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Have fossil fuels been substituted by renewables? An empirical assessment for 10 European countries[☆,☆☆]

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ABSTRACT

The electricity mix worldwide has become diversified mainly by exploiting endogenous and green resources. This trend has been spurred on so as to reduce both carbon dioxide emissions and external energy dependency. One would expect the larger penetration of renewable energies to provoke a substitution effect of fossil fuels by renewable sources, in the electricity generation mix. However, this effect is far from evident in the literature. This paper thus contributes to clarifying whether the effect exists and, if so, the characteristics of the effect by source. Three approaches, generation, capacity and demand, were analysed jointly to accomplish the main aim of this study. An autoregressive distributed lag model was estimated using the Driscoll and Kraay estimator with fixed effects, to analyse ten European countries in a time-span from 1990 until 2014. The paper provides evidence for the substitution effect in solar PV and hydropower, but not in wind power sources. Indeed, the generation approach highlights the necessity for flexible and controllable electricity production from natural gas and hydropower to back up renewable sources. Moreover, the results prove that peaks of electricity have been an obstacle to the accommodation of intermittent renewable sources.

1. Overview

The demand for electricity is growing due mainly to population expansion, but also because of the continuous electrification of the residential, industrial, services and heating sectors. Electricity has been a major driver of economic growth (Hamdi et al., 2014; Omri, 2014), but it is essential that cleaner and green electricity sources should be introduced into electricity systems in order to reduce the effects of climate change, and to obtain sustainable development. In other words, if the shift towards electrification is made through the burning of fossil fuels to generate electricity, then the advantages of that shift are cancelled out. In fact, there is a growing debate about fossil-fuel-based electricity generation and its harmful effects on the environment. At the same time, these harmful effects on the environment could have negative consequences for economic growth and for societies as a whole (International Energy Agency, 2016a). Therefore, the diversification of the domestic electricity mix has been proposed to European (EU) countries. This complex struggle has been motivated by Directive 2009/28/EC of the European Parliament and of the Council, which proposes as objectives for 2020: (i) 20% reduction in EU greenhouse gas emissions; (ii) 20% of EU energy from renewable energy sources (RES); and (iii) 20% improvement in EU energy efficiency. In fact, the EU countries have been designing and implementing public policies to develop and increase the deployment of wind power, solar photovoltaic (PV), bioenergy and hydropower in their electricity production systems (Aguirre and Ibikunle, 2014; Polzin et al., 2015).

The IEA argues that the Paris pledges are mainly focused on the electricity sector, and on their scenario for 2040 of nearly 60% of new power generation capacity coming from RES (International Energy Agency, 2016b). The cleaner RES could increasingly replace fossil fuels, namely highly polluting oil and coal. Globally, the benefits of electricity production from RES are taken for granted. However, the characteristics of RES may be restricting their expected benefits, such as the reduction of carbon dioxide (CO_2) emissions, energy security and energy affordability. The EU countries have deployed high levels of wind power and solar PV, to meet the 20% goal of RES contribution to the energy supply, and they are on the right path, revealing a clear increasing tendency. Nevertheless, as RES increases, the expected decreasing tendency in the installed capacity of electricity generation from fossil fuels, has not been found. Despite the high share of RES in the electricity mix, RES, namely wind power and solar PV, are characterised by intermittent electricity generation. The increase in the

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installed capacities of intermittent renewable energy sources (RES-I) can be compatible with effective generation, but it can also increase idle capacity. So, it should be highlighted that this notion of idle capacity is quite different from traditional excess capacity.

The traditional concept of excess capacity, comes from the industrial economic field, and is sensitive to different points of view. Excess capacity is the set of resources available for firms producing goods or services, to mitigate the effects of demand uncertainty. The industrial economics literature also considers that excess capacity is a market competition strategy. In contrast, none of these strategies is appealing for RES-I producers. The lack of demand, or demand uncertainty, is of no great concern, since they have priority dispatch to the grid. Furthermore, the guaranteed prices over long-term contracts, given by feed-in tariffs, makes excess capacity a pointless market competition strategy for RES-I players. In conclusion, the unexploited installed capacity of RES-I is a consequence of the absence of availability of natural resources, rather than the lack of electricity demand or competition strategy behaviour (Flora et al., 2014). The electricity production systems have maintained or increased the installed capacity of non-renewable energy sources (NRES) to overcome the idle phenomenon of RES-I. Indeed, electricity production systems have required the standby capacity of fossil fuels to satisfy demand when demand is high and renewable source availability is low. This procedure often generates an installed overcapacity of fossil fuels, and therefore also generates economic inefficiencies. To overcome this economic inefficiency, cross-border market capacities have been expanded, mainly in EU countries. They have been essential for managing the surplus and scarcity of electricity production from RES, exporting excess RES in the electricity grid, and importing excess RES from other countries to meet the demand at a lower cost (Fig. 1).

The inability of RES-I to satisfy high fluctuations in electricity consumption on its own constitutes one of the main obstacles to the deployment of renewables. This incapacity is due to both the intermittency of natural resource availability, and the difficulty or even impossibility of storing electricity on a large scale, to defer generation. As a consequence, RES might not fully replace fossil sources, and recent literature has been analysing the causal relationship between RES and NRES, but only from the perspective of production (Al-mulali et al., 2014; Dogan, 2015; Salim et al., 2014). The literature proves the existence of a unidirectional causality running from RES to NRES (Al-mulali et al., 2014; Dogan, 2015; Salim et al., 2014). This unidirectional causality proves the need for countries to maintain or increase their installed capacity of fossil fuel generation, because of the characteristics of RES production. Furthermore, the literature reaches no consensual conclusion on the substitution effect between electricity production from RES and NRES (Al-mulali et al., 2014; Saidi and Ben Mbarek, 2016; Salim et al., 2014). Thus, integrating and promoting RES should not be done just through building new wind farms and PV plants. This solution promotes inefficiency in resource allocation, mainly because RES intermittency does not allow the full exploitation of the installed capacity. Flora et al. (2014) argue that the development of more efficient technology is the solution for overcoming the intermittency phenomenon, and more accurately incorporating RES into the electricity mix. Nonetheless, recent literature claims that the full integration of RES, into electricity systems, should be done by the disciplining consumption (e.g. Meyabadi and Deihimi, 2017). Demand-side management (DSM) could provide virtual resources to accurately accommodate RES-I. Moreover, shifting electricity demand towards periods with a high availability of natural resources also enables RES integration (Meyabadi and Deihimi, 2017).

