

# **European Energy Transition: An analysis on the dynamics of electricity sources in the European nuclear power-producing countries.**

**Thibaut Manuel dos Santos Junqueira**

Dissertação para obtenção do Grau de Mestre em  
**Economia**  
(2º ciclo de estudos ou mestrado integrado)

Orientador: Prof. Doutor António Manuel Cardoso Marques

**junho de 2020**



# Acknowledgements

My first words of thanks are addressed to my parents, for the affection and unconditional support they have always given me.

A special thanks to my sister, who helped me in everything she could and who give me the motivation to always continue the hard work.

Many thanks to my girlfriend, for everything you represent to me, for the affection and patience shown in the most difficult moments when I was not always able to be present.

I'm thankful to my friends and colleagues, for delivering help in the harsh periods and for making everything easier through the good mood and companionship.

My last words go to my advisor, to Professor António Manuel Cardoso Marques, whose I would like to express all my gratitude and appreciation for the support, cordiality, and kindness which he has always received me.



## Resumo

A busca por energia segura na UE está a inspirar uma política de energia nuclear-zero e uma mudança para fontes renováveis. A erradicação da energia nuclear está a ser tomada com prudência para não criar externalidades negativas, mesmo que nem todos os países estejam disponíveis para esse avanço. A transição para a eletrificação sem emissões de carbono é analisada através das interações entre as fontes de eletricidade, o Índice Harmonizado de Preços no Consumidor e as emissões de dióxido de carbono nos países produtores europeus de energia nuclear (estados membros da União Europeia e Suíça), com base em dados mensais, a partir de janeiro de 2014 até dezembro de 2018. Um modelo *Autoregressive Distributed Lag* foi executado usando o estimador *Driscoll e Kraay* com efeitos fixos, permitindo que os impactos de longo e curto prazo sejam reportados. Os resultados afirmam que o CO<sub>2</sub> continua a ser emitido pelo sistema elétrico, embora o efeito de substituição de fontes renováveis por combustíveis fósseis. As principais conclusões são de que a energia nuclear pode ser útil para acomodar eletricidade renovável no sistema, e a geração elétrica a partir de combustíveis fósseis para suporte às fontes renováveis leva a preços mais altos para os consumidores.

## Palavras-chave

Índice Harmonizado de Preços no Consumidor, Sistema Elétrico;ARDL;Eletricidade renovável;Emissões de CO<sub>2</sub>;Energia nuclear;Europa.



# Resumo Alargado

O estudo sobre as dinâmicas da geração de eletricidade é fundamental para analisar as circunstâncias de uma transição energética. A transição energética europeia analisada é determinada pelo desenvolvimento de políticas pró-ambientais que objetivam um sistema energético mais limpo. O plano ecológico é praticamente centrado no setor de energia elétrica, delineado principalmente por energia eólica e solar, com o objetivo de remover a capacidade instalada de combustíveis fósseis do sistema de energético da Europa (EEA, 2018; IEA, 2016). No entanto, a complexidade de qualquer transição energética deve levar em consideração outros fatores. Por exemplo, os governos centrais procuram não negligenciar a sustentabilidade económica durante a mudança para as energias renováveis e prometem que os investimentos necessários não aumentarão as despesas das famílias (Agora Energiewende, 2019).

Além da mitigação da poluição, o aumento do uso das fontes de energia renováveis na UE é visto como uma resposta à promoção de segurança na geração elétrica. Com isso em mente, a energia nuclear tornou-se uma fonte questionável devido ao potencial fator de exposição à radioatividade. O debate sobre a potencial interrupção futura da energia nuclear na UE fortaleceu e teve efeitos nas políticas energéticas dos Estados-Membros da Europa (Aune, Golombek, & Hallre, 2015; Deutsch, 2017). No entanto, ainda existe um grupo de Estados que menciona a energia nuclear como uma importante base energética, alegando que o desmantelamento da frota nuclear pode comprometer as metas ambientais que eles prometeram para a UE ou mesmo sua sustentabilidade económica (Aune et al., 2015).

Portanto, esta pesquisa tem como objetivo analisar a competitividade económica e a sustentabilidade ambiental da transição energética, com foco na compatibilidade das fontes renováveis para substituir as instalações de combustíveis fósseis, num sistema que tradicionalmente depende da energia nuclear na Europa (EU e Suíça). A análise averigua a viabilidade ambiental, estimando a intensidade de carbono por fonte elétrica usando dados do Digest of United Kingdom Energy Statistics 2018 e avalia o equilíbrio económico através da observação dos impactos de diversas fontes elétricas no Índice Harmonizado de Preços ao Consumidor. Dados mensais foram implementados, o período explorado na pesquisa foi de janeiro de 2014 a dezembro de 2018 e um modelo *Autoregressive Distributed Lag* foi executado usando o estimador *Driscoll e Kraay*.

A literatura atual já retrata a diversificação do *mix* de eletricidade e seu impacto na atividade económica de forma abrangente (Afonso, Marques, Fuinhas, & Saldanha, 2018; Antonio C Marques & Fuinhas, 2018; António Cardoso Marques, Fuinhas, & Macedo, 2019). Bem como também demonstra que as economias modernas com tecnologia inovadora mostraram características incomuns das centrais nucleares, com capacidade de operar com flexibilidade, e com compatibilidade à produção renovável (Afonso et al., 2018; António Cardoso Marques et al., 2019; António Cardoso Marques, Fuinhas, & Nunes, 2016). No entanto, esta pesquisa é inovadora em termos de novidade e contribui da seguinte maneira a literatura académica: (1) o efeito que uma fonte específica do sistema de geração de energia pode ter num índice de preço do consumidor e (2) apresenta resultados empíricos através de uma estrutura baseado em dados em painel com uma base de dados de frequência mensal.

A análise preliminar dos dados em estudo ditou que as variáveis estão integradas na ordem de  $I(0)/I(1)$ , fortalecendo a afirmação que abordagem *Autoregressive Distributed Lag* é a mais correta. Após os resultados do teste de Hausman que demonstraram que os efeitos fixos seriam o estimador mais adequado, sucedeu-se uma bateria de testes de diagnóstico. Tais testes que revelaram a existência de heterocedasticidade, *cross section dependence* e autocorrelação de primeira ordem. Perante isto, e de maneira a certificar a veracidade dos modelos estatísticos, o estimador escolhido foi o Driscoll and Kraay (1998).

Em relação aos resultados empíricos sobre interações dinâmicas das fontes de eletricidade, a regressão demonstra que as centrais nucleares estão a fazer produção elétrica de suporte às fontes renováveis no curto prazo, mas no longo prazo, esse efeito desaparece, embora sua capacidade de trabalhar de forma flexível é reivindicada pelo *Error Correct Model*. Tendo como referência, alguns dos países selecionados já foram investigados em estudos individuais (time series) e apresentaram a equivalente função de *backup* pela produção nuclear (Afonso et al., 2018; Antonio C Marques & Fuinhas, 2018; António Cardoso Marques et al., 2019; António Cardoso Marques et al., 2016). Todavia, a regressão afirma que a exploração de renováveis força o sistema elétrico a emitir  $CO_2$ , mas essa indicação não é nova na literatura; um resultado semelhante é legível em Charfeddine and Kahia (2019) and Chen, Zhao, Lai, Wang, and Xia (2019). Resultado justificado pela ineficiência das renováveis para suprir a alta procura de eletricidade, a falta de tecnologia de armazenamento energético adequada e o apoio a fontes poluentes (gás natural) para complementar a produção intermitente renovável.

Na presença dos resultados empíricos obtidos, deduz-se que o esforço notável da UE para transitar seu sistema elétrico com o objetivo de alcançar uma economia de zero-

carbono está ameaçado em grande parte por políticas que promovem o apoio à geração com centrais a gás para suporte à volatilidade de produção renovável. Isso expressa que o alto consumo de eletricidade aumenta as emissões de dióxido de carbono sob as políticas atuais e planeadas.



# **Abstract**

The quest for safe energy in the EU is inspiring a zero-nuclear power policy and a move towards renewable sources. Nuclear power eradication is being taken prudently so as not create negative externalities, even though not all countries are available for such an advance. The transition towards carbon-free electrification is analysed through the interactions between the electricity sources, the Harmonised Index of Consumer Prices and carbon dioxide emissions in European nuclear power producing countries (European Union members states and Switzerland), based on monthly data, from January 2014 to December 2018. An Autoregressive Distributed Lag model was executed using the Driscoll and Kraay estimator with fixed effects, enabling the long-run and short-run impacts to be reported. The results affirm that CO<sub>2</sub> continues to be emitted by the electricity system, albeit the substitution effect from renewable sources to fossil fuels. The key findings are that nuclear energy can be useful to accommodate renewable electricity into the system, and supportive fossil generation for renewable sources leads to a higher prices for consumers.

# **Keywords**

Harmonised Index of Consumer Prices, Electricity system, ARDL, Renewable electricity, CO<sub>2</sub> emissions, Nuclear power, Europe.



# Table of contents

1. Introduction .....	1
2. Overview of the electricity system, CO <sub>2</sub> emissions, and prices in Europe .....	2
3. Literature Review .....	3
4. Data .....	6
5. Method and Model .....	9
6. Preliminary analysis .....	11
7. Results .....	17
8. Discussion.....	24
9. Conclusion.....	25
Webography.....	26
References.....	27



# Tables List

**Tabela 1.** Direct Emissions of CO<sub>2</sub> by Source.

**Tabela 2.** Variable's definition and source.

**Tabela 3.** Summary statistics

**Tabela 4.** Cross section dependence.

**Tabela 5.** Correlation matrix.

**Tabela 6.** VIF statistics.

**Tabela 7.** First generation unit root tests.

**Tabela 8.** Second generation unit test root.

**Tabela 9.** Specification test.

**Tabela 10.** Zivot and Andrews (1992) unit root test with structural break by country.

**Tabela 11.** Phillips and Perron (1988) unit root test with structural break by country.

**Tabela 12.** Estimated results.

**Tabela 13.** Semi- elasticities and elasticities.



# List of Acronyms

RES	Renewable Energy Sources
EU	European Union
NRES	Non-Renewable Energy Sources
CO <sub>2</sub>	Carbon Dioxide
CPI	Consumer Price Index
ENTSO-E	European Network of Transmission System Operators for Electricity
DUKES	Digest of United Kingdom Energy Statistics
ARDL	Autoregressive Distributed Lag
ECM	Error Correction Model
VIF	Variance Inflation Factor
FE	Fixed Effects
D-K	Driscoll and Kraay
FE D-K	Driscoll and Kraay estimator with fixed effects



# 1. Introduction

The study of the dynamics of electricity generation is fundamental for the purpose of analysing the circumstances of an energy transition. The European energy transition analysed is determined by the development of pro-environmental policies that are reaching for a cleaner energy system. The ecological plan is almost completely centred on the electrical power sector, shaped mainly by wind and solar, with the aim of removing the installed capacity of fossil fuels from Europe's power system (EEA, 2018; IEA, 2016). The complexity of any energy transition must take into consideration many factors. For example, central governments seek not to neglect economic sustainability during the move to renewables and give promises that the investments required will not increase household expenses (Agora Energiewende, 2019). Hence, to deduce the adequacy of the political measures and the amendments to the electricity framework, research focussed on the interactions and adjustments between electricity generation sources is needed. Analysing carbon dioxide (CO<sub>2</sub>) emissions from the various generation methods, together with a study of price stability, allows a firm response to accomplish a successful energy transition.

Beyond pollution mitigation, the increase in renewable energy sources (RES) in the EU (European Union) is seen as a response to promoting safety in electrical generation. With this in mind, nuclear power becomes a questionable source due to the potential of radioactivity exposure. The debate on the potential future disruption of nuclear energy in the EU has strengthened and had effects on the European Member States' energy policies (Aune et al., 2015; Deutsch, 2017). However, those in favour of nuclear energy put forward a different point of view. There remains a group of countries that charge nuclear power as an important energy base, claiming that dismissing the nuclear fleet could compromise the environmental targets they have pledged to the EU or even their economic sustainability (Aune et al., 2015). This being said, the electricity generated by nuclear plants is revealing a slightly continuous descent (Agora Energiewende and Sandbag, 2019). The decrease of the net generating capacity of nuclear power plants is made cautionary not to arouse price hikes and increases in CO<sub>2</sub> emissions (Knopf et al., 2014). Besides, the slow reduction comes from a technical ability from new features of nuclear plants that can be interrupted substantially to reduce the curtailment of renewables (Jenkins et al., 2018).

