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Analysing electricity flows and congestions: Looking at locational patterns

Maria Teresa Costa-Campi [a], Daniel Davi-Arderius [a,*], Elisa Trujillo-Baute [b]

[a] University of Barcelona and Chair of Energy Sustainability, Barcelona Institute of Economics, Spain
[b] University of Lleida and Chair of Energy Sustainability, Barcelona Institute of Economics, Spain

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ABSTRACT

Countries are making important efforts decarbonising their electricity generation mix. In this context, improving the operational efficiency enables better use to be made by renewables and the grids. However, the location of new capacity might be relevant from the social welfare point of view when private decisions might affect the power system efficiency.

In this paper, we analyze the Spanish transmission grid with the aim to explore in the power system efficiencies with a high share of renewables in the generation mix. We explore in the location of the generation technologies to see how efficient they are located with regard to the consumption. We find wind is one of the least efficiently located, which has implied relevant grid investments paid by consumers. Moreover, a high concentration of renewables increases grid-congestions, which might constrain locations for future capacity.

Our results highlight there is a trade-off between incomes from RES and grid costs paid by consumers. Therefore, we suggest RES policies should include some locational incentives. We analyze pros and cons from some choices and conclude countries should provide further grid information to incumbents and also include locational incentives in future RES auctions. Indeed, results from this paper represent a first stage in the design of these locational incentives.

1. Introduction

Europe has ambitious climate targets for 2030 aimed to reduce 55% greenhouse emissions through the improvement of the energy efficiency and the connection of new renewable energy sources (RES). Improving the energy efficiency throughout the full energy chain benefits the environment, improves air quality and public health, reduces greenhouse gas emissions, improves energy security by reducing dependence on energy imports, cuts energy costs for households and companies, helps alleviate the energy poverty, and leads to increased competitiveness. Consequently, energy efficiency is recognised as a crucial element and a priority consideration in future investment decisions on the energy infrastructure (European Directive, 2018/2002/EC). Lately, the "Green Deal"[1] (2019) aims to increase RES participation in the economy before 2030. Regardless these targets, a large amount of new RES should be connected and their impact on the power system energy efficiency and social welfare might be relevant. Certainly, this requires studying and deeply understanding the performance and efficiency of the actual electricity systems.

In the past and before the unbundling of the electricity systems, investments in generation and transmission were decided by vertically integrated companies: grids were planned and built to feed main consumption areas from specific large generation plants. Later, the unbundling resulted in transmission as a regulated monopoly, and generation as a liberalised activity with its specific market incentives. This required the adoption of a complex regulatory framework with the overall objective of maximising the social welfare (Joskow, 1997). The unbundling process was contemporary to investments in new large-scale gas fired and coal plants to satisfy the increasing electricity demand. At the same time, environmental awareness gained importance in the United Nations Climate Conferences[2] and countries implemented the first policies to promote RES (Couture et al., 2010). The actual generation mix is based on a diversity of technologies -nuclear, combined cycle, coal, combined heat and power (CHP), hydropower, solar and wind-with different locations, different generation profiles, and different annual hourly productions.

* Corresponding author.
E-mail address: daniel_davi@yahoo.es (D. Davi-Arderius).

[1] Available at: https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf.

[2] Kyoto Protocol (1997) and Conference of Parties (COP21, Paris 2015). See https://unfccc.int/for further details.

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The efficiency of the energy systems at any given moment is influenced by the ability to feed power generated from different technologies into the grid smoothly and flexibly (European Directive 2018/2002/EC). However, power systems have limited capacity to handle electricity flows, which is explained by the network topology, the location of the generation plants operating at each time and where this energy is consumed. This might impact on the social welfare through the final electricity price, which includes compensations to curtailed generators, grid-investments and electricity losses. Moreover, curtailment does not allow a maximum utilisation of RES and might request turning alternative pollutant technologies on. Social rejection to new grids requires alternative costly underground networks and electricity losses should be generated (Daví-Arderius et al., 2017; Costa-Campi et al., 2018a).

The decarbonisation of electricity system implies reconfiguring spatial patterns and changing the location of key energy system components (generators) because the lowest-cost wind power is often in remote locations and far from the demand sites, which implies building costly grid infrastructure (Borenstein, 2012). The transmission planning might promote locating RES in some regions over others depending on the strategy followed by transmission providers (Alagappan et al., 2011; Kemfert et al., 2016). Literature on low-carbon energy transition has paid little attention to questions of space although RES might require extra transmission capacity due to their intermittency and different locations (Bridge et al., 2013). In this context, Hitaj (2015); Joos and Staffell (2018) find higher level of RES impacts on congestions due to their intermittency and locations.

In the literature, the efficiency of the energy systems has been analysed in the scope of the incentives for grid operators (Jamasb and Pollitt, 2003, 2007). Moreover, energy efficiency literature has mainly focused on the analysis related with the end-consumer issues linked to the energy efficiency policies (Bertoldi and Mosconi, 2020; Zuberi et al., 2020). However, the analysis of the energy efficiency within the overall chain of the power systems has been scarcely explored.

In this paper we explore in the efficiencies of the actual generation locations considering the grid infrastructure and the main consumption areas. Indeed, generation is inefficiently sited when is very far from consumption and requires extra grid-investments, which results in higher charges and electricity losses, both paid in the final electricity price. To do so, we make several analyses of the flows in the 400 kV Spanish transmission grid. First, we evaluate the actual locations of each technology w.r.t consumption using a novel indicator in the literature named *Distance Effect*. Second, we analyze grid congestions in each region and third, and we identify the regional surpluses/deficits of generation capacity. From our results, we sort all regions considering potential impacts on future grids-investments when new capacity is allocated in each region. Nowadays, this is especially relevant due to the vast replacement of traditional pollutant technologies by RES, which impacts on the actual grid flows.

We use a gravity model grounded on Newton's law of universal gravitation (Anderson, 1979), mostly applied to the analysis of trade between countries and with little applications to the energy markets (Antweiler, 2016; Costa-Campi et al., 2018a,b; Batalla et al., 2019). Results from gravity provide complementary results to the optimization models used so far to the analysis of grids (Leuthold et al., 2008; Weigt et al., 2010; Schaber et al., 2012; Neuhoff et al., 2013; Hitaj, 2015; Trepper et al., 2015; Van den Bergh et al., 2015). It should be noted some weak points from optimization: they require managing very large datasets with potential convergence problems and the need of using specific big data tools, and results might be highly dependent on the optimization strategy and the constraint definition, both exogenously chosen. Indeed, optimization models aim to validate operative parameters -voltage, current, reactive power flows-in all points of the grid at any time. On the contrary, gravity models can work with slightly smaller datasets -for instance, with smaller time frequency-, and their results does not depend on any exogenous decision and are directly provided by the statistical analysis. As we show in this paper, gravity is a powerful tool to make statistical analyses of flows and reliable simulations of future grid scenarios.

In this paper, we rely on a high-granularity dataset, which includes all the transmission lines with their corresponding flows, the hourly energy production by plants and geographical information about the location of main system component, namely nodes,[3] generation plants and main cities and the grid topology with the length of each line. To our knowledge, this is the first paper that analyses a country-scale electricity system using a gravity model to understand congestions and locational patterns in the transmission grid -at national level-to explore in the power system energy efficiency and provide some policy recommendations to optimally locate new RES.

This analysis is performed in Spain, which had the highest share of energy generated by RES[4] in 2016 (36.61%) among the five biggest economies in Europe. Moreover, past RES ambitious policies aimed resulted in large capacity connected in regions not always close to main consumption. As consequence, important grid investments were necessary and length of the transmission increased 58% between 1990 and 2016.[5] The period analysed is 2015–2017 when new RES was insignificant.[6] Consequently, this provides a suitable and stable RES scenario.