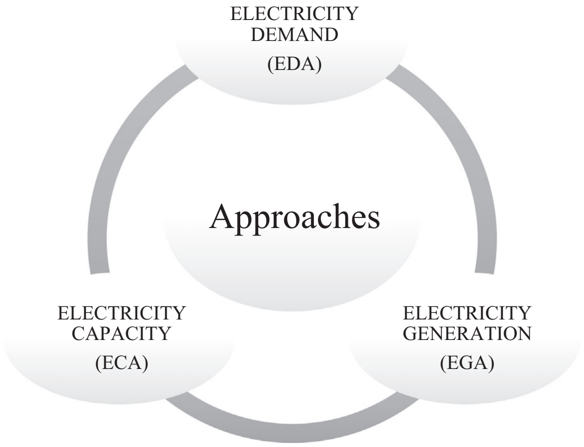

Fig. 1. Approaches applied to explain electricity generation from fossil fuels, hydropower and RES-I.

These facts together constitute the main motivation of this research, which aims to answer the following research questions: (i) does the installed capacity of wind power, solar PV, and bioenergy provoke similar effects on NRES electricity generation?; (ii) is there a substitution effect between hydropower and other RES (wind power, solar PV, bioenergy, geothermal, tide, wave and ocean) and fossil-source electricity generation?; (iii) how is the system dealing with demand peaks? To do this, this paper empirically assesses ten EU countries' electricity production systems, over a time-span from 1990 to 2014, with an autoregressive distributed lag (ARDL) methodology. This methodology allows the short-run dynamics, and the long-run equilibrium of the three approaches applied jointly, to be studied, namely the *electricity capacity approach* (ECA), the *electricity generation approach* (EGA), and the *electricity demand approach* (EDA). The literature that has studied the relationships between NRES and RES, only focused on their electricity generation, and avoided the consequences of installed capacities. However, the substantial difference between the installed capacity of RES and its effective generation must be considered, because of an undesirable phenomenon, namely that of idle capacity. This substantial difference has motivated some literature working on the drivers of the capacity factor and idle capacity (Boccard, 2009; Flora et al., 2014). This research provided new insights into earlier literature, which studied the interactions between electricity sources, and into the literature that studied the RES capacity factor and idle capacity. Accordingly, this paper contributes to the literature by not only analysing the relationships between RES and NRES electricity production, but also, by considering the dynamics adjustments, and the long-run equilibrium of the interactions between RES electricity capacity and NRES electricity generation. This paper also provides new insights by analysing the interactions between the characteristics of electricity consumption and maintaining fossil fuels in the electricity mix. Therefore, the combined econometric approach proposed, with the ECA, EGA, and EDA, represents the barriers and the difficulties that electricity management systems encounter in effectively matching electricity supply with demand, and compared to earlier literature, represents a novel approach.

Firstly, the ECA aims to identify whether additions to installed capacity can cause an increase in electricity generation. The decision to assign licensing is focused on capacity and not on generation. However, additional capacity of RES-I, namely wind power and solar PV, does not correspond to the actual capacity used, and thus does not allow electricity generation from fossil fuels to be abandoned. As the installed capacity of bioenergy has the potential to substitute fossil fuels, because of its flexible electricity generation and storage facilities, it was also scrutinized. Secondly, the objective of EGA is to analyse electricity generation from RES. Because the policy decisions of the European Commission have been focused on the contribution of RES to the energy supply, it is crucial verify whether there is a substitution effect between electricity generated from RES and NRES. In fact, the EGA approach could show whether the share of electricity generation from hydropower, and other RES, have been effective in reducing the burning of fossil fuels to produce electricity. Lastly, the EDA aims to identify the effects on fossil fuel dependency in electricity production systems, of the characteristics of electricity demand, specifically peaks of consumption and the intensity of electricity in the economy. Consequently, the EDA can reveal if the characteristics of electricity demand constitute an obstacle to RES integration, and to reducing electricity generation from fossil sources.

Overall, this research confirms that installed capacity and effective generation capacity, actually produce dissimilar effects on the dependency on fossil fuels to produce electricity. In fact, the characteristics of electricity consumption reinforce the need to burn fossil fuels to satisfy the demand for electricity. Specifically, the ECA results confirm the substitution effect between the installed capacity of solar PV and fossil fuels. In contrast, installed wind power capacity has required all fossil fuels and hydropower to back up its intermittency in the long-run equilibrium. The EGA outcomes show that hydropower has been substituting electricity generation through NRES, but that other RES have needed the flexibility of natural gas plants, to back them up. The EDA reveals that meeting electricity consumption peaks effectively without compromising energy security has also required electricity production from natural gas. In addition, peaks in electricity demand have been a barrier to RES-I integration. Therefore, the three approaches applied in this research, highlight that energy policies are essential to overcome the inefficiencies and ineffective allocation of resources in current electricity production systems, and that DSM policies and measures must be precisely used to accommodate RES-I generation.

The rest of the paper is set out as follows. Section 2 presents the data and describes the methodology. Both the results and their interpretation are discussed in Section 3. Finally, Section 4 presents the conclusions.