National electricity systems differ quite significantly around Europe, given the use of endogenous natural resources for electricity production. Thereupon, the impacts of the European central government adoptions on nuclear power in the context of renewable energy deployment, their consequences on the ecosystem, and consumer expenditures relative to the reference scenario became the incentive for this inquiry. Therefore, this research aims to analyse the economic competitiveness and the environmental sustainability of the energy transition, focusing on the compatibility of RES to replace fossil fuel installations, in a system that traditionally depends on nuclear power in Europe. The environmental analysis retains the sustainable feasibility by estimating the carbon intensity by electric source using data from Digest of United Kingdom Energy Statistics 2018 (DUKES) and evaluates the economic balance via observation of

the impacts from the diverse electric sources on the Harmonised Index of Consumer Prices (HICP).

The present literature already portrays the diversification of the electricity mix and its impact on economic activity comprehensively (Afonso et al., 2018; Antonio C Marques & Fuinhas, 2018; António Cardoso Marques et al., 2019). This research concentrates on the dynamics of the interaction among the various electricity sources. It turns out to be ground-breaking in terms of novelty and contributes in the following manner: (1) the effect that a particular source from the power generation system could have on consumer price range and (2) it presents empirical results through a framework predicated on panel data with a monthly data basis.

A brief mention of the structure of the research. The remaining paper is organized as follows: Section 2 presents a brief description of the European electricity generation systems, the evolution of the CO<sub>2</sub> emissions and latest records of price ranks; Section 3 covers the literature review; Section 4 presents the data collected; Section 5 describes the method and the models elected; Section 6 reveals the preliminary analysis of the data; Section 7 contains the results; Section 8 reports the discussion and in Section 9 the conclusions are given.

## **2. Overview of the electricity system, CO<sub>2</sub> emissions, and prices in Europe**

The European electricity system is designed through diversified sources of generation, formed by a set of fossil fuels facilities, mainly coal and gas, including a variety of RES, above all wind and solar, plus the nuclear fleet and a group of hydroelectricity components. The European electrical power output has experienced numerous amendments through the years, relied on economic prosperity, population growth, urbanization and green proposals. EU's environmental awareness made it reconsider the electrical composition, beginning to boost the installed capacity of RES while reducing the capacity of pollutant resources and implemented obligatory cuts on CO<sub>2</sub> emissions. Since European politics addressed the key primacies, the clean-energy transition progressed constantly increasing the incorporation of RES. The intensification of RES in the electric grid is forwarding in the proper direction, enhancing production's outages from coal plants and reducing the CO<sub>2</sub> flow, coupled with an increase of consumption for four consecutive years.

RES is described by the productive intermittence deriving from the weather conditions' dependence (e.g. wind and solar), and differently from traditional sources, its generation is unable to be adjusted accordingly to electricity demand (Hirth & Ziegenhagen, 2015). Thereby, the capacity expansion of irregular renewable electricity generation entails a complementary structure to balance the equilibrium between supply and demand. On the supply side, the potential structures are flexible plants proper to ramp up fast the generation. The flexible generation is usually handled by gas power plants, recognized as a fossil fuel-less pollutant with a quick ramping rate. The gas generation finds itself as an important part of European energy

reform and according to its transition fuel liability, electricity production by gas raised three years in a row until 2017.

Other flexible fundamental instruments to enable RES are energy storage on a large scale and the extension of the transmission's network (Lund, Lindgren, Mikkola, & Salpakari, 2015). Energy storage on the large scale is still a difficult process to assist the electric distribution, although, hydropower has an important weight in terms of storing capacity, even though, its electric non-pollutant production can fluctuate once in a while. The volatility of hydroelectricity is determined by its dependence on hydrology resources (mostly rainfall and running water). Its scarcity was noted in 2017, but despite this fact, hydropower is losing magnitude in the total of RES share. This loss of share by hydroelectricity stems from conflicts about ambient impacts, as disturbing natural habitats and land use. Confronting this scenario, public fundings and financial schemes are sponsoring the hydropower industry to improve its mechanisms to mitigate the negative effect on the ecosystem, maintaining the industry a vital piece of the European economy decarbonization. For its part, the extension of the transmission network converges on an upscale power interconnection with market liberalization prolonged for foreign countries favouring the load-following role, through a high-speed transmission infrastructure transporting electricity where it is more needed. Recently, the importance of the European interconnection is defined by the balance that electricity exchange creates in the occurrence of nuclear and coal outages and unfavourable hydropower conditions (European Commission, 2018; EEA, 2018).

The complementary structure and the implementation of brand new RES drives for considerable investments and costs, which it leads to the uncertainty of the general price level, since the changes in electricity production have a significant influence on the composition of the inflation rate (Przychodzen & Przychodzen, 2020). In times of an energy transition, economic stability has been taken care of with close attention over the cost of the progress to a low-carbon economy. These costs are formed mainly by the power source used, with the addition of government subsidies, policy industry regulation, merit-order effect<sup>1</sup>, CO<sub>2</sub> allowance prices and other levies. In the recent period, European energy reform tends to progress as the inflation movement tends to rise, also in line with the increase in electricity tariff (Eurostat, 2019; Eurostat, 2019).

### **3. Literature Review**

When looking at the actual structure of the European electrical system, carbon depletion is being enforced at a fast pace by the introduction of renewables. This theme is covered by a vast range of literature explaining the energy-pollution nexus. It transmits knowledge from the most general energy production/consumption (total primary energy) on the environmental impact, going through the discrimination between renewable and non-renewable energy sources (NRES)

---

<sup>1</sup> The merit order effect is a mode of classifying and ordering the available sources of energy, particularly in electrical generation. Based on lower price, electric plants that generate electricity at lower prices are the first to be called upon to supply power until demand is met.

until the decomposition of electricity production by sources and their sustainable management. This energy-centred literature also incorporates analysis studies on the dynamics of adaption of electric generation type, portraying the adjust of the loads supplied on an electrical power grid by the various sources, monitoring the frequency of the power grid, with consideration of the demand balance as well as the intermittency generation and overloads. Lastly, it consolidates an emphasis on the influence between energy and the consumer price index, prolonging to the electricity system and enriching the wisdom for the proposed study.

Throughout the existing literature, it is presented a relationship between CO<sub>2</sub> emissions and energy consumption, determining that energy consumption is responsible for the high intensity of carbon emissions (Andreoni & Galmarini, 2016; Rahman et al., 2016). This clear influence on environmental degradation demonstrates that these two factors should be studied using the same integrated framework, as indicated by Ang (2007). With this purpose, the energy-pollution nexus was studied in various parts of the globe, in various time horizons and using different empirical methods, with the conclusion of a positive impact from energy consumption to CO<sub>2</sub> emissions (Appiah, 2018; Bekun, Emir, & Sarkodie, 2019; Gorus & Aydin, 2019; Mirza & Kanwal, 2017). Stressing in the end, the dominance of fossil hydrocarbon fonts and the urgent necessity of RES progression.

The ecological approach on an energy basis has become an important method for measuring sustainable development targets. Recognizing this responsibility, literature spreads to empirical works that decompose the energy network in two distinct primary sources, renewable energy and non-renewable, regarding the ecosystem condition using CO<sub>2</sub> emissions as the variable observed. The literature encompasses satisfactory conclusions about the performance of RES on environmental changes mitigation (Chen, Wang, & Zhong, 2019; Dong, Sun, & Dong, 2018; Sharif, Raza, Ozturk, & Afshan, 2019) . The energy-pollution nexus extends further to the secondary energy, as an example of electricity. The attention retained by the electrification in the literature permitted the recognition of the RES electricity, revealing improvements on the environmental quality (Belaid & Youssef, 2017; Hdom, 2019).

The European zone is an example of an area with an increasing share of renewables being used in energy generation. Using this fact, certain surveys concentrate on the European power grid to identify the ecosystem improvement after resorting to RES (D Balsalobre-Lorente & Shahbaz, 2016; Bekun, Alola, & Sarkodie, 2019; Dogan & Seker, 2016) and similar results can be found in the electric system (Daniel Balsalobre-Lorente, Shahbaz, Roubaud, & Farhani, 2018; Bento & Moutinho, 2016). Nuclear power is a further source with relative weight in the European energy share. Its installed capacity increasingly turns out to be expressed in climate mitigation literature, affirming that nuclear energy has a beneficial function against pollution (Dong, Sun, Jiang, & Zeng, 2018; Jin & Kim, 2018; Lau, Choong, Ng, Liew, & Ching, 2019), and its benefits appear to be effective as well in the electric framework of European countries (António Cardoso Marques et al., 2019; António Cardoso Marques et al., 2016).

One guaranteed benefit from using RES is a reduction in CO<sub>2</sub> emissions; nevertheless, many inverse results are detectable from the studies carried out. No consensus on the impact between RES and CO<sub>2</sub> exists. Emissions differ too from the capacity of RES development and its intermittency support, eco-friendly ambition, and economic prosperity. Evidence which identifies a positive impact on environmental degradation from integrating RES are perceptible in Charfeddine and Kahia (2019), Chen, Zhao, et al. (2019), Apergis, Jebli, and Youssef (2018) and Khan, Ali, and Ashfaq (2018). Even in Europe, a region experiencing a high penetration of RES in the energy market, CO<sub>2</sub> emissions appear to be rising alongside the renewable exploitation, proved by Saint Akadiri, Alola, Akadiri, and Alola (2019) and Alola, Yalçiner, Alola, and Saint Akadiri (2019). Such results can be explained by the historical record of primary energy and RES consumption - both tend to grow at first - with RES incapable of accomplishing the apex demand by itself; this needs to become fulfilled with non-renewable energy sources (NRES) assistance.

The interaction of NRES with the adaption of new renewable energy is divergent in some cases. The reaction between the two suppliers is justified by policies taken according to the economies of the countries. One of these political decisions is the energy transition from NRES to RES, where a substitution effect is visible (Ito, 2017; Lin & Ankrah, 2019). Withal, the context of an energy transition from NRES toward RES is not a simple operation. The implementation of renewable technology requires a backup system to complement their variable production. Flexible plants are mainly composed of NRES, hence the positive interaction from RES to NRES capacity (Amri, 2017; Dogan, 2015; Furuoka, 2017). The occurrence of feedback interaction between RES and NRES is visible in the management of the power sector (Chen, Wang, et al., 2019; Kahia, Aïssa, & Lanouar, 2017; Sinha, Shahbaz, & Sengupta, 2018). The shared influence between distinct resources consumption can be explained by a division of function, for example, the partition of baseload role, as the demand energy raise, their generation rises too to provide. Although, the feedback behaviour can assume a negative effect between energetic sources (Al-mulali, Fereidouni, & Lee, 2014; Kahia, Aïssa, & Charfeddine, 2016; Salim, Hassan, & Shafiei, 2014), interpreted as a replacement of suppliers depending on the market changes.

When the literature heavily expands on RES and NRES in an aggregated form, some crucial points can be missed in the evaluation of the behaviour between them. An appraisal by disaggregating the generation sources can give a better vision of the interaction amid the technologies. Focusing on electricity generation, as markets progressively incorporate inconstant RES, this form facilitates the perception of how conventional energies can complement its failures through fossil fuels (António Cardoso Marques et al., 2019; António Cardoso Marques, Fuinhas, & Pereira, 2018) or even by another type of RES such as hydroelectricity (António Cardoso Marques, Fuinhas, & Menegaki, 2014), and how the new technology is replacing the functions of the fossil fleet (Antonio C Marques & Fuinhas, 2018; António Cardoso Marques et al., 2016). The incorporation of RES electricity in a power structure where nuclear power has a predominant share is a considerable challenge. Usually, nuclear plants are operated in the baseload mode at maximum rated capacity whenever online. This performance can hamper RES integration as both

have two common aspects: low-carbon and low generation costs. However, modern economies with innovative technology have shown unusual features of nuclear plants, that is, the ability to operate flexibly, with the compatibility of ramping or load following RES scarcity (Afonso et al., 2018; António Cardoso Marques et al., 2019; António Cardoso Marques et al., 2016). Despite this fact, nuclear power curtailment is usual nowadays induced by the introduction of more secure and reliable electricity; thereby the nuclear disruption is replaced by RES (Antonio C Marques & Fuinhas, 2018).

