the simultaneous use of both conventional and alternative TS' energy sources on both economic growth and CO_2 emissions. Indeed, the transition to alternative energy sources should not compromise economic growth, rather it ought to contribute to the reduction of CO_2 emissions. Thus, chapter 2 aims to answer the following central research questions:

(i) What is the role played by both conventional and alternative TS' energy sources on economic growth and CO_2 emissions?

(ii) Are the TS alternative energy sources in the TS replacing the conventional sources?

Empirically, chapter 2 analyses the relationships between TS fossil fuels consumption, TS electricity consumption, TS renewable fuels consumption, CO_2 emissions and economic growth. Accordingly, a Panel-Vector Autoregressive (PVAR) approach, proposed by Abrigo & Love (2015) has been used for 21 high-income OECD countries from 1990 to 2014.

The main findings of chapter 2 indicate that TS' conventional energy use is contributing to economic growth. While renewable fuels are hampering it. Additionally, electricity consumption in the TS is causing economic growth. The decarbonisation of the economies remains dependent upon the abatement of the TS' fossil fuels use and CO_2 emissions. On the one hand, apparently the renewable fuels have contributed to reducing the fossil fuels used in the TS, although this effect is statistically significant only at a low significance level. On the other hand, there is no statistical evidence of the relationship between alternative energy sources and CO_2 emissions. This means that, regarding renewable fuels the social acceptance of these energy sources should be encouraged to increase the statistical significance of the relationship and decrease the CO_2 emissions. Concerning the absence of the causality between electricity use on TS and CO_2 emissions, this could indicate that the CO_2 savings “on road” is compensated for with an increase of the CO_2 emissions in the electricity generation process.

The TS is composed of set ways of mobility, namely railways, roads, navigation and aviation, that allows for the movements of the people, goods and services around the world. Some literature has been concerned with the relationships between different TS’ infrastructure, TS’ energy consumption, economic growth and CO_2 emissions (see e.g. Achour & Belloumi, 2016; Pradhan & Bagchi, 2013; Saidi, Shahbaz, & Akhtar, 2018). Usually, the length of infrastructure, expressed in kilometres is used (see e.g. Achour & Belloumi, 2016; Pradhan & Bagchi, 2013; Saidi, Shahbaz, & Akhtar, 2018). Chapter 3 of this thesis goes further on this point by incorporating the rail infrastructure investment in the analysis of the relationships between economic growth, CO_2 emissions, conventional and alternative TS energy sources. The inclusion of this variable allows for the capturing of the effects of both construction of the new networks and improvement of the existent infrastructures. Therefore, chapter 3 aims to answer the following central questions:

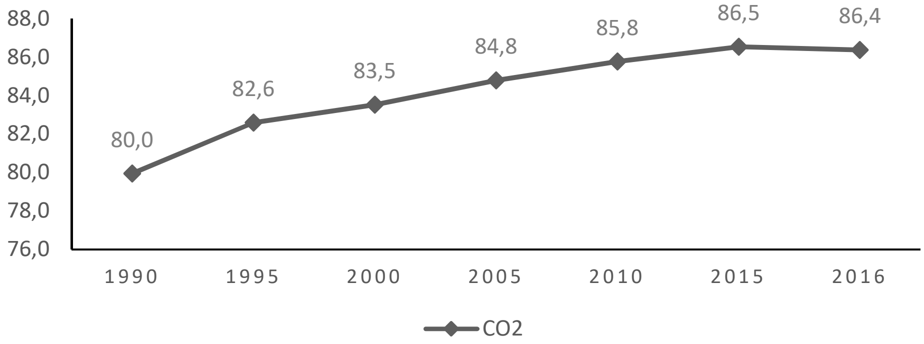
(iii) What are the consequences of using both conventional and alternative energy sources on the transition to electric mobility and on decarbonisation of the TS?

(iv) How have the alternative TS energy sources affected the economic growth?

To answer these questions the Autoregressive Distributed Lag (ARDL) model in a Driscoll-Kraay estimator has been used, analysing 15 OECD countries. Thus, four models have been estimated to analyse the relationships between the variables: Model I- Economic growth, Model II – TS fossil fuels consumption, Model III-TS electricity consumption, and Model IV-TS CO_2 emissions. The use of an ARDL structure allows us to capture both short- and long-run effects individually, as well as, the signs of the relationships.

From this chapter one observes that the reduction of TS fossil fuels use could be achieved by promoting the investment in rail infrastructure. Regarding the use of alternative energy sources, this chapter proves that electricity use in the TS could contribute to decreasing the use of fossil fuels but would actually increase CO_2 emissions. This finding corroborates that mentioned in chapter 2 wherein the reduction of CO_2 emissions caused by electricity use are being compensated for with an increase of the CO_2 emissions in electricity generation. Thus, it is in line with that documented by Ajanovic & Haas (2016), i.e., the electricity use in the TS will be beneficial for the environment only if this electricity is generated from RES. At the same time, the TS’ electricity consumption decreases the economic growth, indicating the high associated cost with the transition to electric mobility. Concerning renewable fuels, it proves that they contribute to reducing both economic growth and CO_2 emissions.

Together, these outcomes represent a focal point that deserves the attention of public policymakers to diversify the TS' energy mix. In fact, the negative externalities of this sector on the environment could be surpassed if the potential of the TS was correctly used. We are alluding to, for instance the potential of batteries to store electricity in low-consumption periods and replace it on the grid during peak periods, i.e. vehicle to grid (V2G) technology. So that potential can be harnessed, the acceptance of electric mobility should be expanded. The road TS is indeed a key action point because it is the main contributor to the TS CO_2 emissions, contributing in 2016 86.4% of the whole TS CO_2 emissions. Figure 1.3 reveals that road TS is showing an increasing trend in its contribution for all TS CO_2 emissions.



Notes: Own elaboration. Data source: UNFCCC Data Interface.

Figure 1.3 - Contribution of the road TS for total TS CO_2 emissions in OECD countries (%)

The current shift in the road TS energy paradigm is faced with several challenges, such as the high relative costs of the clean vehicles (Santos, 2017) and their penetration in the automotive market. Presently, the automotive market share of Electric Vehicles (EV) remains small. However, it is expected that it will increase significantly in the near future, mostly as a result of technological improvements of the batteries (Hannan, Lipu, Hussain, & Mohamed, 2017) and victory over "range anxiety". These evidences inspire us to go further on to furnish evidence to increase the electricity use on road TS, namely by analysing the driving factors of the EV penetration.

Technically, there are three different types of EV: Hybrid Electric Vehicles (HEV), Plug-in Electric Vehicle (PHEV), and The Battery Electric Vehicles (BEV). The HEV has a traditional Internal Combustion Engine (ICE) and an electric motor powered by electricity. These vehicles cannot be charged from an external source of electricity. The electricity accumulated in their batteries is generated by using regenerative brakes that convert the kinetic energy of the vehicle into electricity. The PHEV has an ICE and an electric motor that could be refilled by kinetic energy and additionally by the electricity grid. These vehicles allow combination of the benefits of electricity use for mobility for short distances, without compromising the availability of the vehicle in travelling long distances, since it uses the ICE for it. The BEV, also known as 100% electric vehicles, are characterized by having only an electric motor rechargeable from the electricity grid. These vehicles allow for 0% tailpipe emissions, but currently, still offer a short driving range and the recharge process is quite long. Please note that, throughout this thesis only the BEV and PHEV are considered.

Taking into account the technical differences of the propulsion types of the EV, the second part of this thesis is focused on the analysis of the driving factors of EV adoption, considering individually BEV and PHEV. This part is composed of one empirical analysis, presented in chapter 4. It analyses the role of several factors, namely policy, economic, social, environmental and technical on the enlargement of the EV market share. The proxy used to measure the technological progress of the batteries has been created by employing a Principal Component Analysis (PCA), to capture the main information of battery cost, the Nissan Leaf's battery capacity and driving range. We opted by consider the features of the Nissan Leaf because it is the? best BEV seller. This proxy for the technological innovation of the batteries is, indeed a novelty in the literature focused on the drivers of EV adoption. Moreover, the analysis of these factors by using historical data is scanty. Therefore, this research seems to us of particular relevance not only for the scientific community but also for policymaking. Thus, the main objective of chapter 4 is to answer the following central questions:

(i) What are the factors that promote the penetration of EV?

(ii) Are these factors identical for BEV and PHEV?

(iii) Is technological progress the main driver of EV deployment?

To answer these questions, the EU countries have been analysed. The Panel-Corrected Standard Errors (PCSE) estimator has been used, since it is appropriate in dealing with the data features. The actuality of the topic approached makes the use of the longer time span impractical. Therefore, the robustness of the results has been performed by using the Seemingly Unrelated Regressions (SUR).

The main findings suggest that each vehicle technology should be considered separately, instead of the promotion of electric mobility as a whole. Actually, the factors supporting the adoption of the BEV are quite different from those promoting the PHEV adoption. This chapter highlights that the main challenges for both BEV and PHEV penetration are technological. The proxy used to measure the technological progress of the EV batteries is a significant driver of EV adoption as well as the existence of the charging stations. The RES generation stimulated the BEV adoption but not the PHEV. The outcomes of this chapter also support the idea that the environmental awareness of consumers should be explored to increase the EV market share. The policy supporting electric mobility has been effective on BEV market, but not for PHEV. This means that the policymakers should design effective policies for each type of vehicle technology instead of electric mobility as a whole. The findings of this chapter are crucial for policymakers to increase the EV market share to allow the economies to benefit from the EV potential.

The EV, mainly BEV has an outstanding potential in contributing to improving the economic efficiency of the electricity system, namely by allowing Demand Side Management (DSM) measures to be effective. However, this potential is quite dependent on the policy strategy followed. With an uncontrolled EV charging strategy, the EV users could charge their vehicles in the peak periods. If this occurs, the electricity system has to increase their installed capacity of the flexible sources to satisfy the additional electricity demand. It could even be reflected in an increase of CO_2 emissions in electricity generation. However, the promotion of the EV, with adequate policy supporting and technological development, could contribute to improving the efficiency of the electricity system. This means that EV could allow for the storage of electricity in their batteries during the out-off-peak periods when the RES generation is high and replace it on the grid during the peak periods when RES generation is low (V2G). Moreover, and such as noted by the literature, with a controlled charging strategy, that promotes the EV charging in off-peak periods, the EV could have not the need to increase the installed capacity from flexible sources (Mortaz & Valenzuela, 2018), and contribute to increasing the RES utilization (Seddig, Jochem, & Fichtner, 2017). This equilibrium is indeed a challenge since the electricity systems in the future will be faced with the introduction of large amounts of EV.

Definitively, the potential of the BEV in both managing the electricity system and contributing to the RES has motivated chapter 5 of this thesis. Its main objective is to provide empirical evidence of the main drivers of both peak electricity demand and RES integration. In this chapter, special attention has been provided to the role played by the BEV on both peak load demand and RES integration. In sum, this chapter aims to answer the next central questions:

(iv) What are the roles played by the main drivers of peak electricity demand in managing excess electricity consumption?

(v) What is the relationship between BEV and electricity consumption in peak hours?

To accomplish these chapter objectives, the EU countries have been analysed, by using a PCSE and Driscoll Kraay estimators. We are confident that the period analysed is short as a result of the actuality of the issue addressed. Fully conscious of the limitation of using a short time span, different structure models have been employed to guarantee the robustness of the results.

The main conclusions of chapter 5 support the view that peak reduction is not dependent on the electricity price, once it is fixed over the day. This could indicate that the differentiated electricity tariffs over the day are mandatory to reducing peak electricity demand. It could even contribute to increasing the RES integration if this price is formulated in accordance with RES generation. The policies focused on DSM have promoted RES integration, but they have had no effect on the peak shaving. The penetration of the BEV has contributed to reducing the peak electricity demand, which is indeed desired. At the same time, BEV has had a negative effect on RES integration. This indicates that the potential of the BEV on RES integration is not being realized. Thus, both transport and electricity policies should be jointly designed in order to allow the BEV to contribute to both reducing electricity consumption in peak periods and RES integration.

1.1 Contribution to the literature

This thesis presents several contributions and improvements to the existing literature on the effects of energy mix diversification in the TS that are summarized in this section. The first part (chapters 2 and 3) contributes by providing empirical evidence of the consequences of the diversification of the TS' energy mix on both the economic growth and CO_2 emissions and by using two recent methodologies. The potential existence of the substitution effect between conventional and alternative TS' energy sources is verified. To the best of our knowledge, all of these aspects represent a novelty in the literature. Furthermore, it includes rail infrastructure investment to explain the interactions between conventional and alternative TS' energy sources, economic growth and CO_2 emissions, which represents a novelty in the literature. Usually, the length of the infrastructure is considered (see e.g. Achour & Belloumi, 2016). Appropriateness of this investment in reducing the dependence on fossil fuels is verified, supporting that this operationalization contributes to the literature and to the policymaking.

The contribution performed by chapter 4 to the literature is twofold. Firstly, the empirical analysis of the effects resulting from social, political, economic, environmental, and technical factors on the BEV, PHEV and jointly EV adoption by using an econometric approach, remains scarce. The exception includes Li, Chen, & Wang (2017) that considers only the role of the socioeconomic factors in the EV adoption. Secondly, to the best of our knowledge, the empirical literature that uses historical data has not yet focused on the role played by the technological progress of the batteries on the diffusion of the EV. In fact, this chapter innovates by constructing a variable that represents the technological innovation of the batteries of the BEV. This variable has proved to be crucial in enlarging the EV market share, supporting thus the importance of this novelty for the literature.

The research performed on chapter 5 also represents an improvement in the literature. On the one hand, the analysis of the drivers of the peak electricity demand based on the historical data remains scanty, an exception includes Mirlatifi, Egelioglu, & Atikol (2015). On the other hand, this chapter innovates by analysing the role played by the BEV on both the electricity demand and RES integration, which represents a relevant novelty in the empirical literature.

In sum, this thesis shows a set of contributions not only for the literature but also for the decision-making process. It provides an embracing overview related to the shift in the TS energy paradigm and its consequences. It starts with a general characterization of the TS energy consumption, namely on the consequences of diversification on both economic growth and CO_2 emissions. After that, it focuses on two of the main challenges that this system is faced, the acceptance of electric mobility and its impact on the management of the electricity system.

1.2 Structure and outcomes

This thesis was produced a compilation of articles, following predicted in *Decreto Lei nº 230/2009*. In this way, each chapter that composes this thesis, gives a detailed background of the issue on which it is centered. Thus, the rest of this thesis is organised as follows: Chapter 2 is dedicated to analysing the interactions between TS energy consumption, CO_2 emissions and economic growth by segmenting the TS energy consumption into: fossil fuels, electricity and renewable fuels. Section 2.1 provides the introduction, motivation and objectives of the topic addressed. In Section 2.2, the state-of-the-art regarding the relationships between TS energy consumption, economic growth and CO_2 emissions have been explained. In Section 2.3 the data used, and the methodology applied is described. The results are shown in Section 2.4 and discussed in Section 2.5. Section 2.6 concludes. Chapter 2 resulted on one journal article publication, as well as one conference abstract presented, as described below:

- Neves, Sónia. A., Marques, António C., Fuinhas, José A. 2018. Could alternative energy sources in the transport sector decarbonise the economy without compromising economic growth? Environment, Development and Sustainability. https://doi.org/10.1007/s10668-018-0153-8. Impact factor – 1.379, SJR - Q3

- Neves, Sónia A., Marques, António C. and Fuinhas, José A. “The interactions between conventional and alternative energy sources in transport sector, economic growth and

CO_2 emissions – Panel VAR approach", Heading Towards Sustainable Energy Systems: Evolution or Revolution, 15th IAEE European Conference, Vienna, Austria, 3-6 September 2017

As noted by the literature, the length of the different TS infrastructure could have an important role in explaining the interactions between TS energy consumption, economic growth and CO_2 emissions. Thus, chapter 3 is dedicated to analysing individually the interactions between conventional (fossil fuels) and alternative (electricity and renewable fuels) TS' energy use, economic growth and CO_2 emissions. It considers the role of the rail infrastructure investment in this framework. Therefore, in Section 3.1, a short overview of the related topic is provided. Section 3.2 offers the description of the data and methodology. The results are presented in Section 3.3 and discussed in Section 3.4. Finally, Section 3.5 concludes. The main outcomes of Chapter 3 include an article published, a conference paper presented, and one poster, described below:

- Neves, Sónia A., Marques, António C. and Fuinhas, José A, 2017. Is energy consumption in the transport sector hampering both economic growth and the reduction of CO_2 emissions? A disaggregated energy consumption analysis. Transport Policy 59(July), 64-70. doi:10.1016/j.tranpol.2017.07.004. Impact factor: 1y/5y – 2.269 / 3.025; SJR – Q1

- Neves, Sónia A., Marques, António C. and Fuinhas, José A, "The relationship between economic growth, Transports' energy consumption and CO_2 emissions: Disaggregating energy sources", Proceedings of 3rd International Conference on Energy and Environment: bringing together Engineering and Economics, School of Economics and Management of the University of Porto, Porto, Portugal, pp.552-558, ISSN: 2183-3982, ISBN: 978-989-97050-4-3, Porto, Portugal, 29-30 June 2017

- Neves, Sónia A., Marques, António C., Fuinhas, José A. 2017. Is energy consumption in the transport sector hampering both economic growth and CO_2 emissions? A disaggregated energy consumption analysis. Poster presented at Fórum/conferência de debate "Desafios da Gestão Ativa da Procura de Energia: Eficiência e Resposta – GAPEER'17", 20-21 April, University of Beira Interior

The factors supporting the adoption of the BEV, PHEV, and jointly EV (BEV plus PHEV) have been examined in chapter 4. In Section 4.1, an introduction to the topic approached has been provided as well as the main motivations and contribution to the literature. Section 4.2 revises the state-of-the-art of the research topic focusing on the factors analysed. The data used, and the methodology applied are described in Section 4.3. The results are shown in Section 4.4, and their robustness check performed on Subsection 4.4.1. The findings are discussed in Section 4.5, and the final conclusions provided on Section 4.6. This chapter resulted in a journal article published in Research in Transportation Economics:

- Neves, Sónia A., Marques, António C., and Fuinhas, José A., 2018. Technological progress and other factors behind the adoption of Electric Vehicles: Empirical evidence for EU countries, Research in Transportation Economics. https://doi.org/10.1016/j.retrec.2018.12.001. Impact factor 0.992, SJR - Q1

The last empirical research analysis, chapter 5, is dedicated to analysing the main drivers of the peak electricity demand, giving a special focus on the role played by the BEV. Moreover, it also examines the role of the BEV in the RES integration. Thus, Section 5.1 gives an overview of the topic, motivation, research questions and contribution to the literature. In Section 5.2 the literature review of the research topic is provided. The data and methodology applied are showed and described in Section 5.3. In Section 5.4, the results are shown, and their robustness provided in Subsection 5.4.1. The discussion and policy implications are furnished in Section 5.5. Lastly, Section 5.6 concludes. A short version of this chapter has already been published in one of the top leading journals of this area, namely the *Energy*:

- Neves, Sónia A., Marques, António C., and Fuinhas, José A., 2018. On the drivers of peak electricity demand: what is the role played by battery electric cars? Energy. 159, 905-915. https://doi.org/10.1016/j.energy.2018.06.209. Impact factor 1y/5y 4.968/5.582, SJR - Q1

Lastly, the main conclusions of this thesis development are displayed in chapter 6. Section 6.1 displays the final remarks while Section 6.2 shows the future lines research.

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Chapter 2

Could alternative energy sources in the Transport Sector decarbonise the economy without compromising economic growth?

The transition towards a low-carbon Transport Sector (TS) plays a fundamental role on the decarbonisation of economies. The effects of both conventional (fossil fuels) and alternative (renewable fuels and electricity) energy consumption in the transport sector, economic growth and carbon dioxide emissions were analysed by using a panel Vector Autoregressive of 21 high-income Organization for Economic Co-operation and Development (OECD) countries from 1990 to 2014. The results support the feedback hypothesis between both conventional and alternative TS energy sources and economic growth. In other words, electricity use on TS has enlarged the economic growth while consumption of renewable fuels is actually hampering it. Additionally, TS fossil fuels consumption is contributing to economic growth. With reference to the environmental impacts of TS energy use, this chapter highlights the harmful effect of conventional energy sources on the environment. However, there is no evidence wherein TS alternative energy sources are directly linked with a reduction of carbon dioxide (CO_2) emissions. Accordingly, the promotion of alternative TS energy sources should deserve further attention. On the one hand, there is evidence that the use of renewable fuels is obstructing economic growth. On the other hand, the use of both TS electricity and renewable fuels is not reducing carbon dioxide emissions.

2.1 Introduction

Reducing of the environmental impacts associated with energy use has concerned not only the literature but also policymakers. The renewable deployment within the electricity mix has been pursued bearing this objective in mind. However, sectors which are highly powered by fossil fuels, such as the Transport Sector have led to inertia on the shift towards low-carbon economies. Therefore, intervention in this sector is required. On the one hand, TS is a crucial sector for the entire dynamics of the economy. On the other hand, this sector is intensive in terms of internal combustion engines powered by fossil fuels, namely oil, the latter being highly harmful to the environment. The historical data, disclosed by the World Energy Council (2011), shows that in 2010, TS was responsible for 19% of the global energy consumption, with 96% coming from oil. Moreover, this sector is also responsible for 60% of the global oil used, and 23% of the global CO_2 emissions. Additionally, the European Commission (2016) indicates that in 2014, among the European Union (EU) countries, TS is responsible for 33% of the final energy consumption, with 94% from petroleum products. Furthermore, this sector is responsible for 25.5% of the EU Greenhouses Gases (GHG) emissions.

Over the last decades, the interactions between energy consumption and economic growth (energy-growth nexus) have attracted particular attention from the literature (Omri, 2014; Payne, 2010; Tiba & Omri, 2017). The results of the traditional energy-growth nexus can differ from the aggregate level to sectoral level (Abid & Sebri, 2012). In both these levels, the energy consumption is a critical variable to explain the growth (Camarero, Forte, Garcia-donato, Men-, & Ordo, 2015). Accordingly, the sectoral energy consumption, namely TS, has caught the attention of specialized literature, namely regarding their effects on both economic growth and CO_2 emissions (Burke & Csereklyei, 2016; Costantini & Martini, 2010; Tang & Shahbaz, 2013). Although the literature is quite consensual on the harmful effects of TS energy consumption on the environment, the effects on the economic growth are not so harmonious see. (Costantini & Martini, 2010; Ibrahiem, 2017; Liddle & Lung, 2013; Saboori, Sapri, & bin Baba, 2014).

The transition to low-carbon economies remains entirely dependent on the abatement of the fossil fuels used in TS. Recently, a technological upgrade on the internal combustion engines has been designed to reduce emissions of the pollutant gases. This upgrade included the improvement of the injection systems, modification of gases circulation, combustion chamber, as well as piston head design. Similarly, a survey of this technological upgrade on the internal combustion engines can also be found, for instance in Abdul-Wahhab, Al-Kayiem, A. Aziz, & Nasif (2017). Furthermore, the literature has proven that energy efficiency policies are efficient on TS decarbonisation (Shafiei, Davidsdottir, Leaver, Stefansson, & Asgeirsson, 2017; Talbi, 2017; Xu & Lin, 2015b). Currently, the exigency of CO_2 abatement is growing. The fulfilment of carbon standards had encouraged the vehicle's manufacturer to go further. As a consequence, some manufacturers have announced that they would stop producing new vehicles with internal combustion engines.

Although the improvement in terms of efficiency of internal combustion engines has been pursued, the designed policy intervention was aimed at promoting the use of alternative TS energy sources. In fact, the penetration of renewable fuels and electricity is mandatory so as to reduce both the dependence on fossil fuels and GHG emissions. The literature has not been consensual on the effects of the alternative sources on the environment. As to the renewable fuels, the literature supports that the use of biofuels on TS could reduce CO_2 emissions (H.

Zhang & Chen, 2015). However, Månsson (2016) argues that biofuels could be ineffective on environmental protection if the competition for this kind of sources increases. The use of renewable fuel still face several technical and social challenges that actually hinder their penetration (Bae & Kim, 2017). The efficiency of renewable fuels increases with the increment of octanes in the fuel. For instance, ethanol improves the number of octanes. However, it keeps producing lower heating value, and therefore, it needs to be mixed with an additive, for instance, gasoline so as to increase engine efficiency (Bae & Kim, 2017).

With reference to electricity use on TS, it is also faced with several challenges. Therefore, it will only contribute to reducing CO_2 emissions if the electricity is being generated from renewable sources (Ajanovic & Haas, 2016). The share of TS energy consumption achieved through electricity remains low, mainly occurring on railways. The deployment of large amounts of electric vehicles on the road transport continues quite dependent upon a technological upgrade so as to achieve higher-capacity and therefore enhance the lifecycle batteries of electric vehicles at a lower cost. Electric mobility also remains dependent on the social acceptance, and the improvement on the charging infrastructures (Mahmoudzadeh Andwari, Pesiridis, Rajoo, Martinez-Botas, & Esfahanian, 2017). It is expected that high penetration of electric vehicles will decrease their costs. This occurs due to the economies of scale and the increase in the learning curves. Therefore, batteries of electric vehicles are expected to be more competitive than internal combustion engines by 2030 (Mahmoudzadeh Andwari et al., 2017).

Although the literature has ascertained the relationships between TS energy consumption, economic growth and CO_2 emissions (Chandran & Tang, 2013; Saboori et al., 2014), the empirical literature has not considered, on an individual basis, the role played by conventional and alternative TS energy sources. Moreover, the literature has identified some factors that are hindering the transition to the alternative sources. However, the literature has not yet proved what this transition really implies for the economic growth and TS decarbonisation. Therefore, the novelty of this chapter for the literature is twofold. First, it simultaneously analyses the role played both by conventional and alternative TS energy sources on the economic growth and CO_2 emissions. Second, this approach also allows to check if the conventional sources had been replaced by the alternative, which is a desirable effect within the scope of the shift in TS energy paradigm. To sum up, in order to fill these gaps identified in the literature, this study aims to answer the following central questions: (i) what is the role played by both TS conventional and alternative energy sources on the economic growth and CO_2 emissions, and (ii) are TS alternative energy sources replacing TS conventional energy sources?

Accordingly, a Panel Vector Autoregressive approach (Panel VAR) was used for 21 high-income OECD countries from 1990 to 2014. The option to study these countries comes from the fact that energy consumption is crucial for the dynamics as whole economies. In fact, the levels of energy consumption increase when high-income countries are considered. Therefore, for internal consistency purposes, the largest group of countries among those countries sharing the same characteristics includes high-income OECD countries. Moreover, these countries are faced with several challenges to achieve the sustainable development, namely on the climate protection (Eppel, 1999). At the same time, the analysis of this countries seems us the particular relevance once they are, in general leaders on the diversification of the TS energy paradigm.

Thus, this chapter indicates that both conventional and electricity use on TS is contributing to economic growth. By the contrast, renewable fuels are hampering it. On the one hand, regarding the environmental impacts of the TS energy sources, fossil fuels are increasing CO_2 emissions. On the other, there is no statistical evidence of the relationship of the alternative energy sources on CO_2 emissions. Currently, the TS is in rapid transition for a low-carbon sector dealing with several challenges. Indeed, understanding what has happened in the past is crucial to provide fundamental guidelines for policymakers.

The sections of this chapter will be organized as follows. The state-of-the-art will be presented in Section 2.2. In Section 2.3 the data and the methodology applied will be shown and justified. Subsequently, the results will be disclosed in Section 2.4 and discussed in Section 2.5. Finally, the conclusions will be presented in Section 2.6.

2.2 An overview of the energy consumption in transport sector

With reference to the reduction of environmental impacts associated with energy use, TS has deserved much attention from the literature not only for the technical specificities that hinder the transition for the low-carbon sector but also because of their importance for the economy. In fact, the relationship between TS energy consumption, economic growth and CO_2 emissions is frequently found on the literature. The bidirectional causality between economic growth, CO_2 emissions and road TS energy consumption is supported for 27 OECD countries, employing Fully Modified Ordinary Least Squares (FMOLS) from 1965 to 2008, by Saboori et al. (2014). Similarly, for 5 ASEAN countries, namely Malaysia, Indonesia, Singapore, the Philippines and Thailand, a bidirectional long-run causality between energy consumption in the transport sector and CO_2 emissions was found from 1971 to 2008 (Chandran & Tang, 2013). In fact, the positive effect of energy consumption on CO_2 emissions in the transport sector is frequently found in the literature, as proven by Shahbaz, Khraief, & Jemaa (2015). Although the harmful effects on the environment are well known, the relationship with the economic growth is not so consensual. Table 2.1 shows a brief survey of the literature that analyses the relationships between TS energy consumption, economic growth and CO_2 emissions as well as their conclusions.