2. Methodology

In pursuing the main objective of this research, and as mentioned previously, three approaches were followed and estimated jointly. The *ECA*, focuses on the installed capacity of RES, namely the installed capacity of wind power, solar PV and bioenergy. This approach evaluates whether the growth in the installed capacity of wind power, solar PV and bioenergy leads to a decrease in electricity production from fossil fuels. Nevertheless, due to the intermittency phenomenon, the growth of installed capacity of RES-I could maintain or increase electricity generation from fossil fuels, but the installed capacity of bioenergy is expected to substitute electricity generation from fossil fuels. The EGA concentrates on the share of electricity production from hydropower and the aggregate of other RES, namely wind power, solar PV, bioenergy, geothermal, tide, wave and ocean. Accordingly, the EGA aims to prove the substitution effect between NRES electricity generation and the shares of both hydropower, and other RES, separately. Hydropower is expected to substitute the burning of fossil fuels to generate electricity. In contrast, the intermittency of RES-I and the lack of maturity and reduced implementation of controllable RES, such as bioenergy and geothermal, could provoke a complementary effect between the shares of other RES and the more flexible fossil fuels plants used to backup RES. Meanwhile, this approach also seeks to discover if the share of RES has been substituting base load electricity production from fossil sources. Lastly, the EDA centres round electricity consumption and its peaks. This approach is useful to assess the impact of the intensity and peaks of electricity consumption on the continuing presence of fossil fuels in electricity production systems. In fact, due to the complex effort of matching RES supply with uncertain electricity demand, it is expected that fossil fuels will have to intervene to effectively match electricity supply with demand.

To accomplish the main goal of this study, the installed capacity of wind power, solar PV and bioenergy was used to describe the ECA. It should be noted that this research only uses the installed capacity of wind power, solar PV and bioenergy because they have been the most deployed RES since 1990. The shares of electricity production from both hydropower and other RES explain the EGA. Lastly, the EDA is characterised by electricity consumption intensity in the economy and the highest peak of electricity consumption in a year. Indeed, electricity consumption intensity can explain the continuous electrification of economies, and could also be a proxy for technical progress, specifically explaining the efficiency of electrical systems in the countries under study. The three approaches were used jointly to explain electricity generation from fossil fuels aggregately, and disaggregated by each fossil fuel. Consequently, the four models employed to explain fossil fuel generation are the following, with their respective dependent variables:

- *FOSSIL model* – electricity generation from all fossil fuels, namely oil, coal, and natural gas (*FOSSIL_EG*);
- *OIL model* – electricity production from oil (*OIL_EG*);
- *COAL model* – electricity generation from coal (*COAL_EG*);
- *GAS model* – electricity production from natural gas (*GAS_EG*);

In addition, this paper also assesses the effects of the three approaches and the share of electricity production from the disaggregated fossil fuels, on electricity production from hydropower, as well as on electricity production from RES-I. Furthermore, the literature argues that fossil fuel combustion does not encourage RES-I deployment (Al-mulali et al., 2014; Dogan, 2015; Green and Vasilakos, 2010; Marques and Fuinhas, 2016). Thus, this research also analysed RES-I (wind power and solar PV) generation through CO_2 emissions, energy price, policy-driven and market-driven policies, fossil fuels installed capacity, and import dependency. Therefore, two more models were estimated, namely (with their respective dependent variables):

- *HYDRO model* – electricity production from hydropower (*HYDRO_EG*);
- *RES-I model* – electricity production from wind power and solar PV (*RESI_EG*).

The selection of countries was determined by the following requirement: data is available for the entire time-span, i.e. from 1990 until 2014, specifically for the installed capacities and production of RES, the highest annual demand peak load and electricity production from fossil fuels. Accordingly, the analysis focused on the time-span from 1990 until 2014, with the following ten EU countries: Belgium, the Czech Republic, Denmark, Finland, France, Greece, Portugal, Spain, Sweden and the United Kingdom. Table 1 reveals the definition of variables, sources, and descriptive statistics. The prefixes “L” and “D” denotes the natural logarithms and the first differences of logarithms, respectively. It should be noted that the peaks are a crucial factor for addressing the notion of the load on electricity systems. Consequently, the paper's database did not include some larger countries like Germany, Italy, Austria and the Netherlands due to the lack of data about peak consumption in these countries over the entire period. In regard to the time period, it should be recognised that to study RES, and particularly RES-I, the most relevant period is after 2000. However, considering the absence of available data for all variables with monthly frequency, the principle of using the maximum available data has been followed.

The cross-section dependence test proposed by Pesaran (2004) strongly supports the presence of cross-section dependence in all variables except *LHYDRO_EG*, *LHYDRO_SH*, and *LRXM* (see Table 2). As a consequence of the cross-section test results, only the second generation unit root test CIPS (Pesaran, 2007) was performed, because this test has the advantage of being robust in the presence of cross-section dependence. The CIPS test proved that all variables are I(0) in their first differences, but several variables are borderline in their levels, I(0)/I(1) (see Table 2) (Table 3).

For the group of countries under analysis, incorporating RES is expected to have different effects in the short- and long-run, i.e. dynamic effects, related to the (i) oil price boom and financial crisis, respectively expanding and restricting RES deployment; (ii) the whole take-off phase

Table 1
Data definition, sources and descriptive statistics before logarithm transformation.

Variable	Definition	Source	Obs	Mean	S.D.	Min	Max
FOSSIL_EG	Electricity production from coal, oil and natural gas (TWh)	Eurostat	250	65.0139	74.22352	1.637	308.935
COAL_EG	Electricity production from coal (TWh)	*Idem*	250	36.46262	39.63076	0.516	209.53
OIL_EG	Electricity production from oil (TWh)	*Idem*	250	5.69308	6.39462	0.038	34.676
GAS_EG	Electricity production from natural gas (TWh)	*Idem*	250	22.8582	38.94431	0.04	177.607
HYDRO_EG	Electricity production from hydro power (TWh)	*Idem*	250	20.64136	25.36563	0.013	81.069
RESI_EG	Electricity production from intermittent RES (TWh)	*Idem*	250	4.450816	10.26103	0	68.743
WIND_IC	Installed capacity of wind power (MW)	*Idem*	250	1887.016	4039.114	0	22,975
SOL_IC	Installed capacity of solar PV (MW)	*Idem*	250	407.008	1211.394	0	7087
BIO_IC	Installed capacity of bioenergy (MW)	*Idem*	250	815.28	945.7972	0	4712
FOSSIL_IC	Installed capacity of fossil fuels (MW)	*Idem*	250	18,350.05	17,324.22	4050	72,998
HYDRO_SH	Hydro power contribution to electricity generation (%)	*Idem*	250	13.24692	13.79742	0.0354597	54.12072
RESH_SH	RES excluding hydro power contribution to electricity generation (%)	*Idem*	250	6.918539	8.897181	0	55.82761
COAL_SH	Coal contribution to electricity generation (%)	*Idem*	250	32.16157	23.59706	0.335802	91.51731
OIL_SH	Oil contribution to electricity generation (%)	*Idem*	250	5.706472	7.499577	0.0441737	46.08482
GAS_SH	Natural gas contribution to electricity generation (%)	*Idem*	250	13.25286	11.91464	0.1158715	46.21476
RXM	Coverage rate of electricity imports by exports	*Idem*	249	32.49934	232.524	1.039339	3345.2
PEAK	Highest value of the power absorbed or supplied, in an hour during the year (MW)	IEA	250	31,109.9	27866.58	4924	102,098
CONS	Electricity consumption intensity in the economy (elec. Cons./GDP)	Eurostat	250	0.0000215	9.25E−06	9.75E−06	0.0000415
RXM_FOSSIL	Coverage rate of fossil fuels imports by exports	*idem*	250	5.638228	3.583152	1.536773	18.40292
CO2	Carbon dioxide emissions intensity in the economy (CO2/GDP)	BP statistical review of world energy and Eurostat	250	3.85E−10	2.62E−10	1.21E−10	1.64E−09
PRICE	Total energy real index for industry and households	IEA	250	85.60251	14.63452	55.64257	119.3063
POLI_DRI	Accumulated number of policy-driven instruments	IEA/IRENA	250	6.888	6.550043	1	27
MARK_DRI	Accumulated number of market-driven instruments	*idem*	250	3.76	3.207421	1	15