The energy shift towards clean technology comprises a new power structure and it disables the pollutant sources. These modifications have a sizeable cost and shouldn't be dissociated from environmental pollution analysis. One manner to measure the cost of the energy shift is to identify the potential impact of energy behaviour on price formation. A considerable number of studies already have an overall price rate coupled with energy variables in their econometric approach. Mostly because the debate focuses on the nexus amid total aggregate energy used and price fluctuations, and conditioned on the lack of cohesion in energy price data or their unavailability, academics have proxied energy prices using the Consumer Price Index (CPI) (Carfora, Pansini, & Scandurra, 2019; Murad, Alam, Noman, & Ozturk, 2019). An intended effect, as is interpreted by the environmental policies, is that increasing the penetration of RES results in cheap and plentiful energy with a negative effect on prices index (Campbell, 2018; Komal & Abbas, 2015), until it becomes a point of increased competitiveness and strengthens the economy. Regarding environmental degradation, Alola, Yalçiner, Alola, et al. (2019) and Alola, Yalçiner, and Alola (2019) pronounced a causality from CO<sub>2</sub> emissions to the inflation rate.

There is a gap in the literature about the relationship between the electricity sector and the consumer price index. Due to the lack of studies, the relationship of the different electricity process and price level is still not stabilized, furthermore undetermined with the desegregation of the electrical type. Divergent outcomes are notable, as a unidirectional impact from electricity consumption to CPI (Bekhet & bt Othman, 2011; Iyke & Odhiambo, 2014) or a unidirectional impact from CPI to electricity generation (Altıntas & Kum, 2013).

## **4. Data**

This research will depict the scenario of the electricity generation system in countries that are users of nuclear energy in the European Union with the addition of Switzerland, assessing the dynamics of interaction among various techniques of electricity production. It will take into consideration the influence and needs between the various energy sources, essentially RES which has characteristics of variable generation, as well as its adaption in an electrification plan normally pending for nuclear energy as baseload. With an additional concern about CO<sub>2</sub> emissions, the analysis will consider the environmental performance of each power source and pay special attention as to how the engagement of electricity providers affects consumer prices.

The countries elected to study are exposed in panel data. The management among electricity generation mix was tested in Spain, France, Germany, Belgium, Sweden, Netherlands, United Kingdom, Bulgaria, Romania, Hungary, Slovakia, Slovenia, Czech Republic, Finland, and Switzerland. Adding Switzerland was justified by his localization, in the centre of Europe, and although it is not a member of the European Union, it maintains close energy policy links with its European neighbours, having transmission systems interconnected with other countries in the region and has environmental projects funded in conjunction with EU.

Monthly data were used and the time range explored in the research was January of 2014 to December of 2018; the last date with data available when the data was extracted. Collecting monthly data has quite benefits to understand the regulation of the electric system, quoting the facility to improve short-term forecasts, the easy way to identify seasonality, further the detailed visualization of the effects from the unplanned events and scheduled maintenance. Using a monthly data basis also facilitates the assessment of markets to supports decision making, to reduce market volatility and ensure market stability as the markets struggle with uncertainty or unknowns events. Besides that, it provides an effective base for efficient policies to monitoring a country's ability to face disruption or effective decision-making facing the challenges of energy transition (IEA, 2019).

The variables included in the research are frequently applied in the literature. These variables are able to explain the operation of the electricity generation mix, sustainable conduct and the changes in the price level. For quantification of the electricity net generation, the variables chosen were fossil fuels net generation, nuclear net generation, hydro net generation, renewable net generation, and the balance of electricity exchange transformed into a ratio between electricity imports and exports. The data for electricity net generation by sources were obtained from the European Network of Transmission System Operators for Electricity (ENTSO-E). To value the general price level of goods and services, a specific consumer price index was selected, designated as HICP and the corresponding data were collected from Eurostat, which also included Switzerland's data in its database.

**Table 2.** Variable's definition and source.

Variable	Definition	Source
LFOSSIL	Electricity generated from fossil fuels (GWh).	ENTSO-E
LRES	Electricity generated from RES (GWh).	ENTSO-E
LHYDRO	Electricity generated from hydroelectricity (TWh) <sup>2</sup> .	ENTSO-E
LNUC	Electricity generated from nuclear plants (GWh).	ENTSO-E
LRXM	Rate of coverage of exports by imports.	Calculated through ENTSO-E
LHICP	Harmonised Index of Consumer Prices, all items (2015=100).	Eurostat
LCO <sub>2</sub>	Total of CO <sub>2</sub> emitted by electricity production (Mt/GWH).	Calculated through ENTSO-E and DUKES

Notes: All the variables are converted into natural logarithms.

Due to the difficulty to gather CO<sub>2</sub> data with monthly frequency, the criterion adopted was the multiplication of the electricity generated from the exerted electric technology in the time selected by its correspondent carbon intensity using the estimated data from DUKE's emissions factors for fuels. From fossil fuels, it was highlighted the lignite, coal, oil, and gas.

**Table 1.** Direct Emissions of CO<sub>2</sub> by Source.

Source	Tonnes CO <sub>2</sub> e/GWH
Coal	311,12
Oil	246,65
Gas	183,96
Lignite	323,26

Note: All sources are evaluated as gross calorific value.

The exclusion of oil shale, fossil peat, mixed fuels, and the non-renewable waste was justified by the missing data of the earlier months from the time-span designated. Renewables, hydro, nuclear electricity was not pointed out, these sources were reported as zero-emissions according to the Intergovernmental Panel on Climate Change (IPCC, 2014) carbon accounting guidelines. These conversion factors are presented as direct emissions from electricity generation and it is measured in Tonnes per GWH. Please consider, this process was previously practiced by Oliveira, Varum, and Botelho (2019), (Staffell, 2017) and Schlömer et al. (2014), confirming the viability of the emissions factors assessed through DUKES. The conversion factors are demonstrated in Table 1.

<sup>2</sup> The electricity generated from hydroelectricity was measured in TWh to facilitate the model specification.

**Table 3.** Summary statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
LFOSSIL	900	7.453234	1.566051	3.73767	10.55027
LRES	900	7.201383	1.433599	3.401197	9.954234
LHYDRO	900	0.7217266	0.6257861	0.0009995	2.166
LNUC	900	7.675033	1.149567	3.637586	10.68725
LRXM	900	0.9110931	0.7657372	0.0065253	3.565652
LHICP	900	4.626744	0.0186589	4.587006	4.689511
LCO <sub>2</sub>	900	0.5707082	0.5882422	0.0020297	2.424907
DLFOSSIL	885	-0.0013895	0.2389807	-1.427732	1.158321
DLRES	885	0.0175256	0.2383461	-0.8201923	3.051908
DLHYDRO	885	-0.0004525	0.1098688	-0.4436102	0.8018146
DLNUC	885	-0.0017162	0.2274579	-2.108617	1.386294
DLRXM	885	0.0031363	0.2819894	-1.796839	1.936341
DLHICP	885	0.0008291	0.0053153	-0.0390506	0.0309587
DLCO <sub>2</sub>	885	-0.0008791	0.0801002	-0.4835011	0.4191906

Notes: the operators “L” and “D” denote the natural logarithm and the first differences, respectively.

One value (1 unit) was added in all variables, with the approximation of 0 of some variables, their logarithmization could interfere erratically in the regression. The variables present in the research are in their respective logarithms (L) and first differences (D) and their description and summary statistics are presented in Tables 2 and 3.

## 5. Method and Model

The purpose of this research is an econometric view of the electric power progression for RES development in EU countries (plus Switzerland) where nuclear capacity has part of the electricity generation share. In light of dissecting the adjustment of supplies and the relationship between CO<sub>2</sub> emissions and the price index, the Autoregressive Distributed Lag (ARDL) model was chosen as the most suitable.

With an abundant number of observations, it is expected that the variables under study will have dynamic effects and different behaviours, so the characteristics and assumptions of the ARDL model revealed to be convenient for the case, as the model is useful for forecasting and distinguishing the long-run from short-run relationships. This model is also able to control endogeneity, as endogeneity is present in the variables because the electrical system is characterized by a supply-and-demand framework (Antonio C Marques & Fuinhas, 2018). The method is appropriate being indifferent to the order of integration of the variables in a model if the regressors are I(0), I(1) or a mixture of both unless if it is integrated stochastic trend of I(2) (Pesaran, Shin, & Smith, 2001) and being robust in the placement of variable dummies..

The ARDL model is being used for decades to model the relationship between variables, and it is gradually supported in the literature (Chen, Wang, et al., 2019; Dong, Sun, & Dong, 2018; Mirza & Kanwal, 2017). Its benefits are recommended by the ability to accommodate very general lag structures, can easily be extended to incorporate panel data, a great approach for small time-series samples (Pesaran, Shin, & Smith, 1999). It involves just a single-equation set-up, making it simple to implement and interpret, and both short- and long-run coefficients can be obtained at once. A general ARDL (p,q, q, ..., q) model is specified (Salim et al., 2014) as follows:

$$y_{it} = \sum_{j=1}^p \delta_i y_{i,t-j} + \sum_{j=0}^q \beta'_{ij} x_{i,t-j} + \varphi_i + e_{it} \quad (1)$$

where  $y_{it}$  is the dependent variable,  $(X'_{it})'$  is a  $k \times 1$  vector that is allowed to be purely I(0) or I(1) or cointegrated,  $\delta_{ij}$  is the coefficient of the lagged dependent variable,  $\beta_{ij}$  are  $k \times 1$  coefficient vectors,  $\varphi_i$  is the unit-specific fixed effects including the constant, trend and exogenous variables,  $i = 1, \dots, N$ ;  $t = 1, 2, \dots, T$ ;  $p, q$  are the optimal lag orders,  $e_{it}$  is the error term.

The ARDL model of the cointegrating vector is reparametrized into Error Correction Model (ECM). The reparametrized output offers the short-run dynamics (i.e. traditional ARDL) and the long-run relationships of the variables of a single model (Nkoro & Uko, 2016). The reparameterized ARDL (p,q, q, ..., q) model is specified as:

$$\Delta y_{it} = \theta_i (y_{i,t-1} - \lambda'_{i} x_{i,t}) + \sum_{j=1}^{p-1} \xi_{ij} \Delta y_{it-j} + \sum_{j=0}^{q-1} \beta'_{ij} \Delta x_{i,t-j} + \varphi_i + e_{it} \quad (2)$$

To meet the intended response, several models were designed with different dependent variables. To have a clear interpretation of the models, the various models are described with their dependent variables as follows (The software used in the econometric analysis was Stata 14 and EViews 9.5.):

- Model\_I- Fossil, with the dependent variable as the electricity production by fossil resources (DLFOSSIL);
- Model\_II- Renewable, with the dependent variable as the electricity production by RES (DLRES);
- Model\_III- Hydro, with the dependent variable as the electricity production by hydroelectricity (DLHYDRO);
- Model\_IV- Nuclear, with the dependent variable as the electricity production by nuclear plants (DLNUC);
- Model\_V- HICP, with the dependent variable as the Harmonised Index of Consumer Prices (DLHICP);
- Model\_VI- CO<sub>2</sub>, with the dependent variable as the CO<sub>2</sub> emissions by electricity system (DLCO<sub>2</sub>).

## 6. Preliminary analysis

A preliminary analysis of the data under study is fundamental for a thorough interpretation of the characteristics of all series, in order to conclude which is the most appropriate estimator for the models. The study in question is conducted through a panel data of 15 countries that have common guidelines, belonging to an economic and political union, and another country with socio-economic policy partnerships with the union. Therefore, these facts lead to questioning the existence of common shocks and unobserved distortions between the selected variables. Thus, diagnostic tests were applied to assess the presence of phenomena of collinearity, multicollinearity and cross-sectional dependence, which are usually singularities that occur in panel data. Also, to evaluate the stationarity of the series, the panel root unit tests were used. Meantime, Hausman tests carried out to assess econometric model specification, following a batch of specification tests to detect existence common violations as autocorrelation, cross-sectional dependence, and heteroskedasticity.

Regarding the cross-section dependence (Table 4), the dependence between the variables was verified, displaying significance levels between 1% and 10%, implying that any shock affecting one country in this study will also affect the remaining. Exceptionally, the LRXM variable shows no sectional dependency, but this absence is justified by the independent mode that the present countries commercially transit their electricity production.