Our primary findings can be summarised in three main groups. First, the location of generation does significantly impact on flows, but this differs by technology. Results point out that wind and imports are the least efficiently located with respect to the main consumption areas, while combined cycle is the most efficient. The lowest efficiency related to wind might explain the large amount of grid-investments in Spain in the last decades as these plants seems to be far from main consumption areas. The highest efficiency for combined cycle might be explained by the raw material location, typically in seaports close to main cities. Second, we find regional congestions among regions are not homogeneous and follow locational patterns. Particularly, regions with higher level of RES in the North-West of Spain show congestions 400% upper than the average. This highlights that areas with higher RES production have higher congestions and their future capacity to allocate new RES might be limited. In the opposite side, North-East and South regions have the lowest congestions. Third, we analyze the surplus/deficit of the actual generation and their rate of use of the transmission grids. In line with previous results, higher surpluses are related to regions with higher RES capacity. Finally, we sort all the Spanish regions in four groups considering potential impacts on the social welfare related to the connection of new RES. Although allocating new wind capacity in the most resource-optimal regions (Galicia and Asturias) seems a good choice, this might make worse actual congestions and require new grids investments with the consequent social welfare impact. Therefore, it is essential to make deep Cost-Benefit-Analysis (CBA) and include all potential costs and benefits for both RES investors and consumers.

From all the previous results, we provide some policy recommendations aimed to efficiently locate new RES. Our results show that it is essential to provide open, complete and transparent grid information to all stakeholders. This includes an open grid-dataset identifying nodes

[3] A *node* or substation represents the physical location in the network, where transmission lines intersect between them. They can also connect with generation plants, industrial consumers or transformers to feed the distribution grids.

[4] From 2004 to 2016, the five biggest economies in Europe increased their RES share of energy production from 9.37 to 32.18% in Germany, 3.53–24.62% in the UK, 13.78–19.20% in France, 16.09–34.01% in Italy, and 18.98–36.61% in Spain. Source: Eurostat Database - *Short Assessment of Renewable Energy Sources: SHARES 2016 results (% of electricity generation from all sources)*. Available at https://ec.europa.eu/eurostat/web/energy/data/shares (last consulted on 08 September 2018).

[5] Between 1990 and 2016, transmission grids increased from 27,680 km to 43,800 km (+58%), while distribution from 272,787 km to 336,415 km (+23%) (Ministry of Industry, 2018; REE, 2019b).

[6] In this period, RES capacity increased +0.45% for wind and +0.43% for solar because the first Spanish RES auction took place in 2017 (REE, 2019a).

with their actual congestions and the regional available capacity for new RES without costly grid reinforcements while the power system energy efficiency is not harmed. This enables businesses to invest wisely, facilitate the correct decisions and innovate practices. We also analyze pros and cons from other policy recommendations and conclude that implementing locational incentives in future RES auctions seems to be one of the best choices. Accordingly, there is a range of possibilities as including economic incentives to offset the minor annual wind and solar production in non-optimal regions, including a list of technology-specific RES sites, or including different regional RES quotas. Indeed, our findings are a first step in the definition of these incentives in auctions.

In this paper, next Section provides a literature review about the analysis of energy flows. Energy policy framework for the location of generation is explained in Section 2, empirical approach and data used in this paper are described in Section 3, and results are explained in Section 4. Finally, policy recommendations and conclusions are included in Section 5.

2. Energy policy framework

Before the unbundling of the electricity systems, investments in generation and transmission were decided by vertically integrated companies: grids were planned and built to feed main consumption areas from specific large generation plants. However, the European Directive (1996)/92/EC requires an effective unbundling between the transmission and generation. Unbundling impacts on the grid functioning as transmission is subject to central management and control, and must be operated separately from other activities; while generation is opened to competition and must be independent from grid operators. Moreover, under the unbundling scheme, grid access is opened to promote transparency and facilitate negotiations between grid operators, customers and new generators (Pérez-Arriaga, 2014). This process coincided in time with the connection of the first RES. Actual generation mix is based on a great diversity of technologies: nuclear, combined cycle, coal, combined heat and power (CHP), hydropower, solar and wind.In this Section, we analyze the policy mechanisms that might directly or indirectly influence on the decision of locating generation plants, more specifically RES. The relevance of the locational decision relies on its potential impact on social welfare due to the requirement of subsequent grid investments or their impact on electricity losses (Bridge et al., 2013; Costa-Campi et al., 2018a,b). Indeed, energy policy mediates in these decisions by shaping incentives to agents. Next, we explain several issues related to the general policy framework that might settle locational incentives for new capacity.

2.1. Power system design

Some policies might provide locational incentives for new RES in the power systems. First, congestion pricing is the mechanism to assign congestion costs. In Europe, these costs are shared between all the agents sited within a large geographical area with a common wholesale price, namely bidding zones. Consequently, bidding zones do not provide specific locational incentives. On the contrary, nodal pricing defines locational prices considering the scarcity or surplus of generation in each node. Consequently, generation has locational economic incentives (Pérez-Arriaga, 2014). This is mostly implemented in the US, but also in other countries.

Second, connection charges are fees paid by RES promoters to cover their corresponding grid-connecting costs. As higher is the share of grid-connecting costs covered by RES promoters, higher is their locational incentive to consider the network capacity. There are three different connection charges: *deep cost* includes all connection costs and the upstream grid reinforcements; *shallow cost* includes only direct costs of the dedicated facilities and local reinforcements, but the rest of the upstream grid reinforcements are socialised; and *null cost* fully socialises all connection costs. Due to the grid characteristics, the design of connection charges is challenging to avoid gaming problems (Rious et al., 2008; Pérez-Arriaga, 2014). In Europe, *shallow cost* is the most implemented choice as is in Spain (ENTSO-E, 2018).

Use of System (UoS) charges are paid by consumers and generators when they are connected to the grid and cover the costs of operating, maintaining and building the network. Typically, they include a fix rate by the contracted power (MW) and/or another variable rate by the amount of consumption or generation (MWh) (Pérez-Arriaga, 2014). Most European countries, including Spain, use *postage stamp usage* fee, which are the same rates for analogous generators and consumers regardless their location in the country. However, the UK, Ireland, Norway and Sweden use regional UoS charges instead of *postage stamp usage* fee to reflect geographical deficits or surplus of generation, grid losses and other operational issues (ENTSO-E, 2018). While *postage stamp usage* fee does not provide specific locational incentives for RES, regional UoS charges does.

Transmission planning might also provide some locational incentives for RES depending on the strategy followed. In the *anticipatory planning*, transmission planning anticipates future RES connections and builds the corresponding infrastructure, while in the *reactive planning*, construction is made after RES promoter requests for their connection. Alagappan et al. (2011) observe that *anticipatory planning* improves RES energy development by the lower uncertainty to RES promoters who can better identify when, where and how to connect their plant. However, Spanish transmission planning is based in the *reactive planning*.

2.2. RES support schemes

Since the late 1990s, ambitious environmental targets required important incentives and subsidies as RES technological development was still in a pre-commercial stage. Three *market-pull* policies were mostly implemented: *price*, *quantity* and *voluntary* instruments. A *Price* instrument provides economic incentives for the energy generated and can be either investment subsidies or an extra payment for the production. Thus, producers cash a fixed-price with a subsidy to guarantee a minimum price in Feed-in-Tariff (FIT), while producers cash the electricity market price plus a fixed premium in Feed-in-Premium (FIP). In a *quantity* instrument or green certificate, regulators settle a target quota for all the agents who have to comply by Tradable Green Certificates.[7] Finally, a *voluntary* instrument includes the possibility to sell green electricity for suppliers (Pérez-Arriaga, 2014).

Literature agrees that FIT was very effective at stimulating the fast development of RES in many countries (Couture and Gagnon, 2010; Hiroux and Saguan, 2010), but has some drawbacks related to locational incentives for new RES as project developers do not compete in price but for good sites. FIT resulted in the selection of the highest-performing sites, this is concentrating RES in resource-rich locations (IRENA and CEM, 2015; Newbery et al., 2018). Moreover, some technologies - especially wind - are kept aside from day-to-day operation of electricity markets, etc.

Recently, auctions[8] have emerged as an efficient competitive alternative for setting the remuneration of new RES (Del Río, 2017). They are competitive bidding procurements where the product can either be capacity in MW or energy in MWh (IRENA and CEM, 2015). Due to the high price competition, promoters aim to seek resource-optimal sites, which might result in higher concentration with its corresponding social acceptability affection (Del Río and Linares, 2014). Locational incentives might be implemented including location-specific demand bands, project location components in the winner selection criteria, or

[7] *Tradable Green Certificates* are also known as *Renewable Energy Certificates*, *Green tags*, *Renewable Energy Credits* or *Renewable Electricity Certificates*.