of RES implementation; and (iii) the most recent RES deployment stimulated by the social and political pressure for the development of cleaner energies. Thus, as this analysis aims to assess both short- and long-run adjustments, the use of an autoregressive distributed lag (ARDL) model is recommended. What is more, this model can appropriately handle co-integration, long memory patterns, and borderline variables, such found in the series under study. Besides, the ARDL modelling allows the use of different optimal lags for the variables, and it has a useful modelization of the characteristics of the panel data used, specifically, the endogeneity among variables, different orders of integration of series, and long memory patterns (Jouini, 2014; Narayan, 2005). In fact, the literature (Berk and Yetkiner, 2014; Fuinhas et al., 2015; Papageorgiou et al., 2016), shows that the ARDL model has consistent and efficient parameter estimates, and allows short-run and long-run estimates to be obtained simultaneously. The general ARDL models applied are specified as follows (Eq. (1)).

Table 2
Cross-section dependence and unit roots test.

	Cross section dependence			Unit roots test (CIPS)			
				Level		First differences	
	CD-test	Corr	Abs(corr)	No trend	With trend	No trend	With trend
LFOSSIL_EG	16.04***	0.523	0.572	−6.730***	−1.626*	−9.008***	−7.348***
LCOAL_EG	11.29***	0.374	0.427	−1.755**	−1.528*	−10.368***	−9.726***
LOIL_EG	19.39***	0.631	0.664	−2.512***	−0.075	−8.144***	−6.413***
LGAS_EG	18.42***	0.548	0.641	0.842	2.051	−5.303***	−6.249***
LHYDRO_EG	1.18	0.041	0.306	−5.462***	−5.058***	−12.551***	−11.104***
LRESI_EG	30.12***	0.96	0.96	−0.56	0.952	−6.858***	−5.406***
LWIND_IC	24.71***	0.938	0.938	−0.464	0.917	−5.782***	−5.929***
LSOL_IC	24.17***	0.918	0.918	−0.253	0.051	−4.132***	−2.278***
LBIO_IC	26.53***	0.886	0.886	1.186	−2.060**	−10.419***	−9.529***
LFOSSIL_IC	3.68***	0.139	0.501	0.179	2.902	−6.101***	−4.192***
LHYDRO_SH	0.58	0.018	0.298	−6.765***	−5.669***	−13.342***	−12.177***
LRESH_SH	30.44***	0.919	0.919	−0.61	1.406	−6.896***	−6.422***
LCOAL_EH	20.74***	0.627	0.627	−2.426***	−2.002**	−10.719***	−9.722***
LOIL_SH	24.73***	0.748	0.748	−2.502***	−0.266	−9.579***	−8.004***
LGAS_SH	23.47***	0.708	0.708	0.917	1.483	−6.743***	−7.722***
LRXM	−1.54	−0.046	0.308	−3.770***	−2.248**	−11.088***	−9.521***
LPEAK	18.87***	0.565	0.587	−3.656***	−2.684***	−12.622***	−11.626***
LCONS	3.61***	0.109	0.798	2.926	0.821	−7.629***	−6.823***
LRXM_FOSSIL	1.96**	0.058	0.521	−1.729**	−3.884***	−10.884***	−10.311***
LCO2	28.82***	0.859	0.859	−2.280**	−1.199	−9.016***	−8.271***
LPRICE	28.73***	0.857	0.857	2.37	0.961	−7.407***	−6.088***
LPOLI_DRI	29.22***	0.871	0.871	−0.717	−0.092	−9.309***	−8.610***
LMARK_DRI	28.49***	0.849	0.849	−0.667	−1.388*	−10.649***	−9.398***

Notes: * , * *, * ** , denote statistical significance at 10%, 5% and 1% level, respectively. CD-test has N(0,1) distribution under H0: cross-section independence; panel unit roots test (CIPS) tests the H0: series are I(1).

Table 3
Specification tests.