**Table 4.** Cross section dependence.

Variables	CD-test	corr	abs(corr)
LFOSSIL	36.76***	0.463	0.489
LRES	53.15***	0.670	0.670
LHYDRO	18.13***	0.228	0.280
LNUC	13.29***	0.167	0.205
LRXM	-0.23	-0.003	0.216
LHICP	63.70***	0.803	0.803
LCO <sub>2</sub>	35.10 ***	0.442	0.357
DLFOSSIL	28.44 ***	0.361	0.369
DLRES	18.16***	0.231	0.258
DLHYDRO	10.33***	0.131	0.171
DLNUC	11.18***	0.142	0.177
DLRXM	-1.71*	-0.022	0.152
DLHICP	18.78 ***	0.239	0.309
DLCO <sub>2</sub>	27.44***	0.349	0.357

Note: \*\*\*, \*\*, \*, represents 1%, 5% and 10% of significance, respectively. Cross-section independence test has N (0,1) distribution, under the Ho: cross-section independence.

For the collinearity analysis, a correlation matrix of the variables was conceived and for the multicollinearity calculation, the variance inflation factor (VIF) was performed, which is represented in Tables 5 and 6. Interpreting the tables, only one relationship between variables

has unwanted values because their linear correlation coefficients are above 0.8, namely the linear relationship between the LFOSSIL / LCO<sub>2</sub> variables. Despite the last statement, by observing the VIF statistics, it is stated that the problem between LFOSSIL and LCO<sub>2</sub> is solved because the value amid them is less than 10 in both cases, concluding that collinearity is not a concern.

**Table 5.** Correlation matrix.

Variables	LFOSSIL	LRES	LHYDRO	LNUC	LRXM	LHICP	LCO <sub>2</sub>
LFOSSIL	1.0000						
LRES	0.5128	1.0000					
LHYDRO	-0.1436	0.5609	1.0000				
LNUC	0.2739	0.6359	0.6454	1.0000			
LRXM	0.1103	0.0155	-0.3465	-0.0794	1.0000		
LHICP	0.0533	0.1559	-0.0884	0.0635	0.1274	1.0000	
LCO <sub>2</sub>	0.9003	0.5945	0.0011	0.3207	0.0234	0.0158	1.0000

Variables	DLFOSSIL	DLRES	DLHYDRO	DLNUC	DLRXM	DLHICP	DLCO <sub>2</sub>
DLFOSSIL	1.0000						
DLRES	-0.1121	1.0000					
DLHYDRO	-0.1464	0.3365	1.0000				
DLNUC	0.0803	0.0623	-0.0566	1.0000			
DLRXM	0.0373	-0.1329	-0.0786	-0.2180	1.0000		
DLHICP	-0.0704	-0.0536	-0.0417	-0.0418	0.0004	1.0000	
DLCO <sub>2</sub>	0.7220	-0.1166	-0.2732	0.0632	-0.0015	-0.0705	1.0000

To verify the order of integration of variables the following panel root unit tests were performed, namely, Levin, Lin, and Chu (2002), Breitung (2005), Im, Pesaran, and Shin (2003), ADF-Fisher (Maddala & Wu, 1999) -Lin Chu (2002) and ADF-Choi (Choi, 2001), also designated as first-generation unit root tests. The results of the first-generation unit root tests are presented in Table 7, demonstrating that all variables seem to be borderline I(0)/I(1), except for LHICP that pointed out to be I(1), ascertaining that the series are not I(2). But, as the first-generation tests are not efficient for cross-sectional dependence between units, the evaluation of series integration was continued by the performance of the second-generation unit root test of the CIPS (Pesaran, 2007). This unit root test has the main advantage of being robust for heterogeneity and cross-sectional dependency. The outcome and the interpretation of the second-generation unit root test (Table 8) have similarities with the previous first-generation tests, the variables appear to be integrated in order of borderline I(0)/I(1), fortifying the former affirmation, the series are not integrated in order of I(2) and it sustains the execution of the ARDL approach.

**Table 6.** VIF statistics.

Variable	Model and dependent variable					
	Model_I- Fossil	Model_II- Renewable	Model_III- Hydro	Model_IV- Nuclear	Model_V- HICP	Model_VI- CO <sub>2</sub>
LFOSSIL	-	6.44	5.58	6.33	6.70	2.60
LRES	3.92	-	2.45	4.08	3.68	3.78
LHYDRO	3.61	2.61	-	3.13	3.98	4.35
LNUC	2.25	2.38	1.72	-	2.35	2.38
LRXM	1.34	1.20	1.07	1.31	1.34	1.31
LHICP	1.16	1.04	1.06	1.14	-	1.14
LCO <sub>2</sub>	2.46	5.87	6.35	6.33	6.25	-
Mean VIF	2.45	3.26	3.04	3.72	4.05	2.59
DLFOSSIL	-	2.11	2.11	2.12	2.13	1.04
DLRES	1.15	-	1.04	1.15	1.15	1.15
DLHYDR O	1.22	1.10	-	1.22	1.23	1.15
DLNUC	1.06	1.07	1.06	-	1.07	1.07
DLRXM	1.07	1.07	1.07	1.02	1.07	1.07
DLHICP	1.01	1.01	1.01	1.01	-	1.01
DLCO <sub>2</sub>	1.09	2.24	2.10	2.24	2.23	-
Mean VIF	1.10	1.43	1.40	1.46	1.48	1.08

Working with panel data with a substantial number of observations implies the use of methods that are able to manage the presence of individual-specific variation effects; hence, the following phase is to verify the finest estimator of the models through a test for model specification, specifically the Hausman test. The results of the Hausman test leads to the rejection of null hypothesis, presenting fixed effects (FE) as the most suitable estimator, for a more explicit way, the Hausman test exposed a statistically highly significant value (chi- square values are equal to 84.71, 54.43, 94.69, 265.76, 64.84 and 195.52 corresponding to the models Model\_I- Fossil, Model\_II- Renewable, Model\_III- Hydro, Model\_IV- Nuclear, Model\_V- HICP and Model\_VI- CO<sub>2</sub>), supporting the null hypothesis rejection by presenting the chi- square with a positive value of the Hausman test, as it should be.

**Table 7.** First generation unit root tests.

Variable	First generation unit root tests.								
	LLC		Breitung	IPS		ADF-Fisher		PP-Fisher	
	C	CT	CT	C	CT	C	CT	C	CT
LFOSSIL	-1.02704	-1.15125	-6.84222***	-10.9407***	-13.9057***	194.909***	229.179***	136.372***	103.568***
LRES	-2.44440***	-3.24588***	-5.55083***	-3.55818***	-7.02976***	66.9811***	118.596***	69.5482***	131.063***
LHYDRO	-5.58880***	-4.27978***	-6.06278***	-10.2000***	-6.06278***	166.324***	135.874***	128.837***	90.1276***
LNUC	-9.48301***	-8.33531***	-7.13268***	-16.0621***	-14.7995***	296.008***	248.040***	278.415***	233.630***
LRXM	-8.04601***	-8.68506***	-8.41576***	-9.57243***	-10.1510***	155.949***	160.417***	171.280***	173.306***
LHICP	3.68007	-1.26104*	3.40448	5.43464	1.08542	5.79586	26.1494	7.34647	32.5349
LCO <sub>2</sub>	-1.33209*	2.05969	-5.84853***	-11.8293***	-13.7193***	221.016***	235.849***	136.255***	102.045***
DLFOSSIL	-18.6530***	-17.2976***	-11.0535***	-25.6745***	-24.6913***	518.098***	450.062***	522.004***	457.481***
DLRES	-32.8805***	-31.6224***	-18.3377***	-31.3988***	-29.9995***	603.139***	523.233***	568.946***	509.832***
DLHYDRO	-26.8764***	-26.5238***	-13.6946***	-27.2073***	-26.4438***	542.109***	473.800***	550.798***	492.402***
DLNUC	-14.7023***	-7.19667***	-13.4410***	-28.7390***	-25.3897***	570.901***	471.740***	611.141***	556.755***
DLRXM	-29.2833***	-28.8323***	-18.8370***	-31.3004***	-30.8429***	624.415***	554.899***	627.718***	572.623***
DLHICP	-22.6506***	-15.8598***	-13.6553***	-23.6073***	-34.4085***	429.260***	419.633***	565.635***	469.295***
DLCO <sub>2</sub>	-14.2836***	-12.8100***	-10.5470***	-25.2727***	-24.2632***	511.709***	445.021***	529.881***	462.657***

Note: \*\*\*, \*\* and \* represent significant level for 1%, 5% and 10%, respectively. LLC means for Levin-Lin-Chu test (2002), Breitung mean for Breitung test (2005), IPS mean for Im Pesaran Shin test (2003) ADF-Fisher and PP-Fisher mean for Fisher type test using Augmented Dickey-Fuller and Phillips-Peron test (Maddala and Wu, 1999; Choi, 2001), correspondingly. CT stands for constant and trend; C stands for constant. The null hypotheses are as follows. Levin-Lin-Chu and Breitung: panels contain unit root; Im-Pesaran-Shin: All panels contain unit root; ADF-Fisher and PP-Fisher: Unit root (individual unit root process); Probabilities for Fisher tests are computed using na asymptotic Chi-square distribution. All other tests assume asymptotic normality. The tests were performed using the EViews 9.5 software.

Upon completion of the Hausman test proving the existence of fixed effects on the models, further tests are performed to observe the characteristics of the models. The quality and characteristics of the models were evaluated through a battery of diagnostic tests, specifically designed to test if common violations occur such as autocorrelation, cross-sectional dependence, and heteroskedasticity. These tests are useful to obtain additional information conducive to select the most suitable FE estimator. The executed tests were the Modified test Wald, the Pesaran, Frees and Friedman test, the Breusch-Pagan Lagrangian multiplier test, and lastly, the Wooldridge. Note that the Breusch-Pagan Lagrangian multiplier test was not used to test heteroscedasticity. The detailed results are presented in Table 9.

**Table 8.** Second generation unit test root.

Variable	Second generation unit root tests.	
	CIPS ( $Z_t$ -bar)	
	no trend	with trend
LFOSSIL	-9.128***	-9.170***
LRES	-8.027***	-6.325***
LHYDRO	-8.389***	-6.717***
LNUC	-11.466***	-10.352***
LRXM	-8.027***	-6.958***
LHICP	-1.663**	-5.865***
LCO <sub>2</sub>	-7.800***	-7.536***
DLFOSSIL	-18.070***	-17.457***
DLRES	-16.830***	-15.948***
DLHYDRO	-17.144***	-16.462***
DLNUC	-18.355***	-17.956***
DLRXM	-18.088***	-17.565***
DLHICP	-17.180***	-16.536***
DLCO <sub>2</sub>	-17.899***	-17.334***

Notes: \*\*\*, \*\*, \* denote significance of 1%, 5% and 10%, respectively. The hypothesis (H<sub>0</sub>) is Pesaran (2007) panel unit root test (CIPS): the series are I (1). For the test performed, only 1 lag was included.

The results of Table 9 reject the null hypothesis of the modified Wald test for all models, concluding that there is heteroscedasticity of the residues. The Pesaran test is not significant on Model\_I- Fossil and Model\_VI- CO<sub>2</sub>, but the Friedman test, as well as the Frees test, which, they have a similar function to the Pesaran test, demonstrated that there is cross-section dependence, the same output is observed in the other models, thus, there is a contemporary correlation. Wooldridge tests show to be significant on all models, indicating the existence of the first-order autocorrelation on all studied models. The Breusch-Pagan LM test has failed on Model\_V- HICP due to the correlation matrix

of residuals being singular, nevertheless, the test stated that the residues are correlated for the remaining models.