Table 2.1 - Studies on the effects between TS energy consumption, economic growth and CO_2 emissions

Author(s)	Time and country(ies)	Methodology	Variables	Main findings
Chandran & Tang (2013)	1971 – 2008 5 ASEAN countries	Granger causality (VECM)	CO_2 emissions Road energy consumption (ROAD) Foreign direct investment GDP	CO_2↔ROAD long-run (Malaysia and Thailand) ROAD→CO_2 long-run (Indonesia) CO_2↔ROAD short-run (Philippines and Thailand) ROAD→GDP long-run (Indonesia and Thailand) and short-run (Singapore, and Indonesia) GDP↔ROAD both short- and long-run (Malaysia) GDP→ROAD short-run (Philippines)
Liddle & Lung (2013)	1971-2009 107 countries	Heterogeneous Panel causality CMG	TS energy consumption (TS_EC) GDP	GDP→TS_EC GDP has a positive effect on TS_EC
Ben Abdallah et al. (2013)	1980-2010 Tunisia	Johansen cointegration Granger Causality (VECM)	Transport value added (TVA) Road energy consumption (ROAD) CO_2 emissions from TS Road infrastructure Fuel price	TVA↔CO_2 TVA↔ROAD CO2↔ROAD

Saboori et al. (2014)	1960-2008 27 OECD countries	Fully Modified Ordinary Least Squares cointegration	CO_2 from TS GDP Road energy consumption (ROAD)	GDP↔ROAD GDP↔ CO_2 CO_2↔ROAD
Ibrahiem (2017)	1980-2011 Egypt	Johansen cointegration test Granger Causality (VECM)	Road energy consumption (ROAD) GDP Urbanization Population growth	Short-run GDP↔ROAD Long-run ROAD→GDP
Alshehry & Belloumi (2017)	1971-2011 Saudi Arabia	ARDL Granger Causality (VECM)	CO_2 emissions from TS Road energy consumption (ROAD) GDP	CO_2 ↔ROAD ROAD≠GDP GDP≠CO_2

Notes: ARDL: Autoregressive Distributed Lag, CO_2: Carbon Dioxide emissions; CMG: Correlated Effects Mean Group; OECD: Organisation for Economic Co-operation and Development; VAR: Autoregressive; VECM: Vector Error Correction Mechanism; GDP: Gross domestic product

The need to understand the drivers of TS energy consumption have motivated the literature to go further. In fact, there is a set of country-specific studies that analyse the drivers of TS energy consumption, by considering a sector as a whole or subdividing it according to different infrastructures. For instance, Achour & Belloumi (2016a) analysed the TS in Tunisia, and came to the conclusion that the Gross Domestic Product (GDP), the population, transports intensity, and transports structure expand the TS energy consumption while the energy intensity effect decreases it, since the energy efficiency measures taken on transports are appropriate to reduce the use of fossil fuels. Additionally, despite only considering the road TS energy use, when speaking of the same country, this is positively affected by the vehicle fuel intensity, vehicle intensity, economic growth, urbanised kilometres and national network (Mraihi, Ben Abdallah, & Abid, 2013). Another example of this proves that in the Chinese TS, energy consumption is boosted by the transport activity whereas energy intensity decreases it (M. Zhang, Li, Zhou, & Mu, 2011). Furthermore, Wu & Xu (2014) focused on the cargo transportation in China and found that both the intensity of goods carried and the cargo transportation infrastructure have a negative impact on cargo transport-related energy consumption, whereas the economic growth actually boosts it.

Although the policies aimed at promoting the reduction of energy use (efficiency or conservation) are robust on the TS decarbonisation (Shafiei et al., 2017; Talbi, 2017; Xu & Lin, 2015a), the effects of new energy sources, such as renewable fuels and electricity are not consensual among the scientific community. For example, a simulation-based comparison between scenarios of the transition to hydrogen and electricity shows that the transition to electric mobility is preferable for the reduction of the total fuel use and the goals of economic benefits; however, the mixed transition to electric mobility and hydrogen proves to be desirable to achieve the goal of reducing emissions (Shafiei et al., 2017). Similarly, using a LEAP (long-range energy alternative planning) model, Azam, Othman, Begum, Abdullah, & Nor (2016) showed that the reduction of both the energy consumption in road TS and CO_2 can be achieved by the natural gas scenario, followed by the biofuels scenario and hybrid electric vehicle scenario. However, Månsson (2016) supports that the strategies for new energies sources (biofuels and electricity) are affected by external factors. Biofuels can be inefficient on the decarbonisation if many countries increase the use of these sources, bearing in mind that in this case, the growth in demand actually increases the competition by a set the fixed resources. As to TS, electrification is quite dependent on the technological upgrade in the other countries, which means that it is difficult to implement this technology. In addition, the penetration of alternative sources also aims to reduce the external energy dependence, mainly for non-oil producing countries. For these countries, electric vehicles could be the most efficient technology to reduce the external energy dependence (Marques, Reis, Afonso, & Silva, 2016). The same authors also argue that for Norway, Saudi Arabia and Russia (oil producing countries), the energy dependence is affected in the same way when different vehicles technology was assessed.

The literature has shown that the use of non-fossil combustibles can reduce the emissions of pollutant gases (Nocera & Cavallaro, 2016). For instance, the use of biofuels in China and United States TS is contributing to the reduction of CO_2 emissions (H. Zhang, Chen, & Huang, 2016), which seems to corroborate the results obtained both by H. Zhang & Chen (2015) for Chinese TS and Neves, Marques, & Fuinhas (2017) for OECD countries. Regarding the European Union, there are several policies to promote the use of biofuels (Cansino, Pablo-Romero, Román, & Yñiguez, 2012), although the associated biofuels costs do remain higher than fossil fuels costs (Ajanovic & Haas, 2011; Sanz, Cansino, González-Limón, Santamaría, & Yñiguez, 2014). However, the reduction of global CO_2 emissions will only be reached if all the countries reduce oil consumption. Otherwise, if only some countries reduce oil use, the objective of global oil use reduction will be achieved, despite the fact that a drop in global CO_2 emissions will not be reached (Eliasson & Proost, 2015).

With reference to the electricity penetration within road transportation, it will be beneficial for the environment if the electricity used actually comes from renewable sources (Ajanovic &

Haas, 2016). The shift from fossil fuels consumption to electricity within TS could raise new challenges for the electricity systems, mainly due to the fact that they cannot be able to deal with an additional demand caused by electric mobility. Nevertheless, literature is stating that with a controlled plug-in vehicle loading in out-off peak hour, the impact on electricity costs will be less than 5% and there is no need to increase the installed capacity (Razeghi & Samuelsen, 2016). Likewise, taking into account the environmental impacts, the promotion of vehicle charges is necessary, when there are high levels of renewables production and the adoption of Time-Of-Use tariffs (TOU), so as not to compromise the sustainability of the electricity system (Coffman, Bernstein, & Wee, 2017).

To sum up, the reduction of the environmental impacts associated with energy consumption has caught the attention of the literature. The transition to a low-carbon economy has been hindered by the TS because it remains highly powered by fossil fuels. The analysis of the relationships between CO_2 emissions, economic growth and TS energy consumption has inspired the literature, by considering the TS as whole or subdividing it in the different infrastructures (see Table 2.1). The promotion of more efficient technologies, as well as the use of alternative sources, such as renewable fuels and electricity, has been pursued so as to counteract the harmful effect of this sector on the environment. In fact, energy efficiency measures can be effective at the level of TS decarbonization. However, the literature is not harmonious as to the role played by the alternative sources (renewable fuels and electricity) on the transition towards low-carbon sector both in an economically and environmentally-sustainable way. Additionally, the literature has not analysed the effects resulting from conventional and alternative (renewable fuels and electricity) TS energy sources on the economic growth and CO_2 emissions, by using historical data.

2.3 Data and Methodology

This chapter used yearly panel data, comprising a time span from 1990 to 2014 for 21 high-income OECD countries. The period under analysis started in 1990 considering that it is a milestone, namely as far as environmental protection is concerned. For instance, the Kyoto Protocol highlights that GHG emissions should be reduced as compared with values of 1990. Therefore, following the data availability criterion for the entire period, the selected countries were as follows: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Ireland, Italy, the Netherlands, Norway, Poland, Portugal, Spain, Sweden, Switzerland, United Kingdom, and the United States. All the variables were converted into their per capita value. Since all the variables were converted into their natural logarithm and considering there is a set of zeros on the database, a constant of 1 was added to each variable in order to solve the issue of loss of observations. The prefix “L” shall hereinafter mean a natural logarithm, whereas “D” shall mean a first-differences of the variables. Table 2.2 shows the variables’ description, descriptive statistics, and the sources of the variables.

Table 2.2 - Variables' definition and descriptive statistics

Variable	Description	Obs	Mean	Std. Dev.	Min	Max	Source
LGDP	Ratio between GDP (Constant LCU) and total population	525	10.78	1.03	9.44	13.22	WDI
LFF	Ratio between transports' fossil fuels consumption and population (kg of oil equivalent/person)	525	6.60	0.44	5.17	7.64	IEA
LELE	Ratio between transports' electricity consumption and total population (kg of oil equivalent/person)	525	2.32	0.81	0.33	3.64	IEA
LRES	Ratio between transports' renewable fuels consumption and total population (kg of oil equivalent/person)	525	1.31	1.45	0	4.70	IEA
LEN	Ratio between total energy consumption (except in TS) and total population (kg of oil equivalent/person)	525	7.65	0.40	6.78	8.43	OECD statistics
LCO_2	Ratio between total CO_2 emissions (from consumption of oil, gas and coal), and total population (kg of carbon dioxide equivalent/person)	525	4.10	0.96	1.82	5.298	BP statistics

Notes: obs stands observations; Std. Dev. stands standard deviation; min stands minimum, max stands maximum; WDI stands for World Development Indicators, IEA stands for International Energy Agency (IEA Headline Global Energy Data, (2016 edition), LCU stands for Local Currency Unit, and OECD means Organization for Economic Co-operation and Development.

The Gross Domestic Product per capita (*GDP*), measured into constant Local Currency Unit, was used as economic growth proxy, as usual, (see e.g. Saboori et al., 2014). The TS energy consumption was subdivided into: fossil fuels (*FF*), electricity (*ELE*) and renewable fuels (*RES*[3]) and these were expressed in kg of equivalent oil per capita, as frequently stated in the literature (see e.g. Achour & Belloumi, 2016b; Saboori et al., 2014). CO_2 emissions from consumption of oil, gas and coal are expressed in kg of CO_2 equivalent. Moreover, the total energy consumption in the economy except in TS was used as a control variable.

According to a panel data approach, the technical features of both variables and crosses (countries) must be checked in order to avoid biasing the results. Accordingly, the adopted procedure included checking of: (i) Cross-section Dependence test (CD-test), (ii) Panel unit root tests (see Table 2.3), (iii) Correlation matrix values, and (iv) Variance Inflation Factor (VIF's) (see Table 2.4).

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[3] This variable comprises the direct use of renewable fuels by the transport sector and does not take into account the renewable electricity.

Table 2.3 - Cross-section Dependence test (CD – test) and Second-Generation unit root test (CIPS)

	CD - test			CIPS		
	CD-Test	Corr	Abs (corr)	Lags	Without trend	With trend
LGDP	67.51***	0.932	0.932	0	0.636	-2.863***
				1	-1.130	-1.500*
LFF	32.85***	0.453	0.542	0	1.571	0.732
				1	0.622	0.922
LELE	5.94***	0.082	0.503	0	-0.042	1.228
				1	0.842	1.611
LRES	64.20***	0.886	0.886	0	-1.287*	-3.325***
				1	-0.243	-1.960**
LCO_2	34.34***	0.474	0.544	0	-4.131***	-2.797***
				1	-1.588*	-1.593*
LEN	29.04***	0.401	0.509	0	-2.577***	-4.664***
				1	-1.164	-3.226***
DLGDP	42.66***	0.601	0.601	0	-9.095***	-6.065***
				1	-6.069***	-3.861***
DLFF	19.99***	0.282	0.314	0	-12.820***	-10.779***
				1	-5.525***	-3.466***
DLELE	1.71*	0.024	0.165	0	-12.686***	-11.222***
				1	-5.844***	-4.047***
DLRES	13.44***	0.189	0.246	0	-13.985***	-12.319***
				1	-8.398***	-6.038***
$DLCO_2$	18.69***	0.263	0.316	0	-15.398***	-14.491***
				1	-9.796***	-8.501***
DLEN	26.82***	0.378	0.394	0	-15.905***	-14.550***
				1	-11.505***	-10.889***

Notes: CD – test was performed according to the null hypothesis of the cross-sectional independence. CIPS test was performed under the null hypothesis wherein the variables are I(1). ***, **, and * denotes statistical significance level at 1%, 5%, and 10%, respectively.

First-generation unit root tests are not trustworthy in the presence of cross-sectional dependence. Accordingly, when this phenomenon was found, the second-generation unit root test (CIPS) proposed by Pesaran (2007) should be performed. As stated in Table 2.3, this phenomenon was detected for all the variables with 1% level of statistical significance, except for *DLELE*, which is only statistically significant at 10%. For this variable, both first- and second-generation unit root tests were performed, and both of them suggest that the variable is I(1). Overall, the results presented in Table 2.3 show that all the variables were stationary in their first differences. The correlation matrix values and the Variance Inflation Factor (VIF) were analysed so as to certify that both correlation and multicollinearity did not deserve concern for the estimation (see Table 2.4). The low correlation values verified is supporting that collinearity also does not deserve concern.

Table 2.4 - Correlation matrix and Variance Inflation Factor (VIF's)

Correlation Matrix

	DLGDP	*DLFF*	*DLELE*	*DLRES*	*DLCO₂*	*DLEN*
DLGDP	1					
DLFF	0.4783	1				
DLELE	0.1168	0.1062	1			
DLRES	-0.0301	-0.1327	0.0374	1		
DLCO₂	0.3365	0.3300	0.0686	-0.0779	1	
DLEN	0.3048	0.2143	0.1458	-0.1074	0.6142	1

VIF's

	Dependent variable					
	DLGDP	*DLFF*	*DLELE*	*DLRES*	*DLCO₂*	*DLEN*
DLGDP	-	1.16	1.39	1.39	1.38	1.37
DLFF	1.15	-	1.38	1.36	1.33	1.38
DLELE	1.03	1.03	-	1.03	1.03	1.02
DLRES	1.03	1.01	1.03	-	1.03	1.02
DLCO₂	1.72	1.68	1.74	1.74	-	1.18
DLEN	1.65	1.67	1.65	1.66	1.14	-
Mean VIF	1.32	1.31	1.44	1.44	1.18	1.19

Faced with potentially endogenous variables, i.e. it is likely that the variables have a simultaneous causality, the use of Panel Data Vector Autoregressive (Panel VAR) is suitable. The estimator proposed by Love & Zicchino (2006) supports stationary endogenous variables as well as the unobserved individual heterogeneity. As can be seen in section "2.4 Results" the presence of the endogeneity was confirmed by the blocks of exogeneity analysis. This implies that the error term was correlated with the independent variables. Accordingly, the Panel VAR was appropriated to deal with these data features, and the estimation can be explained as follows:

$$Z_{it} = \Gamma_0 + \Gamma_1 Z_{it-1} + f_i + d_{c,t} + \varepsilon_t \tag{2.1}$$

where, Z_{it} denotes the vector of the endogenous used variables (*DLGDP, DLFF, DLELE, DLRES, DLCO₂* and *DLEN*), Γ_0 represents the vector of the constants, $\Gamma_1 Z_{it-1}$ denotes the matrix polynomial, f_i represents the fixed effects, $d_{c,t}$ denotes the time effects, and ε_t represents the error term.

The presence of fixed effects was tested by using the Hausman test. The null hypothesis predicts that the random effects estimator is appropriated. All variables were tested both as dependent and as independent variables. The existence of the fixed effects was only detected for the model where *DELE* is dependent. Although the presence of fixed effects raises correlation problems between the regressors, this methodology allowed to remove them by using the "*Hermelet procedure*" as proposed by Arellano & Bover (1995). According to this technique, data loss is minimised, once the mean for future observations available was removed (Love & Zicchino, 2006). Therefore, the system was estimated, based on a Generalised Methods of Moments (GMM) and with the regressors lagged as instrumental variables.

The Granger causality test, based on the Wald test (Abrigo & Love, 2015), was performed, showing that the null hypothesis is the absence of causality. Furthermore, Impulse Response Functions (IRF) were estimated by using a Gaussian approximation based on the Monte-Carlo simulations. The Orthogonalized Impulse Response Functions were based on the Cholesky decomposition, and the standard errors and the confidence intervals were estimated according to the 1000 Monte-Carlo simulations. The function revealed reaction of one variable to the shock in another variable. After that, the Forecast-Error Variance Decomposition (FEVD) was performed, based on a Cholesky decomposition of the residual covariance matrix, using 1000 Monte Carlo simulations, and for 15 periods. This function allowed us to understand the percentage that each endogenous variable explains of the forecast error variance of the other specific variable. After carrying out the analysis of the exogeneity blocks, the VAR – Choleski ordering of variables was used, by placing the variables in the decreasing order of the

2.4 Results

Following the three model and moment selection criteria proposed by Andrews & Lu (2001), namely Bayesian information criterion (MBIC), Akaike information criterion (MAIC) and Hannan and Quinn information criterion (MQIC), the selected optimal lags in the PVAR estimation was 1 (see Table 2.5). Indeed, lag 1 minimises all criteria (MBIC, MAIC, and MQIC).

Table 2.5 - Lag order selection criteria

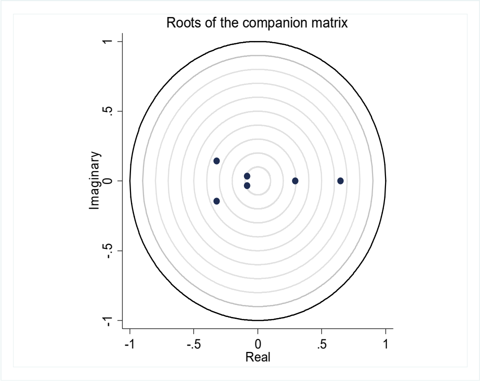
Lag	CD	J	J-pvalue	MBIC	MAIC	MQIC
1	0.421	153.928	0.002	-492.880	-62.072	-232.695
2	0.616	88.856	0.087	-342.349	-55.144	-168.892
3	0.706	33.963	0.566	-181.640	-38.037	-94.911

The first-order PVAR was estimated with an impulse dummy for 2010 as an exogenous variable. The inclusion of this dummy aims to correct the residuals of the estimations since they suffered a breakdown in this year caused by economic recuperation after the economic crisis. The stability of the first-order PVAR was checked. The results are shown in Table 2.6. The stability condition is accomplished once the values are inside the circle. As mentioned by Abrigo & Love (2015), this implies that the Impulse-Response Functions (IRF) and Forecast Error Variance Decomposition (FEVD) have a known interpretation.

Table 2.6 - Eigenvalue stability condition

Eigenvalue		**Modulus**
Real	**Imaginary**	
0.6468	0	0.6468
-0.3206	0.1437	0.3514
-0.3206	-0.1437	0.3514
0.2929	0	0.2929
-0.0843	-0.0340	0.0909
-0.0843	0.0340	0.0909

Notes: All the eigenvalues lie inside the unit circle. pVAR satisfies stability condition.



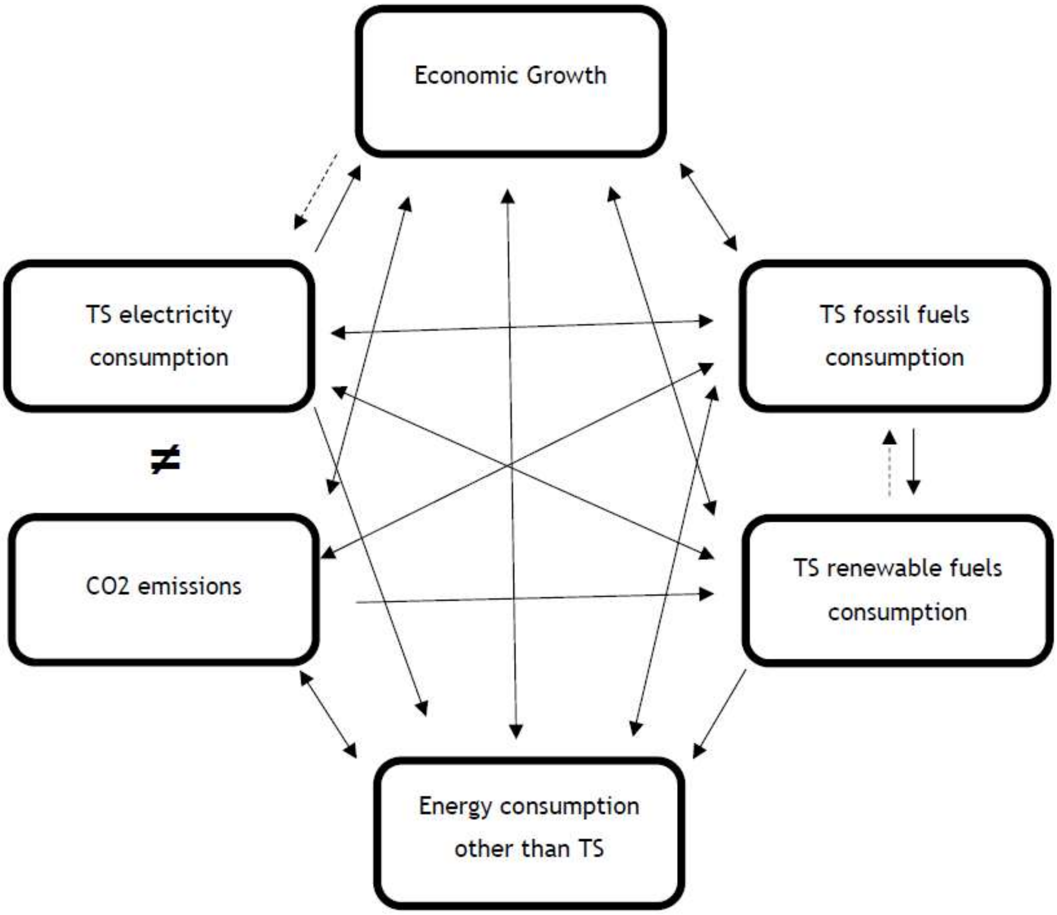
The results of Granger causality, following the first-order PVAR, are shown in Table 2.7. The null hypothesis predicts the absence of the causality. The TS fossil fuels consumption and total energy consumption (except in TS) show the bidirectional causality with the economic growth. This research agrees with the findings of Camarero et al., (2015) that energy consumption is actually a critical variable to explain the economic growth in both aggregate and sectoral level. Moreover, the use of electricity and renewable fuels on the TS is also causing the economic growth. However, these results also sustain that the electricity use on the TS is not significantly dependent on the economic performance from a statistical approach, since the economic growth is only causing the TS electricity use at 10% level of significance. Conversely, the use of renewable fuels on the TS is caused by the economic growth, and vice-versa, supporting a bidirectional causality.

Table 2.7 - Granger causality test

	DLELE	*$DLCO_2$*	*DLEN*	*DLRES*	*DLFF*	*DLGDP*
DLELE does not cause	-	1.406	11.388***	20.566***	5.650**	5.265**
$DLCO_2$ does not cause	0.012	-	0.047	4.626**	13.396***	13.548***
DLEN does not cause	1.016	9.144***	-	4.600**	5.430**	19.377***
DLRES does not cause	1.880	0.578	0.460	-	2.789*	5.790**
DLFF does not cause	7.840***	5.124**	12.453***	12.206**	-	29.012***
DLGDP does not cause	3.159*	67.235***	26.748***	15.627***	10.530***	-
ALL	10.258*	112.266***	81.295***	43.411***	32.499***	54.461***

Notes: ***, **, and * denotes statistical significance at 1%, 5%, and 10% respectively.

Regarding CO_2 emissions, a bidirectional causality is shown with fossil fuels use. Moreover, there is a unidirectional causality running from energy consumption except in TS to the CO_2 emissions. In fact, this finding proves the harmful effect of energy use on the environment. The use of renewable fuels is caused by CO_2 emissions, although the opposite is not true. Although the use of renewable fuels aims to reduce CO_2 emissions, this study indicates that this effect is not taking place now. This result indicates that the renewables penetration within the TS is being promoted by CO_2 emissions. With reference to electricity consumption on the TS, there is no relationship with CO_2 emissions. Figure 2.1 shows a summary of the causalities found according to the Granger causality.



Notes: ⟶ denotes the causality with a statistical significance of the 1% and 5%. -----▶ denotes the causality with a statistical significance of the 10%

Figure 2.1 - Summary of the causalities according to the Granger causality

Taking into account that the Granger causality is not able to reveal all the information about the relationships established between the variables, the IRF were carried out (see Figure 2.2). They provide both information about how one variable reacts (response), faced to a shock or innovation in another variable (impulse), while also revealing the time needed to return to equilibrium. Subsequently, the FEVD was also performed (see Table 2.8). The results allow us to understand the percentage of the forecast error variance that each of the variables explain, faced with a shock or innovation in one specific variable. Moreover, it also indicates both the time needed to and the percentage that each variable contributes to achieve the equilibrium.

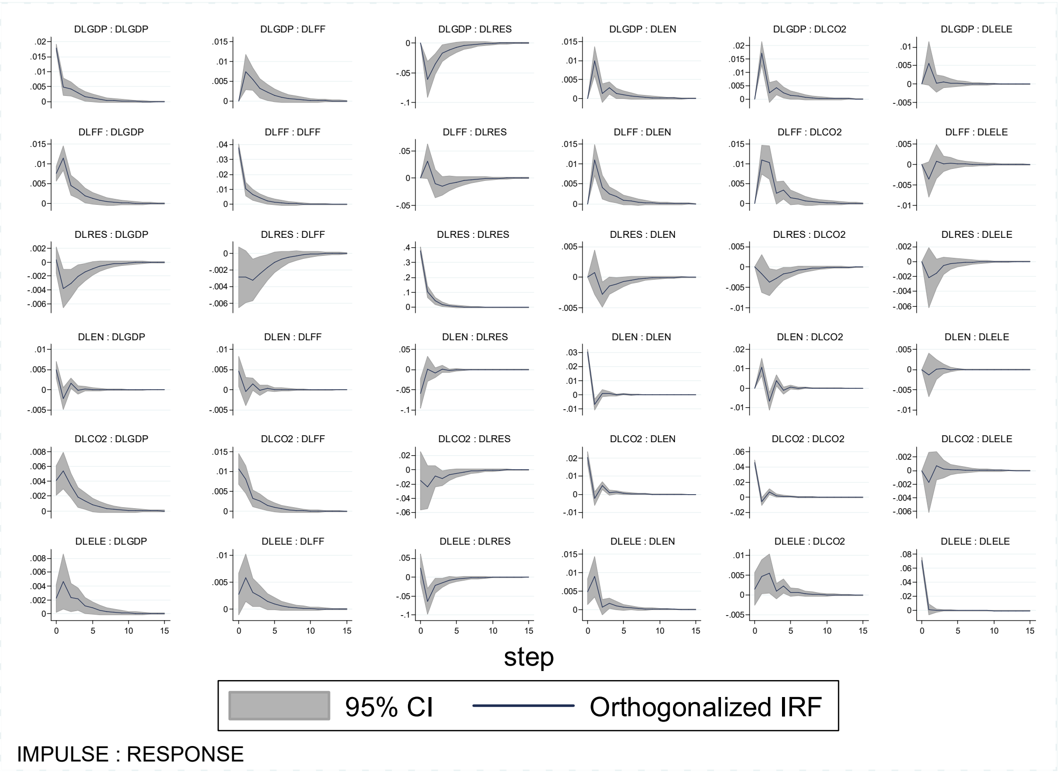


Figure 2.2 - Impulse Response Functions (IRF)

As can be seen in Figure 2.2, faced with a shock or innovation in one variable, all the variables return to the equilibrium. This result supports the stationarity of the variables under study. With reference to an impulse on the *DLGDP*, all the variables respond positively, except *DLRES*, thus meaning that they are achieving the equilibrium in 5 periods, except *DLELE* has managed to achieve it in 3 periods. Conversely, considering the response of the *DLGDP*, facing a shock in the other variables has a positive response in all the variables, except in *DLRES* and *DLEN*.

As to the fossil fuels used on the TS, all the variables react positively faced to a shock on the *DLFF*, except *DLELE*. Although the negative effect of electricity on the fossil fuels consumption has a lower magnitude, this result supports the perspective that the electrification of the transports sector could reduce the use of fossil fuels. Faced with a shock in *DLCO*$_2$, the return to the equilibrium occurs quickly, approximately in 3 years, except for *DLGDP* and *DLFF* that achieve such equilibrium in about 7 years. Facing an impulse in *DLCO*$_2$, special attention is needed for the negative response of the *DLRES*. In contrast, the economic growth and the use of TS fossil fuels reacted positively.

The results of the Forecast error variance decomposition (FEVD) are shown in Table 2.8. In fact, the results allow us to understand the percentage that each endogenous variable explains of the forecast error variance of the other specific variable.

Table 2.8 - Forecast-error variance decomposition (FEVD)

Impulse variable	Forecast horizon	Response variable					
		DLELE	*DLCO*$_2$	*DLEN*	*DLRES*	*DLFF*	*DLGDP*
DLELE	1	1	0	0	0	0	0
	2	0.98928	0.00060	0.00038	0.00092	0.00263	0.00619
	5	0.98835	0.00071	0.00039	0.00150	0.00277	0.00628
	10	0.98831	0.00072	0.00039	0.00151	0.00278	0.00629
	15	0.98831	0.00072	0.00039	0.00151	0.00278	0.00629
DLCO$_2$	1	0.00116	0.99884	0	0	0	0
	2	0.00925	0.78911	0.04447	0.00097	0.04623	0.10998
	5	0.02030	0.71993	0.06048	0.00911	0.08289	0.10729
	10	0.02070	0.71706	0.06030	0.00995	0.08396	0.10802
	15	0.02070	0.71702	0.06030	0.00996	0.08397	0.10803
DLEN	1	0.01678	0.30063	0.68259	0	0	0
	2	0.05948	0.24148	0.57019	0.00037	0.07148	0.05700
	5	0.05914	0.24530	0.54514	0.00660	0.08312	0.06072
	10	0.05930	0.24493	0.54347	0.00710	0.08382	0.06138
	15	0.05931	0.24492	0.54345	0.00710	0.08383	0.06138
DLRES	1	0.00378	0.00160	0.02396	0.97066	0	0
	2	0.02704	0.00489	0.02110	0.91903	0.00566	0.02228
	5	0.03059	0.00633	0.02083	0.90302	0.00803	0.03121
	10	0.03079	0.00656	0.02079	0.90161	0.00860	0.03165
	15	0.03079	0.00656	0.02079	0.90160	0.00861	0.03166
DLFF	1	0.00500	0.07308	0.01342	0.00529	0.90321	0
	2	0.02289	0.09796	0.01159	0.00892	0.82921	0.02943
	5	0.02973	0.09962	0.01168	0.01784	0.79140	0.04973
	10	0.03037	0.09981	0.01161	0.01879	0.78830	0.05112
	15	0.03038	0.09981	0.01161	0.01880	0.78826	0.05114
DLGDP	1	0.01156	0.039566	0.05771	0.00022	0.13319	0.75776
	2	0.04046	0.07082	0.04501	0.02185	0.28966	0.53219
	5	0.04929	0.08270	0.04169	0.03888	0.29543	0.49202
	10	0.05017	0.08319	0.04123	0.04032	0.29577	0.48932
	15	0.05018	0.08319	0.04122	0.04034	0.29577	0.48929

Renewable fuels, as well as electricity consumption on the TS, are self-explanatory as to the most important part of their forecast error variance. In the first period, the *DLELE* and *DLRES* are explaining 98.928%, and 97.066% of their respective forecast error variance. The other endogenous variables are not significant on the explanation of the forecast error variance. In fact, as to the new equilibrium point, *DLELE* contributes in 98.831% for their respective forecast error variance, while *DLRES* explains 90.160% of their forecast error variance. This means that the penetration of alternative energy sources on TS energy consumption are not significantly dependent neither on the other TS energy sources nor on the economic performance.