Models	*FOSSIL*	*COAL*	*OIL*	*GAS*	*HYDRO*	*RESI*
Modified Wald test	375.03***	49.61***	209.46***	172.84***	110.07***	238.33***
Wooldridge test	998.783***	77.669***	129.623***	48.516***	32.300***	42.355***
Pesaran test	1.085	1.207	2.426**	0.969	0.292	3.182***
Frees test	0.495**	0.275***	−0.107	0.202	0.475**	0.337**
Friedman test	9.653	27.404***	14.053	14.507	8.56	9.2
Likelihood-ratio test	1.36	5.24	2.69	2.25	3.89	6.05
Hausman RE vs. FE	59.74***	39.93***	37.75***	58.49***	113.96***	48.51***

Notes: * ** , * * denote statistical significance at 1% and 5% level, respectively; the modified Wald test has χ2 distribution and tests H0: σ_cˆ2 = σˆ2, for c= 1,…,N; the Wooldridge test is normally distributed N(0,1), and tests H0: no serial correlation; Pesaran, Frees and Friedman test the H0: residuals are not correlated; Likelihood-ratio test verify the H0: the restricted model adjusts better than the unrestricted model; Hausman results for H0: difference in coefficient is not systematic including the constant.

$$\Delta\omega_t = \alpha_i + \beta_{i1}\,\Delta\theta_t + \alpha_{1i}\sum\nolimits_{p=1}^{k}\omega_{t-p} + \alpha_{2i}\sum\nolimits_{p=1}^{k}\theta_{t-p} + \mu_{i,t}, \qquad (1)$$

Where Δ operator is for the first differences, ω_t is the vector of the dependent variables, namely *FOSSIL_EG*, *COAL_EG*, *OIL_EG*, *GAS_EG*, *HYDRO_EG*, and *RESI_EG*, α_i is the intercept, β_{i1} is the semi-elasticities, α_{1i} is the error correction mechanism (ECM), α_{2i} is the elasticities, $\mu_{i,t}$ is the error term. The vector of independent variables (θ_t) is dependently of the estimated models, accordingly, to:

- FOSSIL, COAL, OIL, GAS models, $\theta_t = [LWIND\_IC; LSOL\_IC; LBIO\_IC; LHYDRO\_IC; LRESH\_IC; LRXM; LPEAK; LCONS]$;
- HYDRO model, $\theta_t = [LWIND\_IC; LSOL\_IC; LBIO\_IC;$
- $LCOAL\_SH; LOIL\_SH; LGAS\_SH; LRES\_SH; LRXM; LCONS]$;
- RES_I model, $\theta_t = [FOSSIL\_IC; LBIO\_IC; LCOAL\_SH; LOIL\_SH;$

$LGAS\_SH; LCONS; LPEAK; LRXM\_FOSSIL; LCO2; LPRICE; LPOLI\_DRI; LMARK\_DRI]$

The variables included in the models are in natural logarithms and first differences of logarithms, their coefficients are elasticities (long-run) and semi-elasticities (short-run). Moreover, the elasticities are computed from the estimated models by dividing the coefficient of the variables by the coefficient of the ECM, both lagged once, and then multiplying by − 1. As a consequence of using the three approaches jointly, extra attention is needed to check for the possible presence of both collinearity and multicollinearity. However, after inspecting the correlation matrix and the variance inflation factor (VIF) statistics, any risks of collinearity or multicollinearity have been set aside because of the low values in the correlation matrix and VIF statistics. A battery of model specification tests were then performed: (i) the modified Wald statistic for group wise heteroskedasticity (Greene, 2003); (ii) the Wooldridge test for serial correlation (Drukker, 2003); (iii) the test of contemporaneous correlation proposed by Pesaran (2004), Frees (1995), and Friedman (1937); (iv) Likelihood-ratio tests, to test the specification of parsimonious models; and (v) the Hausman test, Fixed Effects (FE) vs. Random Effects (RE), to test for the presence of individual effects against random effects.

In summary, the specification tests indicated (i) heteroskedasticity in all models; (ii) panel first order autocorrelation in all models; (iii) contemporaneous correlation in all but the *GAS* model; (iv) the parsimonious models are well specified; and (v) the FE estimator is adequate for all models. Correspondingly, the specification tests note that the Driscoll and Kraay (1998) estimator with fixed effects is appropriate for handling these data features. In fact, this estimator is a covariance matrix estimator, and its small-sample properties are considerably better than the alternative covariance estimators, particularly when cross-sectional dependence, heteroskedasticity, and autocorrelation are present (Hoechle, 2007). Furthermore, the results of the Driscoll and Kraay estimator were compared to the results of FE and RE estimators, as a benchmark, controlling for the presence of heteroskedasticity, contemporaneous correlation and autocorrelation, and this has corroborated the efficiency of the Driscoll and Kraay coefficient estimations.

3. Results and discussion

The results of the six ARDL models are presented in Tables 4 and 5, the Driscoll and Kraay estimator was used, and the parsimonious principle was followed. As such, only the statistically significant variables have been left in the models. The endogeneity of the interactions between electricity sources reveals the importance of using the ARDL model, given that it is free of serial correlation. Furthermore, the ARDL model is suitable for dealing with the presence of long memory, and allows a breakdown of the total effects into short-run dynamics (semi-elasticities) and long-run equilibrium (elasticities). Therefore, the negative and highly statistically significant values of ECM in the estimated models brings additional confidence in the appropriateness of the econometric technique used, and it leads to two major outcomes. Firstly, this result corroborates the understanding of the presence of long memory in the data. Thus, the electricity systems are stable and able to return to the equilibrium path after a disturbance. Secondly, it reveals that there are differences between the various fossil fuels with regard to the return to the equilibrium path. The value of the ECM for coal indicates that nearly 27% of the disequilibrium is corrected within a year, while for natural gas the correction is nearly 45%. In contrast, RES-I electricity generation is dependent on natural resource availability, which results in a low ECM value. However, it is worth highlighting that the high elasticity values of CO_2 and energy prices are compatible with what has been experienced during the take-off phase of RES technologies, and provide additional proof of the robustness of this

Table 4
Elasticities, semi-elasticities, and adjustment speeds of fossil fuel models.

Models	ALL FOSSIL	COAL	OIL	GAS
Short-run (semi-elasticities)				
DLSOL_IC			−0.0562***	−0.05474*
DLBIO_IC				0.048***
DLHYDRO_SH	−0.3230***	−0.2823***	−0.1794**	−0.2131***
DLRESH_SH	−0.2614***	−0.1589***		
DLRXM	−0.0529***	−0.0718***		−0.0863***
DLPEAK	0.1114***	0.1408***	0.1436***	0.2376***
DLCONS	1.8674***	2.4631***	2.6402***	1.908***
Speed of adjustment				
ECM	−0.3408***	−0.2703***	−0.3454***	−0.4519***
Long-run (elasticities)				
LWIND_IC	0.1822***		0.2581***	0.2266***
LSOL_IC	−0.0479***		−0.1073***	−0.1989***
LHYDRO_SH	−0.3185***			
LRESH_SH		−0.1618***		0.2969***
LRXM	−0.1971***	−0.2037***	−0.3152***	−0.1526***
LPEAK				0.4975***
LCONS	1.5047***	1.9658***	2.4297***	2.2295***
Trend	−0.02***		−0.0428***	
Const	7.1146***	6.6898***	9.7816***	9.3139**
OBS	176	235	176	176
R^2	0.5504	0.4412	0.3066	0.4989

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

Table 5
Elasticities, semi-elasticities, and adjustment speeds of *RES-I* and *HYDRO models*.