**Table 9.** Specification test.

	Model and dependent variable					
	Model_I- Fossil	Model_II- Renewable	Model_III- Hydro	Model_IV- Nuclear	Model_V- HICP	Model_VI- CO <sub>2</sub>
Wooldridge test	23.104***	22.375***	12.897***	26.335***	20.984***	59.048***
Pesaran test	-0.122	14.037***	6.519***	7.075***	14.843***	-0.613
Friedman test	57.220***	162.594***	117.859***	145.943***	229.333***	50.041***
Frees test	1.262***	0.508***	0.321***	0.228***	0.987***	1.045***
Modified Wald test	11754.89***	184.72***	2487.84***	519.94***	484.54***	3212.53***
Breusch- Pagan LM test	541.990***	536.581***	237.787***	207.271***	-	483.894***

Notes: \*\*\*, \*\* and \* denote significance of 1%, 5% and 10%, respectively. Wald test H<sub>0</sub>:  $\sigma^2(i)$  for all i; Pesaran / Friedman/ Frees test H<sub>0</sub>: residues are not correlated; Breusch-Pagan test LM H<sub>0</sub>: the residuals are not correlated; Wooldridge test H<sub>0</sub>: there is no automatic first order correlation.

The previous tests prove that the regression model's assumptions were violated, but they can be explained by the political structure of the selected countries and by the origin of the electrical production. This group of countries shares common energetic implementations namely mutual environmental objectives, and also, they divide the same electric grid, the synchronous grid of Continental Europe, so it's justifiable the presence of cross-section dependence. Given the nature of electricity generation management, which works through consumption forecasting and market expectations, the system is characterized by using the memory of the past to predict the consumption to ensure the efficiency of productive activity and readjustment of prices. Therefore, it is visible the degree of similarity between the values in the data of the same variables over successive time intervals, confirming the existence of autocorrelation. Also, it was affirmed the exhibition of heteroskedasticity, whereby countries demonstrate the exploration of endogenous resources for their energy sustainability and then such energy sources have identifiable seasonal inconsistency corresponding to the wind and solar fonts, which will be a result of variability in the respective data about the different technologies used.

Therefore, having noticed the existence of heteroskedasticity, cross-section dependence, and autocorrelation first order in the diagnostic tests, and in such manner to certify the veracity of the statistical models and recognizing the characteristics of the data, the chosen estimator was Driscoll and Kraay (1998). Driscoll-Kraay standard errors

estimator proved to be the most suitable because it presents particularities to deal with model errors (Fuinhas, Marques, & Couto, 2015; Hoechle, 2007), performing a nonparametric covariance matrix estimator that produces heteroskedasticity and autocorrelation consistent standard errors that are robust to features of cross-sectional and temporal dependence and remaining robust in the inclusion of variable dummies in the regression (Vogelsang, 2012).

## 7. Results

A gentle reminder about how the data was constructed and its intention. It should be emphasized that the observations were collected in monthly frequency. The fossil fuel electricity sources, as also the renewable electricity sources were compiled in an aggregated form, having a special attention to not develop an unbalanced panel data considering the different electricity production's characteristics of the selected countries. The CO<sub>2</sub> emissions are calculated directly through the available data of disaggregated fossil sources during the time- span explored. It is important to consider too the use of HICP and its involvement with the different nature of electricity production, which is a recent point of view in the literature.

Due to the data frequency and its features, the presence of disturbances was expected. A visual inspection of the series was carried out, following with unit root tests with structural break, specifically, the Zivot and Andrews (2002) and Phillips and Perron (1988) unit root tests, to discern the breaks and outliers surrounding the time length selected. The unit root tests with structural break were performed, individually, in the respective series and countries that the visual monitoring implied the existence of disorders, to be more precise, these tests were held responsible for robustness proof from the correlograms analysis and to consider the appropriate procedure to control such disorders and to estimate a trustworthy model. This method is suggested by Hamdi, Sbia, and Shahbaz (2014) and Antonio C Marques and Fuinhas (2018), since the unit root tests with structural break is capable of detecting the presence of a break and to indicate the exact time that arises. Please kindly note that the unit root tests with structural break did not distort the order of integration of the series contested in the previous unit roots tests and the selected methodology. The Zivot and Andrews (2002) and Phillips and Perron (1988) unit root tests with structural break are exhibited in Table 10 and 11.

The visual inspection and the unit root tests with structural break of the series revealed instabilities during the period selected. The instabilities coincided with the price oscillations and seasonal variation in the electricity supply. Therefore, "one-zero" dummies (impulse dummies) were included to control viewed breaks and outliers. These dummies variables were applied as moderately as possible, although, this assay appraises an energy system transition, thus, the structural changes are presumed to be various.

The visual and empirical scrutiny of the series revealed that disturbances were matching with the additional taxes levied in Switzerland. Taxation implemented on heating and process fossil fuels and CO<sub>2</sub> emitted, which entails a production's drop, coinciding also a peak recorded by RES where it had to fill the electrical supply spotted in July 2016, then, the shifts dummies on Model\_I- Fossil and Model\_II- Renewable has been employed to control this effect, enumerated as CH2016M07. But even though it is observed a drop in fossil generation and an outlier in RES, the CO<sub>2</sub> emissions raised as a consequence of an increase from the total electricity supply due to the high rate of immigration, heatwaves, and the CO<sub>2</sub> emitted by the electrical infrastructure of support to RES exploitation this break-point was reiterated by Zivot and Andrews, and Perron's tests, for this reason, the code CH2016M07 additionally capture this effect.

**Table 10.** Zivot and Andrews (1992) unit root test with structural break by country.

Variables	Zivot and Andrews (1992) unit root test with structural breaks.					
	Intercept		Trend		Intercept and Trend	
	t-Statistics	Break	t-Statistics	Break	t-Statistics	Break
LFOSSIL(CH)	-8.760076***	2016M07	-2.812242	2017M06	-10.33509***	2016M07
DLFOSSIL(CH)	-8.791046***	2016M09	-8.199124***	2016M08	-8.921258***	2016M09
LFOSSIL(SI)	-5.380420***	2017M04	-5.265762***	2017M01	-5.510647**	2017M04
DLFOSSIL(SI)	-5.934852***	2017M02	-5.644202***	2018M03	-6.064996***	2018M03
LFOSSIL(SK)	-5.242073**	2018M02	-5.175798***	2017M09	-5.879598***	2017M08
DLFOSSIL(SK)	-10.27748***	2017M09	-	-	-10.34631	2017M09
LRES(CH)	-16.08842***	2016M07	-2.919943	2017M07	-16.58115***	2016M07
DLRES(CH)	-8.607134***	2016M09	-8.229821***	2016M08	-8.694657***	2016M09
LRES(GB)	-5.402441***	2015M11	-6.234484***	2016M05	-6.651947***	2015M11
DLRES(GB)	-5.049140	2016M03	-4.927912***	2018M03	-4.883130	2018M02
LHYDRO(ES)	-6.167896***	2018M03	-5.821216***	2017M11	-6.467528***	2017M04
DLHYDRO(ES)	-5.177418**	2016M06	-	-	-5.327119**	2017M12
LHYDRO(FI)	-4.293878	2015M02	-4.062821	2015M07	-	-
DLHYDRO(FI)	-	-	-8.887428***	2014M12	-9.137917***	2015M06
LNUC(NL)	-6.523146***	2017M04	-6.420937***	2016M04	-6.448692***	2017M04
DLNUC(NL)	-4.404585	2017M08	-4.182695	2017M07	-4.399743	2018M03
LHICP(RO)	-3.475007	2015M06	-4.157128	2017M03	-4.259559	2016M02
DLHICP(RO)	-10.45058***	2015M06	-10.02960***	2015M07	-10.35447***	2015M06
LCO <sub>2</sub> (CH)	-7.157372***	2016M07	-3.295819	2017M06	-8.845149***	2016M07
DLCO <sub>2</sub> (CH)	-8.607134***	2016M09	-8.229821***	2016M08	-8.694657***	2016M09
LCO <sub>2</sub> (SK)	-5.728585***	2015M06	-5.621479***	2016M10	-5.793074***	2015M05
DLCO <sub>2</sub> (SK)	-7.310117***	2017M02	-	-	-	-

Note: \* denotes significance at 1%. The null hypothesis is that the series has a unit root with a structural break in intercept, in trend or in intercept and trend. The test was performed with a maximum lag length of 4. The respective country of the series is shown in parenthesis by the country's abbreviation. (-) due to the near singular matrix error. The tests were performed using the EVIEWS 9.5 software.

The outlier observed in October of 2014 from the United Kingdom regarding the use of RES is the result of increasing the low carbon electricity's share of generation due to falls in nuclear output, and lower production of both coal and oil, in a similar manner, Perron's test stress this date with a structural break. Further, the extreme value reported on hydropower noticed in January of 2018 from Finland is caused by the abundance of rainy days leading to a peak of generation capacity captured from hydropower. In both cases, the shift dummies used in Model\_II- Renewable and Model\_III- Hydro to regulate this impact, respectively identified as GB2014M10 and FI2018M01.

**Table 11.** Phillips and Perron (1988) unit root test with structural break by country.

Variables	Phillips and Perron's (1992) unit root test with structural breaks.					
	Intercept		Trend		Intercept and Trend	
	t-Statistics	Break	t-Statistics	Break	t-Statistics	Break
LFOSSIL(CH)	-9.190511***	2016M06	-2.807271	2017M08	-10.51475***	2016M06
DLFOSSIL(CH)	-15.45390***	2016M07	-8.403555***	2016M07	-15.05742***	2016M07
LFOSSIL(SI)	-5.369025***	2017M03	-5.349779***	2016M12	-6.030466**	2018M03
DLFOSSIL(SI)	-5.919124**	2017M01	-5.843078	2014M12	-6.239994**	2018M03
LFOSSIL(SK)	-9.011596***	2017M08	-5.025195**	2017M10	-8.224382***	2017M08
DLFOSSIL(SK)	-13.07462***	2017M08	-10.19412***	2014M10	-13.60839***	2017M08
LRES(CH)	-15.93959***	2016M06	-2.928739	2017M08	-16.45630***	2016M06
DLRES(CH)	-18.82325***	2016M07	-8.430424***	2016M07	-18.30061***	2016M07
LRES(GB)	-5.355694**	2015M10	-5.180174**	2016M06	-6.681948***	2015M10
DLRES(GB)	-12.23255***	2015M11	-13.05416***	2014M10	-13.42383***	2015M02
LHYDRO(ES)	-6.105029***	2018M02	-5.636018***	2017M09	-6.331805***	2017M03
DLHYDRO(ES)	-5.125530*	2018M03	-4.814283*	2017M07	-5.230599	2017M11
LHYDRO(FI)	-4.293077***	2015M02	-4.086680	2015M08	-4.128517	2014M10
DLHYDRO(FI)	-9.181602***	2015M05	-9.16644***	2014M12	-9.195163***	2015M05
LNUC(NL)	-6.541768***	2018M03	-6.602385***	2016M05	-6.585749***	2017M06
DLNUC(NL)	-11.12763***	2015M05	-11.17882***	2018M02	-11.02274***	2015M05
LHICP(RO)	-3.977402	2017M09	-5.026159**	2017M03	-6.242640**	2016M01
DLHICP(RO)	-11.87867***	2016M01	-10.29247***	2015M08	-12.19452***	2016M01
LCO <sub>2</sub> (CH)	-7.344556***	2016M06	-3.305777	2017M07	-8.840356***	2016M06
DLCO <sub>2</sub> (CH)	-18.82325***	2016M07	-8.430424***	2016M07	-18.30061***	2016M07
LCO <sub>2</sub> (SK)	-6.378263***	2017M09	-5.635205***	2017M10	-6.314289***	2017M09
DLCO <sub>2</sub> (SK)	-7.257870***	2017M01	-7.329038***	2014M10	-7.639613***	2014M12

Note: \*\*\*, \*\*, \* denotes significance at 1, 5 and 10%, respectively. The null hypothesis is that the series has a unit root with a structural break in intercept, in trend or in intercept and trend. The test was performed with a maximum lag length of 4. The respective country of the series is shown in parenthesis by the country's abbreviation. The tests were performed using the EViews 9.5 software.

An increase of CO<sub>2</sub> emitted, and fossil electricity production can be visually observed from Slovakia in August and September 2017, because in 2017, Slovakia still has less than 10% of their electricity production from RES, and their electricity consumption exceeded the historical level this year. Then, a rise of CO<sub>2</sub> emissions and fossil generation was captured in August and September, as well as Zivot and Andrews and Perrons's tests highlighted this breaking-point close

and inside to the date, consequently, one-zero dummies (SK2017M08 and SK2017M09) were included. In Slovenia, the electric production delivered by the fossil fuels installed capacity signalized a high performance in July 2018, coinciding with the Slovenian government's support payments for electricity from fossil cogeneration, and also according to a generation climax from lignite facilities. The dummy SI2018M07 was designed to regulate this outlier.