Faced with a shock on *$DLCO_2$*, in the first period, the forecast error variance is explained in 0.116% by the TS electricity use, and in 99.884% by the *$DLCO_2$*. After a tenth period, the forecast error variance is explained in 71.706% by *$DLCO_2$*, 6.03% by *DLEN*, 8.396% by *DLFF,* and 10.802% by *DLGDP*. Indeed, economic growth, energy use except in TS and the use of fossil fuels are the most important contributors to CO_2 emissions, responding with greater magnitude with a shock in the *$DLCO_2$*. Although the IRF shows that renewable fuels and electricity use on the TS respond negatively faced with a shock or innovation in CO_2 emissions, FEVD results indicate that this variable contributes to a low percentage in explaining the forecast error variance.

With reference to a shock in the *DLFF* variable, in terms of achievement of equilibrium achievement, after a ten-year period, the variables that are explained in the largest part of the forecast error variance are the TS use of fossil fuels (78.830%), CO_2 emissions (9.981%), economic growth (5.112%), and TS electricity consumption (3.037%). As regards a shock in the economic growth, it is self-explanatory in 75.776%, in the first year. As to the equilibrium, the largest part of the forecast error variance is explained by *DLGDP* and *DLFF*, accounting for 49.202%, and 29.543%, respectively, thus showing the importance of the use of TS fossil fuels for the economy.

2.5 Discussions

So far, the analysis of the effects of TS energy consumption on the economic growth and CO_2 emissions has deserved much of the attention of the literature up to now. However, none of these studies have analysed the effects of both conventional and alternative energy sources, on an individual basis. In fact, this approach could provide crucial guidelines for policymakers so as to achieve a low-carbon TS.

It is a well-known fact that the TS is vastly powered by fossil fuels, namely oil, which is harmful to the environment. Although there are several efforts to improve the efficiency of the internal combustion engines to reduce the pollutant gases emissions (Abdul-Wahhab et al., 2017), this paper corroborates the conclusion that the use of these sources is increasing CO_2 emissions. Moreover, the use of fossil fuels on TS is contributing to the economic growth, which is in line with Saboori et al. (2014). Indeed, this outcome shows the importance of TS for the dynamics of the entire economies. However, in order to decarbonise this sector and the economy, it is mandatory to reduce fossil fuels consumption.

Regarding the effects of renewable fuels consumption on the TS, this study supports that they are actually reducing the use of fossil fuels, i.e., there is a substitution effect of fossil fuels by renewable fuels, although with a low level of significance. In fact, the penetration of the alternative sources is still faced with several challenges, namely social and technical (Bae & Kim, 2017), something which can explain the low levels of significance found by this research. In other words, our findings sustain that the goal of reducing the use of fossil fuels on the TS could really be achieved by promoting the use of renewable fuels, contrary to what could happen in the electricity generation due the need of backup from controllable fossils, as stated by Boccard (2009) and Flora, Marques, & Fuinhas (2014). Nevertheless, this paper also indicates that renewable fuels are apparently hampering economic growth. Indeed, this outcome could result from excessive costs associated with supporting these sources, as highlighted by Ajanovic & Haas (2011). The findings of this research also provide some guidelines to make the renewable fuels more attractive and competitive. The advancements to increase their market share are required. Currently, their use remains small, something which could explain the absence of (statistically significant) relationship with CO_2 emissions. Although the use of these sources still does not contribute to directly reducing CO_2 emissions, they are actually contributing to reducing the use of conventional sources, which consequently may reduce CO_2 emissions. At the same time, they are apparently hampering economic growth. This could indicate that more research on the renewable fuels is required. First, it is mandatory to improve the renewable fuels efficiency so as to make their performance competitive with the conventional fuels with an aim towards enlarging their social acceptance. The improvement of the number of octanes accomplished with high heating value could reduce the need for additive conventional fuel. Second, their cost effectiveness also needs to be enhanced so as to avoid the negative effects on the economic growth. Therefore, investments in research and development (R&D) of the renewable fuels could be an efficient way to counteract the undesirable effects found in this paper.

This research indicates that electricity consumption on transports actually affects the economy on a positive basis. Nevertheless, this study also supports that electricity penetration on the TS energy mix is not highly significant dependent on the economic performance. This means that, during the period under study, the electrification of the TS is mainly a case of policy decision-making. Additionally, the electricity use on TS does not have any statistically significant relationship with CO_2 emissions, something which is not expected. In fact, according to the period under study, the electricity use on the TS has occurred mainly on the railways. This unanticipated finding could indicate that CO_2 savings in the tailpipe achieved by using electricity on TS, have actually resulted in an increase of the CO_2 emissions caused in the electricity generation process. As stated by Ajanovic & Haas (2016), it is expected that the environmental benefits associated with the electricity use on the TS will only be reached if the electricity is generated from renewable sources.

Currently, the transition for electric mobility on the road systems remains slight. Indeed, the greatest challenges are upon the social acceptance, the improvement of the charging infrastructure, the new business models and the research of the range extenders (Mahmoudzadeh Andwari et al., 2017). Therefore, in the next few decades or even years, the outcome of this study is expected to change, namely through the development of the lifecycle and capacity of the electric vehicles' batteries. Furthermore, it is also expected that the penetration of the electric vehicles could decrease their cost (Mahmoudzadeh Andwari et al., 2017), thus making the electric vehicles more attractive. Although electricity use is not directly contributing to reducing CO_2 emissions, this chapter indicates that it actually shows a substitution effect with fossil fuels sources. In other words, our findings sustain that the goal of reducing the use of fossil fuels on the TS could be achieved by promoting the use of electricity.

This study indicates that both transport and electricity policies must be followed together. The promotion of the electric vehicles must be pursued. More investment in R&D in battery technology could be an efficient mechanism to improve the battery capacity and lifecycle. It is expected that this progress could result in an increase of the share of electric vehicles in the automotive market. At the same time, policymakers should promote electricity generation through renewables sources. Indeed, the TS must use renewable electricity. Conversely, if the electricity used by TS is generated from conventional sources the reduction of the CO_2 emissions could not be achieved. This means that the consumption of the electricity must be coordinated with the natural resources availability, namely wind and solar photovoltaic. Policymaking must promote the charging of electric vehicles in periods of the high potential to the renewable generation. Users that charge their car in these periods must be encouraged. For instance, promotion of the existence of a charging station in the workplace could incentive the electric vehicle charging in these periods. Also, the existence of a differentiated electricity prices could be an efficient mechanism to achieve it. Actually, the existence of cheaper electricity when there is a high renewable generation, will encourage users to charge their electric vehicles in these periods. The coordination of both transport and electricity policies could be helpful for both, in fact. The penetration of electric vehicles is essential on transition for low-carbon TS. Meanwhile, with the controlled charging process, electric vehicles could contribute to renewables accommodation.

2.6 Conclusions

The transition towards low-carbon TS has led policymakers to promote the use of alternative sources such as electricity and renewable fuels. However, the technical specifications of this sector actually act as a barrier and, as such, do hamper this energy transition. Therefore, this chapter aims to provide some policy suggestions about how the conventional and alternative

TS energy sources are interacting as well as their effects on CO_2 emissions and economic growth. Based on an empirical approach, this study applies a panel VAR for 21 high-income from 1990 to 2014. Their results can be very helpful for political decision-making.

This chapter supports that the use of conventional energy sources in the transport sector is enlarging the economic growth. However, thanks to the broadly documented literature, it also corroborates the harmful effect of these sources on the environment. Moreover, this study indicates that the promotion of TS alternative sources must be pursued, despite the need to have further attention on this topic. With reference to renewable fuels, apparently this is hindering economic growth. Moreover, there is no evidence as to how these sources are obstructing CO_2 emissions. Nevertheless, it also supports that these sources could actually contribute to reducing the dependence on fossil fuels. With reference to the electricity penetration on the TS, the conclusion is that it actually enlarges economic growth; however, this does not have a direct effect on CO_2 emissions.

Nevertheless, it is important to make sure that the results of this chapter reflect what has occurred in the past. In fact, the TS are faced with several challenges to transit for a low-carbon sector, something which is currently in rapid and constant transition, namely on the diversification of their energy mix. The results obtained in this research can be kept in the future or, alternatively, they are likely to evolve.

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Chapter 3

Is energy consumption in the Transport Sector hampering both economic growth and the reduction of CO_2 emissions? A disaggregated energy consumption analysis

The transport sector (hereafter TS) was analysed by studying the interaction between conventional (fossil fuels) and alternative (electricity and renewable fuels) energy consumption, on economic growth and carbon dioxide (CO_2) emissions. To do this, annual data for 15 Organization for Economic Co-operation and Development (OECD) countries from 1995 to 2014 was used. The short- and long-run effects were analysed individually with the robust Driscoll-Kraay estimator in an Autoregressive Distributed Lag (ARDL) structure. The results support the argument that fossil fuels consumption in the transport sector have contributed to increasing both economic growth and CO_2 emissions. In contrast, both electricity and renewable fuels in the transport sector have hampered economic growth. This study supports the idea that the shift to a low-carbon transport sector must be reanalysed. Although the use of renewable fuels is reducing CO_2 emissions, a negative impact on economic growth could reveal that the costs remain high. Furthermore, the transition to electric mobility must be pursued, but policies need to be reconsidered, to avoid obstructing economic growth.

3.1 Overview

The reduction of the environmental impacts associated with the use of the energy has merited the increasing attention of not only academics but also policymakers. In the economy as a whole, the transport sector is one that has most delayed this shift towards a low-carbon economy, such as reported on chapter 2. Therefore, this sector represents a focal point for policymakers for several reasons. Firstly, the transport sector constitutes a key economic sector for the economy. Secondly, the sector is an intensive consumer of energy and is largely powered by fossil fuels due to the widespread use of thermal engines. Lastly, the harmful effect of the TS on the environment is well known.

Energy consumption in the TS can come from fossil fuels (e.g. diesel, gasoline), renewable fuels (e.g. biofuels and hydrogen fuel) and electricity. However, electricity consumption in the TS can be from renewable or non-renewable sources. Indeed, penetration of renewables has mainly occurred in electricity systems, so the objective of the incentives for electrification of the TS is to reduce its dependence on fossil fuels and decarbonise the economy. However, as is well known, the proportion of transportation powered by electricity remains low, and it occurs mainly in rail transport. As road transport is responsible for the largest part of total transport energy consumption, greater penetration by electricity is required (discussed on chapter 4). However, road transport remains heavily dependent on upgraded technological to achieve higher-capacity and enhance the lifecycle of electric vehicle batteries.

The literature is not consensual about the most efficient pathway to achieve a low-carbon TS. On the one hand, the simultaneous use of the both policy instruments and alternative fuels could be more effective in reducing both energy consumption and Greenhouse Gases (GHG) emissions (Ajanovic & Haas, 2016). On the other hand, the simultaneous use of the both hydrogen and electricity could be more effective in reducing GHG emissions (Shafiei, Davidsdottir, Leaver, Stefansson, & Asgeirsson, 2017). An extensive literature review on the effects of the TS' energy consumption was performed in chapter 2 (see Section 2.2). In summary, the literature has analysed the performance of the different pathways to achieve to low-carbon TS (Ajanovic & Haas, 2016; Shafiei et al., 2017). Moreover, the literature has focused on the effects resulting from TS energy consumption on both economic growth and CO_2 emissions (Chandran & Tang, 2013; Costantini & Martini, 2010; Ibrahiem, 2017; Liddle & Lung, 2013; Saboori, Sapri, & bin Baba, 2014). Moreover, different transport infrastructures have been studied, specifically the length of both rail and road networks, in order to analyse the effects of new infrastructures on both economic growth and the environment (Achour & Belloumi, 2016; Saidi, Shahbaz, & Akhtar, 2018). Following the goal of decarbonising the TS, the analysis of the effects of conventional and alternative TS energy sources on economic growth and GHG emissions remains scarce in the literature.

Therefore, this chapter aims to fill this gap, by studying the dynamic linkage between economic growth, TS fossil fuels consumption, TS electricity consumption, TS renewable fuels consumption and TS CO_2 emissions. Moreover, rail infrastructure investment is considered in the analysis of energy consumption within this sector. Our decision to study rail infrastructure investment aims to capture the effects of new railway construction and of improving existing infrastructures (on economic growth, CO_2 emissions and on both conventional and alternative TS energy sources). In short, this chapter aims to answer the following central questions: (i) what are the consequences of using both conventional and alternative sources on the transition to electric mobility, and on decarbonisation of the TS? Moreover, (ii) How have the alternative fuels affected the economic growth?

This chapter is set out as follows. Section 3.2 is dedicated to describing both the data used and the methodology applied. In Section 3.3, the results are presented, and then discussed in Section 3.4. Finally, Section 3.5 presents the conclusions.

3.2 Data and Methodology

This study uses annual panel data from 1995 to 2014 for 15 OECD countries. The countries were selected strictly in accordance with the criteria of data availability for the longest time span and they are: Australia, Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Luxembourg, Slovak Republic, Spain, Sweden, Turkey, United Kingdom, and the United States.

The variables used in the study include: Gross Domestic Product per capita (*GDP_PC*), TS fossil fuels (coal, crude, oil and natural gas) consumption per capita (*FF_PC*), TS electricity consumption per capita (*ELE_PC*), TS renewable fuels consumption per capita[4] (*RES_PC*), total CO_2 emissions from TS (CO_2), total energy consumption in the economy minus that of the TS per capita (*EN_PC*), and rail investment (*RAIL*). It is worthwhile to note that all the transport-related energy consumption variables, includes total sectoral energy use. Since all the variables have been converted into their natural logarithms, a constant of 1 was added to each of them to resolve the issue of observation loss on the database. Hereafter, the prefix “L” means a natural logarithm and “D” means a first-difference of the variables. Table 3.1 shows the variables’ description, descriptive statistics and database source.

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[4] This variable comprises the direct use of biofuels by the transport sector and does not account for renewable electricity in accordance with IEA Headline Global Energy Data, (2016 edition).

Table 3.1 - The variables' description and descriptive statistics

Variable	Description	Obs	Mean	Std. Dev.	Min	Max	Source
LGDP_PC	Ratio between GDP (Constant LCU) and population	300	10.608	1.386	6.924	12.877	WDI
LFF_PC	Ratio between TS fossil fuels consumption and population (kg of oil equivalent/person)	300	6.645	0.673	5.164	8.530	IEA
LELE_PC	Ratio between TS electricity consumption and population (kg of oil equivalent/person)	300	2.421	0.784	0.255	3.642	IEA
LRES_PC	Ratio between TS renewable fuels consumption and population (kg of oil equivalent/person)	300	1.756	1.550	0	4.864	IEA
LRAIL	Investment in rail infrastructure (constant LCU)	300	21.260	1.743	16.717	24.148	OECD statistics
LCO_2	Total CO_2 emissions from TS (Tonnes of CO_2 equivalent)	300	10.611	1.477	8.134	14.451	OECD statistics
LEN_PC	Ratio between total energy consumption, except in TS and population (kg of oil equivalent/person)	300	7.664	0.419	6.421	8.347	IEA

Notes: obs stands observations; Std. Dev. stands standard deviation; min stands minimum, max stands maximum; WDI denotes World Development Indicators, IEA denotes International energy Agency (IEA Headline Global Energy Data, (2016 edition)), and LCU means Local Currency Unit

The GDP per capita is used as an economic growth proxy, as is frequently done in the literature (see e.g. Saboori et al. 2014; Saidi et al. 2018). Energy consumption in the transport sector is expressed in kg of oil equivalent per capita (see e.g. Achour & Belloumi, 2016; Saboori et al., 2014). Regarding the transport infrastructure, usually, the infrastructure expressed in kilometres was used, specifically in both rail and road length (see e.g. Achour & Belloumi 2016; Pradhan & Bagchi 2013; Saidi et al. 2018). Although this variable is capable of analysing the effects of building new infrastructures, it may not be able to capture a technological upgrade of the existing infrastructures, particularly regarding more efficient technologies and the enhancement of the conditions for the users. Therefore, we use the investment in rail infrastructure, measured in constant Local Currency Unit (LCU). To further clarify, this variable comprises the investment in building new infrastructures and the improvement of the existing network, and it is determinant for analysing rail performance (OECD, 2017). Furthermore, road infrastructure investment was tested in the estimations, but its inclusion did not bring additional explanatory power to the models.

The characteristics of both the variables and the countries (cross-sections) under analysis, were exhaustively tested and considered for choosing the estimators to guarantee robust results. The procedure adopted to achieve this data features included: (i) the Cross-section Dependence test (CD-test); (ii) the Panel unit root tests (see Table 3.2); (iii) Correlation matrix values; and (iv) Variance Inflation Factors (VIFs) (see Table 3.3).

Table 3.2 - Cross-section Dependence test (CD – test) and Second-Generation Unit Root test (CIPS)

	CD - test			CIPS	
	CD-Test	Corr	Abs (corr)	Without trend	With trend
LGDP_PC	42.60***	0.930	0.930	2.021	3.909
LFF_PC	10.40***	0.227	0.506	1.350	-0.892
LELE_PC	-0.36	-0.008	0.556	0.312	0.226
LRES_PC	38.39***	0.838	0.838	-1.248	-1.927**
LCO_2	16.39***	0.358	0.550	1.243	1.230
LEN_PC	19.98***	0.436	0.630	-1.645**	-3.114***
LRAIL	10.40***	0.251	0.471	-1.927**	0.644
DLGDP_PC	30.24***	0.677	0.677	-3.282***	-2.444***
DLFF_PC	10.05***	0.225	0.307	-8.041***	-6.030***
DLELE_PC	-0.490	-0.011	0.164	-9.881***	-8.733***
DLRES_PC	5.05***	0.113	0.201	-9.233***	-7.339***
$DLCO_2$	11.22***	0.251	0.327	-6.549***	-4.956***
DLEN_PC	21.99***	0.492	0.496	-11.744***	-10.362***
DLRAIL	-0.04	-0.001	0.187	-7.817***	-6.869***

Notes: CD – tests were performed under the null hypothesis of cross-sectional independence. CIPS test was performed under the null hypothesis wherein the variables are I(1). ***, **, and * denote significance levels at 1%, 5%, and 10%, respectively.

The results of the CD-test suggest the presence of cross-sectional dependence for all the variables, except *LELE_PC, DLELE_PC*, and *DLRAIL*. In fact, when cross-sectional dependence was detected, the first-generation unit root test could not be reliable. Therefore, the second generation unit root test (CIPS) proposed by Pesaran (2007) was performed for all the variables in which the cross sections presented a common development. For variables that exhibited cross-section independence, both first- and second-generation unit root tests were performed.

The results of the first-generation unit root test, Maddala & Wu (1999) revealed that these variables are I(1). The results presented in Table 3.2, suggest the existence of the variables that are stationary in their levels, i.e. I(0), and on their first differences, i.e. I(1). The absence of the variables I(2) make it possible to use the dynamic structure following the ARDL procedure. Lastly, collinearity and multicollinearity must be checked to produce robust estimations. To do this, the correlation matrix values and the VIF were analysed. The results disclosed on Table 3.3 suggest that neither collinearity nor multicollinearity are a concern when calculating the estimations.

Table 3.3 - Correlation matrix and Variance Inflation Factor (VIF's)

Correlation Matrix

	LGDP_PC	*LFF_PC*	*LELE_PC*	*LRES_PC*	LCO_2	*LEN_PC*	*LRAIL*
LGDP_PC	1						
LFF_PC	0.4452	1					
LELE_PC	0.4789	0.2152	1				
LRES_PC	0.2250	0.2433	0.1296	1			
LCO_2	-0.1701	0.1375	-0.4242	0.2451	1		
LEN_PC	0.5566	0.6944	0.4464	0.1335	-0.1213	1	
LRAIL	0.6262	0.1196	0.2037	0.3524	0.4966	0.1288	1

	DLGDP_PC	*DLFF_PC*	*DLELE_PC*	*DLRES_PC*	$DLCO_2$	*DLEN_PC*	*DLRAIL*
DLGDP_PC	1						
DLFF_PC	0.3986	1					
DLELE_PC	0.0376	-0.0204	1				
DLRES_PC	0.0090	-0.7013	0.0367	1			
$DLCO_2$	0.3907	0.8070	0.0032	-0.1233	1		
DLEN_PC	0.3800	0.2049	0.1115	-0.0973	0.2395	1	
DLRAIL	0.0765	0.1931	-0.0596	0.2128	0.1171	0.0721	1

VIF's

	Dependent variable (levels)			
	LGDP_PC	*LFF_PC*	*LELE_PC*	LCO_2
LGDP_PC	-	6.87	8.98	2.96
LFF_PC	2.26	-	3.33	2.14
LELE_PC	2.02	2.28	-	1.45
LRES_PC	1.22	1.19	1.22	1.22
LCO_2	2.41	5.28	5.24	-
LEN_PC	2.43	2.58	2.43	2.65
LRAIL	1.96	7.85	8.79	2.08
Mean VIF	2.05	4.34	5	2.08

	Dependent variable (first-differences)			
	DLGDP_PC	*DLFF_PC*	*DLELE_PC*	$DLCO_2$
DLGDP_PC	-	1.33	1.36	1.35
DLFF_PC	2.95	-	3.02	1.25
DLELE_PC	1.02	1.02	-	1.02
DLRES_PC	1.08	1.09	1.09	1.08
$DLCO_2$	2.95	1.23	2.98	-
DLEN_PC	1.09	1.21	1.20	1.21
DLRAIL	1.11	1.08	1.10	1.11
Mean VIF	1.70	1.16	1.79	1.17

Remembering that the main objective of this chapter is to analyse the interaction between economic growth, TS CO_2 emissions, TS fossil fuels consumption, and TS electricity consumption, four models were estimated, following the ARDL structure, and can be explained as:

Model I: *DLGDP_PC - Economic growth*

$$\begin{aligned}DLGDP\_PC_{it} = {} & \mu_i + \psi_{it}TREND + \xi_{it}SD_{2008} + \lambda_{i1}\sum_{i=1}^{n} DLFF\_PC_{it} + \lambda_{i2}\sum_{i=1}^{n} DLELE\_PC_{it} \\ & + \lambda_{i3}\sum_{i=1}^{n} DLRES\_PC_{it} + \lambda_{i4}\sum_{i=1}^{n} DLRAIL_{it} + \lambda_{i5}\sum_{i=1}^{n} DLCO2_{it} \\ & + \lambda_{i6}\sum_{i=1}^{n} DLEN\_PC_{it} + \chi_{i1}LGDP\_PC_{it-1} + \chi_{i2}LFF\_PC_{it-1} \\ & + \chi_{i3}LELE\_PC_{it-1} + \chi_{i4}LRES\_PC_{it-1} + \chi_{i5}LRAIL_{it-1} + \chi_{i6}LCO2_{it-1} \\ & + \chi_{i7}LEN\_PC_{it-1} + \varepsilon_{it}\end{aligned} \tag{3.1}$$

Model II: *DLFF_PC - TS fossil fuels consumption*

$$\begin{aligned}DLFF\_PC_{it} = {} & \rho_i + \tau_{it}TREND + \beta_{i1}\sum_{i=1}^{n} DLFF\_PC_{it} + \beta_{i2}\sum_{i=1}^{n} DLELE\_PC_{it} \\ & + \beta_{i3}\sum_{i=1}^{n} DLRES\_PC_{it} + \beta_{i4}\sum_{i=1}^{n} DLRAIL_{it} + \beta_{i5}\sum_{i=1}^{n} DLCO2_{it} \\ & + \beta_{i6}\sum_{i=1}^{n} DLEN\_PC_{it} + \alpha_{i1}LGDP\_PC_{it-1} + \alpha_{i2}LFF\_PC_{it-1} \\ & + \alpha_{i3}LELE\_PC_{it-1} + \alpha_{i4}LRES\_PC_{it-1} + \alpha_{i5}LRAIL_{it-1} + \alpha_{i6}LCO2_{it-1} \\ & + \alpha_{i7}LEN\_PC_{it-1} + \eta_{it}\end{aligned} \tag{3.2}$$

Model III*:* *DLELE_PC - TS electricity consumption*

$$\begin{aligned}DLELE\_PC_{it} = {} & \upsilon_i + \phi_{it}TREND + \omega_{it}DUM\_UK + \varphi_{i1}\sum_{i=1}^{n} DLFF\_PC_{it} \\ & + \varphi_{i2}\sum_{i=1}^{n} DLELE\_PC_{it} + \varphi_{i3}\sum_{i=1}^{n} DLRES\_PC_{it} + \varphi_{i4}\sum_{i=1}^{n} DLRAIL_{it} \\ & + \varphi_{i5}\sum_{i=1}^{n} DLCO2_{it} + \varphi_{i6}\sum_{i=1}^{n} DLEN\_PC_{it} + \sigma_{i1}LGDP\_PC_{it-1} \\ & + \sigma_{i2}LFF\_PC_{it-1} + \sigma_{i3}LELE\_PC_{it-1} + \sigma_{i4}LRES\_PC_{it-1} + \sigma_{i5}LRAIL_{it-1} \\ & + \sigma_{i6}LCO2_{it-1} + \sigma_{i7}LEN\_PC_{it-1} + \xi_{it}\end{aligned} \tag{3.3}$$

Model IV: *$DLCO_2$ - TS CO_2 emissions*

$$\begin{aligned}DLCO2_{it} = {} & o_i + \kappa_{it}TREND + \delta_{i1}\sum_{i=1}^{n} DLFF\_PC_{it} + \delta_{i2}\sum_{i=1}^{n} DLELE\_PC_{it} \\ & + \delta_{i3}\sum_{i=1}^{n} DLRES\_PC_{it} + \delta_{i4}\sum_{i=1}^{n} DLRAIL_{it} + \delta_{i5}\sum_{i=1}^{n} DLCO2_{it} \\ & + \delta_{i6}\sum_{i=1}^{n} DLEN\_PC_{it} + \gamma_{i1}LGDP\_PC_{it-} \; + \gamma_{i2}LFF\_PC_{it-1} \\ & + \gamma_{i3}LELE\_PC_{it-1} + \gamma_{i4}LRES\_PC_{it-1} + \gamma_{i5}LRAIL_{it-1} + \gamma_{i6}LCO2_{it-1} \\ & + \gamma_{i7}LEN\_PC_{it-1} + \zeta_{it}\end{aligned} \tag{3.4}$$

where $\mu_i, \rho_i, \upsilon_i$, and o_i represent the intercept; ψ_i, τ_i, ϕ_i, and κ_i represent the coefficient of the trend; $\lambda_i, \beta_i, \varphi_i$, and δ_i represent the estimated parameters in the short-run, while the $\chi_i, \alpha_i, \sigma_i$, and γ_i represent the estimated parameters in the long-run; and $\varepsilon_{it}, \eta_{it}, \xi_{it}$, and ζ_{it} represent the error term. On the estimated ARDL models, the use of similar variables as explanatory and explained makes the presence of endogeneity likely. As the use of the ARDL structure is robust in the presence of endogeneity (Pesaran & Shin, 1999), the robustness and quality of the estimations are not compromised.

In model I – *Economic growth*, total energy consumption (expressed in kg of oil equivalent), excluding transport energy consumption, was used as a control variable. Indeed, the use of this variable is supported on two counts. Firstly, energy consumption is a critical variable to explain growth (Camarero, Forte, Garcia-donato, Men-, & Ordo, 2015). Secondly, in this study, the traditional control variables used in the literature, such as Gross Fixed Capital Formation and Labour Force, cause collinearity and multicollinearity problems for the estimations. Additionally, the bankruptcy of the American Bank Lehman Brothers in 2008 resulted in a crisis felt throughout the world, which was controlled for using a shift dummy (*SD_2008*). In model III – TS electricity consumption, a shift dummy was included for the United Kingdom from 2004 to 2014. In fact, 2004 coincided with the inauguration of the Nottingham Express Transit, a large tramway extension, which resulted in a significant increase of electricity consumption in TS.

The Hausman test was performed to analyse the presence of individual effects on the estimations, testing fixed effects against random effects. The null hypothesis indicates that the random effects estimator is adequate. Consequently, the rejection of the null hypothesis (see Table 3.4) shows that the use of fixed effects in our estimation is suitable. Accordingly, this model is robust to analyse the influence of variables that vary over the time. Moreover, the fixed effects model is the most restrictive model. Therefore, the rejection of the more general model (random effects model) proves that the panel techniques are appropriate. Additionally, the fixed effects model provides an F – test under the null hypothesis that the constant term is equal to the units. The rejection of this hypothesis (see Table 3.4) indicates that the Pooled Ordinary Least Square could produce unreliable results (Baum, 2006).