[8] *Auctions* are also known as public tendering, demand auctions, reverse auctions or procurement auctions.

location requirements for the auction participating projects (IRENA and CEM, 2015).

3. Empirical approach & data

In this Section, we explain the empirical approach followed to explore in the power system efficiencies. Then we present the dataset used for.

3.1. Gravity model

In this paper we apply a gravity model, which allows us to undertake an analysis of network flows for a long period of time to find their determinants and regional characteristics. These models are grounded on Newton's law of universal gravitation (Anderson, 1979, 2011), and are mostly applied to the analysis of trade between countries (De Benedictis and Taglioni, 2011; Baier et al., 2014). Compared to the traditional optimization models, gravity models provide different results and have three great benefits compared to them: their results also consider the actual flows, it is not necessary to exogenously choose an estimation method, and they provide the disaggregated contribution of explicative variables in both flow directions. Indeed, the pre-existent conditions and the disaggregated contributions to bidirectional flows are the essence of the gravity approach.

In the first empirical approach aiming at identifying how each technology impacts on flows, we estimate the determinants of $F_t^{i,j}$ w.r.t. the energy produced by each technology (Equation (1)).

$$logF_t^{i,j} = \widehat{\beta_0} + \left(\widehat{\beta}_i logG_t^i\right) + \left(\widehat{\beta}_j logG_t^j\right) + \widehat{\beta_{17}} logDist^{i,j} + \widehat{\beta_{18}} C_i^d + \widehat{\beta_{19}} C_j^d + \widehat{\beta_{20}} C_i^c + \widehat{\beta_{21}} C_j^c + $$
$$+ \widehat{\beta_{22}} logD^i + \widehat{\beta_{23}} logD^j + \sum_{ri=1}^{14} \widehat{\theta_{ri}} NUTS2_i + \sum_{rj=1}^{14} \widehat{\theta_{rj}} NUTS2_j + seasonality_t + e_{i,j,t} \quad (1)$$

where $F_t^{i,j}$ is the energy flow at each time t in each transmission line between i, j; G_t^i and G_t^j indicate the energy produced by each technology and imports at i and j nodes, respectively; $Dist^{i,j}$ is the transmission line length in kilometres; D^i and D^j are the shortest distance of each node to a main city in km[9]; and $\widehat{\theta_{ri}}$ and $\widehat{\theta_{rj}}$ represent a dummy variable for the r region i and j nodes belong. We control for the relative position of each node w.r.t. the rest by *degree of centrality* (C_n^d) and the *closeness centrality* (C_n^c)[10] (see Equations (9) and (10) in Appendix I). *Seasonality*$_t$ includes some dummy variables[11] to consider time specificities in our estimations, i.e. the network operation, external facts, etc. All spatial data is calculated by a geographical information software (GIS), while the rest comes from OMIE (2019); REE (2019b); Ministry of Industry (2018). $\widehat{\beta}_i$ and $\widehat{\beta}_j$ explain how the energy generated by each technology contributes to flows.

In the second empirical approach aiming at identifying how the energy produced in each region contributes to flows, we estimate the determinants of $F_t^{i,j}$ w.r.t. the energy generated by each technology located in each r region (Equation (2)).

$$logF_t^{i,j} = \widehat{\beta_0} + \sum_{r=1}^{14} \widehat{\beta}_i^r logGr_t^i + \sum_{r=1}^{14} \widehat{\beta}_j^r logGr_t^j + \widehat{\beta_1} logDist^{i,j} + \widehat{\beta_2} C_i^d + \widehat{\beta_3} C_j^d + $$
$$+ \widehat{\beta_4} C_i^c + \widehat{\beta_5} C_j^c + \widehat{\beta_6} logD^i + \widehat{\beta_7} logD^j + seasonality_t + e_{i,j,t} \quad (2)$$

where Gr_t^i and Gr_t^j indicate the energy produced in i and j sited in region r, respectively and the rest of variables are the same than Equation (1). $\widehat{\beta}_i^r$ and $\widehat{\beta}_j^r$ explain how the energy generated in nodes located in r contributes to flows.

Regarding the estimation methodology and due to the presence of zeros in the endogenous variable, we cannot use ordinary least square (OLS) approach because these observations are dropped when logs are applied. Instead, we use the Poisson Pseudo Maximum Likelihood (PPML) estimator[12] following Silva and Tenreyro (2006), which also solves heteroscedasticity problems with the error terms.

3.2. Data description

We use an hourly dataset from 2015 to 2017 with almost 20 million observations and our geographical area is Continental Spain. The hourly dataset is transformed into a twice-daily frequency - peak and off-peak hours - calculating the average values during each daily period. Moreover, we include a $PEAK_t$ dummy variable that takes 1 during peak hours[13] and 0 otherwise. This energy flow definition has been previously used in the literature (Albadi and El-Saadany, 2008; Chevalier et al., 2003; Costa-Campi et al., 2018a,b).

[9] Madrid, Barcelona, Valencia, Sevilla, Zaragoza, Malaga, Murcia, Bilbao, Alicante, Cordoba, Valladolid, Vigo, Gijon, Hospitalet de Llobregat, Vitoria and A-Coruña. All them represent 25% of the population in Spain.

[10] C_n^d considers the number of transmission lines connected to n and the *closeness centrality* C_n^c considers the closeness of n w.r.t. the rest (De Benedictis and Tajoli, 2011).

[11] D_{dt} for the day of the week; M_{mt} for the month, Y_{yt} for the year and $PEAK_t$ for the peak time.

[12] Any concern on endogeneity problems from explicative variables in Equations (1) and (2) should be discarded since past decisions of locating generation were exogenous from flow and there were not clear locational incentives in the regulatory framework considering the existing flows.

[13] This classification is used for those low voltage consumers in Spain with two period tariffs (2.0DHA and 2.1DHA), with the peak period covering from 12 p.m. to 10 p.m.

Fig. 1. Network (red lines) and nodes (black dots) considered in this paper.
Source: own elaboration based on Google Maps. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Energy flows ($F_t^{i,j}$) are calculated using Marginal Loss Factors[14] and published by REE (2019a) (see Fig. 1). In our dataset, each pair of nodes is included twice: $F_t^{i,j} \geq 0$ when the flow comes from i to j and $F_t^{i,j} = 0$ otherwise.

In the first empirical approach, we use N_t^i, N_t^j, CC_t^i, CC_t^j, CO_t^i, CO_t^j, H_t^i, H_t^j, W_t^i, W_t^j, SOL_t^i, SOL_t^j, I_t^i, I_t^j, CHP_t^i and CHP_t^j, which is the energy generated in i and j by nuclear, combined cycle, coal, hydropower (also includes Pumping Generation), wind, solar, imports and combined heat and power, respectively (OMIE, 2019; REE, 2019a; Ministry of Industry, 2018).

In the second empirical approach, we use Gr_t^i and Gr_t^j, which is the energy generated at each i and j located in each r region[15] (see Fig. 4 in Appendix 0):

$$Gr_t^i = N_t^i + CC_t^i + CO_t^i + H_t^i + W_t^i + SOL_t^i + I_t^i + CHP_t^i \quad for \quad \forall i \in r \tag{3}$$

$$Gr_t^j = N_t^j + CC_t^j + CO_t^j + H_t^j + W_t^j + SOL_t^j + I_t^j + CHP_t^j \quad for \quad \forall j \in r \tag{4}$$

Finally, Table 1 shows the summary statistics of all the variables.

4. Results

In this Section, we present the results from our estimations. First, we estimate how efficiently sited are generation technologies with regard to the consumption and we identify locational patterns related to congestions. Second, we study specific regional surpluses and deficits of generation capacity. Next, we combine all results to sort all regions considering potential impacts on the social welfare related to the installation of new RES.

4.1. Locational efficiency for each technology

First, we analyze how efficient is the location of each technology by

[14] See Appendix II for further details about energy flow calculations.

[15] r takes the following values: 1 for Andalucia, 2 for Aragon, 3 for Asturias, 4 for Cantabria, 5 for Castilla y Leon, 6 for Castilla y La Mancha, 7 for Catalunya, 8 for Valencia, 9 for Extremadura, 10 for Galicia, 11 for Madrid, 12 for Murcia, 13 for Navarra and Rioja, and 14 for Pais Vasco.