In Spain, the very low rainfall registered in February 2014 made it difficult the maintenance of the regular levels of hydropower, further, the only nuclear plant of Netherlands had its production reduced to the integration of new wind power capacity June 2017 and May 2018, this nuclear generation's breaks also were pointed out near and within the date by Zivot and Andrews, Perron's tests. The inclusion of dummies encoded as NL2017M06 and NL2018M05 capture the favorable windy months, and ES2014M02 controls the effect of dry weather. Moreover, nuclear power also had a break visible in all countries, it stumbled during the August 2018 heatwave, influenced by solar outperform, ALL2018M08 was created to adjust this effect.

Deflation was noted in the HICP series through partial correlogram and Zivot and Andrews and Perron's tests, this occurrence took place in Romania during three consecutive months, the fall of prices was recorded in December 2015, January 2016 and February 2016 and it was tended by the drop of food prices, energy prices and continuous taxes cuts. The dummies identified as RO2015M12, RO2016M01, and RO2016M02 capture the impact of deflation. Another fall in prices was registered in January 2018, corresponding to the EU area, a decrease of monthly rate about 0.7%, liable by the decrease in energy prices and unprocessed food, the dummy denoted as ALL2018M01 was created to control this deflation effect.

Mostly, the results demonstrate coherence according to the actual literature and consonant with the characteristics of the European electricity system and its reform. The coefficients of the variables, in first differences, state for the short-run, and they shall be interpreted as semi-elasticities. In the long-run, the estimated coefficients were used to compute the elasticities, by dividing them by the coefficient of the ECM and then multiplying by -1. The ARDL estimated results are shown in Table 12, and the semi- elasticities and elasticities are shown in Table 13.

All the estimations displayed a negative and highly statistically significant speed of adjustment (ECM), more specifically, they revealed a medium and a low speed of adjustment for all the models, with the highest speed of adjustment belonging to Model\_IV- Nuclear. The weak value of the ECM from Model\_III- Hydro can be explained by the structural changes that hydroelectricity was faced in the analyzed period. This slowness marks the hydropower's function as a baseload source, but aside from this, it also marks the hydrology dependency that hydropower is related. The time length under view is noted by the scarcity of hydrology resources, formed by the continuous dry weather, heatwaves, and lack of precipitation that Europe confronted. Additionally, the ECM revealed a long-run relationship among the variables. Solely the Model\_I-Fossil has the reference values corresponding to the model's characteristics, in other words, the

option with no unrestricted intercept and no unrestricted trend was practiced. The critical values of the Model\_II- Renewable and Model\_V- HICP was extracted with the option with unrestricted intercept and unrestricted trend, in turn of the Model\_III- Hydro, it was employed with the unrestricted trend and no intercept, and lastly, in the Model\_IV- Nuclear and Model\_VI- CO<sub>2</sub>, the option with intercept and no trend was applied in both.

Regarding the empirical results from the dynamic interactions of electricity sources, in Model\_I- Fossil, semi-elasticities disclosed that RES has a positive impact on electricity generation by fossil fuels, however, in the long- run the substitution effect has been observed from RES to fossil fuel generation. Still in Model\_I- Fossil, open the borders for electricity transition increase fossil sources exploitation, since the LRXM has a positive impact on fossil generation, in both in the short and long- run. Nonetheless, open electricity trade deploys renewables progression in the long-term. The Model\_III- Hydro indicates that RES has a positive effect on hydroelectricity, signal established in semi- elasticities, and in elasticities. Regarding this, further, RES and hydroelectricity generation have a positive feedback effect in the short- run. Hydroelectricity also shares a feedback effect with nuclear power in the short- run, but with a negative signal, being substitutes technologies to each other. In Model\_IV- Nuclear a positive effect is visible and is detected from RES to nuclear power, in the short- run, however, this relevance is neutral in the long- run. Furthermore, LRXM has a short and long-run negative impact on nuclear power.

**Table 12.** Estimated results.

Variables	Model and dependent variable					
	Model_I- Fossil	Model_II- Renewable	Model_III- Hydro	Model_IV- Nuclear	Model_V- HICP	Model_VI- CO <sub>2</sub>
	FE D-K	FE D-K	FE D-K	FE D-K	FE D-K	FE D-K
DLFOSSIL	-	-	0.0684067***	0.1367121***	-	0.2479064***
DLRES	0.0410019**	-	0.1342335***	0.0773873**	-	-
DLHYDRO	0.1132716***	0.665767***	-	-0.209989***	-	-0.1238371***
DLNUC	0.0816137***	0.0795461*	-0.0488064***	-	-	-0.0203025***
DLHICP	-	-2.363272*	-	-	-	-0.5247651*
DLCO <sub>2</sub>	2.18405***	-	-0.5021044***	-0.2880169**	-0.0068177**	-
DLRXM	0.0543134***	-	-0.0348043***	-0.1765328***	-	-0.0164039**
LFOSSIL(-1)	0.2063273***	-	0.0717624***	0.1241714***	0.0012627**	0.0735867***
LRES(-1)	-0.026862**	-0.1294087***	0.0294186***	-	-0.0007085*	0.0067098***
LHYDRO(-1)	-	-	-0.0696179***	-0.0337419***	0.0004898*	-0.0162047***
LNUC(-1)	0.0726658**	0.0831708*	-	-0.6145303***	0.0016862*	-0.0312178***
LHICP(-1)	-	-2.749119***	-	-	-0.1260147***	-0.3058612***
LCO <sub>2</sub> (-1)	0.4587141***	-	-0.2033862***	-0.1815175**	-0.0055621***	-0.2985949***
LRXM(-1)	0.0685816***	0.0326718**	-0.0365904***	-0.1489396***	-	-0.0270804***
C	-	10.86207***	-	5.846061***	0.5031182***	1.277336***
TREND	-	0.0050598***	-0.0010797**	-	0.0001479***	-
Time Dummies						
ES2014M02	-	-	-0.1653724***	-	-	-
GB2014M10	-	0.9788116***	-	-	-	-
RO2015M12	-	-	-	-	-0.0024934***	-
RO2016M01	-	-	-	-	-0.007558***	-
RO2016M02	-	-	-	-	-0.007558***	-
CH2016M07	-1.373867***	2.907305***	-	-	-	0.3385266***
NL2017M06	-	-	-	-0.6604076***	-	-
SK2017M08	-	-	-	-	-	0.3206141***
SK2017M09	0.9547399***	-	-	-	-	-
FI2018M01	-	-	0.083128***	-	-	-
ALL2018M01	-	-	-	-	-0.0045783***	-
NL2018M05	-	-	-	-1.146011***	-	-
SI2018M07	0.7006836***	-	-	-	-	-
ALL2018M08	-	-	-	-0.1228813***	-	-

Note: \*\*\*, \*\*, \* denotes significance at 1, 5 and 10%, respectively. 'CH', 'ES', 'GB', 'NL', 'RO', 'SI' and 'SK' denotes a dummy variable for a specific country by the country's abbreviation and 'ALL' denotes a dummy variable for all countries. 'FE D-K' means the use of Driscoll and Kraay estimator with fixed effects.

In terms of the impacts on overall prices from electricity suppliers, relating the Model\_V-HICP, the results reveal that fossil, hydro, and RES generation have relevance on consumer prices (long- run). In their turn, fossil and hydroelectricity sources have a positive impact on price formation, while in the case of RES a negative effect on price range appears. With concern to CO<sub>2</sub> emissions by electricity sources, in Model\_VI- CO<sub>2</sub>, the semi- elasticities reveal consistency with the environmental theory. Fossil fuels have a positive impact on CO<sub>2</sub> emissions, nuclear power and hydroelectricity decrease the development of this pollutant gas. In contrast, RES show to be neutral concerning CO<sub>2</sub> production. About the long-run impacts: CO<sub>2</sub> emissions are still reduced with the use of hydroelectricity and nuclear power. On the other hand, RES and fossil electricity production raise the CO<sub>2</sub> emissions.

**Table 13.** Semi- elasticities and elasticities.

Variables	Model and dependent variable					
	Model_I- Fossil	Model_II- Renewable	Model_III- Hydro	Model_IV- Nuclear	Model_V- HICP	Model_VI- CO <sub>2</sub>
	FE D-K	FE D-K	FE D-K	FE D-K	FE D-K	FE D-K
DLFOSSIL	-	-	0.0684067***	0.1367121***	-	0.2479064***
DLRES	0.0410019**	-	0.1342335***	0.0773873**	-	-
DLHYDRO	0.1132716***	0.665767***	-	-0.209989***	-	-0.1238371***
DLNUC	0.0816137***	0.0795461*	-0.0488064***	-	-	0.0203025***
DLHICP	-	-2.363272*	-	-	-	-0.5247651*
DLCO <sub>2</sub>	2.18405***	-	-0.5021044***	-0.2880169**	-0.0068177**	-
DLRXM	0.0543134***	-	-	-0.1765328***	-	-0.0164039**
LFOSSIL(-1)	-	-	1.030805***	0.2020591***	0.0100203**	0.2464431***
LRES(-1)	-0.1301914**	-	0.4225728***	-	-0.0056225**	0.0224714***
LHYDRO(-1)	-	-	-	0.0549068***	0.0038872*	-0.05427***
LNUC(-1)	0.3521871**	0.6426986**	-	-	-	-0.104549***
LHICP(-1)	-	-21.24371***	-	-	-	-1.024335***
LCO <sub>2</sub> (-1)	2.223235***	-	-2.921465***	-0.2953759**	0.0441385***	-
LRXM(-1)	0.3323922***	0.25247**	-0.5255894***	-0.2423633***	-	0.0906926***
ECM	0.2590319***	0.1294087***	0.0696179***	0.6145303***	0.1260147***	0.2985949***

Note: \*\*\*, \*\*, \* denotes significance at 1, 5 and 10%, respectively. 'FE D-K' means the use of Driscoll and Kraay estimator with fixed effects.

Four other observations to note, with reference to Model\_IV- Nuclear presented along with the highest speed adjustment, this parameter expresses how fast nuclear power reaches the equilibrium. The second point is the positive feedback effect shared between fossil fuel generation and nuclear power (short and long- run), as well as the two-way causality between hydroelectricity and fossil production in the short-term (third point). The last observation refers to the positive coefficient from RES to all other sources, in the short-term, exemplifying the contribution from

other sources to integrate RES in the electric system. The interpretation and discussion of the results will be mentioned in Section 8.

## **8. Discussion**

In this dissertation, an analysis was carried out of the dynamics of the interaction between electricity sources, their effect on pricing, and CO<sub>2</sub> emissions in nuclear power generating EU countries, plus Switzerland. This case provides an interesting assessment of the energy transition that is being carried out toward nuclear and coal phase-out and the deployment of RES. In addition, there is a focus on nuclear power performance, assessing its adequacy for the integration of new technology.

The advance of RES structures has required complementation from other sources to support their intermittency or to collaborate along with the variability of demand. This regression has shown that hydroelectric systems seem to be an important mechanism in supporting RES. An identical feedback effect was already mentioned by António Cardoso Marques et al. (2014). The backup role is supported by fossil fuels (namely gas) as well, and by the opening of the cross-borders for electricity transportation. The last affirmation is a clear objective for the EU, and it is archivable in the long-run, even though, the electricity services across borders propagate fossil electricity production (short and long- run). It seems that the ramp-up role required by commercial electricity transition is filled up by gas fuel.

Nuclear plants are backing up RES in the short run, but in the long run, this effect disappears, although its ability to work claims flexibly by the ECM model. Having as a reference, some of the selected countries were already investigated in an individual time series study and presented the equivalent backup function from nuclear generation to RES (Afonso et al., 2018; Antonio C Marques & Fuinhas, 2018; António Cardoso Marques et al., 2019; António Cardoso Marques et al., 2016). Nuclear sources are one of the lowest emitters of CO<sub>2</sub> available to generate electricity, and this property has been proven in this paper. Nonetheless, nuclear power has other positive sides (Jenkins et al., 2018) as it is capable of diminishing the dependence on fossil fuels. For that reasons it is one of the main options to baseload the electricity system. The baseload function by the nuclear plant still dominant alongside fossil fuels, confirmed through the feedback impact share among the sources, furthermore, nuclear generation appears to be a multi-task electric source able to run in baseload, load-following and backup function.