Model	RES-I	Model	HYDRO
Short-run (semi-elasticities)		**Short-run (semi-elasticities)**	
DLFOSSIL_IC	−0.9577***	DLWIND_IC	−0.0705**
DLCOAL_SH	−0.1733***	DLCOAL_SH	−0.3822***
DLGAS_SH	0.2573***	DLGAS_SH	−0.1247*
DLPEAK	0.1221***	DLRESH_SH	−0.2610***
DLPRICE	0.9657***	DLCONS	1.0372**
LPOLI_DRI	−0.2484*		
Speed of adjustment		**Speed of adjustment**	
ECM	−0.1420***	ECM	−0.8190***
Long-run (elasticities)		**Long-run (elasticities)**	
LFOSSIL_IC	−3.8606***	LWIND_IC	0.0391***
LCOAL_SH	−1.5562***	LSOL_IC	−0.0149*
LGAS_SH	0.9624***	LCOAL_SH	−0.2275**
LPEAK	−1.2192**	LOIL_SH	0.1436***
LRXM_FOSSIL	1.288***	LGAS_SH	−0.1382**
LCO2	8.0105***	LRXM	−0.0847***
LPRICE	8.9895***	LCONS	0.4024**
LPOLI_DRI	−1.3717**		
LMARK_DRI	1.7614***		
Trend	0.0231***		
Const	26.1730***	Const	5.9137***
OBS	224	N	176
R^2	0.3972	r2_w	0.5668

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

model.

Remembering that there are substantial differences between the installed capacity of RES and effective generation, this paper studies the difference between the ECA and the EGA. In addition, the EDA assesses how the characteristics of electricity demand affect the electricity generation from fossil fuels, and the accommodation of RES. In fact, the three approaches are references for energy policy decisions and, as such, all the required steps have been taken to assure that their simultaneous use does not provoke undesirable phenomena in the database, and in the models. Firstly, regarding the semi-elasticities of EDA, in the short-run, an increase of 1pp (percentage point) in *DLCONS* provokes an increase of 1.87pp, 2.46pp, 2.64pp, and 1.87pp in electricity production from all-fossil, coal, oil, and natural gas, respectively. In the long-run, an increase of 1% in *LCONS* generates an increase of 1.51%, 1.97%, 2.43%, and 2.22%, in electricity generation from all fossil, coal, oil and natural gas, respectively. However, for hydropower, in the long-run, an increase of 1% in *LCONS* only causes an increase of 0.40%. Accordingly, the results of the EDA indicate the need to preserve fossil fuels and hydropower, in both the short- and long-run. The electrification of the residential, services and industrial sectors has been continuously pursued to diminish the consumption of fossil sources. Nevertheless, the increased electricity consumption intensity in the economy has been satisfied by fossil fuel burning, which has cancelled out the advantages of that shift. Furthermore, it only motivates electricity generation from hydropower, and does not motivate RES-I.

Peaks in electricity consumption have increased electricity generation from both fossil fuels and RES-I, in the short-run dynamics. However, the significant finding is that, in the long-run equilibrium, natural gas is the only fossil fuel source that fulfils consumption peaks. In fact, an increase of 1% in electricity consumption peaks provokes an increase of around 0.50% in electricity production from natural gas. This outcome is not at all unexpected and it is a sign of the overall consistency of the research. Natural gas plants are the most commonly used to manage the scarcity of RES electricity supply and the uncertainty of electricity demand. Indeed, the flexibility and storage facilities of natural gas plants allow the electricity production systems to effectively match the electricity demand with the electricity supply. Hence, this implies that the greater the electricity consumption peaks, the larger the capacity for generation from natural gas plants must be and, consequently, the longer and larger the capacity needed on standby status. Therefore, it is evident that the preferred main backup source is natural gas, which is a cleaner, but not endogenous, fossil source. Furthermore, digging deeper into the analysis, it seems that electricity consumption peaks have been a barrier to RES-I exploitation, in the long-run equilibrium. In fact, an increase of 1% in peak consumption, in the long-run, decreases the exploitation of RES-I by around 1.22%. Accordingly, this outcome raises concerns, and reveals that RES deployment implies cutting off-peak consumption. However, little has been done to ensure that electricity demand will be well-ordered and smoothed.

Regarding the ECA, an increase of 1% in the installed capacity of solar PV decreases electricity production from oil and natural gas by nearly 0.11%, and 0.20% respectively in the long-run. In contrast, an increase of 1% in the installed capacity of wind power provokes an increase of 0.26%, and 0.22% in electricity generation from oil and natural gas, respectively in the long-run. These results are in line, with the literature that has studied the effects on electricity generation of wind power and solar PV (Marques et al., 2016; Marques and Fuinhas, 2016). Accordingly, these results demonstrate that the installed capacity of RES provokes dissimilar effects on NRES preservation. The substitution effect between solar PV and fossil fuels has been proven by the results, except for coal. Indeed, the installed capacity of solar PV has been increased over time by major players and by consumers, through the installation of solar PV panels in their homes. Moreover, the technological efficiency of solar PV operation has been enhanced. The substitution effect between solar PV and the other sources must be carefully considered in the design of public energy policies. In fact, this finding could result from the fact that this kind of source is more predictable and, as such, needs smaller backup capacity. Furthermore, solar PV reveals strong potential to be a source that could allow consumers to employ DSM strategies, since consumers can generate their own electricity and, moreover, can schedule their consumption for periods when the sun is more readily available. Therefore, consumers who generate their electricity through solar PV panels could help to avoid and remove some load from the entire electricity system. Moreover, considering the viability of solar PV on a small scale, there are significant multiplier effects from the use of this technology on the economy as a whole. Given that, it gives rise to a network of smaller installers, which creates local jobs and makes the economy more dynamic. Furthermore, this RES-I might be the solution to the lost advantages of the electrification of the industrial and services sector since its main activity occurs at the same time as solar PV electricity generation is maximised. Therefore, solar PV can compete with base load plants powered by fossil fuels during the daytime.