Table 1
Summary statistics.

	N	Mean	Std.Dev.	Min.	Max.
$F_t^{i,j}$	678,900	0.0062388	0.0109806	0	0.1817
N_t^i, N_t^j	20,818,140	64.59839	305.0923	0	2,017.1
CC_t^i, CC_t^j	20,818,140	30.65951	115.3714	0	2,178.95
CO_t^i, CO_t^j	20,818,140	50.17001	184.4638	0	1,378.5
H_t^i, H_t^j	20,818,140	24.82642	46.75551	0	734.7238
W_t^i, W_t^j	20,818,140	49.20318	87.72776	0	1,248.627
SOL_t^i, SOL_t^j	20,818,140	15.82529	35.69988	0	258.7267
I_t^i, I_t^j	20,818,140	27.37232	119.6494	0	1,667.933
CHP_t^i, CHP_t^j	20,818,140	36.26291	36.26901	0	191.2189
$G1_t^i$, $G1_t^j$	20,818,140	42.63293	161.6872	0	2,430.652
$G2_t^i$, $G2_t^j$	20,818,140	15.67784	76.97765	0	1,085.627
$G3_t^i$, $G3_t^j$	20,818,140	17.04793	120.0196	0	2,141.392
$G6_t^i$, $G6_t^j$	20,818,140	2.342647	17.17407	0	243.8766
$G7_t^i$, $G7_t^j$	20,818,140	30.23989	102.9536	0	1,386.241
$G8_t^i$, $G8_t^j$	20,818,140	25.58127	122.6711	0	1,227.28
$G9_t^i$, $G9_t^j$	20,818,140	51.53446	263.025	0	2,374.776
$G10_t^i$, $G10_t^j$	20,818,140	20.84302	120.2706	0	1,834.653
$G11_t^i$, $G11_t^j$	20,818,140	27.34457	197.3159	0	2,146.636
$G12_t^i$, $G12_t^j$	20,818,140	34.86667	185.2269	0	2,599.453
$G13_t^i$, $G13_t^j$	20,818,140	2.092436	10.15576	0	180.0169
$G14_t^i$, $G14_t^j$	20,818,140	5.656881	48.5767	0	2,284.322
$G15_t^i$, $G15_t^j$	20,818,140	9.873682	100.7776	0	2,105.36
$G16_t^i$, $G16_t^j$	20,818,140	13.18393	81.9428	0	1,718.192
D^i, D^j	20,818,140	81.3507	57.61394	8.251244	276.4956
C_i^d, C_j^d	20,818,140	.032085	0.0145708	0.0103093	0.0824742
C_i^c, C_j^c	20,818,140	.0018513	0.0003356	0.0012386	0.0025592
$Dist^{i,j}$	20,818,140	551.8508	259.8601	7	1,342

Table 2
Distance effects (DE_g) for each technology.

Technology	g	$\widehat{\beta}_i$	$\widehat{\beta}_j$	DE_g
Wind	W_t	+0.044***	−0.018***	3.48
Imports	I_t	+0.012***	+0.003***	3.37
Hydropower	H_t	+0.029***	0.010***	1.83
Solar	SOL_t	+0.140***	−0.212***	1.66
Coal	CO_t	+0.038***	−0.061***	1.62
Nuclear	N_t	+0.033***	−0.061***	1.55
Combined Cycle	CC_t	+0.049***	+0.023***	1.10
Combined Heat and Power	CHP_t	−0.200***	0.078***	−3.58

* ($p < 0.10$), ** ($p < 0.05$), *** ($p < 0.01$).

Table 3
Average flow congestions.

r = NUTS2	$\widehat{\theta}_{ri}$	$Congest_r$
Galicia	1.726	+461.95%
Asturias	1.603	+396.99%
Pais Vasco	0.797	+121.91%
Castilla-Leon	0.602	+82.50%
Cantabria	0.496	+64.29%
Madrid	0.262	+30.01%
Aragon	0.192	+21.16%
Extremadura	−0.191	−17.43%
Ctat Valenciana	−0.738	−52.18%
Castilla-la-Mancha	−0.936	−60.80%
Catalunya	−0.980	−62.48%
Andalucia	−1.606	−79.93%

Note: $Congest_r$ calculated by $(exp(\widehat{\theta}_{ri}) - 1) * 100$ [%].
$\widehat{\theta}_{ri}$ comes from Table 6 in Appendix I.

the study of the impact of each production on flows (Equation (1)).[16] Detailed estimations are represented in Table 5 in Appendix I.

We evaluate the efficiency of the location for each g generation technology by the *Distance Effect* indicator (DE_g).[17] Results are shown in Table 2. Higher DE_g means lower efficiency and technologies sited further to consumption. The highest DE_g, 3.48 and 3.37, corresponds to wind and imports, respectively. In the opposite, combined cycle coefficient is very low (1.10) due to their closeness to seaports as they need gas liquefying plants. Finally, CHP coefficient is the lowest (−3.58) as these plants are indeed self-consumption installations, i.e. generation plants connected in the same consumption point. This shows wind production should travel further, which clearly impacts on two specific grid-costs fully funded by consumers: grid investments and electricity losses. Actually, higher distance between generation and consumption requires building or reinforcing grids, and higher losses as they are directly proportional to the distance traveled by flows. Moreover, higher electricity losses also affect the power system energy efficiency.

We calculate the average congestions of the transmission grid ($Congest_r$) in each r region. Results are shown in Table 3 and depicted in Fig. 2. It is interesting to highlight how coefficients corresponding to the Northwest areas have higher congestions ($Congest_r$), precisely where most of the wind capacity is installed and more than a half of the annual wind production is generated (REE, 2019a). Indeed, higher congestions also affect the grid-costs and the power system energy efficiency by a higher curtailment on RES, additional grid-investments and extra electricity losses.

4.2. Regional generation capacity

Second, we analyze regional surpluses and deficits of capacity by the study on how the energy produced in each region impacts on flows (Equation (2)), which allow us to identify a surplus or deficit of generation capacity. Admittedly, regions with higher generation capacity

[16] We focus in results from column (4) in Table 5, having the richest set of controls. As all variables are in logs, estimates ($\widehat{\beta}_i$, $\widehat{\beta}_j$) are the elasticities of flows w.r.t. the energy produced by each technology. We estimate how flows ($F_t^{i,j}$) evolve when generation (G_t^i, G_t^j) changes (Equations 5 and 6): $\widehat{\beta}_i = \frac{\partial F_t^{i,j}/F_t^{i,j}}{\partial G_t^i/G_t^i} = \frac{[\%]}{[\%]}$ (5) $\widehat{\beta}_j = \frac{\partial F_t^{i,j}/F_t^{i,j}}{\partial G_t^j/G_t^j} = \frac{[\%]}{[\%]}$ (6).

[17] *Distance Effect* (DE_g) for each technology g evaluates to what extent is relevant increasing the production of this technology where the plant is located (i) in comparison to where the flow travels to (j).This is calculated as $DE_g = (\widehat{\beta}_i - \widehat{\beta}_j)/|\widehat{\beta}_j|$ in pu. We divide each one by $\widehat{\beta}_j$ to make all technologies comparable between them.