The energy transition towards RES enforcement diminishes living costs due to the low operation cost of RES, and the sequence of electricity supply with lower prices by merit order. However, the backup role played by hydroelectricity and fossil fuels raises inflation. The positive effect of hydroelectricity on inflation is the response to high incentives and investments for hydrology infrastructures imposed by the EU or the respective governments to improve its ecological status. Fossil generation also develops higher prices, mainly caused by the gradual rise of carbon taxation and fossil fuel levies to promote the obligation of no use of NRES. Implying the

late statement, the introduction of natural gas plants in the electricity mix for the flexible generation to manage the scarcity of the RES, as well as, base loading with fossil fuels signifies a pricier life and more CO<sub>2</sub> emitted into the environment. Apart from that, the substitution effect is visible from RES to fossil electricity in the long- term, confirming the plausible EU's pathway of climate change mitigation.

Although the regression claims that RES exploitation forces the electric system to emit CO<sub>2</sub>, this indication is not new in the literature; a similar outcome is legible in Charfeddine and Kahia (2019) and Chen, Zhao, et al. (2019) but also it is possible to find this empirical evidence from Europe (Alola, Yalçiner, Alola, et al., 2019; Saint Akadiri et al., 2019), even with the remarkable work against environmental degradation. In this case, such a fact is established from the trend for a large demand for electricity consumption in Europe (Agora Energiewende and Sandbag, 2019); a consequence of a high rate of immigration (OECD, 2019), high rate of tourism (UNWTO, 2018), extreme seasonal values of temperature (Hu, Huang, & Cherubini, 2019) and constant economic converge (Vaughan-Whitehead & Vazquez-Alvarez, 2019). As Europe is facing a ramp-up of electricity consumption, the inefficiency of RES to supply high electricity consumption demand, the lack of adequate storage technology and the backing up with pollutant sources (natural gas supplies) are the reasons why RES and CO<sub>2</sub> increase simultaneously.

EU's nuclear plants generated around 25.5 % of the electricity produced in the EU in 2018, at the same time, RES achieved 32.3 % share of electricity generation (Agora Energiewende and Sandbag, 2019). In this context, it is visualized a fast integration of new low-carbon technology on the electric grid, outperforming a long- date dominant source. The order of adjustment amid them requires a close observation on their characteristics and their influence on each other. The two electric fonts are no-CO<sub>2</sub> emitters on their generation, collectively can attain sustainable energy goals, nevertheless, nuclear power remains a questionable source in public opinion. Nuclear power outages are common in the EU and it was been proven in this investigation that hydropower can replace nuclear generation, as well the international trade of electricity. The use of HICP in the regression went to be appropriate to aware of the costs of carbon monoxide mitigation, but also it affirmed that a low and stable inflation rate improves the wealth of an economy (Adão, 2019), but also decreases the ecologic deterioration.

## **9. Conclusion**

The primary purpose of this investigation was to scrutinize the behaviour between electricity generation sources, relating to the electricity system's CO<sub>2</sub> emissions and consumer prices in countries with operational nuclear power plants in the EU's area, adding Switzerland as it shares common energy and environmental directives. From this perspective, it was designed using a panel data with 15 selected countries with extracted data of the electricity mix generation on a monthly basis (January 2014 until December 2018) and thoroughly analysed using an ARDL approach. This approach revealed to be appropriate, as the number of collected observations

turned out to be ample, it was possible to capture dynamic effects between the variables, and it displays the short and long-term impacts separately.

European energy transition appears to be going in the right direction. This is reflected in the replacement of fossil fuels by RES and the cost-effectiveness of RES development, simultaneously. However, background support for inherently inconsistent RES has the effect of lifting general prices. Nevertheless, a ramp-up supply system is needed as the electric power system requires a much larger volume of renewable capacity to enhance the provision of low-carbon electricity and to reach its maximum potential. As such, the electricity network continues to emit CO<sub>2</sub> into the environment. The noteworthy effort of the EU to transit its electric system with the target to reach a zero-carbon economy is endangered for the most part by policies promoting the support of generation with gas plants. This expresses that high electricity consumption raises CO<sub>2</sub> emissions under current and planned policies. Policymakers have to be careful to meet the equilibrium between carbon-neutral electricity and competitive prices, reviewing the strategy of the deployment of renewables, more precisely, the technology of sustenance for generation volatility, regarding a carbon-free and affordable assistance contributing to a more environmentally sustainable economy.

Nuclear power is a less pollutant and viable alternative to support the instability of renewable production. Yet, the EU's nuclear fleet is prone to breaking with age and facing this issue, policymakers can reflect on three feasible options. Two of those choices focus on a nuclear plant's audition concerning the lifetime extension of the reactor or the construction of Small Modular Reactors to replace the disabled stations. These progressive technologies are fast to develop, secure and affordable and it promotes the flexible operation. The last possibility to be mentioned is permitting the nuclear reactor to operate over its potential lifetime. A hasty retiring of nuclear installations can enlarge the CO<sub>2</sub> emitted by the electricity sector, therefore nuclear installations must be kept generating until the validity date, or upgraded till the commercialization of new technology to support renewable's variability with clean energy.

The last note underlines the importance of hydropower, although the inflation effect is noticeable given by the financial incentives policies. These monetary strategies are convenient for this source to emerge nature-benevolent because it is a notable no-pollutant base charge and it allows the RES production on the grid. However, there is the possibility to build on a small scale. Small pumped energy storage is a versatile storage framework, as comparatively smaller than the regular plant, reducing the geological issues, the amount of land needed and the investment costs, while being economically viable with stable generation and environmentally acceptable.

## **Webography**

Agora Energiewende and Sandbag (2019): The European Power Sector in 2018. Up-to-date analysis on the electricity transition.: The European Power Sector in 2018. Up-to-date analysis on the electricity transition.

- Agora Energiewende (2019): European Energy Transition 2030: The Big Picture. Ten Priorities for the next European Commission to meet the EU's 2030 targets and accelerate towards 2050.
- European Commission. Guidance on The requirements for hydropower in relation to Natura 2000. European Commission, 2018
- European Environment Agency. Overview of electricity production and use in Europe, European Environment Agency 2018. Available online: <https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricityproduction-2/assessment-4>
- Eurostat. Electricity price statistics- Statistics Explained. Eurostat, 2019. Available online: [https://ec.europa.eu/eurostat/statistic-explained/index.php/Electricity\\_price\\_statistics](https://ec.europa.eu/eurostat/statistic-explained/index.php/Electricity_price_statistics)
- Eurostat. Inflation in the euro area- Statistics Explained. Eurostat, 2019. Available online: [https://ec.europa.eu/eurostat/statistics-explained/index.php/Inflation\\_in\\_the\\_euro\\_area](https://ec.europa.eu/eurostat/statistics-explained/index.php/Inflation_in_the_euro_area)
- International Energy Agency, 2016b. International Energy Agency, 2016b. World Energy Outlook 2016 (Executive Summary). Iea Weo. <[http://www.iea.org/publications/freepublications/publication/WEB\\_WorldEnergyOutlook2015ExecutiveSummaryEnglishFinal.pdf](http://www.iea.org/publications/freepublications/publication/WEB_WorldEnergyOutlook2015ExecutiveSummaryEnglishFinal.pdf)> .
- International Energy Agency. Annual and Monthly Data Relationship the IEA, an example Erica Robin – Head of Section - Oil and Natural Gas Statistics - IEA Energy Data Transparency Workshop – 30 April 2019, Cape Town.
- Organisation for Economic Co-operation and Development. 2019 International Migration and Displacement Trends and Policies Report to the G20. OECD 2019.
- Schlömer S., T. Bruckner, L. Fulton, E. Hertwich, A. McKinnon, D. Perczyk, J. Roy, R. Schaeffer, R. Sims, P. Smith, and R. Wisner, 2014: Annex III: Technology-specific cost and performance parameters. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Schlömer, S., Bruckner, T., Fulton, L., Hertwich, E., McKinnon, A., Perczyk, D., et al., 2014. Annex III: technology-specific cost and performance parameters. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K. (Eds.), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
- World Tourism Organization. European Union Tourism Trends. UNWTO, 2018.

## References

- Adão, B. (2019). Economics Synopsis Why is price stability a key goal of central banks? *Volume V*, 67.
- Afonso, T. L., Marques, A. C., Fuinhas, J. A., & Saldanha, e. M. M. (2018). Interactions between electricity generation sources and economic activity in two Nord Pool systems. Evidence from Estonia and Sweden. *Applied Economics*, 50(29), 3115-3127.
- Al-mulali, U., Fereidouni, H. G., & Lee, J. Y. (2014). Electricity consumption from renewable and non-renewable sources and economic growth: Evidence from Latin American countries. *Renewable and Sustainable Energy Reviews*, 30, 290-298.
- Alola, A. A., Yalçiner, K., & Alola, U. V. (2019). Renewables, food (in) security, and inflation regimes in the coastline Mediterranean countries (CMCs): the environmental pros and cons. *Environmental Science and Pollution Research*, 26(33), 34448-34458. Retrieved from <https://link.springer.com/article/10.1007/s11356-019-06576-y>
- Alola, A. A., Yalçiner, K., Alola, U. V., & Saint Akadiri, S. (2019). The role of renewable energy, immigration and real income in environmental sustainability target. Evidence from Europe largest states. *Science of The Total Environment*, 674, 307-315.
- Altıntaş, H., & Kum, M. (2013). Multivariate granger causality between electricity generation, exports, prices and economic growth in Turkey. *International Journal of Energy Economics and Policy*, 3(4S), 41-51.

- Amri, F. (2017). The relationship amongst energy consumption (renewable and non-renewable), and GDP in Algeria. *Renewable and Sustainable Energy Reviews*, 76, 62-71.
- Andreoni, V., & Galmarini, S. (2016). Drivers in CO<sub>2</sub> emissions variation: A decomposition analysis for 33 world countries. *Energy*, 103, 27-37.
- Ang, J. B. (2007). CO<sub>2</sub> emissions, energy consumption, and output in France. *Energy Policy*, 35(10), 4772-4778.
- Apergis, N., Jebli, M. B., & Youssef, S. B. (2018). Does renewable energy consumption and health expenditures decrease carbon dioxide emissions? Evidence for sub-Saharan Africa countries. *Renewable Energy*, 127, 1011-1016.
- Appiah, M. O. (2018). Investigating the multivariate Granger causality between energy consumption, economic growth and CO<sub>2</sub> emissions in Ghana. *Energy Policy*, 112, 198-208.
- Aune, F. R., Golombek, R., & Hallre, H. (2015). Phasing out nuclear power in Europe.
- Balsalobre-Lorente, D., & Shahbaz, M. (2016). Energy consumption and trade openness in the correction of GHG levels in Spain. *Bull Energy Econ*, 4(4), 310-322.
- Balsalobre-Lorente, D., Shahbaz, M., Roubaud, D., & Farhani, S. (2018). How economic growth, renewable electricity and natural resources contribute to CO<sub>2</sub> emissions? *Energy Policy*, 113, 356-367.
- Bekhet, H. A., & bt Othman, N. S. (2011). Causality analysis among electricity consumption, consumer expenditure, gross domestic product (GDP) and foreign direct investment (FDI): Case study of Malaysia. *Journal of economics and international finance*, 3(4), 228.
- Bekun, F. V., Alola, A. A., & Sarkodie, S. A. (2019). Toward a sustainable environment: Nexus between CO<sub>2</sub> emissions, resource rent, renewable and nonrenewable energy in 16-EU countries. *Science of The Total Environment*, 657, 1023-1029.
- Bekun, F. V., Emir, F., & Sarkodie, S. A. (2019). Another look at the relationship between energy consumption, carbon dioxide emissions, and economic growth in South Africa. *Science of The Total Environment*, 655, 759-765.
- Belaid, F., & Youssef, M. (2017). Environmental degradation, renewable and non-renewable electricity consumption, and economic growth: Assessing the evidence from Algeria. *Energy Policy*, 102, 277-287.
- Bento, J. P. C., & Moutinho, V. (2016). CO<sub>2</sub> emissions, non-renewable and renewable electricity production, economic growth, and international trade in Italy. *Renewable and Sustainable Energy Reviews*, 55, 142-155.
- Breitung, J. (2005). *The local power of some unit root tests for panel data*: Humboldt-Universität zu Berlin, Wirtschaftswissenschaftliche Fakultät.
- Campbell, A. (2018). Price and income elasticities of electricity demand: Evidence from Jamaica. *Energy Economics*, 69, 19-32.
- Carfora, A., Pansini, R. V., & Scandurra, G. (2019). The causal relationship between energy consumption, energy prices and economic growth in Asian developing countries: A replication. *Energy Strategy Reviews*, 23, 81-85.
- Charfeddine, L., & Kahia, M. (2019). Impact of renewable energy consumption and financial development on CO<sub>2</sub> emissions and economic growth in the MENA region: A panel vector autoregressive (PVAR) analysis. *Renewable Energy*, 139, 198-213.
- Chen, Y., Wang, Z., & Zhong, Z. (2019). CO<sub>2</sub> emissions, economic growth, renewable and non-renewable energy production and foreign trade in China. *Renewable Energy*, 131, 208-216.
- Chen, Y., Zhao, J., Lai, Z., Wang, Z., & Xia, H. (2019). Exploring the effects of economic growth, and renewable and non-renewable energy consumption on China's CO<sub>2</sub> emissions: Evidence from a regional panel analysis. *Renewable Energy*, 140, 341-353.
- Choi, I. (2001). Unit root tests for panel data. *Journal of international money and Finance*, 20(2), 249-272.
- Deutsch, N. (2017). The Changing Role of Nuclear Power in the European Union: Reflections from Official Scenarios Released before and after the Fukushima Daiichi Accident. *Theory Methodology Practice: Club of Economics in Miskolc*, 13(1), 17-36.
- Dogan, E. (2015). The relationship between economic growth and electricity consumption from renewable and non-renewable sources: A study of Turkey. *Renewable and Sustainable Energy Reviews*, 52, 534-546.
- Dogan, E., & Seker, F. (2016). Determinants of CO<sub>2</sub> emissions in the European Union: The role of renewable and non-renewable energy. *Renewable Energy*, 94, 429-439.