The installed capacity of wind power preserves fossil fuel generation to back up its electricity generation. In fact, the installed capacity of wind power has been deployed in large amounts to increase the exploitation of natural resources. But, the intermittency phenomenon, more noticeable in wind power, means that, unlike fossil fuels, the installation of this RES capacity does not correspond to growth by the same amount of electricity generation. On the one hand, this can cause a lack of energy in the grid, i.e., the excess of installed capacity does not correspond to the effective generation to satisfy the entire demand. On the other hand, it can cause an excess of energy in the grid, i.e., the installed capacity of wind power deployed can result in effective generation being able to satisfy the entire demand and provoke an excess of electricity in the grid. Consequently, the idle capacity of wind power has been increasing the overcapacity of fossil fuels to back up its intermittent generation, which provokes economic inefficiencies. Therefore, the intermittency, unpredictability and volatility of wind power have put pressure on electricity production systems, since the electricity supply must be continuous to avoid shortages. In fact, the installed capacity of wind power has monopolized attention in electricity systems, which has led to the entire electricity production mix being determined in advance by predictions of the effective generation capacity of wind power.

It should be noted that the installed capacity of bioenergy is not statistically significant in the explanation of models, with the exception of the *GAS* model. EU countries have a tremendous potential to explore bioenergy, namely biomass and renewable waste. Electricity production from bioenergy has similar characteristics to natural gas plants, with flexible electricity generation and storage facilities. Thus, bioenergy could be a key RES to substitute fossil fuels in the backup role. What is more, bioenergy permits the reutilisation of wood, especially firewood from forestry and industrial waste, renewable waste, municipal waste, biofuels and biogas, which could create new diversified and decentralized streams of income and employment. However, the lack of effectiveness in both decreasing electricity production from fossil fuels and in incorporating RES-I, highlight that countries have not taken advantage of the properties of this RES. It is crucial to devise public energy policies that promote the deployment and spread the use of bioenergy. In fact, the proper use of this renewable energy source could mitigate the negative consequences of fossil fuels, and it could also produce positive effects on both income and employment for several economic activities.

Regarding the EGA, the RES, other than hydropower electricity generation, have been substituting base load electricity production from coal. In fact, this result proves that RES-I, bioenergy and geothermal are on the right track and are substituting fossil fuels that cause severe pollution damage. An increase of 1% in the *LRESH_SH* decreases electricity production from coal by around 0.16%. However, in the long-run equilibrium, a complementary effect between RES and natural gas is verified, which increases the dependency on natural gas, in the electricity system by nearly 0.30%. In fact, the share of electricity production from RES other than hydropower, in the countries under analysis, is mainly constituted by wind power and solar PV electricity generation. Consequently, the intermittent electricity production from RES-I has required electricity generation from natural gas to compensate for the scarcity of RES-I generation. Furthermore, the integration of EU domestic electricity production systems in cross-border markets has produced desirable effects, as external trading is commonly used to manage the surplus and scarcity of electricity. Imports and exports of electricity have played an important role in the internal adjustment of electricity mixes, and have reduced fossil fuel dependency by around 0.20%, in the long run. Accordingly, management of the scarcity and excess of RES-I production has been provided either internally or externally, by natural gas plants or cross-border markets, respectively. Furthermore, the EGA confirms the substitution effect between generation from hydropower and both fossil fuels and other RES, in the short-run dynamics. But, in the long-run equilibrium, the substitution effect between hydropower and both fossil fuels and RES fades away. This result proves that, in the short-run, hydropower plays the role of base load, mainly in countries accomplishing a 20% contribution by RES to the energy supply goal.

Regarding the results of hydropower, it is essential to take into consideration the results of EGA and ECA. As mentioned previously, the EGA, in the short-run dynamics, confirms the substitution effect between hydropower and all other sources. Indeed, this result suggests that the base load is being met by resorting to thermal sources and the contribution of RES is guaranteed mainly by hydropower. However, as expected, and moreover, as is desirable, in the long-run equilibrium, it seems that hydropower is trying to play the backup role instead of polluting thermal sources. Accordingly, the ECA proves that, in the short-run dynamics, hydropower and the installed capacity of wind power are substitutes. In the long-run, an increase of 1% in wind power capacity increases electricity generated through hydropower by around 0.04%. So, in the long-run equilibrium, with the increase of the RES portfolio in EU countries, achieved mainly by deploying wind power, hydropower and its energy storage capability make it a natural reservoir for wind energy, enabling the installation of more wind power capacity. Hydropower has considerable potential in this regard, and can compete with natural gas in terms of flexibility, storage ability and low level of pollution. Besides, EU electricity production systems have other controllable and flexible RES, such as bioenergy and geothermal, that together with hydropower could be an effective solution to reduce the dependency on fossil fuels.

Electricity generated from fossil fuels carries considerable weight in the dependency on external electricity sources, energy security, CO_2, and energy affordability. EU countries have imported a substantial amount of fossil fuels to produce electricity, mainly because of the electrification of their sectors, which has caused an increase in the energy price for industries and households and an incremental increase in CO_2 emissions. For this reason, EU countries have instructions to adopt a clean energy policy and endogenous electricity production. In turn, energy affordability, CO_2 and energy security have been important to RES-I exploitation, having a positive impact on their production, which has also been proven by the literature (Aguirre and Ibikunle, 2014; Polzin et al., 2015). Indeed, the results shows that an increase in energy price, CO_2 emissions or fossil fuel import dependency by 1%, generates an increase of 8.99%, 8.01%, and 1.29% respectively, in electricity production from RES-I in the long-run. At the same time, the regulatory instruments introduced by the EU authorities to regulate the sales of CO_2 and the quotas of RES production, in the long run play a fundamental role in market diffusion and in fostering market competition between RES and NRES. However, electricity production from coal and the installed capacity of fossil fuels have decreased the propensity to exploit RES-I. In fact, an increase of 1% in the installed capacity of fossil fuels causes a decrease of 3.86% in RES-I generation. Therefore, hydropower, natural gas plants and cross-border markets have been the major drivers of electricity production systems to accommodate RES-I in the grid, which means that policymakers must try to design and implement public policies to successfully accommodate RES-I, without compromising economic growth and with rapid allocation.