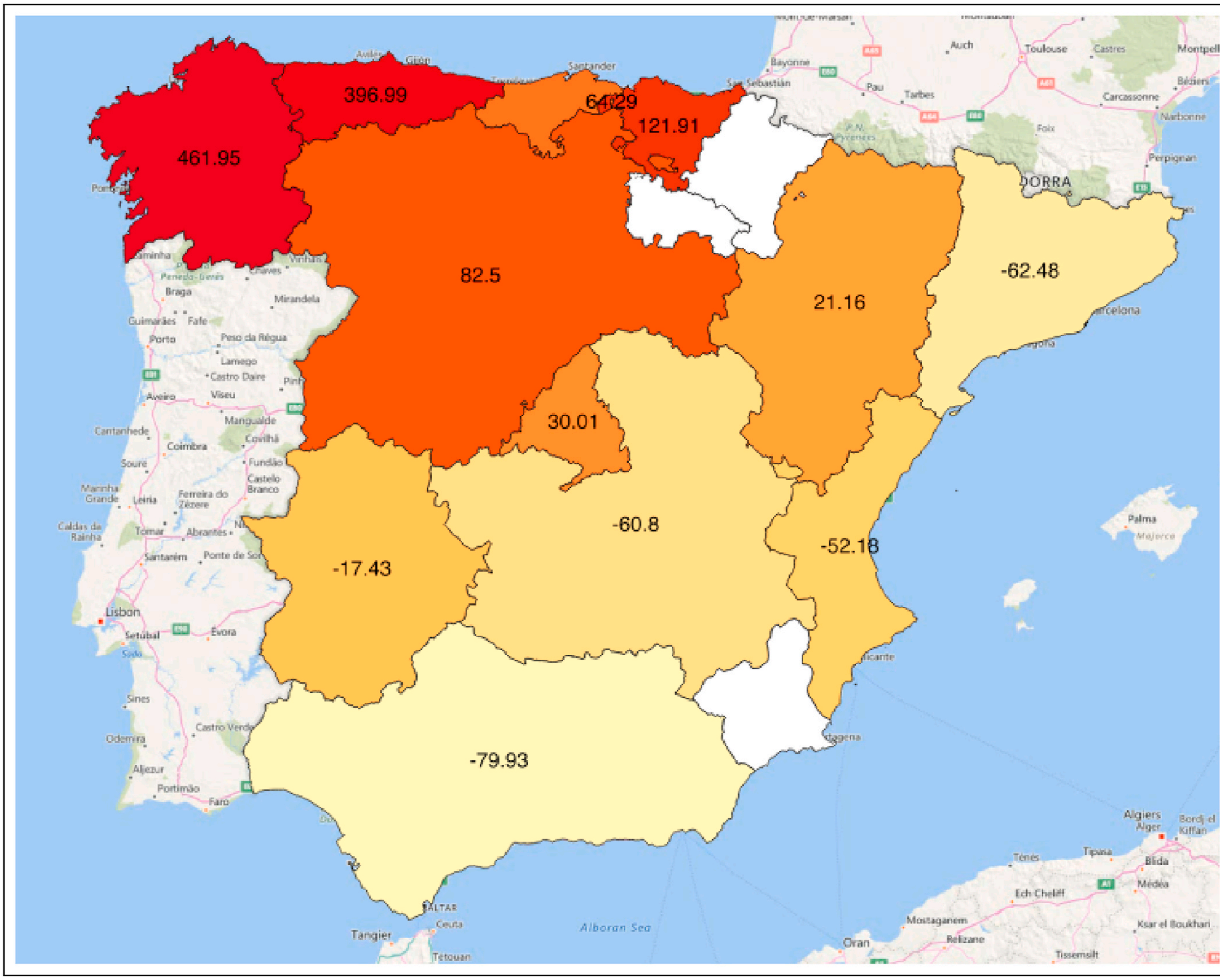

Fig. 2. Average flow congestions (*Congest$_r$*) in %.

Source: own elaboration based on Google Maps and using *Congest$_r$* from Table 3. Non-significant $\widehat{\theta}_{ri}$ are represented in white colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 4
Impact of regional generation in transmission flows.

r = NUTS2	elasticity
Navarra-Rioja	1.072
Asturias	1.038
Galicia	0.748
Castilla-Mancha	0.645
Andalucia	0.271
Catalunya	0.222
Pais Vasco	0.222
Extremadura	0.196
Castilla-Leon	0.194
Aragon	0.1
Madrid	0.067
Ctat.Valenciana	−0.0334
Murcia	−0.113
Cantabria	−0.124

Note: elasticity corresponds to $\widehat{\beta}_i^r$ in Equation 7.

would make a greater use of the transmission grid to send their production energy far.[18] Detailed estimations are represented in Table 7 in Appendix I.We analyze the elasticity of the transmission flows w.r.t. the energy generated within each region. Positive coefficients mean increasing regional production increases transmission flows as this energy should travel far. In the opposite, negative coefficients mean regional production is consumed in the same region. It should be emphasized that coefficients close to 1 correspond to regions with the highest amount of RES, while negative coefficients to regions with the lowest amount of RES (REE, 2019b). This complements previous Section results and highlights there is a surplus of RES in some regions, while a deficit in other. Results are shown in Table 4.

4.3. Social welfare analysis by regions

In order to better exploit our results to define future policies, we

[18] We focus in results from column (4) in Table 7, having the richest set of controls. We estimate how flows ($F_t^{i,j}$) evolve when regional generation (Gr_t^i, Gr_t^j) change (Equations 7 and 8): $\widehat{\beta}_i^r = \frac{\partial F_t^{i,j}/F_t^{i,j}}{\partial Gr_t^i/Gr_t^i} = \frac{[\%]}{[\%]}$ (7)$\widehat{\beta}_j^r = \frac{\partial F_t^{i,j}/F_t^{i,j}}{\partial Gr_t^j/Gr_t^j} = \frac{[\%]}{[\%]}$ (8).

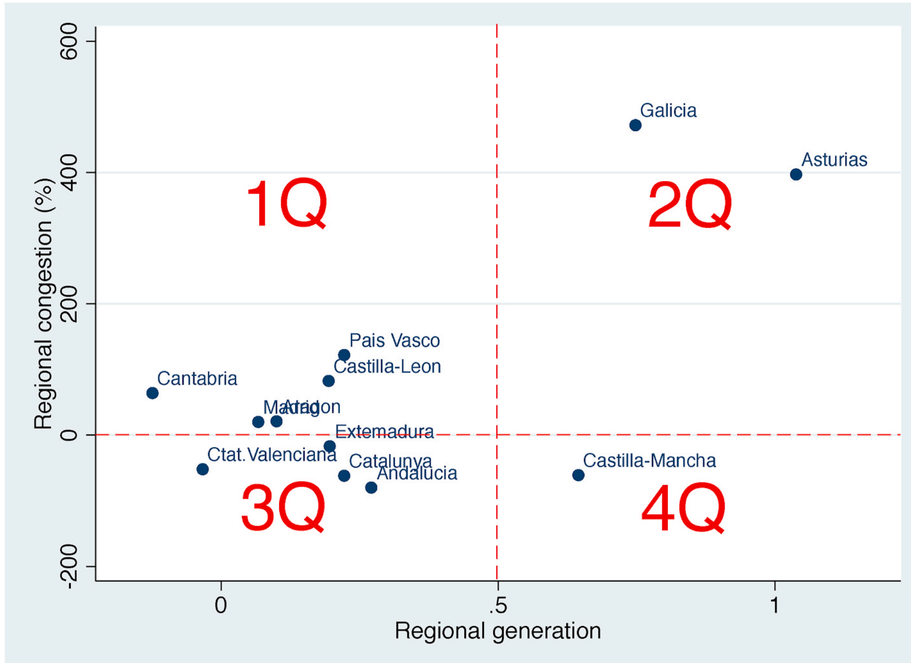

Fig. 3. Regional congestions (*Congest$_r$*) and regional contribution of generation to flows ($\widehat{\beta_i^r}$).
Source: own elaboration.

combine the results from the first and the second set of regressions.[19] Regions are sorted in four groups (Fig. 3):

- 1Q: regions with a deficit of generation capacity, but high regional congestions. Installing more RES would require extra grid-investments to solve congestions, but at the same time would reduce electricity losses as their production should not travel far.
- 2Q: regions with a surplus of generation capacity and high regional congestions. Installing more RES would require extra grid-investments to solve congestions and would increase electricity losses as their production should travel far. This is the least optimal choice from the power system energy efficiency and the social welfare point of view.
- 3Q: regions with a deficit of generation capacity and low regional congestions. Installing more RES would not require important grid-investments and would reduce electricity losses as their production should not travel far. This is the most optimal choice from the power system energy efficiency and the social welfare point of view.
- 4Q: regions with a surplus of generation capacity and low regional congestions. Installing more RES would not require important grid-investments, but would increase electricity losses as their production should travel far.

As is shown in Fig. 3, installing new RES in Galicia and Asturias (2Q) is the worst choice. Indeed, these two regions have already a large amount of RES, but more RES would aggravate congestions, require important grid-investments and increase electricity losses, which means worsen the power system energy efficiency. In the opposite, Ctat. Valenciana, Extremadura, Catalunya and Andalucia (3Q) represent the best choice. Finally, regions in 1Q and 3Q should be analysed case by case: Castilla-Leon and Pais Vasco are close to borders (imports); Cantabria is close to main RES areas (Galicia and Asturias); Madrid is the main consumption area; Aragon is close to Castilla-Leon.