- Dong, K., Sun, R., & Dong, X. (2018). CO<sub>2</sub> emissions, natural gas and renewables, economic growth: assessing the evidence from China. *Science of The Total Environment*, *640*, 293-302.
- Dong, K., Sun, R., Jiang, H., & Zeng, X. (2018). CO<sub>2</sub> emissions, economic growth, and the environmental Kuznets curve in China: What roles can nuclear energy and renewable energy play? *Journal of cleaner production*, *196*, 51-63.
- Driscoll, J. C., & Kraay, A. C. (1998). Consistent covariance matrix estimation with spatially dependent panel data. *Review of economics and statistics*, *80*(4), 549-560.
- Fuinhas, J. A., Marques, A. C., & Couto, A. P. (2015). Oil-growth nexus in oil producing countries: macro panel evidence. *International Journal of Energy Economics and Policy*, *5*(1), 148-163.
- Furuoka, F. (2017). Renewable electricity consumption and economic development: New findings from the Baltic countries. *Renewable and Sustainable Energy Reviews*, *71*, 450-463.
- Gorus, M. S., & Aydin, M. (2019). The relationship between energy consumption, economic growth, and CO<sub>2</sub> emission in MENA countries: Causality analysis in the frequency domain. *Energy*, *168*, 815-822.
- Hamdi, H., Sbia, R., & Shahbaz, M. (2014). The nexus between electricity consumption and economic growth in Bahrain. *Economic Modelling*, *38*, 227-237.
- Hdom, H. A. (2019). Examining carbon dioxide emissions, fossil & renewable electricity generation and economic growth: Evidence from a panel of South American countries. *Renewable Energy*, *139*, 186-197.
- Hirth, L., & Ziegenhagen, I. (2015). Balancing power and variable renewables: Three links. *Renewable and Sustainable Energy Reviews*, *50*, 1035-1051.
- Hoechle, D. (2007). Robust standard errors for panel regressions with cross-sectional dependence. *The stata journal*, *7*(3), 281-312.
- Hu, X., Huang, B., & Cherubini, F. (2019). Impacts of idealized land cover changes on climate extremes in Europe. *Ecological Indicators*, *104*, 626-635.
- Im, K. S., Pesaran, M. H., & Shin, Y. (2003). Testing for unit roots in heterogeneous panels. *Journal of econometrics*, *115*(1), 53-74.
- Ito, K. (2017). CO<sub>2</sub> emissions, renewable and non-renewable energy consumption, and economic growth: Evidence from panel data for developing countries. *International Economics*, *151*, 1-6.
- Iyke, B. N., & Odhiambo, N. M. (2014). The Dynamic Causal Relationship between Electricity Consumption and Economic Growth in Ghana: A Trivariate Causality Model. *Managing Global Transitions: International Research Journal*, *12*(2).
- Jenkins, J., Zhou, Z., Ponciroli, R., Vilim, R., Ganda, F., De Sisternes, F., & Botterud, A. (2018). The benefits of nuclear flexibility in power system operations with renewable energy. *Applied energy*, *222*, 872-884.
- Jin, T., & Kim, J. (2018). What is better for mitigating carbon emissions—Renewable energy or nuclear energy? A panel data analysis. *Renewable and Sustainable Energy Reviews*, *91*, 464-471.
- Kahia, M., Aïssa, M. S. B., & Charfeddine, L. (2016). Impact of renewable and non-renewable energy consumption on economic growth: New evidence from the MENA Net Oil Exporting Countries (NOECs). *Energy*, *116*, 102-115.
- Kahia, M., Aïssa, M. S. B., & Lanouar, C. (2017). Renewable and non-renewable energy use-economic growth nexus: The case of MENA Net Oil Importing Countries. *Renewable and Sustainable Energy Reviews*, *71*, 127-140.
- Khan, M. T. I., Ali, Q., & Ashfaq, M. (2018). The nexus between greenhouse gas emission, electricity production, renewable energy and agriculture in Pakistan. *Renewable Energy*, *118*, 437-451.
- Knopf, B., Pahle, M., Kondziella, H., Joas, F., Edenhofer, O., & Bruckner, T. (2014). Germany's nuclear phase-out: Sensitivities and impacts on electricity prices and CO<sub>2</sub> emissions. *Economics of Energy & Environmental Policy*, *3*(1), 89-106.
- Komal, R., & Abbas, F. (2015). Linking financial development, economic growth and energy consumption in Pakistan. *Renewable and Sustainable Energy Reviews*, *44*, 211-220.
- Lau, L.-S., Choong, C.-K., Ng, C.-F., Liew, F.-M., & Ching, S.-L. (2019). Is nuclear energy clean? Revisit of Environmental Kuznets Curve hypothesis in OECD countries. *Economic Modelling*, *77*, 12-20.
- Levin, A., Lin, C.-F., & Chu, C.-S. J. (2002). Unit root tests in panel data: asymptotic and finite-sample properties. *Journal of econometrics*, *108*(1), 1-24.

- Lin, B., & Ankrah, I. (2019). On Nigeria's renewable energy program: Examining the effectiveness, substitution potential, and the impact on national output. *Energy*, *167*, 1181-1193.
- Lund, P. D., Lindgren, J., Mikkola, J., & Salpakari, J. (2015). Review of energy system flexibility measures to enable high levels of variable renewable electricity. *Renewable and Sustainable Energy Reviews*, *45*, 785-807.
- Maddala, G. S., & Wu, S. (1999). A comparative study of unit root tests with panel data and a new simple test. *Oxford Bulletin of Economics and statistics*, *61*(S1), 631-652.
- Marques, A. C., & Fuinhas, J. A. (2018). On the Dynamics of Renewable Energy Consumption (Aggregated and Disaggregated) and Economic Growth: An Approach by Energy Sources. In *The Economics and Econometrics of the Energy-Growth Nexus* (pp. 77-112): Elsevier.
- Marques, A. C., Fuinhas, J. A., & Macedo, D. P. (2019). The impact of feed-in and capacity policies on electricity generation from renewable energy sources in Spain. *Utilities Policy*, *56*, 159-168.
- Marques, A. C., Fuinhas, J. A., & Menegaki, A. N. (2014). Interactions between electricity generation sources and economic activity in Greece: A VECM approach. *Applied energy*, *132*, 34-46.
- Marques, A. C., Fuinhas, J. A., & Nunes, A. R. (2016). Electricity generation mix and economic growth: What role is being played by nuclear sources and carbon dioxide emissions in France? *Energy Policy*, *92*, 7-19.
- Marques, A. C., Fuinhas, J. A., & Pereira, D. A. (2018). Have fossil fuels been substituted by renewables? An empirical assessment for 10 European countries. *Energy Policy*, *116*, 257-265.
- Mirza, F. M., & Kanwal, A. (2017). Energy consumption, carbon emissions and economic growth in Pakistan: Dynamic causality analysis. *Renewable and Sustainable Energy Reviews*, *72*, 1233-1240.
- Murad, M. W., Alam, M. M., Noman, A. H. M., & Ozturk, I. (2019). Dynamics of technological innovation, energy consumption, energy price and economic growth in Denmark. *Environmental Progress & Sustainable Energy*, *38*(1), 22-29.
- Nkoro, E., & Uko, A. K. (2016). Autoregressive Distributed Lag (ARDL) cointegration technique: application and interpretation. *Journal of Statistical and Econometric Methods*, *5*(4), 63-91.
- Oliveira, T., Varum, C., & Botelho, A. (2019). Econometric modeling of CO2 emissions abatement: Comparing alternative approaches. *Renewable and Sustainable Energy Reviews*, *105*, 310-322.
- Pesaran, M. H. (2007). A simple panel unit root test in the presence of cross-section dependence. *Journal of applied econometrics*, *22*(2), 265-312.
- Pesaran, M. H., Shin, Y., & Smith, R. J. (2001). Bounds testing approaches to the analysis of level relationships. *Journal of applied econometrics*, *16*(3), 289-326.
- Pesaran, M. H., Shin, Y., & Smith, R. P. (1999). Pooled mean group estimation of dynamic heterogeneous panels. *Journal of the American statistical association*, *94*(446), 621-634.
- Phillips, P. C., & Perron, P. (1988). Testing for a unit root in time series regression. *Biometrika*, *75*(2), 335-346.
- Przychodzen, W., & Przychodzen, J. (2020). Determinants of renewable energy production in transition economies: A panel data approach. *Energy*, *191*, 116583.
- Rahman, M. S., Noman, A. H. M., Shahari, F., Aslam, M., Gee, C. S., Isa, C. R., & Pervin, S. (2016). Efficient energy consumption in industrial sectors and its effect on environment: A comparative analysis between G8 and Southeast Asian emerging economies. *Energy*, *97*, 82-89.
- Saint Akadiri, S., Alola, A. A., Akadiri, A. C., & Alola, U. V. (2019). Renewable energy consumption in EU-28 countries: Policy toward pollution mitigation and economic sustainability. *Energy Policy*, *132*, 803-810.
- Salim, R. A., Hassan, K., & Shafiei, S. (2014). Renewable and non-renewable energy consumption and economic activities: Further evidence from OECD countries. *Energy Economics*, *44*, 350-360.
- Sharif, A., Raza, S. A., Ozturk, I., & Afshan, S. (2019). The dynamic relationship of renewable and nonrenewable energy consumption with carbon emission: A global study with the application of heterogeneous panel estimations. *Renewable Energy*, *133*, 685-691.
- Sinha, A., Shahbaz, M., & Sengupta, T. (2018). Renewable energy policies and contradictions in causality: a case of Next 11 countries. *Journal of cleaner production*, *197*, 73-84.
- Staffell, I. (2017). Measuring the progress and impacts of decarbonising British electricity. *Energy Policy*, *102*, 463-475.

- Vaughan-Whitehead, D., & Vazquez-Alvarez, R. (2019). Convergence in the EU: What role for industrial relations? In *Towards Convergence in Europe*: Edward Elgar Publishing.
- Vogelsang, T. J. (2012). Heteroskedasticity, autocorrelation, and spatial correlation robust inference in linear panel models with fixed-effects. *Journal of econometrics*, 166(2), 303-319.
- Zivot, E., & Andrews, D. W. K. (2002). Further evidence on the great crash, the oil-price shock, and the unit-root hypothesis. *Journal of business & economic statistics*, 20(1), 25-44.