Table 3.4 - Hausman test and F - test

	Model I - *DLGDP_PC*	Model II – *DLFF_PC*	Model III – *DLELE_PC*	Model IV – *DLCO$_2$*
F – Test	4.28***	5.08***	5.57***	3.48***
Hausman test – FE vs RE	37.14***	56.92***	61.52***	33.38***

Notes: *** denotes statistical significance at 1% level.

Furthermore, a battery of specification tests were performed, namely: the Cross-sectional dependence test, Pesaran's test, Frees' test, Friedman's test; the modified Wald test for groupwise heteroscedasticity and the Wooldridge test for autocorrelation. The null hypothesis of specification tests predicts the existence of cross-sectional independence, homoscedasticity, and no first order serial autocorrelation, respectively. Accordingly, the Driscoll-Kraay estimator is robust to handle these data features (Driscoll & Kraay, 1998). In this nonparametric estimator, the standard errors are robust for several characteristics, such as cross-sectional dependence, heteroscedasticity and autocorrelation, and allows the fixed effects within the regression to be performed (Fuinhas, Marques, & Couto, 2015; Hoechele, 2010).

The semi-elasticities and elasticities allow short- and long-run effects between the variables to be shown. The semi-elasticities are provided by the short-run coefficients and relate to short-run relationships. The elasticities represent the long-run relationships, and they are calculated through the ratio between the coefficient of the variable, in the long-run, and the Error Correction Mechanism (ECM), and multiplied by -1.

3.3 Results

The results of the specification tests are presented in Table 3.5. They show the presence of heteroscedasticity and first-order serial correlation for all the models. Concerning the cross-sectional dependence phenomena, it was found for model I – Economic growth and model IV - TS CO_2 emissions. In fact, when this data feature is found, the estimator needs to be carefully chosen to avoid producing unreliable results. Indeed, the Driscoll-Kraay estimator is robust in the presence of cross-sectional dependence, heteroscedasticity, and first-order serial correlation, and it allows the use of fixed effects within the regression (Hoechele, 2010). Although cross-sectional dependence was not found in model II - TS fossil fuels consumption or model III - TS electricity consumption, this phenomenon was found for most of the variables under study. Moreover, the Driscoll-Kraay estimator is almost invariant to changes in terms of cross-sectional and temporal correlation (Hoechele, 2010). Therefore, the Driscoll-Kraay estimator was used for all the estimated models, following the ARDL structure described in the equations (3.1), (3.2), (3.3), and (3.4).

Table 3.5 - Specification tests

	Model I – *DLGDP_PC*	Model II – *DLFF_PC*	Model III – *DLELE_PC*	Model IV- *DLCO₂*
Modified Wald test	505.77***	3587.06***	3579.76***	1760.54***
Pesaran's test	17.930***	-0.049	-0.761	0.038
Frees' test	106.669***	20.261	16.703	22.661*
Friedman's test	1.868***	0.328	0.547	0.029***
Wooldridge test	48.220***	312.543***	47.080***	724.001***

Notes: *** and * denote statistical significance at 1% and 10% level, respectively

Accordingly, Tables 3.6, 3.7, 3.8, and 3.9 show the results of the estimated parameters and calculated elasticities for models I, II, III, and IV, respectively. Column FE shows the results of fixed effects regression, column FE-Robust displays the results of fixed effects robust to the heteroscedasticity and column DK-FE presents the results of Driscoll-Kraay-fixed effects. In fact, the significance levels of fixed effects and fixed effects–robust may not be reliable, as these estimators are not robust for the data features.

Table 3.6 shows the results of model I – *Economic growth*. Regarding the short-run dynamics, both TS fossil fuels consumption and total energy consumption (except in TS) contribute to economic growth. In fact, an increase of 1 pp (percentage point) in TS fossil fuels consumption (*DLFF_PC*) and in the total energy consumption except in TS (*DLEN_PC*) increases economic growth by 0.1267pp, and 0.1620pp, respectively. Concerning long-run dynamics, fossil fuels consumption in the transport sector increases economic growth, while both TS electricity consumption and TS renewable fuels consumption hamper economic growth. These findings deserve further consideration in the 4.5 Discussion, below.

Table 3.6 - Model I – *DGDP_PC*

	Coefficients	FE	FE - ROBUST	DK – FE
DLFF_PC	0.1267	***	***	***
DLEN_PC	0.1620	***	**	**
ECM	-0.1612	***	***	***
LFF_PC (-1)	0.0607	***	***	***
LELE_PC (-1)	-0.0147	**		***
LRES_PC	-0.0037	*		**
SD_2008	-0.0269	***	***	***
TREND	0.0043	***	***	***
CONSTANT	1.3273	***	***	***
ELASTICITIES				
LFF_PC	0.3767	***	***	***
LELE_PC	-0.0913	**		***
LRES_PC	-0.0232	*	*	**

Notes: ***, ** and * denote statistical significance at 1%, 5% and 10% level, respectively. The elasticities show the long-run relationships while the semi-elasticities result in short-run relationships. The ECM means Error Correction Mechanism. FE shows the results of fixed effects regression, FE-Robust displays the results of fixed effects robust to the heteroscedasticity, and DK-FE presents the results of Driscoll-Kraay-fixed effects.

The results of model II – *TS fossil fuels consumption*, presented in Table 3.7 show that CO_2 emissions from the transport sector increase TS fossil fuels consumption in both the short- and long-run. The *GDP_PC* increases fossil fuels in the short-run, showing a kind of the feedback hypothesis. An increase of 1pp in the economic growth (*DLGDP_PC*) increases fossil fuels consumption by 0.1418pp. Investment in rail infrastructure decreases fossil fuels use. In fact, a rise of 1% in rail investment generates a decrease of 0.045% in fossil fuels use. Albeit only with a 10% level of significance (DK-FE), electricity consumption exhibits a negative effect on TS fossil fuels consumption.

Table 3.7 - Model II – *DLFF_PC*

	Coefficients	FE	FE - ROBUST	DK – FE
DLGDP_PC	0.1418	*	***	*
DLCO$_2$	0.8991	***	***	***
ECM	-0.2157	***	***	***
LELE_PC (-1)	-0.0230	**		*
LCO$_2$ *(-1)*	0.1822	***	***	***
LRAIL (-1)	-0.0098	**	***	**
TREND	-0.0011	***	***	***
CONSTANT	-0.2316			
ELASTICITIES				
LELE_PC	-0.1067	**		*
LCO$_2$	0.8448	***	***	***
LRAIL	-0.0453	**	***	***

Notes: ***, ** and * denote statistical significance at 1%, 5% and 10% level, respectively. The elasticities show the long-run relationships while the semi-elasticities result in short-run relationships. The ECM means Error Correction Mechanism. FE shows the results of fixed effects regression, FE-Robust displays the results of fixed effects robust to the heteroscedasticity, and DK-FE presents the results of Driscoll-Kraay-fixed effects.

The results of the model III- *TS electricity consumption* are displayed in Table 3.8. Fossil fuels use exhibits a substitution effect with electricity consumption in the transport sector. Correspondingly, the elasticity value shows that an increase of 1% in TS fossil fuels consumption generates a decrease of 0.8699% in electricity consumption. Moreover, CO_2 emissions also increase electricity use. Renewable fuels increase electricity consumption in the transport sector in the short-run, however, it only exhibits significance in the Driscoll-Kraay estimator.

Table 3.8 - Model III – *DLELE_PC*

	Coefficients	FE	FE - ROBUST	DK – FE
DLRES_PC	0.0151			**
ECM	-0.3184	***	***	***
LFF_PC (-1)	-0.2769	***	**	***
LCO_2 *(-1)*	0.2742	***	*	***
DUM_UK	0.2621	***	***	***
TREND	-0.0017			**
CONSTANT	-0.2904			
ELASTICITIES				
LFF_PC	-0.8699	***	***	***
LCO_2	0.8613	***	***	***

Notes: ***, ** and * denote statistical significance at 1%, 5% and 10% level, respectively. The elasticities show the long-run relationships while the semi-elasticities result in short-run relationships. The ECM means Error Correction Mechanism. FE shows the results of fixed effects regression, FE-Robust displays the results of fixed effects robust to the heteroscedasticity, and DK-FE presents the results of Driscoll-Kraay-fixed effects.

Regarding Model IV – *TS* CO_2 *emissions* (see Table 3.9), as expected, the biggest contributor to the TS CO_2 emissions is the TS fossil fuels consumption, presenting high levels of significance in both the short- and long-run. Indeed, in the short-run, an increase of 1pp in TS fossil fuels use generates an increase of 0.6847pp in CO_2 emissions. Concerning the long-run, a 1% rise in fossil fuels use increases CO_2 emissions by 0.8995%. In contrast, the consumption of renewable fuels in the transport sector reduces CO_2 emissions in both the short- and long-run, though with lower significance levels. Lastly, electricity consumption and rail infrastructure investment increase CO_2 emissions in the long-run. Quantitatively, an increase of 1% in electricity use and rail investment generates an increase of 0.1415% and 0.6285% in CO_2 emissions, respectively.

Table 3.9 - Model IV – DLCO$_2$

	Coefficients	FE	FE - ROBUST	DK – FE
DLFF_PC	0.6847	***	***	***
DLRES_PC	-0.0074	**		*
ECM	-0.1607	***	***	***
LFF_PC (-1)	0.1445	***	***	***
LELE_PC (-1)	0.0227	**		***
LRES_PC (-1)	-0.0071	***		**
LRAIL (-1)	0.0101	***	*	**
TREND	0.0019	***	***	***
CONSTANT	0.4740	***	***	**
ELASTICITIES				
LFF_PC	0.8995	***	***	***
LELE_PC	0.1415	***	*	**
LRES_PC	-0.0440	***		**
LRAIL	0.6285	***	**	**

Notes: ***, ** and * denote statistical significance at 1%, 5% and 10% level, respectively. The elasticities show the long-run relationships while the semi-elasticities result in short-run relationships. The ECM means Error Correction Mechanism. FE shows the results of fixed effects regression, FE-Robust displays the results of fixed effects robust to the heteroscedasticity, and DK-FE presents the results of Driscoll-Kraay-fixed effects.

Lastly, a special note regarding the ECM values. They are highly significant in all the models. Moreover, in all the models the values show a moderate speed of adjustment from the short- to the long-run.

3.4 Discussions

The effects of energy consumption by the TS on economic growth and CO$_2$ emissions has been an object of analysis in the literature. However, the study of the disaggregation of this consumption into fossil fuels, electricity, and renewable fuels remains scarce. In the current trend of transition towards electric mobility and decarbonisation of the TS, studying the effects that result from both conventional and alternative sources could be very helpful for political decision-making. Indeed, the use of renewable fuels plays a fundamental role. In fact, the use of these sources is contributing to reduce CO$_2$ emissions. However, the policies to promote it require further analysis as these sources are apparently hampering economic growth. This outcome could result from the excessive costs associated with implementing these sources.

The decarbonisation of the TS must pursue the reduction of fossil fuels use, namely oil. Indeed, this study supports the argument that investment in rail infrastructure is reducing fossil fuels use. In other words, new railway infrastructures and the improvement of existing infrastructures have contributed to reduce fossil fuels use by the TS. Meanwhile, this investment is apparently increasing CO_2 emissions. Firstly, these outcomes could reveal that the new railways incorporate more energy efficient technologies. Secondly, this result could indicate that improvements in conditions on the trains have made them more attractive to users and consequently reduced the use of private cars. This finding is line with that observed by Lin & Du (2017) who argue that the construction of rail transit can reduce energy consumption by cars in China.

Another relevant outcome of this research is the proof that the use of electricity by the TS is reducing TS fossil fuels use. Consequently, incentives must be used to encourage transition to electric mobility, but the policies to promote this transition must be reconsidered. Firstly, during the period under study, transport electrification has been mainly focused on the rail infrastructure. Therefore, a negative effect on economic growth could reveal a high cost associated with electrification. Secondly, a positive effect on CO_2 emissions could indicate that electricity system remains fairly dependent on fossil fuels to generate electricity.

Lastly, a special note on the highly significant role of fossil fuels in this sector. In fact, TS is substantially powered by fossil fuels and this consumption is important for economic growth. Moreover, this study also confirms that they are frequently found to have a harmful effect on the environment. In the countries under study, the transition to electric mobility is being blocked by this source. Therefore, incentives are required to reduce fossil fuels use, as are improvements in the technology of electric vehicles to make them more competitive.

3.5 Conclusions

This chapter is focused on the analysis of the transport sector, by assessing the relationships of the energy sources used in that sector, with both economic growth and carbon dioxide emissions. In particular, it employs a Driscoll-Kraay fixed effects estimator, following an ARDL structure, to analyse the interaction between economic growth, TS fossil fuels consumption, TS electricity consumption and TS CO_2 emissions. The use of the ARDL structure proved to be appropriate when the short- and long-run effects are significantly different. The TS is in current and fast transition, particularly in diversifying its power sources, such as in electric mobility, which has been accompanied by innovations in battery and storage technologies.

This study highlights that the ongoing trend for electrification of the TS must be pursued carefully. On the one hand, greater electricity use is contributing to reducing fossil fuels use, confirming the expected substitution effect. However, the historical data provides two disconcerting findings, namely the negative effect on economic growth and the positive effect on CO_2 emissions from electrification. The negative effect on economic growth could reflect the high associated costs of TS electrification, namely those coming from the diversification of the electricity mix, particularly renewables. Regarding the non-desirable positive effect on carbon dioxide emissions, this could be a consequence of the continuous use of burning fossil fuels both to provide baseload on the national electricity systems, namely cheap coal, and the need to back-up intermittent renewables. It is worthwhile to highlight the limitations of using historical data, namely by stressing that empirical evidence from what has already happened does not guarantee that the relationships will be the same in the future. These findings could provide some guidance for the policymakers to reverse these effects in the near future.

At first glance, one would expect that a reduction in fossil fuels consumption by transportation could be achieved by increasing investment in rail infrastructure. However, this chapter finds that investment in railways has not reduced CO_2 emissions. This outcome could mean that improvements in conditions on both new and existing trains have made them more attractive to users, reducing the use of private cars powered by fossil fuels. However, greater use of rail causes an increase in electricity demand, thereby contributing to larger CO_2 emissions. This effect could be explained as follows. On the one hand, by the expansion of the rail mainly powered by electricity, which may be generated by burning fossil fuels. This finding is consistent with that found for electricity. On the other hand, the investment in infrastructure requires larger amounts of energy, particularly in the steel industry and, as such, larger CO_2 emissions.

Regarding renewable fuels, although they are reducing the harmful environmental effects traditionally associated with the transport sector, the negative effect observed on economic growth should not be overlooked. This effect could reveal the high costs associated with these sources. In view of this, policymakers should guarantee that the substitution of energy sources for transport do not constrain economic growth, potentially by exploring new renewables to generate electricity, such as wind and solar photovoltaic, which are increasingly cost-effective.

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Chapter 4

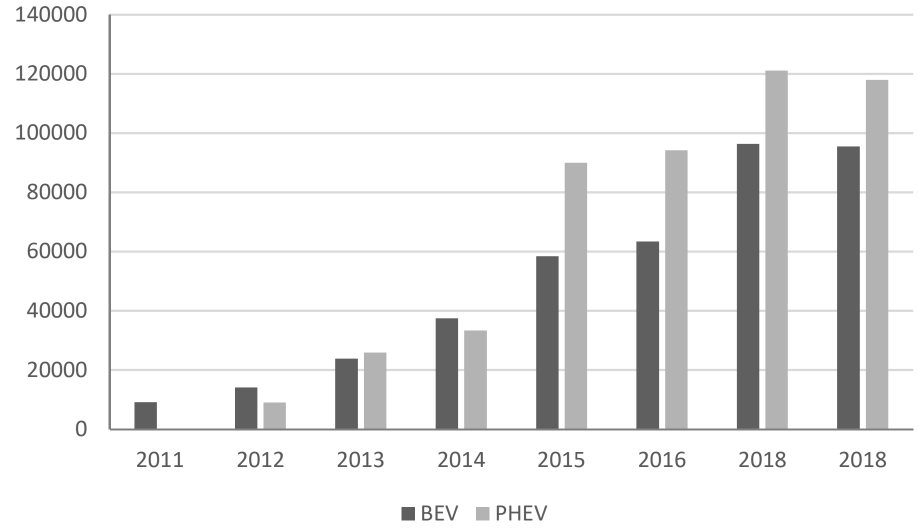
Technological progress and other factors behind the adoption of Electric Vehicles: Empirical evidence for EU countries

The chapters 2 and 3 was crucial not only for understand the complexity of the simultaneous use of the both conventional and alternative energy sources in Transport Sector (TS) but also for motivate this chapter. Overall, it is focused on one of the main challenges of the electricity use in TS: the penetration of the electric vehicles. Therefore, this chapter aims to analyse the factors supporting the transition to new forms of mobility, namely Electric Vehicles (EV). For a deep understanding of these effects, we analysed EV, by dividing them into individual Battery Electric Vehicles (BEV), which are 100% electric, and Plug-in Hybrid Electric Vehicles (PHEV). The factors examined include: policy, social, economic, environmental, and technical. This chapter uses data from 2010 to 2016 for a panel of the 24 European Union (EU) countries. A Panel-Corrected Standard Errors (PCSE) estimator is used. When comparing the results of analysing BEV and PHEV individually, and all EV together, they prove to be quite different. This finding indicates that policies should be tailored to each individual technology, rather than a single one for all EV. The proxy used for technological progress is the increased use of both BEV and PHEV. The evidence is also provided that charging stations are drivers of electric mobility.

4.1 Introduction

The penetration of renewable sources within the electricity mix, is one of the measures intended to support the transition to low-carbon economies. However, sectors intensive in fossil fuels, such as the TS continue to hamper this transition. The IEA (2016) indicates that this sector is accountable for 23% of global carbon dioxide (CO_2) emissions, with road transport being responsible for around 17%. Therefore, to decarbonise economies, there has to be a change in the TS energy paradigm.

The penetration of EV within the automotive market has been pursued with this objective in mind. EV can be categorized into: Hybrid Electric Vehicles (HEV), PHEV, and BEV. Technically, HEV is characterized as having both an Internal Combustion Engine (ICE), powered by gasoline, diesel, methane or liquid gas, and an alternative electric motor, which is powered by electricity stored in a battery. The batteries of these cars are charged by regenerative braking systems and by their ICE. In the same way, PHEV use both an electric motor powered by batteries and an ICE powered by fossil sources. In general, PHEV have larger batteries than HEV and can also be charged directly from the electricity grid. These vehicles can be powered solely by electricity or by a specific fossil fuel. BEV (also known as 100% EV) only use batteries, charged from the electricity grid, to power an electric motor. Although BEV still hold a lower share of the automotive market, the number of these vehicles is increasing significantly (Brenna, Foiadelli, Roscia, Zaninelli, & Member, 2012). Figure 3.1 is supporting it by showing the yearly new registrations of the both BEV and PHEV in the EU 28.



Notes: Own elaboration. Data source: European Alternative Fuels Observatory

Figure 4.1 - BEV and PHEV new registrations EU-28

Although the market share of EV is expected to be much more significant within a few decades, currently it remains small. This expected increase remains heavily dependent on technological improvements in batteries (Hannan, Lipu, Hussain, & Mohamed, 2017). Furthermore, there are other factors that may encourage or inhibit decisions to acquire EV (Adnan, Nordin, & Rahman, 2017; Coffman, Bernstein, & Wee, 2017a; Hardman, Chandan, Tal, & Turrentine, 2017; W. Li, Long, Chen, & Geng, 2017; Rezvani, Jansson, & Bodin, 2015). However, empirical analyses based on historical data, of the role played by these factors remain scarce. Some exceptions include Li, Chen, & Wang (2017), who analysed the role of socioeconomic factors and renewables on EV adoption in 14 countries from 2010 to 2015.

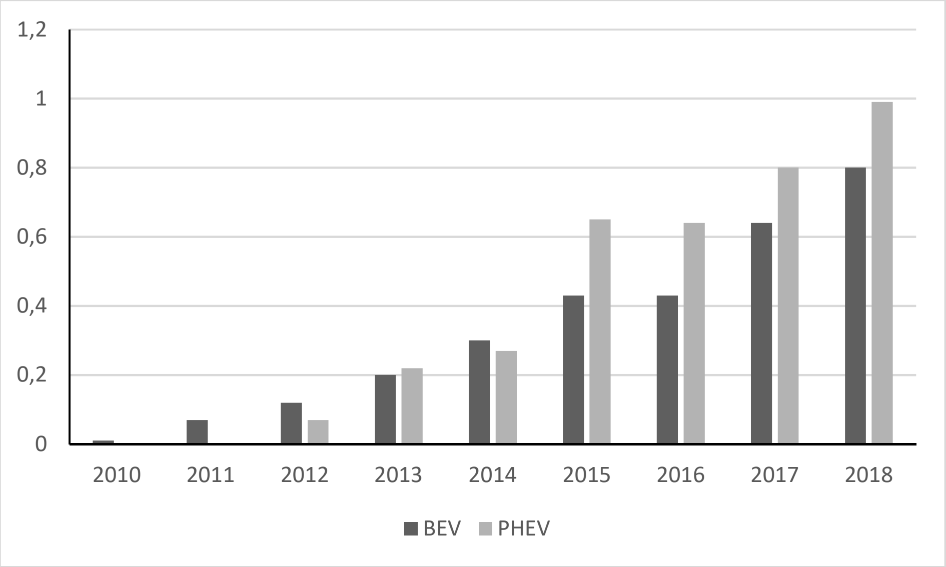
The contribution made by this chapter to the literature is twofold. Firstly, it empirically analyses the role of several factors, namely policy, social, economic, environmental, and technical on EV adoption of both BEV and PHEV. In fact, this chapter represents a considerable improvement on the scant literature that has analysed the factors supporting EV adoption. Secondly, to the best of our knowledge, the literature has not yet focused on the role played in the diffusion of EV by progress in battery technology, via an empirical approach using historical data. In summary, this chapter aims to answer the following central questions: (i) what are the factors that promote the penetration of EV?; (ii) are these factors identical for BEV and PHEV?; and (iii) is technological progress the main driver for EV deployment?

The analysis of these effects was performed using annual data from 2010 to 2016 for a panel of 24 EU countries. Accordingly, three models were estimated (BEV, PHEV, and EV) by using the PCSE estimator, because it is appropriate for dealing with the features of the data. The robustness of the results was performed by employing a Seemingly Unrelated Regressions (SUR). The results suggest that each EV vehicle type must be analysed individually rather than jointly as a whole. Policy factors have been effective in increasing the market share of BEV, but not of PHEV. Regarding social factors, both education level and employment rate increase the BEV market share. Only the number of charging stations and the proxy for technological development have a similar effect on both BEV and PHEV, and jointly analysis of the EV. In fact, both of them increase the likelihood of deciding to acquire a BEV or PHEV. Renewable electricity generation proves to be appropriate for increasing the number of BEV and PHEV.

The remainder of this chapter is organized as follows: Section 4.2 revises the literature focused on EV adoption; Section 4.3 describes the data used and the methodology applied. The results are presented in Section 4.4 and their robustness is checked in the Subsection 4.4.1. In Section 4.5, the results are discussed, and some policy guidelines are provided. Lastly, Section 4.6 presents the conclusions.

4.2 Factors supporting the EV, BEV, and PHEV adoption - state of the art

The transition towards electric mobility has been promoted to accomplish several objectives, particularly environmental protection and a reduction in fossil-fuel dependence. Additionally, it could even contribute to rationalizing the electricity system as a whole, specifically by storing electricity in off-peak periods and cutting electricity demand during peak periods. Currently, this kind of mobility, particularly for road transportation, represents only a tiny share of the total vehicles in use. It could be verified, actually in Figure 3.2 that shows the evolution of the market share of the both BEV and PHEV for EU 28.



Notes: Own elaboration. Data source: European Alternative Fuels Observatory

Figure 4.2 - BEV and PHEV market share in EU-28 (%)

To enable EV to contribute to a sustainable future, a new paradigm of electric mobility must be created and encouraged to take advantages of the diversification of the electricity mix, specifically the increased generation from renewable sources. The analysis of the factors supporting the adoption of EV has recently become a hot topic in the literature. However, its conclusions remains far from consensual (Adnan et al., 2017; Al-Alawi & Bradley, 2013; Coffman et al., 2017a; Hardman et al., 2017; W. Li et al., 2017; Rezvani et al., 2015), which indicates that further and deeper research still needs to be carried out.

The literature has already identified a series of factors that could influence a decision to acquire an EV and has aggregated it into a set of the categories. In this study, we opted to focus on the factors: policy, social, economic, environmental, and technical. Consequently, there now follows a brief review of the effects of these factors on EV adoption.

4.2.1 Policy factors

Policies incentives have already been offered in many countries, such as free car parking and privileged road access. According to Matthews, Lynes, Riemer, Del Matto, & Cloet (2017) incentive programmes should also be created for sales staff and dealers, because they could provide information that could encourage buyers to opt for an EV rather than conventional vehicles. Programmes should also be developed to inform car salesmen and dealers, so that they are more knowledgeable about this innovative technology, and can explain to consumers which model and battery type is most suitable for their needs (Cahill, Davies-Shawhyde, & Turrentine, 2014). Sellers and resellers should have information about vehicle costs, EV-related incentives, and the different types of charging stations (normal or fast) as well as charging duration (Matthews et al., 2017).

In order to be efficient, incentive policies must be tailored to the behaviour of potential clients, people who are more likely to change their behaviour and are less sensitive to changing prices (Langbroek, Franklin, & Susilo, 2016). The government should create measures focused on people in the early stages of changing their behaviour and create specific incentives for them. Indeed, the literature suggests that people in advanced stage-of-change could be less price sensitive and be more disposed to adopt EV (Langbroek et al., 2016). Accordingly, financial incentives are a driver for EV adoption (Sierzchula, Bakker, Maat, & Van Wee, 2014). However, incentives based on use could be less expensive and they are relatively effective in encouraging EV adoption, compared to subsidies or registration tax rebates (Langbroek et al., 2016). Nonetheless, purchase incentives are more effective for PHEV adoption than VAT or purchase tax exemptions or grants (Hardman et al., 2017).

The accumulated number of policies is used to operationalize the policy factor. This variable of policy has been taken in an aggregate way, i.e., it considers all the policies focused on electric mobility as a whole. To the best of our knowledge, this represents some novelty in the literature focusing on the factors supporting electric mobility. The exception includes Vergis & Chen (2015), who analysed the role of the purchase incentives and other policies and measures on PHEV adoption in the United States, by using a dummy variable to represent the purchase incentives and the cumulative number of policies to operationalize other policies and incentives. The findings of this study suggest that both purchase incentives and other policies increase the market share of PHEV. In this way, the assessment of the effectiveness of the policy-driven mechanism on the deployment of electric mobility seems to be of particular relevance. Indeed, public intervention could play a critical role in the transition of paradigm from conventional fossil fuel powered vehicles towards electric vehicles. The use of the accumulated number of policies to operationalize the policy variables is quite rare in the literature focused on the drivers of EV, but it is actually a traditional practice in the more general literature. For instance, Aguirre & Ibikunle (2014) used the accumulated number of policies supporting the renewable energy to analyse the determinants of renewable growth. In the same way, this approach also was followed by Marques & Fuinhas (2012) and Polzin, Migendt, Täube, & von Flotow (2015). The advantages of the using this policy variable operationalization is discussed below, in Section 4.3.

4.2.2 Social factors

Another category analysed by the literature is that of social factors. In fact, it is expected that social factors, such as education, employment rate, age, and household size could influence the decision to opt for an EV. The literature indicates that the education level is a driver of EV acceptance (Javid & Nejat, 2017; Li et al., 2017). Similarly, Carley, Krause, Lane, & Graham (2013) found that the highly educated consumers typically show an earlier interest in buying an EV than consumers with a lower education level. Additionally, the same author claims that the acceptance of PHEV is boosted by a consumer perception of the limitations of EV. Other social factors have also been analysed, such as age, population density and employment rate (Higgins et al., 2012; Li et al., 2017).

4.2.3 Economic factors

The debate around the economic factors that may influence a decision to buy an EV is increasing significantly in the literature. A series of economic variables has been analysed in the literature, such as Gross Domestic Product (GDP) per capita and household income. However, the findings have not always have been consensual, with evidence of three effects of income on EV adoption: positive (Javid & Nejat, 2017; Soltani-Sobh, Heaslip, Stevanovic, Bosworth, & Radivojevic, 2017; Zhang, Yu, & Zou, 2011), and neutral (Hidrue, Parsons, Kempton, & Gardner, 2011; Sierzchula et al., 2014; Bjerkan, Nørbech, & Nordtømme, 2016; X. Li et al., 2017). The neutral effect found in Norway could indicate high competition in the market (Bjerkan et al., 2016). According to Sierzchula et al. (2014) the absence of the statistical significance of GDP in explanation of the EV market share could be a consequence of the low market share that this kind of vehicles represents of the total vehicles. Otherwise, the EV users have typically high income (Jochem, Plötz, Ng, & Rothengatter, 2018; Peters, Wer, & Steg, 2018; Ystmark, Nørbech, & Elvsaas, 2016). Which could mean that users with medium or low income are not disposable to acquire an EV, once they are not willing to pay for it.