In summary, our results show the location of actual technologies determines the power system energy efficiency and constraints the location of new RES. We find the location decisions impact on the necessary grid-investments and the resultant electricity losses that, in turn, affects the power system energy efficiency. In last, this impacts on the social welfare by the final electricity price paid by consumers.

5. Conclusions and policy implications

Studying and deeply understanding the performance and efficiency of electricity systems is essential to successfully connect new RES, maximise the social welfare and improve the energy efficiency of the power systems. To this end, we study the regional flows, congestions and generation capacity at national level. Moreover, we explore the potentials from the implementation of the gravity models instead of the traditional optimization models. As we show, gravity is a fully valid tool to analyze electricity flows, which also provide novel results to the literature without requiring very big datasets as in optimization models. Indeed, the use of past data in gravity models gives very realistic results, which might complement outcomes from other approaches such as optimization and might be very useful for simulating future scenarios.

First, we estimate the efficiency from each technology location with a new indicator named *Distance Effect*. We find that wind and imports are the least efficiently located: wind capacity is mainly located in the North-West regions and far from main consumption areas, while import connections are in the borders between France, Portugal and Morocco and also far from main cities. On the contrary, combined cycle capacity is efficiently located because it is mostly sited close to seaports and main cities. These results, along with those of other technologies, are a novelty in the literature and confirm that the locations of generation technologies impact on flows, which might result in different uses of the grids and different contributions to the power system energy efficiency.

Second, we study the regional congestions. We find the highest congestions in the North-West regions, while the lowest in the North-East and in the South regions, which highlight the existence of grid bottlenecks related with large RES installed capacity. Third, we analyze

[19] We have not represented Navarra/Rioja and Murcia, whose regional generation coefficient is +1.072 and −0.113, respectively, because coefficients related to congestion are not significant in Table 5. In the first, there is an important surplus of generation, while a deficit in the second.

how the energy produced in each region contributes to flows to detect the potential surplus or deficit of installed generation. Finally, combining both the locational patterns related to congestions and the regional contribution to the flows, we classify all regions between the least and the most optimal to connect new RES from the social point of view. In the top, we have Ctat. Valenciana, Extremadura, Catalunya and Andalucia, while in the opposite, Galicia and Asturias.

The above highlights that locating new generation capacity cannot be overlooked as might impact on the system costs and the power system energy efficiency. Although it seems obvious siting new wind capacity in the most resource-optimal regions -Galicia and Asturias-, this might aggravate congestions and require extra grids investments. In other words, private location decisions for RES might harm social welfare and ultimately affect the energy transition affordability.

Therefore, it is essential to implement policies aimed to efficiently locate RES. First and foremost, our results show that it is necessary to provide open, complete and transparent grid information to all stakeholders. This includes an open grid-dataset identifying nodes with their actual congestions and the regional available capacity for new RES without costly grid reinforcements while the power system energy efficiency is not harmed. This policy recommendation enables businesses to invest wisely, facilitate the correct decisions and innovate practices. Moreover, this guarantees the non-discriminatory access to all grids users and allows to efficiently de-risk the financing of investments. The last is a main principle of the electricity regulation (Newbery et al., 2018) as the clean electricity systems are becoming more capital intensive. According to IEA (2018), an efficient clean transition requires good polices and data insufficiency could lead to unfavourable choices.

Second, splitting the unique Spanish bidding zone in two -North and South-following the regionals congestions we find in the results. However, this requires further analyses as the replacement of conventional generation plants by RES might change the actual congestion picture, which in turn might determine the future allocative efficiency. Third, replacing the uniform UoS charges by different regional charges, which could also offset lower RES incomes in non-optimal regions. Indeed, our findings shed light on their definition, but this also impacts on the RES incumbents and might shrink their future revenues. As the previous policy, the connection of large amount of RES in a short period of time might change the actual congestions, what makes difficult to maintain the same regional charges for a long period of time.

Fourth, moving from *shallow* connection to *deep* connection charges could provide stronger locational incentives. However, its practical implementation cannot always be transparent and fair, especially in the highest voltage grids −400kV- since a transmission line can be used by multiple generators and the first generator funds it. Fifth, improving the transmission planning criteria to align the actual grid capacity with the resource-optimal RES locations, which is especially useful in the Southern regions -Andalucia and Extremadura-whose potential solar production is higher than some Northern regions, such as Galicia, Asturias and Cantabria. This would also reduce the RES connection times as the grid investments would be prepared for allocating RES. However, this policy recommendation requires challenging agreements between national, regional governments and the grid-operators. In addition, building new grids in anticipation of future RES might encourage grid operators to make non-viable over-investments funded by all the consumers.

Sixth, implementing some locational incentives in future RES auctions to align new generation capacity with the actual grid congestion picture. In this context, there are several alternatives as including economic incentives to offset the minor annual wind and solar production in some regions, including a list of technology-specific RES sites, or including different regional RES quotas. All them have two main advantages compared to the previous policies: they only impact on the entrants and does not require a stable grid congestion picture in the long run as locational incentives are recalculated in each auction. However, these incentives might impact on the proper functioning of the wholesale market as some generators would not take the same market risk as incumbents. Moreover, the definition of regional RES quotas or a list of technology-specific RES sites also require challenging agreements between national, regional governments and the grid-operators. In this context, some regional governments might provide specific tax benefits or different legal permits, which affects the efficiency from implementing locational incentives in the auctions.

In summary, each policy recommendation has its pros and cons, which need deep analyses case by case. Future empirical studies could use our results to study how locating new RES impacts on grid congestions and electricity losses, which is essential to define efficient locational incentives in auctions.

CRediT authorship contribution statement

Maria Teresa Costa-Campi: Conceptualization, Supervision, Project administration, Funding acquisition. **Daniel Davi-Arderius:** Conceptualization, Methodology, Software, Data curation, Formal analysis, Writing – original draft. **Elisa Trujillo-Baute:** Validation, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix I

Centrality controls

In this paper we control for the relative position of each node w.r.t. the rest by *degree of centrality* (C_n^d) and the *closeness centrality* (C_n^c):

$$C_n^d = \frac{d}{N-1} \tag{9}$$

$$C_n^c = \frac{N-1}{\sum_{i \neq j}^{N-1} \delta_{ij}} \tag{10}$$

where d is the number of transmission lines connected to n, N the total number of n ($N = 98$) and δ_{ij} its geodesic distance, i.e. the shortest path through lines between each two pair of n.