In short, the results indicate that the EU's domestic electricity production systems have preserved fossil fuel generation, and include several economic inefficiencies and inefficiencies in resource allocation. On the one hand, as RES deployment increases, the idle capacity of RES increases by the same amount. This generates idle capacity and electricity production systems have to maintain or increase the installed capacity of fossil fuels in order to back up the RES, thus generating installed overcapacity in fossil fuels too. On the other hand, both the electrification of the residential, industrial and services sectors and consumption peaks also require fossil fuels, because RES are unable to satisfy them without resorting to fossil fuels. However, in the long run, the results show that hydropower, cross-border markets and natural gas plants, the least polluting fossil fuel, have played a fundamental role in matching RES production to the electricity supply. The policymakers have to design and implement energy policies to curb electricity source dependency and to achieve a successful shift towards electrification through RES exploitation. In fact, it is not enough to focus only on building and operating new wind farms or new solar PV plants. Instead, it is essential that both economic agents and economies globally, become more responsive to the fluctuation of available electricity resulting from the intermittence of most renewable sources.

4. Conclusion and policy recommendations

This research applies an ARDL approach to ten EU countries, with a time-span from 1990 to 2014. The paper also focuses on the relationship between electricity generation from fossil fuels and both RES deployment and the characteristics of electricity demand. To accomplish the main aim of this study, three approaches are used, the ECA, EGA and EDA focusing on the installed capacity of RES-I and bioenergy, the shares of electricity production from RES and hydropower, and electricity demand and its consumption peaks, respectively. The three approaches have been used to explain the electricity production from all fossil fuels aggregately, and disaggregated into oil, coal and natural gas.

The paper also explains electricity production from both hydropower and RES-I, separately. However, in order to explain RES-I electricity production, this research also uses variables such as the ratio of coverage of fossil fuel imports to exports, CO_2, public policies to support RES and energy prices for households and industries. A battery of model specification tests was carried out, which indicated that the Driscoll and Kraay estimator with fixed effects is the most suitable estimator to deal with the data features, and with the apportionment of both the short- and long-run effects. Indeed, the high ECM values corroborate the robustness of the models, and their stability.

Overall, the results support that the integration of both RES and the characteristics of electricity demand, have quickly been internalised in electricity production systems. The results highlight that electricity production systems have maintained and increased fossil fuels to back up RES and to satisfy electricity demand. In fact, RES cannot satisfy electricity consumption without resorting to fossil fuel electricity generation. This has hindered the shift from fossil fuels to RES, and has cancelled out the advantage of the shift to electrification, because of the need to burn fossil fuels. Furthermore, it should be stressed that natural gas, hydropower and cross-border markets are flexible, and their contribution to the electricity grid has been essential to back up RES intermittency and to satisfy peaks of demand.

Accordingly, there are three answers to the research questions in this paper. Firstly, the two new RES-I effects are not similar. The substitution effect has been effective in solar PV, contrary to wind power. In fact, the unpredictability and variability of wind power has put pressure on the electricity production system, because of its need for backup. However, it should be stressed that solar PV might be the solution for successfully achieving the shift to electrification of the industrial and services sectors. Bioenergy, a non-intermittent RES, offers flexible electricity generation and storage families, similar to the natural gas plants. Nevertheless, the installed capacity of bioenergy has not been statistically significant in reducing fossil fuels dependency. Secondly, the share of electricity production from RES, excluding hydropower, has replaced electricity production from coal, which is a good thing in itself, considering the severe pollution damage from that source. However, in the long-run equilibrium, high levels of RES require electricity production powered by natural gas. In fact, this flexible and least-polluting fossil source plays a crucial role in backing RES-I. Furthermore, hydropower, and its energy storage capability, make it a natural reservoir for wind power, but it has not proven to be sufficient, which implies backup from fossil fuels. Consequently, there is a need to increase or maintain the installed capacity of fossil fuels on standby. Lastly, the third answer, whether the peaks in electricity demand constrain the development of RES. In fact, in the short-run dynamics the peaks have been satisfied by all fossil fuels, increasing dependency on them. However, in the long-run equilibrium, the peaks of electricity consumption are satisfied by natural gas electricity production. Therefore, demand-side management policies and measures are essential to reshape electricity demand, in order to achieve electrification using RES rather than fossil fuels.

Governments and policymakers must try to disseminate the advantages of bioenergy. Bioenergy could be a key RES for accurately accommodating RES-I, as well as responding to consumption peaks. Thus, their use would enable fossil fuels to be cut, while having multiple effects on several economic activities, such as the collection of wood waste from forestry and industry, and waste management at local, municipal and national levels, as well as in the energy sector. In addition, policymakers should devise and implement energy policies to: (i) promote a shift in electricity consumption from peak to off-peak or valley periods; (ii) store electricity in different forms, through hydropower or thermal stores; (iii) increase the use of e-vehicles, to create effective vehicle to grid and grid to vehicle strategies; (iv) improve electric mobility, by providing an electric charger grid as well as domestic chargers at a reasonable cost; (v) reward changes in consumption routines, for instance through electricity tariffs; and (vi) further promote the generation by consumers of their own electricity. Once EU countries meet these challenges and others beyond these listed above, they will be closer to achieving success in the diversification of the energy mix.

Further research is needed to understand the relationship between RES and NRES with high frequency data, namely daily and hourly. In fact, it is crucial to analyse the daily substitution effects and the interaction between all electricity sources, to comprehend the endogeneity of electricity production systems. It is also essential to help policymakers develop policies to smooth non-guided electricity demand, to effectively achieve the shift to electrification through RES production. What is more, energy storage systems and cross-border markets have to be studied so that electricity production systems can efficiently manage the excess and scarcity of RES production without resorting to fossil fuels.

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