Another economic factor which is usually analysed in the literature is the purchase cost of the EV. In fact, the purchase cost appears as a barrier to EV adoption. However, the low operating costs of these vehicles, namely the electricity price, are a driver of EV adoption, such as noted by Barth, Jugert, & Fritsche (2016); and Tamor, Gearhart, & Soto (2013). As such, one expects that, in the long-run, electric vehicles are more cost competitive than conventional vehicles (Ystmark et al., 2016). In this sense, the price of the energy utility used, such as conventional fuel or electricity has also been in focus, because it could influence a decision to purchase an EV. In fact, these prices are external to the consumers and vehicles (Sierzchula et al., 2014). However, these prices could be directly related to EV deployment and could influence a decision to acquire an EV. The effect of conventional fuel prices has also been considered in the literature, and differing effects have been found for each vehicle type. For instance, X. Li et al. (2017) found that the average petrol price is not significant for explaining the market share of either EV or PHEV. However, it has a positive impact on BEV. In the same way, such as in Brazil, the gasoline price stimulates the propensity of acquisition of a BEV (Ystmark et al., 2016). On contrary, the literature also indicates that the average of diesel and gasoline prices is not a good predictor for explaining EV adoption. Indeed, an increase in fuel prices could make BEV more attractive than PHEV because of the latter's continued dependence on fuel to power an ICE. This is supported by the Vergis & Chen (2015), who found a positive impact of gasoline prices on the market share of BEV, but no significant impact on that of PHEV.

Regarding the price of electricity, it may not be significant in explaining the adoption of EV (Sierzchula et al., 2014) or PHEV (Javid & Nejat, 2017). Nonetheless, Soltani-Sobh et al., (2017) found a negative effect of electricity prices on decisions to acquire an EV. Indeed, the price of electricity may vary significantly between countries (Wu, Inderbitzin, & Bening, 2015). As the decision to obtain an EV could be dependent on the electricity price, it must be considered in the analysis.

4.2.4 Environmental factors

The promotion of EV has been pursued to reduce GHG emissions in the transport sector (Manjunath & Gross, 2017). In fact, EV could contribute positively to achieving the targets established by the EU because they have zero emissions on the road (Nanaki & Koroneos, 2016). Nonetheless, the literature indicates that the environmental benefits associated with EV can only be achieved if the electricity is being generated from renewable sources. Conversely, if the electricity is generated from non-renewables, the environmental benefits may not be achieved (Ajanovic & Haas, 2016). According to Nienhueser & Qiu (2016), countries that have a large percentage of electricity generated from renewable energy, such as Norway and Spain, should be developing PHEV or BEV industries, not only to reduce GHG emissions but also to reduce the need for oil. However, countries where the electrical power structures are generating electricity from non-renewable sources, such as coal, should develop HEV industries, which are more appropriate for reducing both electricity consumption and emissions (Nienhueser & Qiu, 2016). Indeed, there is another crucial reason, which is the rational use of an excess of electricity supplied at certain times of the day.

Although it is expected that the people's awareness of climate change might stimulate the decision to adopt EV, the literature does not always find this. On the one hand, Graham-Rowe et al. (2012) find that environmental concerns are not a relevant driver for the EV adoption. On the other hand, Noppers, Keizer, Bolderdijk, & Steg, (2014) argue that environmental protection is an important factor in EV penetration. Additionally, environmentalism positively increases the PHEV market share (Vergis & Chen, 2015). Nevertheless, some doubts are arising regarding the real impact of EV on the environment, particularly from the pollution caused by both batteries (assembly and recycling) and electricity generation using polluting sources (Axsen, TyreeHageman, & Lentz, 2012).

4.2.5 Technical factors

Although the transition to electric mobility is currently being deployed, there are several technical factors that are still hindering its acceptance. Improvements in batteries to achieve a longer driving range and longer life at less cost are fundamental to achieve a large EV market share (Mahmoudzadeh Andwari, Pesiridis, Rajoo, Martinez-Botas, & Esfahanian, 2017). Consequently, the technological level is decisive to EV deployment (Liu, You, Xue, & Luan, 2017). Moreover, the charging of EV could have a significant impact on the power grid, as they can make use of energy produced from renewable sources (Habib, Kamran, & Rashid, 2015).

The introduction of EV could require changes in the power grid. In fact, the system may be unable to deal with the additional energy demand caused by the EV charging. On the one hand, there is evidence that with controlled charging during off-peak periods, there may be no need to increase the installed capacity (Razeghi & Samuelsen, 2016). On the other hand, it may become necessary to implement Demand Response (DR) programmes, which reduce electricity peaks and valleys (valley-filling), and consequently reduces electricity costs.

The interaction of EV with renewable energy production is particularly suited for the implementation of such programmes (Coffman, Bernstein, & Wee, 2017b; Nienhueser & Qiu, 2016). DR programmes aim to control the demand for electricity and lead to a reduction in the costs of an electrical system (López, Torre, Martín, & Aguado, 2015). Therefore, it is fundamental to rethink electrical systems, especially with respect to the management of electricity demand. Demand Side Management (DSM) aims to implement capacity-utilization measures through changes in the demand for electricity, to provide information, such as tariffs for consumers, and to promote devices that control consumption (Riesz, Sotiriadis, Ambach, & Donovan, 2016). EV are a tool of DSM and, by charging these vehicles, it is possible to reduce peak demand (high demand peaks are "clipped") and thereby reduce loads at peak periods. This makes it possible to reduce dependence on fossil fuels since EV can be an instrument in reinforcing the use of renewable sources.

4.3 Data and Methodology

This chapter uses data from 2010 to 2016 for a panel of 24 European countries. The countries were selected under the criterion of data availability for all the variables used. Accordingly, the countries analysed are: Austria, Belgium, Croatia, Cyprus, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, Italy, Latvia, Lithuania, Luxembourg, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and the United Kingdom.

The debate in Section 4.2 on the factors for the EV adoption, indicates that the variables be tested, in accordance with several factors, namely: policy, social, economic, and environmental, as shown in Table 4.1. Hereafter the prefix "L" means natural logarithm.

Table 4.1 - Factors and variables

Factors	Variables
POLICY	• Accumulated number of policies on electric mobility (*POLICIES*)
SOCIAL	• Employment rate (*LEMP*) • Education level (*LEDU*)
ECONOMIC	• Industrial Production Index (*LIPI*) • Gross Domestic Product per capita (*LGDP_PC*) • Fuel price (*LCRUDE*) • Electricity price (*LELE*)
ENVIRONMENTAL	• GHG emissions (*LGHG_PC*)
TECHNICAL	• Number of charging stations per 100 thousand people (*LCHARG_PC*) • Main information on battery costs, Nissan Leaf range and battery capacity (*TECHNICAL*) • Renewable electricity generation per capita (*LRES_PC*) • Patents registered in the transport sector (*LPAT*)

A careful analysis was made of the literature to justify the choice of the variables used. Nonetheless, several innovations were introduced as described below. For the social factors, education levels and employment rates were analysed. Firstly, because education levels may be a driver for EV adoption, and highly-educated people may express an earlier interest in buying EV (Carley et al., 2013), the analysis considered people with tertiary education (*LEDU).* Secondly, the employment rate was used as an explanatory variable (Higgins et al., 2012; Mersky, Sprei, Samaras, & Qian, 2016), as it can be a sign of income status.

Regarding the economic factors, this study uses the IPI, GDP per capita, crude oil prices and electricity prices. The IPI has been used as a proxy to measure the economic activity and the GDP per capita have been used as an income's proxy. Additionally, as affirmed by Kaplan, Gruber, Reinthaler, & Klauenberg (2016), the industrial sector could be associated with positive attitudes on EV adoption. Furthermore, considering the tendency of companies benefiting from exclusive tax incentives to acquire EV, the IPI is likely to be more effective in explaining EV following the industrial perspective, while the GDP could be effective as a proxy for the income level.

In order to analyse the role of the policy factors, the accumulated number of the policies focused on electric mobility were used. In fact, it is a usual practice in the literature that operationalizes the policy variable econometrically, to analyse, for instance, their impact on renewables deployment (Aguirre & Ibikunle, 2014). Following this rationality, and focusing on literature centred on drivers of the electric mobility, Vergis & Chen (2015) analysed the role of the policy and incentives on BEV and PHEV adoption, other than purchase incentives by using the cumulative number of policies. Please note that, although the use of this variable is a usual practice in the literature, it shows some limitations. On the one hand, this policy variable operationalization does not allow for the capture of the different magnitudes of the effects caused by the policies. On the other hand, it does not permit the study of each policy individually. However, we have to report the reasons behind this option. Firstly, being it a recent topic, the detailed data is very scarce, and even were it available it would lead us to have an excess of "zeros" in the database which could promote a severe handicap for the estimations. Secondly, the individual analysis of the policies and measures would promote an overfitting problem in the regression, i.e. there are too many independent variables for a panel that contains a short time span. Despite the reported limitations, this variable operationalization proved to be an efficient way to analyse the role of the policy factors in parsimonious regressions.

With regard to technical factors, the registration of patents in the transport sector was used as a proxy for investment in Research and Development (R&D) (Burhan, Singh, & Jain, 2016). Additionally, the literature argues that EV penetration has been hampered by their limited range, lack of charger availability and purchasing costs (Axsen & Kurani, 2013). Therefore, we introduced the number of charging stations, relative to the population, as used by Li et al. (2017). Moreover, we used the average battery pack price (*LBAT_COST*). The inclusion of this variable aimed to capture the effect of the cost of purchasing EV, as a large part of the cost of EV is represented by their batteries. To consider the battery range (*LRANGE*) and battery capacity (*LBAT_CAP*) we used the characteristics of the Nissan Leaf car. The choice of the Nissan Leaf model as a proxy for technological development can be explained as follows. It is the top selling battery electric vehicle in the world, having won several awards, namely, 2010 Green Car Vision Award, 2011 World Car of the Year and European Car of the Year, and 2011-2012 Car of Year Japan, and is accepted as a key reference in the EV market (Nhamo, 2015).

To ascertain the technological progress on EV batteries a Principal Component Analysis (PCA) was carried out. This method allows us to obtain the essential information on each variable and convert it into a single variable. It is useful when we are working with highly correlated variables, such as battery cost, the range of the battery, and battery capacity. In fact, an inspection of the correlation matrix values makes the individual use of these variables in the models unfeasible, because they have high correlation matrix values, and reveal multicollinearity problems. Consequently, these high correlations indicate that the use of the PCA could be appropriate.

Table 4.2 - Adequacy of the PCA

Determinant of the correlation matrix	0.007
Bartlett's test of sphericity	818.512***
Kaiser-Meyer-Olkin Measure of sampling adequacy	0.740

Notes: *** denotes statistical significance at 1%. The Bartlett test of sphericity was performed under the null hypothesis of the variables are not intercorrelated.

The suitability of the PCA usage was evaluated by using Bartlett's test of sphericity and the Kaiser-Meyer-Olkin Measure of sampling adequacy. The results exhibited in the Table 4.2, reveal that the null hypothesis wherein the variables are not intercorrelated was rejected, indicating that the variables are sufficiently correlated to apply this method. Additionally, the value of 0.740 for the Kaiser-Meyer-Olkin Measure of sampling adequacy, reveals the suitability of using the PCA on these variables, as suggested by Kaiser (1974), as values above 0.5 are acceptable. Table 4.3 discloses the variables used, description, statistics descriptive and sources.

Table 4.3 - Variables' definition and descriptive statistics[5]

Variable	Description	Obs	Mean	Std. Dev.	Min	Max	Source
LEV_SH	Market share of EV (BEV+PHEV), per thousand of vehicles	168	1.0531	0.9952	0	4.6082	EAFO
LBEV_SH	Market share of BEV, per thousand of vehicles	168	0.7671	0.7293	0	3.2995	EAFO
LPHEV_SH	Market share of PHEV, per thousand of vehicles	168	0.5880	0.8475	0	4.5315	EAFO
LBAT_COST	Average of the cost of battery production ($/kWh)	168	6.2107	0.5334	5.2700	6.9088	ELETRECK
LRANGE	Nissan Leaf driving range (km)	168	5.4506	0.1289	5.2983	5.6348	PUSHEV
LBAT_CAP	Nissan Leaf battery capacity (kWh)	168	3.2816	0.0981	3.2189	3.4340	PUSHEV
TECHNICAL	Composite variable index created by using PCA of the logarithm of battery cost, range and battery capacity	168	-8.87e-09	1.6911	-1.8177	2.7469	*LRANGE, LBAT_CAP and LBAT_COST*
LEDU	Population having tertiary education (% of the population between 25-64 years)	168	3.3798	0.2970	2.6810	3.8480	PORDATA
LIPI	Industrial production index (2010=100)	168	4.6473	0.1052	4.2850	5.9294	EUROSTAT

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[5] Since all the variables were converted into their natural logarithm, the constant of 1 was added to all of them, to solve the issue of observation loss.

LGDP_PC	Gross Domestic Product per capita, Chain linked volumes (2010) (€/person)	168	9.5175	1.0688	6.6233	11.3479	EUROSTAT
LGHG_PC	Total greenhouse gases emissions per capita (kg CO_2 equivalent /person)	168	8.9342	0.3613	8.2989	9.7	UNFCCC
LCHARG_PC	Number of the publicly accessible charging positions (per 100 thousand people)	168	1.1933	1.2842	0	5.0642	EAFO
LPAT	Number of patent registrations in the transport sector	168	1.1965	0.9442	0.0387	3.5025	WIPO
LCRUDE	Bent crude oil price constant prices of 2010 (€/barrel)	168	4.3729	0.3693	3.6424	4.7302	FRED
LELE	Electricity price at constant prices of 2010 (€/kWh)	168	0.1558	0.0404	0.0884	0.2559	EUROSTAT
LRES_PC	Electricity generation from renewables per capita (kWh/person)	168	0.9847	0.5168	0.0854	2.4443	IRENA
POLICIES	Number of accumulated policies supporting electric mobility	168	1.3095	0.9218	1	5	New Climate Policy

Notes: obs, observations; Std. Dev., standard deviation; min, minimum, max, maximum; EAFO, European Alternative Fuels Observatory; FRED, Federal Reserve Economic; IRENA, International Renewable Energy Agency; UNFCCC, United Nations Framework Convention on climate change; WIPO, World Intellectual Property Organization

The presence of correlation and multicollinearity were assessed. The correlation matrix values and the Variance Inflation Factor (VIF) indicated the suitability of the data for the estimations.

After that, all the variables used was submitted to the unit root test, namely the residual-based Lagrange multiplier method, proposed by Hadri (2000). In this, the cross-interdependencies were removed, and it included heteroskedasticity and time trends, as did Li et al. (2017). The null hypothesis proves that the panels are stationary.

In the model estimations, the set of independent variables were subdivided into two main groups. This procedure was adopted because this study was comprised of 24 crosses and seven years. As such, considering that the panel data set is small, no more than seven explanatory variables should be used simultaneously. Bearing in mind that the main objective of this chapter is to analyse the factors driving EV adoption, three models were estimated, Model I – *100% Electric Vehicles,* Model II – *Plug-in Hybrid Electric Vehicles,* and Model III – *Electric Vehicles*. Each model was estimated by using different functional forms, A and B, i.e., two different groups of independent variables (see Table 4.4).

Table 4.4 - Description of the models

Model	Description of the dependent variable	Description of the independent variables
Model I – *100% Electric Vehicles* (A)	Battery Electric Vehicles market share (*LBEV_SH*)	*TECHNICAL, LRES_PC, LIPI, LELE, LEMP,* and *POLICIES*
Model I – *100% Electric Vehicles* (B)	Battery Electric Vehicles market share (*LBEV_SH*)	*LCHARG_PC, LPAT, LGDP_PC, LGHG_PC, LEDU,* and *LCRUDE*
Model II - *Plug-in Hybrid Electric Vehicle* (A)	Plug-in Electric Vehicles market share (*LPHEV_SH*)	*TECHNICAL, LRES_PC, LIPI, LELE, LEMP,* and *POLICIES*
Model II – *Plug-in Hybrid Electric Vehicle* (B)	Plug-in Electric Vehicles market share (*LPHEV_SH*)	*LCHARG_PC, LPAT, LGDP_PC, LGHG_PC, LEDU,* and *LCRUDE*
Model III – *Electric Vehicles* (A)	Electric Vehicles joint market share, both BEV and PHEV (*LEV_SH*)	*TECHNICAL, LRES_PC, LIPI, LELE, LEMP,* and *POLICIES*
Model III – *Electric Vehicles* (B)	Electric Vehicles joint market share, both BEV and PHEV (*LEV_SH*)	*LCHARG_PC, LPAT, LGDP_PC, LGHG_PC, LEDU,* and *LCRUDE*

The traditional Hausman test was performed to examine the presence of fixed effects compared to random effects Hausman (1978). However, the results of the traditional Hausman test could be biased in small samples and it is not robust in the presence of the heteroscedasticity and/or serial correlation. To overcome this limitation, the robust Hausman specification test was performed once it had been appropriated in presence of the heteroscedasticity and/or serial correlation (B. Kaiser, 2015). Table 4.5 shows the results of both the traditional and the robust Hausman tests.

Table 4.5 - Traditional and robust Hausman test

	Traditional Hausman test FE vs RE	Robust Hausman test FE vs RE
Model I – *100% Electric Vehicles* (A)	4	2.68
Model I – *100% Electric Vehicles* (B)	10.87*	11.52*
Model II - *Plug-in Hybrid Electric Vehicle* (A)	3.64	3.09
Model II – *Plug-in Hybrid Electric Vehicle* (B)	8.54	6.59
Model III – *Electric Vehicles* (A)	4.8	6.18
Model III – *Electric Vehicles* (B)	12.91**	16.50**

Notes: ** and * denotes statistical significance at 5% and 10%, respectively.

The null hypothesis of the Hausman test predicts that the random effects model is appropriated. Table 4.5 reveals that the null hypothesis, wherein the random effects model is appropriate, cannot be rejected, for all the estimated models, except Model III – *Electric Vehicles* (B). These findings will be very determinant for the models' estimation, i.e. in all the models' estimation the random effects estimator has been used, except in Model III – *Electric Vehicles* (B) which will be estimated by using fixed effects. Subsequently a series of specification tests were performed, namely the contemporaneous correlation test, Pesaran's test, the modified Wald test for groupwise heteroscedasticity, and the Wooldridge test for autocorrelation. The null hypothesis of these specification tests predicts the existence of cross-sectional independence, homoscedasticity, and no first-order serial autocorrelation, respectively. The results shown in Table 4.6 indicate the presence of heteroscedasticity, contemporaneous correlation, and first-order serial correlation for all the models, excepting the contemporaneous correlation for the structure (B) of models II and III.

Table 4.6 - Specification tests

	Model I - *100% Electric Vehicles*		Model II –*Plug-in Hybrid Electric Vehicles*		Model III - *Electric Vehicles*	
	(A)	(B)	(A)	(B)	(A)	(B)
Modified Wald test	1778.60***	1626.28***	2552.71***	9154.79***	5531.59***	5038.84***
Pesaran's test	5.950***	3.279***	5.337***	0.934	8.518***	-0.351
Wooldridge test	8.527***	6.768**	47.211***	69.081***	11.477***	11.540***

Notes: *** and ** denotes statistical significance at 1% and 5%, respectively. The Pesaran's test for the model III – (B) were performed in the fixed effects model.

To deal with these phenomena, the PCSE or Feasible Generalized Least Squares (FGLS) estimators should be applied. However, the FGLS becomes biased if the cross-sectional dimension (N) is larger than time dimension (T). As in this study T<N, i.e. this study comprises

24 crosses (N) and 7 years (T), the PCSE is the appropriate estimator and, conversely, the use of FGLS is inappropriate (Hoechele, 2010; Reed & Ye, 2011).

4.4 Results

The results of the unit root test shown in Table 4.7 indicate that the null hypothesis of stationarity could not be rejected and supports the stationarity of the almost of the variables. In fact, the stationarity could not be a noteworthy problem in panels that contain a short time span. However, for the variables that exhibit unit root in the Hadri test, the Maddala & Wu (1999) unit root test was checked and supported the stationarity of the variables.

Table 4.7 - Residual-based Lagrange multiplier method for the unit root test

Variable	z-statistic	Variable	z-statistic
LEV_SH	1.6158*	*LGHG_PC*	1.3856*
LBEV_SH	0.7634	*LCHARG_PC*	2.9598***
LPHEV_SH	0.8208	*LPAT*	-0.3909
TECHNICAL	0.2229	*LCRUDE*	1.8084**
LEDU	1.0690	*LELE*	0.9522
LEMP	1.9589**	*LRES_PC*	0.1759
LIPI	3.9393***	*POLICIES*	-3.3799
LGDP_PC	4.9339***		

Notes: * denotes statistical significance at 10% level of significance.

Remembering that the main objective of this chapter is to analyse the role of various factors, namely policy, social, economic, environmental, and technical, on the adoption of BEV, PHEV, and the joint market share of all EV, three models were estimated. Please note that all the models were estimated by using two different functional forms, namely A and B. For the model I - *100% Electric Vehicles*, in both A and B structures, the specification tests indicate the presence of heteroscedasticity, first-order serial correlation, and contemporaneous correlation. The simple random effects model (CSE), and the random effects model with the robust option to correct heteroscedasticity (RSE) were estimated, as was the random effects model with AR1 disturbances (AR1). To deal with contemporaneous correlation, the PCSE model was estimated (CORR(IND)), as were the PCSE estimator with the option for heteroscedasticity (HET). The PCSE estimator with the option for first-order serial correlation (AR1) was also performed to compare the PCSE estimator with the options for both heteroscedasticity and first-order serial correlation (HET-AR1). The results of the Model I -*100% Electric Vehicles* in both A and B specifications are shown in Table 4.8.

Table 4.8 - Model I – 100% Electric Vehicles

	Random effects			PCSE			
	CSE	RSE	AR1	CORR(IND)	HET	AR1	HET-AR1
(A)							
TECHNICAL	0.1941***	0.1941***	0.1743***	0.1927***	0.1927***	0.1541***	0.1541***
LRES_PC	0.2104	0.2104	0.1955	0.1653***	0.1653**	0.2027**	0.2027*
LEMP	3.4173***	3.4173***	3.5726***	3.8295***	3.8295***	3.4755***	3.4755***
POLICIES	0.1525**	0.1525*	0.1614**	0.1670***	0.1670***	0.1601***	0.1601***
CONS	-14.3061***	-14.3061***	-14.9907	-16.0496***	-16.0496***	-14.5984***	-14.5984***
(B)							
LCHARG_PC	0.3853***	0.3853***	0.3797***	0.4028***	0.4028***	0.3611***	0.3611***
LGDP_PC	-0.0883	-0.0883	-0.07773	-0.0824***	-0.0824**	-0.0657*	-0.0657
LEDU	0.6099***	0.6099***	0.5152***	0.4380***	0.4380***	0.4722***	0.4722***
CONS	-0.9139	-0.9139*	-0.6949	-0.4094	-0.4094	-0.6522	-0.6522

Notes: ***, **, and * denotes statistical significance at 1%, 5% and 10% level of significance, respectively. CSE denotes conventional standard error, RSE means robust standard errors, and AR1 assumes the first-order serial correlation; CORR(IND) assumes independent correlation structure and HET denotes estimation robust to the heteroscedasticity HET-AR1 assumes estimation robust to both heteroscedasticity and first-order serial correlation.

Overall, there is considerable consistency and stability between the estimators. For the technical factors, the composite variable for technical progress of the battery proxy, and the number of charging stations, are highly significant drivers for BEV deployment. Moreover, the statistical significance of renewables for the BEV market share should also be highlighted. In fact, increased renewable electricity generation stimulates BEV adoption. This is a desirable effect for the electricity system as a whole, as is discussed in the next section.

Additionally, the increase in the market share of BEV is statistically dependent on the employment rate and education level. The income' proxy proves to have a negative effect on the BEV market share but at a low level of statistical significance. The policies supporting the electric mobility proves to be a driver of the BEV deployment.

The specification tests for the Model II - *Plug-in Hybrid Electric Vehicles,* following the A structure, suggest the presence of heteroscedasticity, contemporaneous correlation and first-order serial correlation, while for the B structure suggest the presence of the heteroscedasticity and first-order serial correlation. Following the reasoning described in the model I, the simple random effects model (CSE), and the random effects model with the robust option to correct heteroscedasticity (RSE) were estimated, as was the random effects model with AR1 disturbances (AR1). Additionally, the PCSE model was estimated (CORR(IND)), as were the PCSE estimator with the option for heteroscedasticity (HET). The PCSE estimator with the option for first-order serial correlation (AR1) was also performed to compare the PCSE estimator with the options for both heteroscedasticity and first-order serial correlation (HET-AR1). The results are shown in Table 4.9.

Table 4.9 - Model II – Plug-in Hybrid Electric Vehicles

	Random effects			PCSE			
	CSE	RSE	AR1	CORR(IND)	HET	AR1	HET-AR1
(A)							
TECHNICAL	0.2908***	0.2908***	0.2196***	0.2779***	0.2779***	0.2237***	0.2237***
LIPI	-2.5410***	-2.5410**	-1.7105***	-1.8662***	-1.8662***	-1.7780***	-1.7780***
LEMP	3.2771**	3.2771*	3.8977***	4.0245***	4.0245***	3.8924**	3.8924***
CONS	-1.6676	-1.6676	-8.1999	-8.0116*	-8.0116**	-7.8541	-7.8541
(B)							
LCHARG_PC	0.3463***	0.3463***	0.2500***	0.3830***	0.3830***	0.2842***	0.2842***
LPAT	0.1918**	0.1918***	0.1741**	0.1388***	0.1388***	0.1676***	0.1676***
LGDP_PC	0.0952	0.0952***	0.1323*	0.0995***	0.0995***	0.1248**	0.1248***
LGHG_PC	-0.5024**	-0.5024**	-0.5872***	-0.4457***	-0.4457***	-0.5415**	-0.5415***
LEDU	0.3942	0.3942**	0.5584**	0.3503***	0.3503***	0.4809***	0.4809***
LCRUDE	-0.3847***	-0.3847**	-0.4415***	-0.3306***	-0.3306***	-0.4203***	-0.4203***
CONS	3.8771**	3.8771*	4.0847**	3.2618***	3.2618**	3.8922***	3.8922***

Notes: ***, **, and * denotes statistical significance at 1%, 5% and 10% level of significance, respectively. CSE denotes conventional standard error, RSE means robust standard errors, and AR1 assumes the first-order serial correlation; CORR(IND) assumes independent correlation structure and HET denotes estimation robust to the heteroscedasticity HET-AR1 assumes estimation robust to both heteroscedasticity and first-order serial correlation.

The empirical results for the factors supporting the use of PHEV are quite different from those obtained in model I. The IPI has a negative role in the PHEV market share, while the *LGDP_PC* increases it. The proxy for R&D investment increases the PHEV. Considering the coefficients of the PCSE (HET-AR1), an increase of 1% in Research and Development (R&D) investment, increases PHEV market share by 0.1676%. Both the employment rate and education level are shown to be a predictor of PHEV market deployment.

To ascertain if the factors supporting BEV and PHEV differ between the individual and joint analysis, Model III in both specifications A and B were estimated focusing on hybrid plug-in vehicles and 100% electric vehicles. In this estimation, the phenomena of serial correlation and heteroskedasticity were found. Please note that in the specification B the Hausman test supports the existence of the fixed effects. Therefore, in the Model III, specification A, the PCSE estimator with the option for first-order serial correlation (AR1) was also performed to compare the PCSE estimator with the options for both heteroscedasticity and first-order serial correlation (HET-AR1). For the structure B, the PCSE estimations previously described, the fixed effects were included, by recurring to a dummy variable for each one country. The results are disclosed on Table 4.10.

Table 4.10 - Model III –*Electric Vehicles*

	PCSE			
	CORR(IND)	HET	AR1	HET-AR1
(A)				
TECHNICAL	0.2994***	0.2994***	0.2418***	0.2418***
LRES_PC	0.1618***	0.1618	0.2363**	0.2363
LEMP	5.7962***	5.7962***	5.2368***	5.2368***
POLICIES	0.1395***	0.1395***	0.1388***	0.1388***
CONS	-24.1647***	-24.1647***	-21.8912***	-21.8912***
	PCSE – Fixed Effects			
	CORR(IND)	HET	AR1	HET-AR1
(B)				
LCHARG_PC	0.4604***	0.4604***	0.4492***	0.4492***
LPAT	0.7222**	0.7222**	0.6061*	0.6061**
LEDU	2.3546***	2.3546***	2.4695***	2.4695***
CONS	-8.4871***	-8.4871***	-8.5887***	-8.5887***

Notes: ***, **, and * denotes statistical significance at 1%, 5% and 10% level of significance, respectively. CORR(IND) assumes independent correlation structure and HET denotes estimation robust to the heteroscedasticity

Despite some similitudes, the results of this model support the idea that each vehicle type really should be considered individually. The results confirm that the technological development of batteries is a driver for the penetration of EV in the automotive market.

Moreover, both the employment rate and the policies focused on electric mobility stimulate the EV market share, i.e. all the vehicles together. Both *LGDP_PC* and *LIPI* are not statistically significant drivers for the joint EV market. In fact, these variables show contradictory signs on the BEV and PHEV, which will reflect in a null effect in the joint analysis, this means all vehicles together.

Regarding the technical factors, the number of charging stations also has a positive statistical effect on EV market share. Indeed, an increase of 1% in charging stations increases EV market share by 0.4604%. The patents registration, used in this study as a proxy for the investment in R&D, is an effective predictor of the deployment of EV, as is the education level.

The policies focus on EV deployment are enlarging the market share of both EV and BEV, unlike PHEV. Concerning the social factors, both educational level and the employment rate increase BEV, PHEV, and EV. However, there is some dissimilitude at the statistical levels of significance found. Apparently, education has a positive and highly statistical effect on 100% electric vehicles in all the estimators used, in contrast with that observed for the PHEV. This outcome will deserve further attention in the robustness subsection. However, the dissimilar statistical significances found in these variables should be noted.

Please note that during the period under analysis several historical events have occurred that may have increased the demand for electric vehicles. Among which it can be pointed out that policies limiting the maximum of the emissions per kilometre or a circulation ban of the most pollutant vehicles in some cities. This ambitious environmental objective led to some vehicle manufactures misrepresenting emissions tests, as in the case of the Volkswagen scandal in 2015. For these reasons, temporal dummies were tested into the models, namely a dummy for 2015. However, they have proved to be not a statistically significant predictor of the BEV, PHEV, and EV adoption.