Geographical information

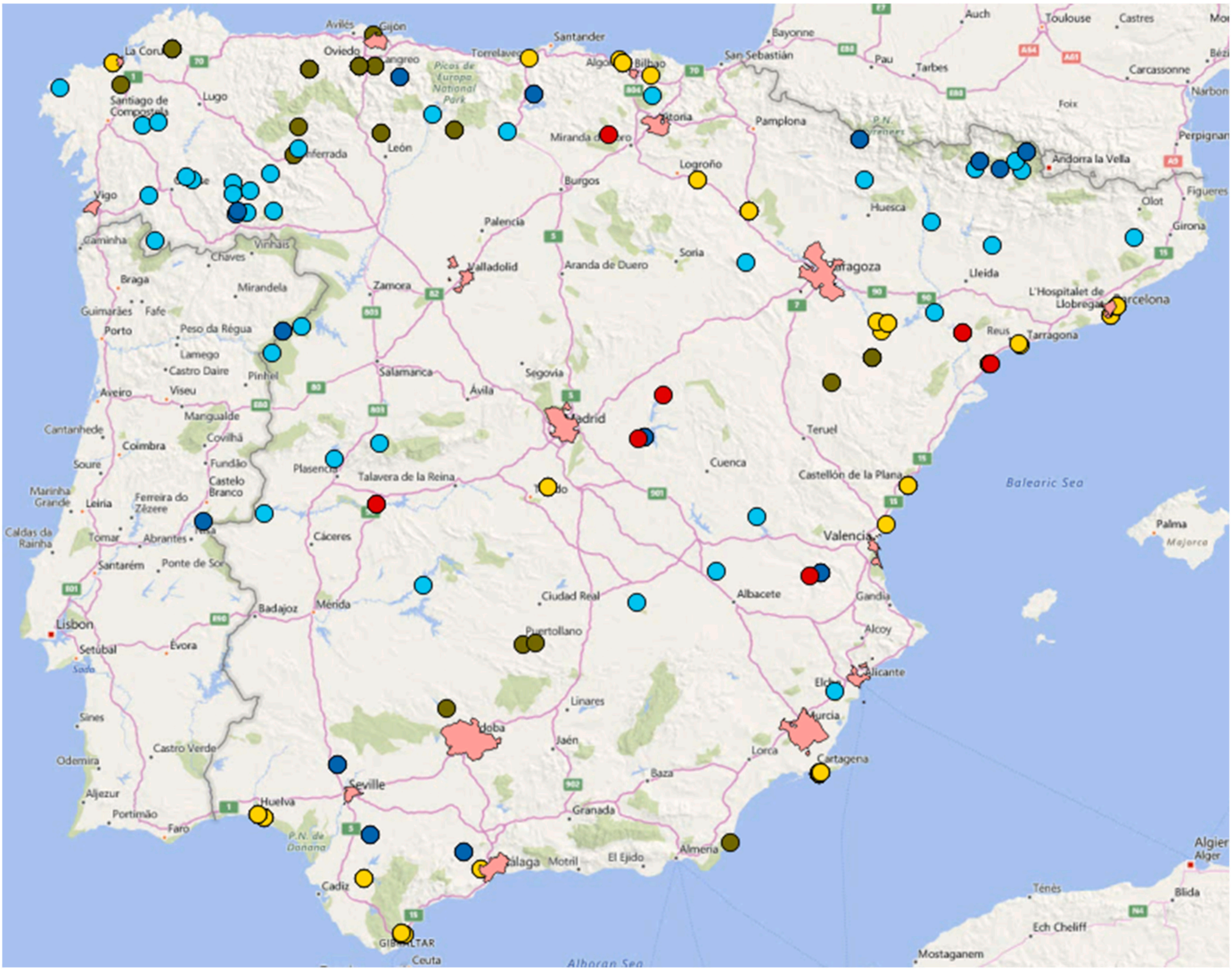

Fig. 4. Main generation plants (circles) and cities (rose areas) considered.
Note: Circle colours indicate the technology: red for nuclear, yellow combined cycle, brown coal, clear blue hydropower and dark blue pumping.
Source: own elaboration based on Google Maps.

Estimations

Table 5
Generation impacts on flows.

	(1)	(2)	(3)	(4)
	$F_t^{i,j}$	$F_t^{i,j}$	$F_t^{i,j}$	$F_t^{i,j}$
PEAK	−0.0629***	−0.0844***	−0.104***	0.164***
	(0.00447)	(0.00445)	(0.00457)	(0.00677)
N_t^i (log)	0.0259***	0.0238***	0.0240***	0.0331***
	(0.000305)	(0.000310)	(0.000310)	(0.000405)
CC_t^i (log)	0.0364***	0.0435***	0.0437***	0.0490***
	(0.000414)	(0.000436)	(0.000437)	(0.000493)
CO_t^i (log)	0.0313***	0.0405***	0.0414***	0.0378***
	(0.000292)	(0.000302)	(0.000306)	(0.000371)
H_t^i (log)	0.0304***	0.0445***	0.0432***	0.0290***
	(0.000915)	(0.000867)	(0.000863)	(0.00110)
W_t^i (log)	0.0266***	0.0241***	0.0245***	0.0445***
	(0.000428)	(0.000407)	(0.000407)	(0.000807)
SOL_t^i (log)	0.0624***	0.0525***	0.0578***	0.140***
	(0.00133)	(0.00143)	(0.00146)	(0.00299)

(continued on next page)

Table 5 (*continued*)

	(1)	(2)	(3)	(4)
	$F_t^{i,j}$	$F_t^{i,j}$	$F_t^{i,j}$	$F_t^{i,j}$
I_t^i (log)	0.00858***	0.0211***	0.0216***	0.0118***
	(0.000469)	(0.000504)	(0.000503)	(0.000497)
CHP_t^i (log)	−0.111***	−0.133***	−0.137***	−0.200***
	(0.00149)	(0.00159)	(0.00162)	(0.00278)
N_t^j (log)	−0.0454***	−0.0422***	−0.0421***	−0.0606***
	(0.000615)	(0.000606)	(0.000605)	(0.000657)
CC_t^j (log)	0.0159***	0.0212***	0.0219***	0.0233***
	(0.000358)	(0.000392)	(0.000394)	(0.000443)
CO_t^j (log)	−0.0551***	−0.0524***	−0.0511***	−0.0608***
	(0.000625)	(0.000635)	(0.000637)	(0.000540)
H_t^j (log)	−0.0420***	−0.0403***	−0.0406***	0.0102***
	(0.000583)	(0.000567)	(0.000570)	(0.00110)
W_t^j (log)	−0.00416***	−0.00704***	−0.00698***	−0.0180***
	(0.000463)	(0.000423)	(0.000423)	(0.000619)
SOL_t^j (log)	−0.0111***	0.0107***	0.0158***	−0.212***
	(0.00125)	(0.00131)	(0.00134)	(0.00286)
I_t^j (log)	−0.0110***	−0.0138***	−0.0132***	0.00269***
	(0.000572)	(0.000635)	(0.000637)	(0.000653)
CHP_t^j (log)	−0.0567***	−0.0693***	−0.0734***	0.0776***
	(0.00166)	(0.00177)	(0.00180)	(0.00288)
D^i (log)	0.153***	0.152***	0.146***	0.213***
	(0.00298)	(0.00319)	(0.00321)	(0.00441)
D^j (log)	−0.311***	−0.344***	−0.350***	−0.245***
	(0.00254)	(0.00249)	(0.00251)	(0.00349)
$Dist^{i,j}$ (log)	0.338***	0.374***	0.371***	0.383***
	(0.00362)	(0.00344)	(0.00345)	(0.00286)
Constant	−5.577***	1.055***	1.312***	0.900***
	(0.0347)	(0.0959)	(0.0972)	(0.293)
Observations	678,900	678,900	678,900	678,900
$R2$	0.180	0.211	0.213	0.329
Centrality:				
Degree		Y	Y	Y
Closeness		Y	Y	Y
Seasonality:				
Year			Y	Y
Month			Y	Y
Day of week			Y	Y
Fixed effects:				
NUTS2:				Y

Standard errors in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 6
NUTS2 FE dummies from column (4) in Table 5.

(NUTS2)	Dummy	NUTS2 Fixed Effects
Andalucia	$\widehat{\theta}_{1i}$	−1.606***
		(0.0256)
Aragon	$\widehat{\theta}_{2i}$	0.192***
		(0.0215)
Asturias	$\widehat{\theta}_{3i}$	1.603***
		(0.0332)
Cantabria	$\widehat{\theta}_{6i}$	0.496***
		(0.0321)
Castilla-Leon	$\widehat{\theta}_{7i}$	0.602***
		(0.0218)
Castilla-La-Mancha	$\widehat{\theta}_{8i}$	−0.936***
		(0.0230)
Cataluña	$\widehat{\theta}_{9i}$	−0.980***
		(0.0249)
Ctat Valenciana	$\widehat{\theta}_{10i}$	−0.738***
		(0.0252)
Extremadura	$\widehat{\theta}_{11i}$	−0.191***
		(0.0252)
Galicia	$\widehat{\theta}_{12i}$	1.726***
		(0.0289)
Madrid	$\widehat{\theta}_{13i}$	0.262***

(*continued on next page*)

Table 6 (*continued*)

(NUTS2)	Dummy	NUTS2 Fixed Effects
		(0.0346)
Murcia	$\widehat{\theta}_{14i}$	−0.032
		(0.0268)
Pais Vasco	$\widehat{\theta}_{16i}$	0.797***
		(0.0282)

Standard errors in parentheses.
* (p < 0.10), ** (p < 0.05), *** (p < 0.01).

Table 7
NUTS2 Generation impacts on flows.