4.4.1 Robustness Check

As stated before, all the available data has been used in this research, which is focused on a very current topic, electric mobility. This decision to study such a current and relevant issue could lead to certain risks or limitations, namely those related to the robustness of the findings. Indeed, the small number of observations of the dataset could raise doubts about the robustness of the results. In fact, on the one hand, although all the available data has been used, this chapter is composed of a relatively short time period (only seven years). On the other hand, the nature of the variables could improve the suspicions of endogeneity between the variables. As such, the results of the pooled Ordinary Least Squares could be biased if the exogeneity property is violated. In addition to that, in order to guarantee that the results obtained by using the PCSE estimator have been robust and persistent, this subsection is dedicated to exhaustively assessing the robustness of the procedures and of the main findings provided.

Herein, the models were estimated by using Seemingly Unrelated Regressions (SUR). This method allows for the estimate of the parameters of the variables by using a system of equations that permit the existence of heteroscedasticity and contemporaneous correlation. Moreover, when correctly specified, this methodology allows for the error term of the equation being correlated (Cameron & Trivedi, 2010). This means that, when the equations have precisely the same regressors, this estimator runs an OLS, that are not able to deal with endogeneity. Two systems of equations have been estimated, 1 and 2. These systems are similar to the specifications described above in the results section, regarding the specifications A and B, respectively. Please note that, in order to guarantee that the models are robust to endogeneity, small differences in the explanatory variables used have been introduced in the models' specifications. Table 4.11 shows the independent variables considered in each equation within the system of equations.

Table 4.11 - Description of the equations estimated in SUR 1 and SUR 2

Model	Description of the dependent variable	Description of the independent variables
SUR 1	• Battery Electric Vehicles market share (*LBEV_SH*)	*TECHNICAL, LRES_PC, LIPI, LGHG_PC, LEMP,* and *POLICIES*
	• Plug-in Electric Vehicles market share (*LPHEV_SH*)	*TECHNICAL, LRES_PC, LIPI, LELE, LEDU* and *POLICIES*
	• Electric Vehicles joint market share, both BEV and PHEV (*LEV_SH*)	*TECHNICAL, LRES_PC, LGDP_PC, LELE, LEMP,* and *POLICIES*
SUR 2	• Battery Electric Vehicles market share (*LBEV_SH*)	*LCHARG_PC, LPAT, LGDP_PC, LELE, LEDU,* and *LCRUDE*
	• Plug-in Electric Vehicles market share (*LPHEV_SH*)	*LCHARG_PC, LPAT, LGDP_PC, LGHG_PC, LEMP,* and *LCRUDE*
	• Electric Vehicles joint market share, both BEV and PHEV (*LEV_SH*)	*LCHARG_PC, LPAT, LIPI, LGHG_PC, LEDU,* and *LCRUDE*

The results of the estimated SUR 1 are disclosed in Table 4.12. In this system of equations estimation, there are some restrictions on the parameters that have been applied. The difference between the coefficients of the regressors were tested. In fact, intuition predicts that some regressors could have a similar effect on the equations. By testing the cross-equation restrictions, three constraints have been created: 1) for the *LRES_PC* in both *LBEV_SH* and *LPHEV_SH* equations, i.e. the coefficient of the variable *LRES_PC* is equal in both *LBEV_SH* and

LPHEV_SH equations; 2) for the electricity price in *LPHEV_SH* and *LEV_SH* equations, and 3) for the employment rate *(LEMP)* in *LBEV_SH* and *LEV_SH* equations.

Table 4.12 - Estimated SUR 1

	Equations		
	100% Electric Vehicles	*Plug-in Electric Vehicles*	*Electric Vehicles*
TECHNICAL	0.1784***	0.2874***	0.3119***
LRES_PC	0.2383***	0.2383***	0.2912**
LIPI	1.1056***	-1.5872***	-
LGDP_PC	-	-	0.0172
LELE	-	-0.3725	-0.3725
LGHG_PC	-0.02817	-	-
LEMP	3.1993***	-	3.1993
LEDU	-	0.1529**	-
POLICIES	0.1755***	-0.0281	0.1288**
CONS	-18.3147***	7.3075***	-13.2387***

Notes: ***, **, and * denote statistical significance at 1%, 5% and 10% level of significance

The suitability of using this methodology has been verified by analysing the residual correlation matrix and the Breusch-Pagan test of independence. The high correlation between the residuals of the equation supports the suitability of this method, once the equations have similar determinants. The results of the Breusch-Pagan test of independence sustain the rejection of the null hypothesis, i.e. it indicates that the residuals are not independent. In fact, these high correlations indicate that the estimation of the SUR has a relative efficiency gain compared with those obtained in the Pooled OLS.

Table 4.13 - Correlation matrix of the residuals and Breusch-Pagan test of independence

	LBEV_SH	*LPHEV_SH*	*LEV_SH*
LBEV_SH	1		
LPHEV_SH	0.2952	1	
LEV_SH	0.8160	0.7083	1
Breusch-Pagan test of independence (chi-sq)		210.788	

The results of the SUR 1 displaced in Table 4.12 shows that the proxy for technological progress, *TECHNICAL*, incentivizes both BEV and PHEV market share corroborating with those obtained in the results section. In fact, the adoption of electric vehicles remains dependent on the technological characteristics of the batteries. Regarding the economic factors, one observes dissimilar effects. The *LIPI* increases the adoption of BEV, but on the contrary, it decreases the acceptance of the PHEV. It could indicate the real contribution of the industrial sector to BEV adoption. This finding is in line with the well documented fiscal benefits that the firm benefits in changing their fleet of cars from the conventional vehicles to BEV. Regarding the policies supporting electric mobility, they have been effective in promoting BEV, contrary to what happened with the PHEV. This outcome is absolutely in line with the results obtained by using the PCSE estimator.

The results of the SUR 2 are described in Table 4.14. As with SUR 1, this method proves to be appropriated once the residuals are correlated, only the equation of the *LBEV_SH* and *LPHEV_SH* having a low residual correlation (see Table 4.15), but the Breusch-Pagan test of independence supports the suitability of this method.

Table 4.14 - Estimated SUR 2

	Equations		
	100% Electric Vehicles	*Plug-in Electric Vehicles*	*Electric Vehicles*
LCHARG_PC	0.3880***	0.3880***	0.5700***
LPAT	0.0336	0.1650***	0.1016*
LGDP_PC	-0.0764***	0.1133***	-
LIPI	-	-	0.1970
LELE	-0.0879	-	-
LGHG_PC	-	-0.3714***	-0.1619**
LEDU	0.3595***	-	0.3595***
LEMP		0.1692	-
LCRUDE	-0.0889	-0.3658**	-0.1712
CONS	0.1789	3.0395**	0.3160

Notes: ***, **, and * denote statistical significance at 1%, 5% and 10% level of significance

The existence of charging stations is a crucial driver for penetration of the both BEV and PHEV into the automotive market. The used proxy for the investment in R&D proves to be a driver of the PHEV, but not for BEV. This is an additional robustness proof of the result found in the model II - *Plug-in Electric vehicles* following specification A. This could indicate the efforts that the vehicles' producers had performed of combining highly energy efficient Internal Combustion Engines (ICE) with electric batteries. Apparently, the deployment of the more efficient ICE seems to have merited more attention in the R&D than the promotion of the more efficient batteries. Currently, the batteries remain faced with high production costs. The crude price decreases the adoption of PHEV, but it has no effect on BEV, which once again goes against the results previously found by using PCSE.

Table 4.15 - Correlation matrix of the residuals and Breusch-Pagan test of independence

	LBEV_SH	*LPHEV_SH*	*LEV_SH*
LBEV_SH	1		
LPHEV_SH	0.0387	1	
LEV_SH	0.7344	0.6665	1
Breusch-Pagan test of independence (chi-sq)		165.492	

To sum up, the technical factors namely *TECHNICAL* and *LCHARG_PC* prove to be the main drivers for electric mobility. The IPI increases the BEV market share and decreases the PHEV: Meanwhile, economic growth boosts the adoption of PHEV, but obstructs the acquisition of BEV. Both employment rate and education levels are positive predictors for BEV adoption. Policies supporting the electric mobility increases the BEV market share but has no effect on PHEV. The renewable electricity generation increases individual and joint analysis of the electric vehicles. This subsection provides proof of the robustness of the results found previously.

4.5 Discussions and policy implications

The transition to electric mobility has stimulated academic research to analyse the factors that are driving this transition. The number of EV acquired and their share of the automotive market has been used to measure the commitment to electric mobility. EU countries are pursuing common environmental-protection objectives and facing numerous challenges to achieve a low-carbon economy. This makes this analysis all the more urgent, as it can help policymakers design effective energy policies to encourage citizens to adopt electric mobility, and thus help to accomplish a low-carbon economy.

This research analysed the role of several factors affecting electric mobility, namely policy, social, economic, environmental, and technical factors. EV can be categorized into two main categories: (a) BEV (100% electric), and (b) PHEV (powered by electricity and ICE). A joint analysis of all EV has been undertaken, and an assessment has been made by vehicle type, because of the technical differences between BEV and PHEV. Specifically, this involved: (i) analysing the factors that are affecting BEV market share; (ii) assessing factors driving PHEV adoption; and (iii) scrutinizing the factors that affect the implementation of both BEV and PHEV.

This chapter proves that the factors driving BEV and PHEV must be analysed individually, as their effects are quite different, as also argued by Rezvani et al. (2015). Policymaking should be tailored for each EV type, and not for electric mobility as a whole. The design of electric mobility policies for BEV or PHEV must be largely conditioned by endogenous natural electricity resources. This research argues that renewable electricity generation increases the use of both

BEV and PHEV. However, the effect on the BEV seems to be more persistent than those in the PHEV, such as expected. However, as noticed by Ajanovic & Haas (2016) the environmental benefits of vehicle electrification can only be achieved if the electricity is generated from renewable sources. Conversely, if the electricity is generated from fossil sources, then a reduction in GHG emissions will not be achieved. Therefore, policymakers must focus on the electricity generation mix and transport policies simultaneously. In other words, one requires continuous and integrated strategies do develop renewables and electric mobility together.

Countries with larger renewable electricity production should design policies encouraging more BEV than PHEV. In turn, countries with a low percentage of electricity generated from renewables, the PHEV could be more attractive than the BEV. The reasons for that seems to be obvious. The larger the consumption of electricity by the vehicles, the larger the demand for electricity on the system would be. The PHEV will not require, *ceteris paribus*, so much electricity. This means that the smaller amount of electricity they require could be easily satisfied by the already installed renewable capacity. Moreover, it is worthwhile to note that PHEV could be interesting allied to the strategy of promoting decentralized electricity generation, namely on photovoltaic capacity on the industry level or even on the household level. In short, the development of electric mobility, in accordance with the countries' characteristics, should be used to promote measures in the Demand Response area.

Policymakers should also be concerned with certain social factors in promoting BEV or PHEV. The results prove that enlarging the BEV market share remains heavily dependent on the educational level and employment rate. At first glance, this could be seen as an obvious outcome. Notwithstanding, this finding should inspire awareness-raising actions of the benefits of the BEV, namely by showing the advantages of the preservation of the environment and responsible consumption and sustainable development. These actions will be so much more effective for those people with a high educational level.

This chapter finds that the electricity price, on the one hand, has not been a significant driver for BEV adoption. On the other hand, an increase in the electricity price decreases PHEV adoption. Regarding the crude oil price, it reduces the use of PHEV. With the increase of the traditional fuel price, the share of the PHEV in the automotive market decreases. This finding deserves further discussion. Indeed, to travel, for instance, 50 km, the cost of the electricity used is significantly cheaper than diesel or gasoline. Therefore, for the PHEV the saving in 100% electric mode may not be enough to compensate for their higher purchase cost and the high conventional fuel price. Therefore, the increase in both electricity and fuel prices makes the PHEV less attractive, which could compromise the increase of the market share of these vehicles. Accordingly, the policymaking focused on the price strategy, such as the regulatory framework, should be carefully designed. As such, on the one hand, additional taxation on the oil products promotes the penetration of the BEV, but, there is no evidence supporting its impact on the PHEV. On the other hand, the increase in the electricity price decreases the PHEV market share, and it is expected that could have the same effect for the BEV. Given that the price strategy is so sensitive, namely because electric mobility is yet at an early stage, the policymaking should focus on other drivers, such as firms benefits, technological progress, or regulatory mechanisms promoting environmental awareness. Even so, the promotion of the PHEV could indeed be an efficient way to introduce electric mobility into the automotive market, once it shows some advantages when compared with the 100% electric vehicles. On the one hand, it allows for capturing the advantages of using electricity for mobility in traveling short distances. On the other hand, it enables that the users do not suffer from the “range anxiety”, once these vehicles allow for travelling long distances by using the ICE.

The findings of this study reveal the crucial role played by the industrial sector in the adoption of BEV. In fact, the IPI increases the market share of the BEV. This finding could be indicating that the industrial sector, and firms in general, are pioneering the introduction of BEV. It agrees with the well documented fiscal benefits and privileges for firms that shift their car fleet from traditional vehicles to EV, such as, free parking or exemption from road tax. This policy approach must be followed, i.e., policymakers should keep encouraging managers of EV fleets, usually belonging to firms, to increase their use of BEV. The individual preference for an EV could change significantly after actual experience with it (Jensen, Cherchi, & Mabit, 2013). So, incentives to fleet managers in the industrial sector promoting BEV use, i.e. actual experience with these vehicles, could be effective in expanding BEV use. Conversely, PHEV are not supported by industrial production. This could indicate that vehicle fleet managers in the industrial sector do not see advantages in using this kind of vehicles. Possible reasons for that: Firstly, the autonomy of these vehicles 100% electric mode remains scarce, and as such, they need conventional fuels to power an ICE. Secondly, the purchase cost of these vehicles is generally higher than the 100% electric vehicles. This higher value reflects the cost of producing both an ICE and the batteries. Finally, in contrast to BEV, these vehicles cannot guarantee a significant reduction of the costs on road.

Regarding the effects of the income proxy, they are, actually quite different. It has hampered the adoption of the BEV. This could indicate that higher income promotes the adoption of the other vehicles, instead of BEV. It is likely that the consumers assign greater utility to the other vehicles, with other features such as maximum speed or technology than BEV. Meanwhile, consumers with high income are not concerned with the potential savings that they could gain on the road by using a BEV. By itself, the income level does not promote the awareness of the sustainable development. On the contrary, income promotes the adoption of the PHEV. Although the PHEV are, generally more expensive than BEV, these vehicles offer the same features to the users as the conventional vehicles do, with the advantage of fuels savings on the road by using the electrical motor. For this reason, these vehicles could be more attractive for the users with high income than BEV once they allow achieving the same utility as a traditional vehicle.

In European Union countries, people's environmental awareness is growing. This propensity towards sustainability could encourage policymakers to make people more aware of the benefits of EV use. This environmental consciousness must be explored, and the consumers should be informed about the environmental impact at all the stages, mainly from electricity production and dismantling batteries, as suggested by Axsen et al. (2012). This should be accompanied by investments in R&D. The R&D investment proxy increases the market share of PHEV, but not BEV. This could indicate that the investments have been carried out in the production of the more efficient ICE instead promotion of more efficient batteries. Therefore, research focused on 100% electric mobility is required, not only to achieve 0% emissions on the road, but also to achieve an improvement in battery technology, allowing economies of scale that are reflected in reduced purchase prices. This equilibrium is likely to be the best way to achieve the largest market shares for BEV and it could reduce "range anxiety", as stated before, one of the main barriers to BEV deployment.

Indeed, nowadays, the main challenge for EV is technological. The information on battery range, capacity, and cost reveal that their development is contributing to increasing EV implementation, both BEV and PHEV. Moreover, the penetration of EV is dependent on improvements in charging infrastructure. This chapter confirms that policymakers should invest in the construction of charging infrastructure, especially in the urban areas, and large population clusters. These are the places where citizens spent sufficient time to recharge their cars. This policy approach could successfully increase the market share of the both BEV and PHEV.

Concerning the direct role played by the governments in this context, specifically by devising and implementing policy incentives, this study corroborates what has been amply documented in the literature; that policy incentives have increased the EV market share (Lévay, Drossinos, & Thiel, 2017). However, the effects of these policies on BEV and PHEV are actually different. For BEV, the policies enlarge their market share. This reveals the crucial role of fiscal and non-fiscal incentives in promoting the use of clean energy. Regarding PHEV, these policies are not a critical factor in determining their market share. In fact, it could be concluded from this unexpected outcome, that more policy incentives supporting PHEV are essential to increase their penetration in the automotive market.

Lastly, a special note for the results obtained from this research. They reflect what has occurred in the past, as they are based on historical data. In the near future, these results may remain the same, or instead, they could change. The results of this paper provide a basis for guidelines to achieve a sustainable transport sector from the environmental and economic point of view. Therefore, policymakers should consider these results and intervene to maintain desirable effects and change undesirable effects.

4.6 Conclusions

This chapter empirically analyses the factors driving BEV, PHEV, and jointly EV. It uses annual data from 2010 to 2016 for a panel of the 24 EU countries by applying a PCSE estimator because it is appropriate for dealing with the characteristics of the data. The robustness of the results was checked by using a Seemingly Unrelated Regression estimator. There is a great internal consistency between the estimators. The main novelty of this study is the creation of a measure to capture technological progress, specifically for batteries, and contemplating their range, capacity and cost by using Principal Component Analysis.

This study finds that policymakers should promote policies focused on specific vehicle technologies, instead of electric mobility as a whole. Indeed, it was found that the factors supporting BEV are quite different from those driving PHEV.

This chapter evidences the great potential of the industries in BEV adoption, contrary to what is happening with the PHEV. The high-income level is a driver for PHEV adoption, however, it is a barrier for BEV penetration. It could be a result of the disadvantages associated with BEV use, namely driving range or maximum speed. Coherently, the investment in R&D is required to reduce the disadvantages of the BEV when compared with traditional or PHEV vehicles. The competitiveness of these vehicles with traditional vehicles powered by an ICE must be increased, and improved batteries are crucial to achieving this task. Furthermore, charging infrastructure is a driver for BEV and PHEV deployment. So, not only is more charging infrastructure essential but the especially fast-charging infrastructure that allows the vehicle battery to be recharged more quickly.

The market mechanism of price has not affected the decision to acquire an EV. Therefore, the policymaking should focus on other drivers or regulatory mechanisms to improve the attractiveness of the EV. The policies focused on electric mobility as a whole only have been efficient in the BEV acquisition. To improve the PHEV adoption, specific policies must be tailored, once the actual policies are seen as not being efficient regarding PHEV adoption.

Future research must include other technical factors, such as charging times (normal or fast) and the differential between EV and conventional vehicles purchase and maintenance cost.

Moreover, the average distance travelled daily and the income of the families acquiring vehicles may be crucial to understanding what drives the adoption of BEV and PHEV. Notwithstanding, the policies factor should be subdivided into fiscal and non-fiscal incentives, in order to tailor the appropriate policy strategy to increase the penetration of EV in the automotive market.

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Chapter 5

On the drivers of peak electricity demand: What is the role played by battery electric cars?

The enlargement of the electric vehicles (EV) market share could be achieved by considering the findings of chapter 4 of this thesis. This enlargement represents an important challenge for the electricity system, namely on their capacity to deal with the additional electricity demand mainly in the peak periods. Notwithstanding, the electric vehicles could have a great potential in both managing the electricity system and contributing to the Renewable Energy Sources (RES) integration. In general, these evidences motivated this chapter. It analyses of the drivers of both peak electricity demand and renewable electricity generation. Data from 2010 to 2016 for a panel of 20 European Union (EU) countries were used. Two models were estimated using both Panel-Corrected Standard Errors (PCSE) and Driscoll-Kraay (DK) estimators with fixed effects. These estimators were robust in the presence of cross-section dependence, first-order serial correlation and heteroscedasticity. The main results suggest that renewable electricity generation and the penetration of battery electric vehicles (BEV) into the automotive market are helping to decrease peak electricity demand. At the same time, it was confirmed that employment in this industry sector is increasing peak electricity demand. The existence of peak periods was shown to be the main barrier to the integration of renewables into electricity systems. It seems that policies focused on Demand Side Management (DSM) have been effective in integrating renewables in contrast to their lack of success in reducing peak electricity demand.

5.1 Introduction

The use of clean energies is growing throughout the world. This transition has occurred mainly through the increasing use by electricity systems of new RES such as wind and solar photovoltaic. However, the variability of RES generation has introduced economic inefficiencies into these electricity systems. Ideally, there would be a consistent demand throughout the day, but the well-known intermittency of RES generation is incompatible to satisfy it. The electrification of sectors which are currently highly dependent on fossil fuels, such as the transport sector, will have to draw on a diversified electricity mix, but could benefit by making better use of intermittent RES.

New challenges for electricity systems are arising from both diversification of the electricity mix and a shift to electricity in the transport energy paradigm. The new RES, mainly wind and solar power, produced intermittently and, currently have a low capacity factor. Accordingly, the accommodation of RES, i.e. the maximisation of intermittent RES generation that is effectively consumed, is one challenge faced by current electricity systems. Overcoming this challenge requires more efficient ways of storing electricity when there is surplus generation from renewables. However, another way to cope with this challenge is to promote changes in consumption habits, specifically incentivising consumption when there are high levels of generation from RES and discouraging electricity consumption when RES production is lower.

The greater penetration of BEV could create new challenges for electricity systems. Currently, these systems would probably be unable to deal with the additional demand caused by BEV charging, particularly if this additional demand occurs during the peak consumption period, and this would be reflected in increased economic inefficiencies of electricity systems. To benefit from BEV penetration, it will be essential to take advantage of instantaneous RES availability, thereby contributing to the accommodation of RES in the electricity system. With uncontrolled BEV charging, electricity consumption in peak periods could increase significantly (Fernandes, Frías, & Latorre, 2012). However, directing charging to periods when there is oversupply, could contribute to improving the efficiency of distribution networks. This could be further assisted by storing electricity in BEV batteries during periods of excess electricity production from RES. Vehicle to grid (V2G) systems could also be an excellent way of achieving this. This technology allows electricity stored in BEV batteries to be reintroduced into the system when generation is insufficient to satisfy demand.

Knowing that the existence of peak periods throughout the day increases economic inefficiencies in electricity systems, the principal objective of this paper is to ascertain the main drivers for peak electricity demand, with a special focus on the role played by BEV. Therefore, it aims to answer the following central questions: (i) what are the roles played by the main drivers of peak electricity demand in managing excess electricity consumption? Additionally, it also aims to answer (ii) what is the relationship between BEV and electricity consumption in peak hours?

This chapter represents a contribution and improvement to the previously existing literature. Firstly, using historical data to analyse the main drivers of peak electricity demand is a topic whose great potential has not been fully explored in the empirical literature. In fact, this type of empirical analysis is still quite scarce, with one exception being Mirlatifi, Egelioglu, & Atikol (2015), who argued that the number of customers, tourists, population and heating degree days are positively correlated with peak demand, while the price of electricity plays a negative role in annual peak electricity demand. Secondly, this paper focuses on the effects of market penetration by BEV on both peak electricity demand and RES integration. In fact, knowing which has occurred in the past is crucial to designing appropriated policies.

Concretely, this chapter is focused on the main challenges that the current electricity systems are faced, namely the management of peak electricity demand, integration of the renewable sources and, more ambitious, the impact of electric mobility on the electricity systems. In fact, the approach adopted provides fundamental guidelines for policymaking. On the one hand, it evidences the impact of the economic and social factors on peak electricity demand. Coherently, the policymakers could reduce peak electricity demand by considering these factors. On the other hand, it provides a preliminary empirical evidence of the effect that BEV penetration has created on peak demand and RES integration. Therefore, both transport and electricity policymaking could benefit by considering the results of this study.

The rest of this chapter is organised as follows. A review of the state-of-the-art is described in Section 5.2. Section 5.3 is dedicated to showing the data used and the methodology applied. The results are described in Section 5.4 and their robustness are showed on the Subsection 5.4.1. In Section 5.5 the results are discussed and finally, Section 5.6 concludes.

5.2 Literature Review

Environmental sustainability is a priority on the political agenda. To achieve this target, it is required that the use of non-renewables sources be reduced. The penetration of the renewables sources in the electricity mix aims attend to this objective. Meanwhile, it is expected that the consumption of energy will grow in the next years. This increase is accentuated when we consider only electricity. In fact, the digitalisation of the economies as well as electrification will increase significantly electricity consumption. In the EU countries, it is expected that electricity consumption will grow 40% by 2050 (McKinsey & Company, 2010). However, the electricity systems are still faced with several challenges, such as the improvement of RES use and economic efficiency.

The efficiency of the electricity system as a whole, should not be dissociated from peak-shaving strategies. The existence of peak periods each day results in economic inefficiencies for distribution networks. In fact, to maintain the electricity supply during peak demand periods, Transmission System Operators (TSOs) need to import electricity and/or require elevated levels of installed capacity from flexible sources. Potential peak load shaving strategies already identified in the literature are (i) Demand Side Management (DSM); (ii) integration of Energy Storage Systems (ESS); and (iii) integration of Electric Vehicles (EV) (Uddin et al., 2017). In addition, peak load shaving strategies and load diagram smoothing must be pursued to improve the economic efficiency of electricity systems that take advantage of RES generation.

Currently, there is some expectation of the future of the electric grid, namely the smart grid with the introduction of the prosumers, i.e. the consumers of the electricity that also are producers. This new active part of the grid could contribute to improve the efficiency of the electricity system and to manage peak electricity demand. Information and communication, as well as optimisation, are identified as key concepts for the prosumers to contribute to electricity system efficiency. An overview of the impact that the prosumers could have on system sustainability can be found for instance in Zafar et al. (2018).

DSM measures could be a mechanism to successfully reduce peak load demand and shift electricity demand from the peak to off-peak periods. Basically, it can be defined in two main ways: Demand Response and Energy Efficiency. The Demand Response policies, in which pricing is set according to the instantaneous cost of generation, or time-of-use (TOU) tariffs, have been used to smooth the electricity demand curve. An overview of the experience of this by EU countries can be found, for instance, in Torriti, Hassan, & Leach (2010). However, some literature has shown that electricity consumption has an inelastic elasticity, this means that, high electricity prices could not be reflected in a significant reduction of electricity consumption (Arisoy & Ozturk, 2014; Woo et al., 2018). Accordingly, the effect of the differentiated electricity price could be different when it is considered in different sectors. For example, the Japanese industrial sector is less responsive to the variances in electricity prices than the residential sector (Wang & Mogi, 2017).

Energy Efficiency have been pursued, i.e. through the acquisition of more energy-efficient equipment, or by incentivising changes in electricity consumption patterns, to reduce not only the peak load demand but also electricity consumption throughout the day. Although there were relevant developments in the technology over the last few years, the efficiency of the equipment remains dependent on technological progress (Lima, Ribeiro, & Perez, 2018). In fact, this is an area with great potential that needs to be applied in all the industries, such as for example the Brazilian dairy industry (Lima et al., 2018) or manufactory factories (Weeber, Ghisi, & Sauer, 2018). Notwithstanding, also the consumers have to be motivated to improve their efficiency in consumption habits. To achieve this task, Trotta (2018) analysed the factors that support British households energy saving and investment in energy efficiency. For example, they concluded that women are more likely to invest in efficient equipment than men. Meanwhile, also high levels of income promote energy efficiency. In this sense, the residential sector is more sensitive to the price than the industrial sector (Wang & Mogi, 2017), and as such, has attracted the attention of the literature, namely on the factors supporting energy saving and some conclusions could be found for instance in Jones et al. (Jones, Fuertes, & Lomas, 2015).

Another solution indicated by the literature to reduce peak load demand and integrate renewables into the electricity systems is the use of ESS (Energy Storage Systems). Currently, the intensive use of ESS remains dependent on technological improvements to increase the amount of energy that can be stored per unit volume (energy density), battery life cycle, battery efficiency, and a reduction in production costs. For example, Prasatsap, Kiravittaya, & Polprasert (2017) design an optimal ESS for peak shaving, reducing the electricity costs in Naresuan University and concluded that with an increase of the ESS capacity in small size, ESS could reduce efficiently the peak load demand, but for large size ESS the reduction of the peak load could not be efficiently achieved. Additionally, an overview of the current state of ESS can be found for instance in Zhang, Wei, Cao, & Lin (2018). Several types of material have been used to produce batteries. However, all of them continue to have disadvantages that preclude their intensive use. For instance, lead-acid batteries have low capital costs, but they also have a limited life cycle and long charging times (Spanos, Turney, & Fthenakis, 2015). Lithium-ion batteries and sodium-ion batteries have high energies densities and efficiency but their production costs continue to be high (Kee, Stackpool, Ho, & Lee, 2015; Xu, Chen, & Zhang, 2015).

Pumped hydro has been used as a mechanism to store water in hydro systems by using excess electricity at certain times of the day to pump water up the hydro system for regenerating electricity when it has become necessary. Although unable to store electricity, it increases generation capacity. Therefore, this technology allows the use of excess electricity generated in periods when natural resources are available (Dursun & Alboyaci, 2010; Marques, Fuinhas, & Neves, 2018; António Cardoso Marques, Fuinhas, & Afonso, 2015; Padrón, Medina, & Rodríguez, 2011), and has proved to be crucial for RES integration (Marques et al., 2018).

Nowadays, a transition to electric mobility is underway, specifically using road infrastructure. This shift in the transport energy paradigm from conventional energy sources to electricity could actually contribute to improving the efficiency of the electricity system as a whole. Currently, the main challenge for BEV is increasing their penetration into the automotive market. In the future, the introduction of considerable numbers of BEV could raise new challenges and opportunities for electricity systems. This means that, with uncontrolled charging, the system may be unable to satisfy the additional demand of electricity for electric mobility. The literature warns that the introduction of a large number of BEV in charging mode could have a negative influence on electricity distribution networks (Fernandes et al., 2012). However, if there is controlled charging in off-peak periods, it may not be necessary to install additional capacity from flexible sources and the impact on the cost of electricity could be less than 5% (Razeghi & Samuelsen, 2016). Price differentiation could be a mechanism to influence the charging schedule. In fact, with electricity price differentiation, consumers would be more inclined to change their preferred charge schedule (Langbroek, Franklin, & Susilo, 2017).

Furthermore, V2G technology could be a way to avoid the economic inefficiencies of electricity systems caused by BEV charging. This technology could contribute by storing electricity in off-peak periods and putting it back in the system during peak periods (Sousa, Morais, Vale, Faria, & Soares, 2012). Indeed, it could also reduce the need for flexible sources, and thus electricity costs (Mortaz & Valenzuela, 2018). Nevertheless, it remains dependent on technological improvements to reduce electricity losses in the process (Apostolaki-Iosifidou, Codani, & Kempton, 2017), and to overcome the negative effect of this technology on battery life cycles. To guarantee the sustainability of electricity systems, the charging/discharging of BEV must be managed (Fazelpour, Vafaeipour, Rahbari, & Rosen, 2014). To improve load factors without significantly increasing operating costs, the management of BEV charging may be more important than the management of BEV discharging (Morais, Sousa, Vale, & Faria, 2014). Exchanging information between BEV aggregators and the distribution grid could greatly assist in accommodating large numbers of BEV (Bharati & Paudyal, 2016).

Electric mobility could actually, make even greater use of RES by promoting the charging of BEV when production from renewables is higher. Seddig, Jochem, & Fichtner (2017) argue that, with an optimised charging strategy, the utilization of RES could double, compared with an uncontrolled charging strategy. In this sense, the utilization of unused wind-generated electricity could be improved with the introduction of BEV (Anastasiadis et al., 2017), and the use of natural gas to generate electricity could be significantly reduced (Nunes & Brito, 2017). An increase in electricity consumption from BEV charging during off-peak periods and when there are high levels of intermittent RES generation, could reduce energy spillage and better accommodate RES (Fernandes et al., 2012). Therefore, the operating costs of power systems would benefit from a combination of both BEV charging and RES production (Fernandes et al., 2012).

In summary, a reduction in peak electricity demand and a shift in electricity consumption from peak to off-peak hours is fundamental to making electricity systems more economically efficient and to integrating new RES. DSM policies, ESS and the integration of BEV could all be effective mechanisms to achieve this objective. However, all of these mechanisms currently face several challenges. The promotion of DSM policies is required. To make the use of ESS more attractive and competitive in the market, technological improvements in ESS that increase storage capacity and lower production costs are crucial. Currently, these technologies are not competitive without fiscal subsidies. With respect to the integration of BEV into the electricity market, V2G technologies are a promising solution for reducing peak load demand

and smoothing the electricity demand curve. Although there is some literature on the drivers of electricity demand, and peak load demand (Mirlatifi et al., 2015) none of these studies has empirically analysed the drivers of both peak load demand and RES integration.

5.3 Data and Methodology

This study uses annual data from 2010 to 2016 considering a panel of 20 European Union countries. The countries were selected in accordance with the data available for the selected period. As is well known, the introduction of EV in EU countries started in 2010. Therefore, the use of a longer time span is unjustified for the purpose of this chapter. The countries considered are: Austria, Belgium, the Czech Republic, Denmark, Finland, France, Greece, Hungary, Ireland, Italy, Luxembourg, the Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden and the United Kingdom.

The variables used as well as their description and statistics are showed in Table 5.1, where the prefix “L” means natural logarithm.

Table 5.1 - Variables' definition and descriptive statistics

Variable	Description	Obs	Mean	Std. Dev.	Min	Max	Source
LPEAK_PC	The highest value of the electricity demand satisfied during the year, per capita (kWh/person).	140	0.8072	0.3128	0.4926	1.7815	IEA
LHDD	Heating degree days (°C*d)	140	7.9543	0.3923	6.9815	8.7334	EUROSTAT
LEIE	Electricity intensity on economy (kg of oil equivalent/1000 LCU)	140	2.4389	0.9733	0.0981	3.6731	EUROSTAT/WDI
LSERV	Services added value (% total value added)	140	4.2813	0.1027	4.0630	4.4847	OECD Data
LEMP_IND	Employment in industry (Thousands of Persons)	140	6.9534	1.2476	3.2347	8.7711	OECD Statistics
LBEV_SH	Market share of BEV, per thousand of vehicles	140	0.9343	0.9813	0	5.1487	EAFO
LGCF_PC	Gross capital formation per capita (constant LCU/person)	140	8.9713	2.6994	-0.7888	13.3203	World Bank
LLF	Total labour force	140	15.9478	2.7356	12.3796	26.8654	
LELE	Electricity price at constant prices of 2010 (€/kWh)	140	0.1627	0.0323	0.1035	0.2559	EUROSTAT
LRES_PC	Electricity generation from renewables, per capita (kWh/person)	140	7.4241	1.0677	0.1035	0.2559	IEA Headline Energy Data, 2016
LRMX	Ratio between imports and exports plus 1	140	1.0857	0.3345	0.7118	2.4453	EUROSTAT
POL_DSM	Number of accumulated policies on DSM	140	0.8286	0.5619	0	2	IEA

Notes: DSM, Demand Side Management; EAFO, European Alternative Fuels Observatory; IEA, International Energy Agency; IRENA, International Renewable Energy Agency; LCU, Local Currency Unit; OECD, As described in Section 2, the literature defines peak load shaving strategies as including: (i) integration of EV, (ii) DSM policies and measures, and (iii) integration of ESS (Uddin et al., 2017). In this paper, we used the accumulated number of DSM policies and the share of the BEV in the automotive market to analyse these factors. Moreover, the rate of coverage of imports by exports (*LRMX*) was used as an independent variable to ascertain the role of cross-border interconnection to satisfy peak load demand. Additionally, some socioeconomic factors were included and assessed. The variables used were electricity intensity in the economy (*LEIE*), Gross Capital formation *per capita* (*LGCF_PC*), Total labour force (*LLF*), gross added value of services (*LSERV*), and employment in the industry sector (*LEMP_IND*). Furthermore, the price of electricity was considered, and has actually been found to be a determinant of the intensity of electricity consumption (Gutiérrez-Pedrero, Tarancón, del Río, & Alcántara, 2018). Electricity generated from RES (*LRES_PC*) was used as an explanatory variable and as a dependent variable to determine the drivers of RES integration. Lastly, Heating Degree Days (*LHDD*) were considered as an explanatory variable. This variable has been previously used in the literature (Mirlatifi et al., 2015), and was used to quantify the energy required to heat buildings over a year.

Good econometric practices indicate that the features of both variables and countries must be checked to confirm they will not skew the results. The methods commonly used include (i) Cross-Sectional Dependence test (CD – test); (ii) Panel unit root test; (iii) correlation analysis; and (iv) Variance Inflation Factors (VIFs).

Table 5.2 - Cross-sectional Dependence test (CD – test) and Second-Generation Unit Root test (CIPS)

	CD - test			CIPS		Hadri
	CD-Test	Corr	Without trend	Without trend	With trend	Without trend
LPEAK_PC	10.21***	0.280	0.422	-3.098***	-1.224	
LHDD	26.54***	0.728	0.769	-2.796***	-2.089***	
LEIE	20.47***	0.561	0.757	-4.219***	-1.110	
LSERV	0.48	0.013	0.472	0.035	0.077	1.2591
LEMP_IND	4.23***	0.116	0.581	-1.472*	-2.449***	
LBEV_SH	30.42***	0.834	0.834	-4.313***	-1.810**	
LGCF_PC	4.91***	*0.135*	*0.498*	*-2.359****	*-2.391****	
LLF	7.64***	0.209	0.748	2.581	0.184	
LELE	2.10**	0.058	0.536	-4.621***	-3.015***	
LRES_PC	19.66***	0.539	0.569	-3.765***	-2.127**	
LRMX	0.88	0.024	0.450	1.346	2.338	0.8415
POL_DSM	35.87***	0.984	0.984	3.906	1.435	

Notes: CD – test was performed under the null hypothesis of the cross-sectional independence. The CIPStest was performed under the null hypothesis wherein the variables are I(1). Hadri unit root test was performed under the null hypothesis of the stationarity. ***, **, and * denote significance level at 1%, 5%, and 10%, respectively.

The results of the CD-test and second-generation unit root tests presented in Table 5.2 revealed the presence of cross-section dependence for most of the variables except *LSERV* and *LRMX*. As the first-generation unit root test is not reliable in the presence of the phenomenon of cross-section dependence, the second generation unit root test (CIPS) proposed by Pesaran (2007) was performed. For the variables that did not exhibit cross-sectional dependence, both the first-generation unit root test proposed by Hadri (2000) and the second-generation unit root test were performed. Overall, the results did not unequivocally prove the stationarity of these variables. Although the use of non-stationary variables could bias the results, the stationarity tests could not be robust in the presence of a small T. In fact, considering this sample, the results shown in Section 4.4 proved their robustness.

The preliminary analysis of the correlation matrix values and the Variance Inflation Factor (VIF) display the existence of the correlation and multicollinearity between *LGCF_PC* and *LLF* variables. In fact, the presence of these phenomena could promote biased estimations. Therefore, to overcome this obstacle and produce robust estimations these variables were not employed simultaneously in the models. When these variables were applied in the models individually, the correlation matrix values, as well as the VIFs, showed that both correlation and multicollinearity are unlikely to be a concern in producing robust estimates. Bearing in mind that the main objective of this chapter is to analyse the role that several factors have had on peak load demand, and RES integration, two models were estimated: model I – *LPEAK_PC*, and model II – *LRES_PC*. Each one model was estimated two different functional forms. *Ceteris paribus*, the functional form (A) includes *LGCF_PC* as explanatory variables while the functional form (B) uses *LLF* once these variables cannot be used in the regressions simultaneously. Accordingly, the functional forms followed are described in equations (5.1) - (5.4), and the descriptions of the models in Table 5.3.

Model I - *Peak Demand (A)*

$$\begin{aligned} LPEAK\_PC_{it} = {} & \omega_0 + TREND + \omega_{i1}LHDD_{it} + \omega_{i2}LEIE_{it} + \omega_{i3}LSERV_{it} + \omega_{i4}LEMP\_IND_{it} \\ & + \omega_{i5}LBEV\_SH_{it} + \omega_{i6}LGCF\_PC_{it} + \omega_{i7}LELE_{it} + \omega_{i8}LRES\_PC_{it} \\ & + \omega_{i9}LRMX_{it} + \omega_{i10}POL\_DSM_{it} + \vartheta_{it} \end{aligned} \tag{5.1}$$

Model I - *Peak Demand (B)*

$$\begin{aligned} LPEAK\_PC_{it} = {} & \theta_0 + TREND + \theta_{i1}LHDD_{it} + \theta_{i2}LEIE_{it} + \theta_{i3}LSERV_{it} + \theta_{i4}LEMP\_IND_{it} \\ & + \theta_{i5}LBEV\_SH_{it} + \theta_{i6}LLF_{it} + \theta_{i7}LELE_{it} + \theta_{i8}LRES\_PC_{it} + \theta_{i9}LRMX_{it} \\ & + \theta_{i10}POL\_DSM_{it} + \xi_{it} \end{aligned} \tag{5.2}$$

Model II - *RES Integration (A)*

$$\begin{aligned} LRES\_PC_{it} = {} & \beta_0 + TREND + \beta_{i1}LPEAK\_PC_{it} + \beta_{i2}LHDD_{it} + \beta_{i3}LEIE_{it} + \beta_{i4}LSERV_{it} \\ & + \beta_{i5}LEMP\_IND_{it} + \beta_{i6}LBEV\_SH_{it} + \beta_{i7}LGCF\_PC_{it} + \beta_{i8}LELE_{it} \\ & + \beta_{i9}LRMX_{it} + \beta_{i10}POL\_DSM_{it} + \varepsilon_{it} \end{aligned} \tag{5.3}$$

Model II - *RES Integration (B)*

$$\begin{aligned} LRES\_PC_{it} = {} & \delta_0 + TREND + \delta_{i1}LPEAK\_PC_{it} + \delta_{i2}LHDD_{it} + \delta_{i3}LEIE_{it} + \delta_{i4}LSERV_{it} \\ & + \delta_{i5}LEMP\_IND_{it} + \delta_{i6}LBEV\_SH_{it} + \delta_{i7}LLF + \delta_{i8}LELE_{it} + \delta_{i9}LRMX_{it} \\ & + \delta_{i10}POL\_DSM_{it} + \psi_{it} \end{aligned} \tag{5.4}$$

where, *i* denotes the countries and *t* represents the time. $\omega_0, \theta_0, \beta_0, \text{and}\ \delta_0$ designate the intercept. $\omega_i, \theta_i, \beta_i, \text{and}\ \delta_i$ denote the coefficients of the parameters estimated, and $\vartheta_{it}, \xi_{it}, \varepsilon_{it}\ \text{and}\ \psi_{it}$ indicate the error terms. The presence of fixed or random effects was tested by using a Hausman test under the null hypothesis in which the random effects were found to be appropriate. The null hypothesis was rejected, which suggested that the fixed effects were adequate for these estimations (see Table 5.3).

Table 5.3 - Description of the models and the *Hausman* test

Model	Description of the dependent variable	Hausman test FE vs RE
Model I – *Peak Demand* (A)	Peak load demand *per capita* (*LPEAK_PC*)	113.36***
Model I – *Peak Demand* (B)	Peak load demand *per capita* (*LPEAK_PC*)	134.45***
Model II – *RES Integration* (A)	Electricity generation from renewables *per capita* (*LRES_PC*)	56.51***
Model II – *RES Integration* (B)	Electricity generation from renewables *per capita* (*LRES_PC*)	56.95***

Notes: *** denotes statistical significance at 1% level.

A set of specification tests were carried out namely, Pesaran's test for cross-sectional dependence, the modified Wald test for groupwise heteroscedasticity, and the Wooldridge test for autocorrelation. The null hypothesis of these specification tests predicts the existence of cross-sectional independence, homoscedasticity, and no first-order serial autocorrelation, respectively.

The results of the specification tests provided fundamental indications for choosing appropriate estimators to produce unbiased results. The results shown in Table 5.4 suggested the presence of the phenomenon of heteroscedasticity. Although Pesaran's test found no evidence of the presence of contemporaneous correlation (see Table 5.4), an individual analysis of the variables suggested the existence of cross-section dependence in almost all the variables (see Table 5.2). Therefore, the estimators had to be robust in the presence of this phenomena.

Table 5.4 - Specification tests

	Model I - *Peak Demand*		Model II –*RES integration*	
	(A)	(B)	(A)	(B)
Modified Wald test	567.64***	252.42***	343.32***	361.09***
Pesaran's test	0.545	0.814	-0.939	-0.746
Wooldridge test	0.075	0.115	16.056***	19.070 ***

Notes: *** denotes statistical significance at 1% level.

To deal with these phenomena, the Panel Corrected Standard Errors (PCSE), the Feasible Generalized Least Squares (FGLS), or the Driscoll & Kraay, (1998) estimators should be applied. However, the FGLS becomes biased if the cross-sectional dimension (N) is larger than the time dimension (T) (Beck et al., 2015). As this study comprised 20 crosses (N) and seven years (T), both the Driscoll Kraay and the PCSE were appropriate for dealing with the data characteristics, but conversely the use of FGLS was inappropriate (Hoechele, 2010; Reed & Ye, 2011).

5.4 Results

The results of the estimated models are showed and described below. We opted to show both the full and the parsimonious models. Faced with the sensitivity of this study to the empirical conditions, namely its small sample proprieties, the consistency between the full and parsimonious models was the first evidence of the robustness in the results found. Moreover, the models were estimated by using several estimators namely, the fixed effects estimator (FE), the fixed effects estimator robust to heterogeneity (FER), the Panel-Corrected Standard Errors estimator with fixed effects and robust to the heterogeneity (PCSE - FEHET) and the Driscoll-Kraay fixed effects estimator (DK – FE). We used the PCSE - FEHET as a benchmark for the results found by using the DK – FE estimator. Although they can both deal with the same data features, namely heteroscedasticity, cross-sectional dependence and autocorrelation, the DK-FE performs better with small samples than the PCSE (Hoechele, 2010).

The results from parsimonious model I – *Peak Demand*, in both the specifications (A) and (B) following the equations (5.1) and (5.2) are shown on the Table 5.6, and the respective complete models are presented in Table 5.5. They exhibit a remarkable internal correspondence, not only in the significances shown but also in the magnitude of the coefficients, emphasising the strength of the relationships found. As for *LHDD*, *LELE*, *LRXM*, and *POL_DSM*, they did not prove to be statistically significant predictors of peak electricity demand in the parsimonious models. In other words, the accumulated number of policies focused on DSM have not been effective as peak-shaving strategies, which was an unanticipated outcome. Similarly, the price of electricity had no relationship with peak demand. The *LHDD* shows a low level of significance in the complete models, however it remains insignificant in the parsimonious models. The positive effect on peak electricity demand is coherent with the evidence, however, it is a weak result that needs additional proof of the robustness.

Table 5.5 – Model I – Peak electricity demand (A) and (B) – Complete model

	FE		FER		PCSE - FEHET		DK - FE	
	(A)	(B)	(A)	(B)	(A)	(B)	(A)	(B)
LHDD	0.0291	0.0339	0.0291*	0.0339*	0.0291	0.0339*	0.0291**	0.0339**
LEIE	0.3240***	0.2305	0.3240***	0.2305***	0.3240***	0.2305***	0.3240***	0.2305***
LSERV	-0.1662**	-0.1341*	-0.1662	-0.1341	-0.1662***	-0.1341**	-0.1662**	-0.1341**
LEMP_IND	0.1807***	0.2110***	0.1807***	0.2110***	0.1807***	0.2110***	0.1807***	0.2110***
LBEV_SH	-0.0116**	-0.0120**	-0.0116**	-0.0120**	-0.0116**	-0.0120**	-0.0116**	-0.0120**
LGCF_PC	0.0320	-	0.0320	-	0.0320	-	0.0320**	-
LLF	-	-0.2185*	-	-0.2185**	-	-0.2185**	-	-0.2185***
LELE	0.0746	-0.0914	0.0746	-0.0914	0.0746	-0.0914	0.0746	-0.0914
LRES_PC	-0.0384***	-0.0329**	-0.0384***	-0.0329***	-0.0384***	-0.0329***	-0.0384***	-0.0329***
LRXM	-0.0069	-0.0088	-0.0069	-0.0088	-0.0069	-0.0088	-0.0069	-0.0088
POL_DSM	-0.0024	-0.0023	-0.0024	-0.0023	-0.0024	-0.0023	-0.0024	-0.0023
TREND	0.0050**	0.0054***	0.0050**	0.0054**	0.0050**	0.0054***	0.0050***	0.0054***
CONS	-0.7724	2.8273	-0.7724	2.8273	-0.9081*	2.5881	-0.7724**	2.8273**
R^2/*Within* R^2	0.5619	0.5726	0.5619	0.5726	0.9974	0.9975	0.5619	0.5726

Notes: ***, **, and * denote statistical significance at 1%, 5%, and 10%, respectively. R^2 for the PCSE estimations, and within R^2 for the FE, FER, and DK – FE estimations.

Table 5.6 – Model I – Peak electricity demand (A) and (B) – Parsimonious model

	FE		FER		PCSE - FEHET		DK - FE	
	(A)	(B)	(A)	(B)	(A)	(B)	(A)	(B)
		0.0346		0.0346*		0.0346*		0.0346**
LEIE	0.3349***	0.1943***	0.3349***	0.1943***	0.3349***	0.1943***	0.3349***	0.1943***
LSERV	-0.1673**		-0.1673**		-0.1673**		-0.1673**	
LEMP_IND	0.1683***	0.2341***	0.1683***	0.2341***	0.1683***	0.2341***	0.1683***	0.2341***
LBEV_SH	-0.0136***	-0.0155***	-0.0136**	-0.0155**	-0.0136***	-0.0155***	-0.0136***	-0.0155***
LGCF_PC	0.0360	-	0.0360	-	0.0360	-	0.0360***	-
LLF	-	-0.2577***	-	-0.2577***	-	-0.2577***	-	-0.2577***
LRES_PC	-0.0383***	-0.0318**	-0.0383***	-0.0318***	-0.0383***	-0.0318***	-0.0383***	-0.0318***
TREND	0.0045***	0.0055***	0.0045***	0.0055***	0.0045***	0.0055***	0.0045***	0.0055***
CONS	-0.5074	2.7696*	-0.5074	2.7696*	-0.6402	2.5228**	-0.5074**	2.7696*
R^2/*Within* R^2	0.5519	0.5584	0.5519	0.5584	0.9974	0.9974	0.5519	0.5584

Notes: ***, **, and * denote statistical significance at 1%, 5%, and 10%, respectively. R^2 for the PCSE estimations, and within R^2 for the FE, FER, and DK – FE estimations.

Regarding the parsimonious model (see Table 5.6), the proxies for economic structure, *LSERV*, and *LEMP_IND*, proved to have quite different effects. On the one hand, this paper's findings suggest that the services sector could reduce peak load demand. However, this result is not the sufficient robustness once in the structure (B) the *LSERV* proves not be significant. On the other hand, employment in the industry increased peak load demand with high levels of significance and in both (A) and (B) structures. As such, assuming everything else is constant, economies specialising in the services sector could be more successful in peak shaving.

The analysis proved that *LBEV_SH* decreased peak electricity demand. This is actually a desirable effect, but it is important to remember that the market share of BEV is still negligible. If larger amounts of BEV are deployed, with no other supporting policy, this effect could change significantly. Indeed, peak electricity demand will increase significantly if these vehicles are charged during peak periods, which is likely to occur in the absence of any strategy to control BEV charging. *LGCF_PC* increase the peak load demand while the labour force decreases it. This could indicate that the capital formation is still requiring high levels of the electricity, and as such this consumption occurs in the peak periods. Additionally, RES generation contributed to reducing peak demand. This is a desirable effect for the electricity market as a whole, in terms of integrating RES.

Focusing now on model II – RES integration, the rationale described in model I – Peak Demand is followed. The specification tests predicted the existence of heteroscedasticity and first-order serial autocorrelation. As a consequence, for the PCSE estimator, the options for both heteroscedasticity and first-order serial correlation were included (PCSE – FEHETAR1). The complete models II following the specifications (A) and (B), described in the equation (5.3) and (5.4) are showed in the Table 5.7 and the respective parsimonious models are disclosed in Table 5.8.

Table 5.7 – Model II – RES integration (A) and (B) – Complete model

	FE		FER		PCSE – FEHETCORRAR1		DK - FE	
	(A)	(B)	(A)	(B)	(A)	(B)	(A)	(B)
LPEAK_PC	-1.8034***	-1.6248**	-1.8034**	-1.6248**	-1.7959***	-1.6322***	-1.8034***	-1.6248***
LHDD	-0.0249	-0.03774	-0.0249	-0.03774	-0.0192	-0.0320	-0.0249	-0.03774
LEIE	0.2715	-0.1281	0.2715	-0.1281	0.2286	-0.1492	0.2715	-0.1281
LSERV	-0.4284	-0.8022	-0.4284	-0.8022	-0.4713	-0.7987*	-0.4284*	-0.8022
LEMP_IND	0.1566	0.4774	0.1566	0.4774	0.1417	0.4578	0.1566	0.4774
LBEV_SH	-0.0667*	-0.0552	-0.0667*	-0.0552	-0.0648**	-0.0523**	-0.0667***	-0.0552***
LGCF_PC	0.3761*	-	0.3761	-	0.33551**	-	0.3761*	-
LLF	-	0.6313	-	0.6313	-	0.5741	-	0.6313
LELE	2.2752*	2.8162**	2.2752	2.8162	2.0905*	2.6534**	2.2752**	2.8162**
LRXM	-0.0915	-0.0905	-0.0915	-0.0905	-0.0876	-0.0874	-0.0915	-0.0905
POL_DSM	0.0955**	0.07227*	0.0955**	0.07227*	0.0941***	0.0726**	0.0955***	0.07227***
TREND	0.0448***	0.0444***	0.0448***	0.0444***	0.0443***	0.0443***	0.0448***	0.0444***
CONS	5.3195	-1.1561	5.3195	-1.15608	6.9101*	1.5122	5.3195	-1.15608
R^2/*Within* R^2	0.6084	0.5984	0.6084	0.5984	0.9887	0.9887	0.6084	0.5984

Notes: ***, **, and * denote statistical significance at 1%, 5%, and 10%, respectively. R^2 for the PCSE estimations, and within R^2 for the FE, FER, and DK – FE estimations.

Table 5.8 – Model II– RES integration (A) and (B) – Parsimonious model

	FE		FER		PCSE – FEHETAR1		DK - FE	
	(A)	(B)	(A)	(B)	(A)	(B)	(A)	(B)
LPEAK_PC	-1.5329***	-1.3646**	-1.5329**	-1.3646**	-1.5519***	-1.4005***	-1.5329***	-1.3646***
LSERV	-	-1.1142**		-1.1142***		-1.1179***		-1.1142***
LBEV_SH	-0.0833***	-0.0521	-0.0833**	-0.0521	-0.0811***	-0.0517**	-0.0833***	-0.0521***
LGCF_PC	0.3894***	-	0.3894*	-	0.3811***	-	0.3894**	-
LLF		1.0989		1.0989		1.0345*		1.0989**
LELE	2.1911**	2.0580*	2.1911**	2.0580	2.1911**	1.9049*	2.1911**	2.0580***
POL_DSM	0.0960**	0.0523	0.0960**	0.0523	0.0951***	0.0531	0.0960***	0.0523***
TREND	0.0464***	0.0469***	0.0464***	0.0469***	0.0459***	0.0466***	0.0464***	0.0469***
CONS	4.6241***	-4.7458	4.6241***	-4.7458	5.8948***	-1.8116	4.6241***	-4.7458
R^2/Within R^2	0.6003	0.5819	0.6003	0.5819	0.9885	0.9881	0.6003	0.5819

Notes: ***, **, and * denote statistical significance at 1%, 5%, and 10%, respectively. R^2 for the PCSE estimations, and within R^2 for the FE, FER, and DK – FE estimations.

The model II – *RES integration,* in both (A) and (B) forms, indicated that the *LHDD* variable was statistically insignificant. Indeed, intermittent RES are unable to increase their output to meet an increase in the need to heat buildings. Moreover, RES production was not dependent on *LEMP_IND* neither the electricity intensity on economy (*LEIE*).

This study also suggests that peak periods have hindered RES generation. This proves that RES integration remains dependent on reducing peak electricity consumption. To satisfy electricity in these periods still requires high levels of fossil fuel capacity. As expected, the price of electricity increased RES generation. In fact, the price of electricity was higher than the marginal cost of RES generation. As such, the RES producers are incentivised to produce electricity from RES sources. DSM policies increased RES production. In the countries under study, DSM policies have been more effective in promoting RES than in reducing peak demand. The battery electric vehicles prove be a barrier for the RES integration. In fact, the electricity used in BEV charging could not come from RES. Controlling the BEV charging schedule is a challenge not only for the transport sector but also for the electricity system in order to maximise RES utilization.

5.4.1 Robustness check

The empirical conditions of this chapter could awaken some doubts about the results' robustness, given the short time span under analysis, consisting of only seven years. Please note that all the available data were used. Therefore, with the full awareness of the empirical limitations, the models were estimated by using different structures in order to proof the robustness of the results. Indeed, we opted by subdividing the explanatory variables in two main groups. These subdivisions were performed accordingly with VIF's values. When the results are strong and persistent, changes in the model structures should not produce different results, i.e. the parameters signs and the significance levels should not be dissimilar. Accordingly, the consistency between parsimonious models (I and II) and disaggregated parsimonious models (III, IV, V, and VI) is a clear sign of the robustness of the results.

Therefore, four models were estimated, keeping the main objective of this chapter, i.e. analyse the drivers of peak electricity demand and RES electricity generation. The models were estimated by employing a double log functional form, and by using the variables showed in the Table 5.9.

Table 5.9 - Description of the dependent and independent variables used in the models

Model	Dependent variable	Explanatory variables
Model III – *Peak Demand*	*LPEAK_PC*	*LGCF_PC, LELE, LEIE, LSERV,* and *LBEV_SH*
Model IV - *Peak Demand*	*LPEAK_PC*	*LLF, LHDD, LEMP_IND, LRES_PC, LRXM,* and *POL_DSM*
Model V – *RES Integration*	*LRES_PC*	*LGCF_PC, LEMP_IND, LRXM, LBEV_SH,* and *POL_DSM*
Model VI - *RES Integration*	*LRES_PC*	*LLF, LEIE, LSERV, LELE, LPEAK_PC,* and *LHDD.*

Following the good econometric practices, all the models were submitted to a set of specifications tests to select an appropriated estimator. For all, the Hausman test prove that the fixed effects are adequate. The results of the model III and IV (*Peak demand*) are disclosed in Table 5.10 and 5.11. For this model, the specification tests predict the existence of the heteroskedasticity and the suspicion (albeit with low level of significance) of the existence of the contemporaneous correlations. Accordingly, following the rationality described on the methodology, the appropriated estimators to deal with these data features are the PCSE – FE and DK - FE. The Fixed effects (FE) and Fixed effects robust to the heteroskedasticity (FER) were also performed as benchmark for the obtained results.

Table 5.10 - Model III – *LPEAK_PC (1)*

	FE	FER	PCSE – FEHET	DK - FE
LGCF_PC	0.0783***	0.0783**	0.0783***	0.0783***
LELE	-0.3679**	-0.3679**	-0.3679***	-0.3679***
LEIE	0.3514***	0.3514***	0.3514***	0.3514***
LSERV	-0.1316	-0.1316	-0.1316*	-0.1316***
LBEV_SH	-0.0098***	-0.0098**	-0.0098***	-0.0098***
CONS	0.1404	0.1404	0.1404	0.1404
R^2/Within R^2	0.4697	0.4697	0.9969	0.4697

Notes: ***, **, and * denote statistical significance at 1%, 5%, and 10%, respectively. R^2 for the PCSE estimations, and within R^2 for the FE, FER, and DK – FE estimations.

The results disclosed in Tables 5.10 and 5.11 show greater internal consistency than those obtained in model I – *Peak Demand* (A) and (B). In fact, only the trend proves not be significant in this specification. All the variables kept showing high significance levels, as well as the same sign of the relationships found in model I. Additionally, the electricity prices decrease the peak electricity demand. Although this variable was not significant in the parsimonious models I, they are extremely cohesive with energy and economy theory. In fact, a high electricity price decreases the electricity peak demand. Coherently, this corroborates with the amply documented in the literature wherein the differentiated electricity tariffs, for example Time of use tariffs (TOU), are an efficient mechanism to reduce peak electricity demand.

Table 5.11 - Model IV – *LPEAK_PC (2)*

	FE	FER	PCSE – FEHET	DK - FE
LLF	-0.3341***	-0.3341***	-0.3341***	-0.3341***
LHDD	0.0525**	0.0525**	0.0525**	0.0525**
LEMP_IND	0.1703***	0.1703***	0.1703***	0.1703***
LRES	-0.0384***	-0.0384***	-0.0384***	-0.0384***
LRXM	-0.0270**	-0.0270*	-0.0270**	-0.0270**
CONS	4.8483***	4.8483***	4.8483***	4.8483***
R^2/Within R^2	0.4604	0.4604	0.9968	0.4604

Notes: ***, **, and * denote statistical significance at 1%, 5%, and 10%, respectively. R^2 for the PCSE estimations, and within R^2 for the FE, FER, and DK – FE estimations.

The rationality described for the models III and IV (*LPEAK_PC*) was also followed in the models' V and VI (*LRES_PC*). Likewise, these models reveal outstanding internal harmony with those obtained in models II – *RES Integration* (A) and (B). The variables that are significant in the parsimonious models (model II (A) and (B)) also show high levels of significance in model V and VI, which is a clear sign of the strength of the results found.

Table 5.12 - Model V – *LRES_PC (1)*

	FE	FER	PCSE – FEHETAR1	DK - FE
LGCF_PC	0.5281***	0.5281**	0.5091***	0.5281**
LEMP_IND	-0.6699**	-0.6699**	-0.6373**	-0.6699***
LBEV_SH	-0.0681**	-0.0681*	-0.0638***	-0.0681***
POL_DSM	0.1028**	0.1028***	0.1005***	0.1028***
TREND	0.0473***	0.0473***	0.0467***	0.0473***
CONS	7.1339***	7.1339***	8.2937***	7.1339***
R^2/Within R^2	0.5542	0.5542	0.9869	0.5542

Notes: ***, **, and * denote statistical significance at 1%, 5%, and 10%, respectively. R^2 for the PCSE estimations, and within R^2 for the FE, FER, and DK – FE estimations.

The labour force and employment in industry sector only shows statistical significance in model V. This means that these results could not be sufficiently strong and robust. Additionally, the outcome showed in the models II are also supported in model V, *LBEV_SH* decreases the RES generation while the policies focused on the DSM increases it.

Table 5.13 - Model VI – *LRES_PC (2)*

	FE	FER	PCSE – FEHETAR1	DK - FE
LLF	1.2914*	1.2914*	1.2311**	1.2914***
LSERV	-1.2269***	-1.2269***	-1.2269***	-1.2269***
LELE	2.6326**	2.6326*	2.4801***	2.6326***
LPEAK_PC	-1.1585**	-1.1585**	-1.1941**	-1.1585***
TREND	0.0.440***	0.0.440***	0.0.440***	0.0.440***
CONS	-7.5867	-7.5867	-4.6431	-7.5867
R^2/*Within* R^2	0.5651	0.5651	0.9876	0.5651

Notes: ***, **, and * denote statistical significance at 1%, 5%, and 10%, respectively. R^2 for the PCSE estimations, and within R^2 for the FE, FER, and DK – FE estimations.

The results of model VI are in accordance with those obtained in models II (A) and (B). Accordingly, this model confirms that the *LSERV* decreases the RES generation. Additionally, the labour force increases the RES generation as well as the electricity price. The *LPEAK_PC* proves is hampering RES generation.

Figure 5.1 summarises the main outcomes of the estimated models. Please note that the main objective of this study is to analyse the main drivers of both peak electricity demand and renewable integration. The results show that the electricity intensity of the economy and gross capital formation affect positively peak electricity demand. Meanwhile, renewable generation has a negative effect on it. Regarding renewables integration, this chapter supports that the electricity price and DSM policies have a positive impact. On the contrary, the existence of the peak electricity demand is the main barrier for the RES integration.

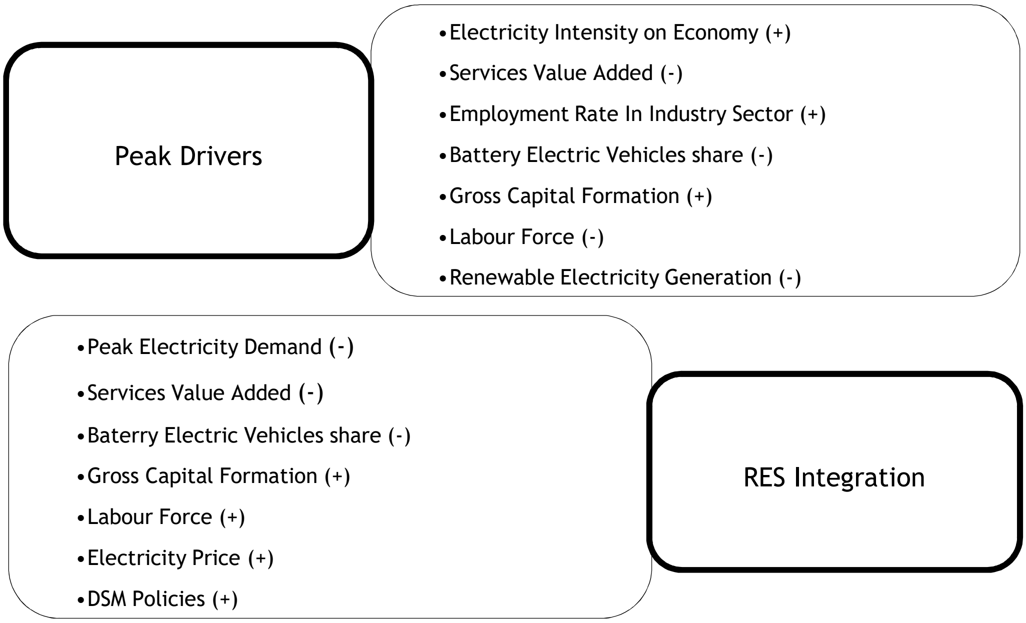

Figure 5.1 - Summary of the main findings

In short, the results of this subsection provide an additional strength of proof for those obtained in Section 5.4. In fact, faced with different models structures the main findings in the Results section are maintained which is a clear sign of their robustness. In sum, the services value added, BEV market share, labour force and RES electricity generation decrease the peak load demand. Meanwhile, the electricity intensity of the economy, employment in the industry sector and gross capital formation increase it. The existence of the peak periods over the day proves to be a barrier for RES integration. Additionally, also the penetration of the BEV into the automotive market is hampering RES electricity generation. The policies focused on the DSM proves to be an efficient mechanism to increase RES generation, however, they prove to not be efficient in the peak load demand smoothing. The Gross Capital Formation and Labour force increase the RES electricity generation, while services value added decreases it.

5.5 Discussions and policy implications

The main findings indicate that those devising peak shaving measures must consider the different economic structures of each economy. This means that economies specialised in the services sector could be more effective in peak electricity reduction than economies focused on the industrial sector. In fact, this latter sector is increasing peak load demand. Therefore, to reduce peak electricity, it is essential that policymaking focuses on this sector, particularly on energy efficiency. To attain this, not only must the acquisition of more efficient equipment be stimulated, but changes should also be made in processes, such as the promotion of consumption monitoring in real-time and the intervention in critical areas to reduce waste.

Notwithstanding, economic development increases the peak demand once the electricity intensity on economy increases the peak demand. Being that electricity consumption is crucial for economic growth, policymakers should promote energy efficiency in the productive sectors. Moreover, also the investment in better-insulated and more energy-efficient buildings could be an efficient way to reduce peak demand. Policymakers should prioritise this type of construction and improve existing infrastructure, particularly through building refurbishment programmes.

Peak electricity demand is not reliant on electricity prices. This finding is unsurprising given that the electricity prices studied were fixed for all times of the day. With this kind of tariff, consumers have no pricing incentive to changing their consumption routines by consuming during off-peak periods. This finding indicates that electricity pricing should be differentiated to reduce peak load demand, namely in the residential sector, as noted by (Wang & Mogi, 2017). This suspicion is in line with the amply documented in the literature wherein the differentiated electricity tariffs contribute to reduce electricity demand during the peak periods (Woo et al., 2018). The need for this pricing approach is further accentuated with the introduction of BEV. Without any incentive, consumers will be prone to charge their cars in the evening. This charging time would probably coincide with the peak time of 8 p.m and could compromise energy security.

Although this chapter finds that BEV penetration has led to a reduction in peak demand, the introduction of large numbers of BEV may threaten the reliability of the energy system and even lead to an exponential growth in electricity costs due to the greater resulting use of both flexible sources and imported electricity. However, V2G technology has the potential to avert these effects. With BEV being charged during off-peak times, and returning electricity to distribution systems during peak periods, the security of the electricity systems would be guaranteed, and they could even help accommodate RES. Coherently, it could contribute to advert the findings of this chapter that suggest that these vehicles have a negative effect on RES integration. Therefore, both electricity systems and vehicles should incorporate V2G technology to exploit the advantages of RES generation.

Higher electricity prices stimulate RES generation. The marginal costs of RES generation are close to zero, which means that the prices paid by household consumers in the countries analysed were significantly larger than the cost of RES production. For RES producers, the electricity prices paid by consumers are augmented by the well-documented grants received for new RES. Therefore, RES producers are strongly incentivised to produce electricity from RES, as the return is significantly higher than its cost, even if none of this electricity is consumed. Differential electricity pricing should be designed to better correlate with RES generation. It should promote cheaper electricity when there are higher levels of RES generation and increase electricity prices when renewable sources are unavailable. In fact, the policymakers should promote the smart grid, by using real time pricing that contemplates the real costs of generation. This mechanism will promote high levels of consumption when there is high renewable generation. This could reflect not only on the improvement of the electricity system efficiency, but also on the renewable electricity that is effectively consumed.

Regarding DSM policies, in the period under analysis, they had no impact on peak electricity demand, and neither enhanced nor reduced these peaks. Policymakers should now focus on designing new DSM policies, particularly ones that discourage electricity consumption during peak periods, for example by promoting more expensive electricity during these periods. In contrast, this study supports DSM policies effectiveness in promoting RES generation. It seems that the DSM policies analysed in the study were focused on RES generation and failed to smooth load demand curves. These policies must be rethought. To this end, demand response measures, particularly those involving pricing, could help to achieve this target.

As expected, this chapter corroborates that the existence of peak periods during each day is an obstacle to RES integration. However, these periods did not always coincide with the times when RES intermittent generation was higher. Therefore, electricity systems resorted to flexible sources or to importing electricity, thus reducing the utilisation of RES. To reduce this dependency on imports, and improve the autonomy of electricity systems, new and more efficient ESS is essential. This ESS could enable the further integration of RES, if it stores surplus electricity during high RES generation, and reintroduces it into the system when demand is higher than supply. Policymakers should promote research in ESS, and crucially to the development of lower cost batteries with higher capacity. Moreover, the promotion of BEV incorporating V2G technology could be extremely useful to achieve this purpose.

Economies need electricity to power economic growth. In this study, the electricity generated from RES is not dependent on the electricity intensity on economy. This may have been because intermittent RES generation did not occur in periods when productive sectors of the economies required electricity. However, bearing in mind the current transition in the electricity paradigm, this finding could be interpreted to mean that policymakers should redouble their investment in RES deployment. Indeed, this research finds that capital formation has stimulated RES generation. Thus, policymakers should continue to pursue this investment, while this investment should also promote the reduction of peak demand, which is not occurring. Indeed, the policymakers should formulate the investments by considering the outcomes of this chapter. Firstly, it is necessary to invest in more efficient ESS and V2G technologies. In this sense, the investment in research and development for this progress could be an efficient mechanism to achieve it. These technologies could contribute not only to RES generation but also to the reduction of peak electricity consumption. Secondly, the consumers should become more active players in this scenario, because changes in consumption routines could be an efficient solution not only to reduce peak electricity demand but also to accommodate RES.

The creation of smart power grids could be very helpful in peak reduction and RES integration. This smart grid, together with electricity prosumers (who both produce and consume electricity), could play a crucial role in peak shaving. Policymakers should incentivise self-production of electricity through financial and non-financial incentives. In order to reduce peak electricity demand and improve RES integration, the role played by prosumers could be fundamental, particularly through prosumer-based energy management and sharing (PEMS) (Zafar et al., 2018). In fact, by producing their own electricity they could relieve pressure on the electricity system, primarily in peak periods. Moreover, they could feed their surplus electricity to the grid, thereby using RES electricity to satisfy demand.

5.6 Conclusions

This chapter is focused on the empirical analysis of the main drivers for both peak electricity demand and RES generation, with special focus on the role played by BEV. For this, it employed annual data from 2010 to 2016 for a panel of 20 EU countries. The characteristics of the data made the use of PCSE and Driscoll-Kraay estimators appropriate. The uniformity found between the full and parsimonious models, as well as between the PCSE and Driscoll-Kraay estimators supported the robustness of the results found. This robustness was also confirmed by applying different structures in the regressions.

One concludes that technological improvements in ESS are crucial for reducing peak electricity demand and increasing RES integration. For ESS to be used intensively, it must be made more attractive and cost effective. The promotion of BEV must also be pursued, but it must be done prudently. On the one hand, the times when these vehicles are charged must be controlled, as the charging of large numbers of BEV at the same time could compromise energy security. On the other hand, these vehicles should incorporate V2G technology, not only to exploit the advantages of RES generation, but also to improve the economic efficiency of electricity systems. More efficient DSM measures are required to reduce peak demand, and consumers should be incentivised to change their electricity consumption habits. Smart technology and self-generated electricity could be instrumental in achieving this.

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Chapter 6

Conclusions

This thesis has aimed to analyse the transition of the energy paradigm in an economic sector that still remains extremely dependent on fossil fuels, that is the Transport Sector (TS). The policymaking should deal to avert two great effects caused by this sector. On the one hand, the TS is responsible for high levels of Greenhouse Gases (GHG) emissions. On the other hand, it has blocked both the transition to electrification and renewable energy sources (RES) penetration in economies. This means that, even with high levels of RES penetration, the dependence of the economies on fossil fuels is maintained to satisfy TS needs. Therefore, the intervention of policy guidance is crucial to diversify the energy mix of the economies, thus reducing the dependence on fossil fuels.

The deployment of alternative energy sources, such as electricity and renewable fuels in the TS is crucial to reducing GHG emissions and the dependence of the economies on fossil fuels. If the potential of the TS was achieved, the electrification could even be an efficient solution to improving electricity system efficiency and accommodating RES. We refer to, for instance, the potential of this sector to storing electricity when there is high RES generation and replacing it on the grid when RES generation is lower (vehicle to grid (V2G)). These evidences have motivated this thesis that provides fundamental guidelines for policymakers.

6.1 Final Remarks

Overall, the conductive question purposed analyses how the diversification of the energy mix has impacted the TS. To provide empirical evidence to answer this central question, this thesis has been structured in three main parts, composed of four analyses. The first part is composed of two analyses and aims to analyse the interactions between conventional and alternative TS' energy sources, economic growth and carbon dioxide (CO_2) emissions. The findings of this part have motivated the second and third parts, that are focused basically on the main challenges with which electric mobility is faced, namely the penetration of Electric Vehicles (EV) and the impact of the EV on both management of the electricity system and RES integration.

The empirical evidence of this thesis was performed by the Organization for Economic Co-operation and Development (OECD) and the European Union (EU) countries. The analysis of these countries seems to us to be of special relevance for policymakers due to their being in general leaders regarding diversification of the energy mix, in both the TS and electricity system. To accomplish the objective of this thesis, several econometric techniques have been employed in accordance with the data features and research objectives. Since the current nature of the topic had been addressed, the available data was found to be scarce. Thus, several panel data models have been used since it allows for obtaining a reasonable observation number that allows the econometric operationalization. Additionally, several robustness techniques have been employed to confirm the strength of the results.

Let us consider in more detail each chapter's contents. For the purpose of the diversification of the TS' energy mix, new energy sources have been introduced, such as renewable fuels and electricity. Chapter 2 aims to perform the general analysis of the TS by considering 21 high-income OECD countries. A Panel-Vector Autoregressive (PVAR) has been applied to accomplish these objectives. The findings of this chapter corroborated the intuition that the alternative TS energy sources decreased the TS fossil fuels use, although in small magnitude. It is in fact a desirable effect to transit to a low-carbon TS, supporting that the promotion of the TS alternative energy sources must be pursued. Regarding the effects of the TS alternative energy sources on economic growth, they have not been not consensual, indeed. On the one hand, it seems that renewable fuels have been decreasing economic growth. On the other hand, TS electricity use has increased economic growth. This means that for high-income countries the deployment of electric mobility could be indeed more attractive for the economy. However, this electricity apparently has no relationship with CO_2 emissions, evidencing that the electricity used by TS could be not coming from RES. In other words, if the electricity is generated from non-renewable sources the dependence on fossil fuels is maintained and consequently the GHG reduction is not achieved.

Chapter 3 went further when compared with chapter 2. On the one hand, it includes the rail infrastructure investment to explain the interaction between both conventional and alternative TS' energy sources, economic growth and CO_2 emissions. On the other hand, it uses an Autoregressive Distributed Lag (ARDL) structure with the Driscoll-Kraay estimator. This methodology has some advantages. First, the ARDL allows for capturing the short- and the long-run effects individually. Second, it also allows for obtaining the magnitude of the effect through the semi-elasticities and elasticities. Third, this structure deals with the endogeneity. Last but not least, faced with 15 OECD countries that have a similar policy guidance, the DK estimator allows for dealing with the cross-sectional dependence. The empirical approach has been performed using the time span 1995 to 2014.

The findings of chapter 3 indicate that the reduction of the TS fossil fuels use could really be achieved by promoting not only the substitution of TS electricity consumption, but also through the investment in rail infrastructure. During the period analysed for this analysis, the electricity used in the TS is occurring mainly in the railways. In fact, the existence of improved railway infrastructure could be an efficient way to decarbonise the TS. The existence of the for example, comfort trains stimulates users to utilize them, reducing thus the use of private cars usually powered by diesel or gasoline. At the same time, the use of renewable fuels contributed to decrease the CO_2 emissions, while the TS electricity consumption has increased it. This outcome is in line with those obtained on chapter 2, i.e. the electricity is being generated from non-renewable sources. Meanwhile, apparently, the alternative TS energies sources have jeopardized economic growth. This could be a result of the high relative costs associated with alternative energy sources. Policymakers should improve the cost-effectiveness of alternative energy sources to avoid this negative effect on economic growth

To allow the economies to benefit from the potential of electric mobility, the EV market share must be enlarged. Consumers continue to resist buying an EV. The social acceptance of EV must be explored and incentivised for the purpose of increasing the EV market share. These evidences have motivated the development of chapter 4, which analyses the factors supporting the adoption of the BEV and PHEV, individually and joint EV (BEV plus PHEV). The role of policy, be it economic, social, environmental and technical factors on EV adoption have been analysed. We have to highlight that a proxy has been used for the technological progress of the EV batteries. To do that, the Principal Component Analysis (PCA) has been used to capture the main information of the battery cost and both the Nissan Leaf's driving range and battery capacity. Faced with the actuality of the topic addressed and the restrictions of the available data, we have to note that the time span analysed is short. As such, the robustness of the results has been confirmed by using Seemingly Unrelated Regression.

The findings supported that, presently, the main challenge for the EV is technological, since it remains quite dependent upon the developments of the batteries. The proxy used for battery innovation has been a significant driver. The competitiveness between EV and traditional vehicles powered by an Internal Combustion Engine (ICE) must be expanded, not only in regard to the purchase price, but also in the driving range and refuelling times. Also, the existence of the charging infrastructures has been a significant driver for EV deployment. To overcome these technological challenges, the investments in Research and Development (R&D) could play a crucial role. This investment should be focused not only on the promotion of more efficient batteries at a lower cost, but also on for instance improved fast charging stations.

This research has proved that each one EV technology should be analysed individually. In fact, the driving forces of the BEV are different than those of PHEV. As previously noted, the penetration of EV will only be advantageous for the environment if the electricity generated is coming from renewables. This means that countries with low RES endogenous potential should promote more PHEV than BEV, given that they are less intensive on electricity. These countries should promote RES initially, and only after that, invest in BEV deployment. On the contrary, the implementation of the BEV could lead to an exponential increase of the installed capacity of the flexible sources, such as coal, to satisfy the additional electricity demand. As such, the reduction of the environmental impacts as a result of the vehicles use “on road” will be compensated for with an increase of the emissions in the electricity generation process. Thus, the economies do not reduce their dependence on fossil fuels. This risk deserves particular attention from policymakers. Accordingly, the penetration of the PHEV instead of BEV could be an efficient way to introduce electric mobility in these countries. The PHEV has some advantages when compared with BEV. On the one hand, they gain the advantages of electricity use in mobility in short trips. On the other hand, they permit the users not to suffer from “range anxiety” which has been an effective barrier to BEV deployment. Therefore, the pressure of these vehicles on the electricity system is less than what occurs when BEV are used, since their batteries have less capacity.

Additionally, from 2010 in the EU countries the policies supporting electric mobility have been effective in promoting BEV deployment, but they have not affected the enlargement of the PHEV market share. This finding is an additional proof that the policymaking should be focused on each type of vehicle technology, instead of the EV as a whole. Regarding the effects of crude and electricity prices, they have been actually different. For instance, additional taxation of the crude oil products has decreased the attractiveness of the PHEV, while the electricity price has not yet been a significant driver for the BEV or PHEV deployment.

Once the factors behind the enlargement of the electric vehicles share have been studied, the effects of the BEV on the management of the electricity demand constitutes the main objective of chapter 5. Actually, the integrated transport and electricity policies are required to transit to a low-carbon TS, contributing to accommodate the renewable sources without compromising the normal operation of the system. We are referring to for instance controlled EV charging strategy in out-off peak periods and when there is a high renewable generation. As is well known, the existence of the peak periods creates economic inefficiencies for the system, namely due to the peak installed capacity which is off most of the time. The introduction of large amounts of BEV in charging mode could accentuate this problem, namely if this charging process occurs during peak periods. On the one hand if it occurs the system could not be able to deal with the additional demand and could be necessary to improve the installed capacity of the flexible sources, such as coal. On the other hand, the penetration of EV, mainly BEV, could contribute to creating another peak period over the day.

For this reason, the analysis of the drivers of peak electricity demand could be crucial in the policymaking strategy. In fact, the peak shaving strategies should be accompanied by RES integration in the electricity system. In chapter 5, the driving factors of the peak load demand and RES integration have been evaluated, giving special attention to the BEV. As in chapter 4, the current nature of the topic addressed makes impossible the use of a longer time span. Fully aware of these empirical limitations, the robustness of the results found have been confirmed by employing different models' structures. The findings have indicated that the peak shaving strategies should be delineated in accordance with the economic structures of the countries. Indeed, for economies specialized in the industrial sector, the reduction of the peak load demand is more challenging than for economies specialized in the services sector. The energy efficiency of the industrial sector must be explored and incentivized.

Apparently, the introduction of the BEV in the automotive market has contributed to reducing the peak load demand which is the desired effect. However, this should be carefully analysed. These findings have outgrown the analyses of the early years of BEV deployment in the EU countries. Their market share remains small. Accordingly, with the enlargement of the BEV market share, this desired effect could actually change without any policy supporting it. Conversely, the BEV has not contributed to RES integration. It is supporting the idea wherein both transport and electricity policies should be designed together. In fact, the BEV has a great potential to accommodate the RES if properly harnessed. Public guidance should take this into account, promoting the BEV charging schedule in periods with high RES generation.

Peak shaving has not been dependent upon electricity price, once the considered electricity price is fixed over the day. Actually, the differentiated electricity price could be an efficient way to reducing electricity consumption in peak periods and increase it in out-off peak periods. Furthermore, this price differentiation could also stimulate the BEV users to charge their cars when there is high renewables' production and the demand for electricity is low. The policy supporting Demand Side Management (DSM) has been effective in renewables integration, but they have had no effect on peak electricity demand. In fact, DSM policies should contribute to reducing peak electricity demand, smoothing the electricity demand curve. This thesis has proved that it is not occurring. Thus, the policymakers should revise this policy formulation and implement policies that discourage electricity consumption in peak periods. The demand response measures, such as the previously mentioned differentiated electricity prices could be an efficient way to achieve this.

To sum up, the policymakers should promote the use of the alternative energy sources in TS in order to attain their environmental goals. However, this promotion should be carefully formulated. This means that electricity and transport policies should be jointly designed. The introduction of EV, mainly BEV should not compromise the energy security and should contribute to accommodating the RES in the electricity system. At the same time, the alternative TS energy use should contribute to reducing the pollutant gas emissions and should contribute to economic growth. The cost-effectiveness of the alternative TS energy sources must be enlarged. Accordingly, the EV must be competitive with traditional vehicles. The investment in R&D for battery development should be promoted in order to increase the EV cost-effectiveness. The factors supporting the adoption of the BEV and PHEV should be explored by policymakers to increase their market share. The EV market share enlargement should also be accompanied with the reduction of peak electricity demand. The existence of peak load demand causes inefficiency for the electricity systems. This issue could even be emphasized if the economies apply an uncontrolled EV charging strategy without any policy supporting it.

Please note that the findings of this thesis are based on the analysis of historical data from the past. In the near future, many new challenges will emerge, and steps should be taken to correct the unexpected relationships that this study has revealed. For instance, electric mobility, which still holds a small market share, could become far more significant in the next few decades or even years. The impressive development of the capacity and lifecycle of electric vehicle batteries, together with their potential to help manage the whole electricity system through V2G, could mean a real revolution not only for mass transit but also for personal transportation. Therefore, the results found by this research could be updated in the future by an appropriate policy approach. We have to highlight again that TS is not only a sector that needs to diversify their energy mix. The TS has a great potential to improve the efficiency of the electricity system and RES integration. Thus, TS could allow the economy to easily adapt to the new energy paradigm with supportable costs. Accordingly, this sector must be more flexible not only by permitting the bidirectional electricity movements between EV and grid but also in the EV charging schedule. These electricity movements and charging schedules are essential aspects that should be considered and potentialized by the DSM policies. In this way, the EV could reduce peak electricity consumption in peak periods (as proved in chapter 5) and improve the RES integration enlarging this the electricity system efficiency.

6.2 Future research

The shift in the TS energy paradigm, namely on road TS is currently in an intense debate. We are confident that this thesis has contributed to that literature with robust evidence about the economic growth and the interaction of sources in the sector; with the analysis of the drivers of electric mobility; and with the high potential of this sector to smooth the demand load, making easier and cheaper higher penetration of renewables. We are pleased with the reconnaissance of the peers of these contributions in the already published articles. This notwithstanding, the need for additional contributions to the full understanding of the complexity of the sector is both real and welcome. This transition is, even more, a priority of the political agenda of most of the developed countries. Therefore, in the near future, several changes will be introduced in the transport system, increasing the attractiveness of it for researchers.

In the current context, the promotion of more efficient public transportation could be an efficient way to reduce the fossil fuels use in the TS. In fact, with developed public transportation, the users can reduce the use of their private cars, reducing thus, diesel or gasoline consumption. The finding of this thesis wherein the investment in rail infrastructure is contributing to reducing fossil fuels consumption should be explored in future research. Not only the rail infrastructure should be considered but also the road, namely by improving the conditions of public transportation such as buses.

Additionally, we consider that the efficiency of the transport and electricity system should be jointly achieved. This means that self-electricity production, associated with DSM measures will promote the efficiency of both. Moreover, the V2G technology should play a crucial role to achieve this equilibrium. Therefore, in the future, the research should be focused on the potential role that both prosumers and V2G technology could play in achieving the equilibrium between transport and electricity systems. The last analysis of this thesis gives a short contribution to the literature, namely regarding the potential effects of the BEV introduction on the management of the electricity system, specifically on the peak periods and RES integration. This potential of EV for management of the electricity system should be further explored by enlarging the data frequency to for instance hourly data. In the future, significant changes will occur, namely with the expansion of the EV market share. Thus, this research topic is and will continue to be a hot topic for the literature and crucial for policymaking.

Moreover, additional proof of the role of the BEV on CO_2 emissions is needed. Although these cars have 0% emissions on the road, their introduction could contribute to enlarging the flexible sources of electricity generation such as coal, contributing thus to increase the CO_2 emissions in the electricity generation process. This suspicion should be further examined. Moreover, other ways to reduce private investment in electric mobility, as a way to improve consumers' profitability should be explored. Car sharing could be an efficient way to allow consumers to benefit from EV use with lower investment.

Last but not least, other methodologies should be used to analyse the shift in the TS energy paradigm. The findings of this thesis have been based on the econometric analysis by using historical data. In fact, knowing which have occurred in the past is crucial to designing appropriate transport and electricity policies. However, future research should also be applying other methodologies, such as modelling and simulation in order to study which of these changes could be imply in the near future, namely for the environment and economic growth.