	(1)	(2)	(3)	(4)
	$F_t^{i,j}$	$F_t^{i,j}$	$F_t^{i,j}$	$F_t^{i,j}$
PEAK	0.0119***	0.00929**	0.00952**	0.0258***
	(0.00374)	(0.00372)	(0.00372)	(0.00317)
$G1^i$ (log) (Andalucia)	0.188***	0.182***	0.182***	0.271***
	(0.00195)	(0.00202)	(0.00203)	(0.0105)
$G2^i$ (log) (Aragon)	0.298***	0.284***	0.284***	0.100***
	(0.00207)	(0.00207)	(0.00207)	(0.0121)
$G3^i$ (log) (Asturias)	0.309***	0.301***	0.301***	1.038***
	(0.00193)	(0.00196)	(0.00196)	(0.0295)
$G4^i$ (log) (Cantabria)	0.270***	0.259***	0.259***	−0.124***
	(0.00244)	(0.00251)	(0.00251)	(0.0429)
$G5^i$ (log) (Castilla-Leon)	0.316***	0.302***	0.301***	0.194***
	(0.00210)	(0.00215)	(0.00215)	(0.00417)
$G6^i$ (log) (Castilla-Mancha)	0.231***	0.216***	0.216***	0.645***
	(0.00204)	(0.00210)	(0.00210)	(0.0102)
$G7^i$ (log) (Catalunya)	0.247***	0.237***	0.237***	0.222***
	(0.00189)	(0.00194)	(0.00194)	(0.0143)
$G8^i$ (log) (Ctat.Valenciana)	0.223***	0.213***	0.213***	−0.0334***
	(0.00205)	(0.00210)	(0.00210)	(0.00999)
$G9^i$ (log) (Extremadura)	0.250***	0.239***	0.239***	0.196***
	(0.00197)	(0.00204)	(0.00204)	(0.00591)
$G10^i$ (log) (Galicia)	0.318***	0.314***	0.314***	0.748***
	(0.00202)	(0.00204)	(0.00204)	(0.0171)
$G11^i$ (log) (Madrid)	0.226***	0.207***	0.207***	0.0670**
	(0.00225)	(0.00232)	(0.00232)	(0.0315)
$G12^i$ (log) (Murcia)	0.262***	0.257***	0.257***	−0.113***
	(0.00210)	(0.00208)	(0.00208)	(0.0127)
$G13^i$ (log) (Navarra-Rioja)	0.307***	0.292***	0.292***	1.072***
	(0.00208)	(0.00214)	(0.00214)	(0.0540)
$G14^i$ (log) (Pais Vasco)	0.288***	0.278***	0.278***	0.222***
	(0.00215)	(0.00218)	(0.00218)	(0.0136)
$G1^j$ (log) (Andalucia)	−0.143***	−0.129***	−0.130***	−0.347***
	(0.00241)	(0.00249)	(0.00251)	(0.00816)
$G2^j$ (log) (Aragon)	−0.264***	−0.241***	−0.242***	−0.147***
	(0.00270)	(0.00289)	(0.00292)	(0.0324)
$G3^j$ (log) (Asturias)	−0.290***	−0.273***	−0.274***	−1.137***
	(0.00248)	(0.00262)	(0.00264)	(0.0366)
$G4^j$ (log) (Cantabria)	−0.226***	−0.205***	−0.206***	0.300***
	(0.00270)	(0.00284)	(0.00286)	(0.0228)
$G5^j$ (log) (Castilla-Leon)	−0.250***	−0.226***	−0.226***	−0.222***
	(0.00261)	(0.00275)	(0.00277)	(0.00674)
$G6^j$ (log) (Castilla-Mancha)	−0.181***	−0.159***	−0.159***	−0.526***
	(0.00249)	(0.00266)	(0.00268)	(0.00874)
$G7^j$ (log) (Catalunya)	−0.186***	−0.172***	−0.173***	−0.183***
	(0.00254)	(0.00262)	(0.00265)	(0.00826)
$G8^j$ (log) (Ctat.Valenciana)	−0.132***	−0.113***	−0.113***	−0.106***
	(0.00255)	(0.00268)	(0.00271)	(0.00808)
$G9^j$ (log) (Extremadura)	−0.197***	−0.180***	−0.181***	−0.217***
	(0.00276)	(0.00280)	(0.00282)	(0.00522)
$G10^j$ (log) (Galicia)	−0.289***	−0.278***	−0.279***	−0.515***
	(0.00239)	(0.00244)	(0.00246)	(0.0176)
$G11^j$ (log) (Madrid)	−0.182***	−0.156***	−0.157***	−0.216***
	(0.00270)	(0.00297)	(0.00299)	(0.0193)
$G12^j$ (log) (Murcia)	−0.116***	−0.103***	−0.104***	0.178***
	(0.00249)	(0.00260)	(0.00262)	(0.0193)
$G13^j$ (log) (Navarra-Rioja)	−0.240***	−0.216***	−0.217***	−1.129***
	(0.00257)	(0.00276)	(0.00279)	(0.0661)
$G14^j$ (log) (Pais Vasco)	−0.252***	−0.234***	−0.235***	0.264***
	(0.00253)	(0.00271)	(0.00273)	(0.0200)
D^i (log)	0.159***	0.192***	0.192***	−1.927***

(*continued on next page*)

Table 7 (*continued*)

	(1)	(2)	(3)	(4)
	$F_t^{i,j}$	$F_t^{i,j}$	$F_t^{i,j}$	$F_t^{i,j}$
	(0.00368)	(0.00420)	(0.00419)	(0.330)
D^j (log)	−0.172***	−0.194***	−0.194***	0.497**
	(0.00358)	(0.00345)	(0.00346)	(0.228)
$Dist^{i,j}$ (log)	0.362***	0.368***	0.368***	−0.818***
	(0.00311)	(0.00327)	(0.00327)	(0.220)
Constant	1.222**	2.233***	2.149***	26.23***
	(0.485)	(0.507)	(0.509)	(5.741)
Observations	678,900	678,900	678,900	678,900
(R2)	0.292	0.296	0.297	0.559
Centrality:				
Degree		Y	Y	Y
Closeness		Y	Y	Y
Seasonality:				
Year			Y	Y
Month			Y	Y
Day of week			Y	Y
Fixed effects:				
TL:				Y

Standard errors in parentheses.
* ($p < 0.10$), ** ($p < 0.05$), *** ($p < 0.01$).

Appendix II

Electricity networks are composed by high voltage lines that connect nodes, also known as substations. A node represents the physical location in the network, where transmission lines intersect between them. They can also connect with generation plants, industrial consumers or transformers to feed the distribution grids. A pair of nodes (i, j) represents a HV line and its temporal flow ($F_t^{i,j}$) can be easily estimated using the Marginal Loss Coefficients (MLC_t^n) associated to both nodes. Next, we define Marginal Loss Coefficients and then we show to estimate flows ($F_t^{i,j}$) for each HV line. Precisely, this is the endogenous variable in this paper.

Marginal Loss Coefficients

As is defined in REE (2019b), MLC_t^n indicates how total system losses (LT_{t0}) would change if energy generated (G_t^n) and injected in this specific n node increased (Equation (11)):

$$MLC_t^n = \frac{\partial LT_{t0}}{\partial G_t^n} \tag{11}$$

For each t and n, TSO makes a ceteris paribus simulation, which consists on $\Delta G_t^n = 1$ MWh, and recalculates all the new flows in the electricity system and the resultant electricity losses (LT_{t1}^n). Comparing both the initial losses (LT_{t0}) and (LT_{t1}^n), MLC_t^n is calculated (Equation (12)):

$$MLC_t^n = \frac{LT_{t1}^n}{LT_{t0}^n} - 1[pu] \tag{12}$$

Therefore, MLC_t^n inform us if there is a deficit or surplus of generation for each node:

- When MLC_t^n There is a deficit of generation, or surplus of consumption, at the$n$at time$t$.
- When $MLC_t^n > 0 \rightarrow$ There is a surplus of generation, or deficit of consumption, at the n at time t.

Flows

Hourly flows ($F_t^{i,j}$) are calculated as follows (Equation (13)):

$$F_t i, j = MLF_t^i - MLF_t^j \tag{13}$$

Three-phase apparent electric power (S_t) is defined as (Equation (14)):

$$S_t = \sqrt{P_t^2 + Q_t^2} = \sqrt{3} * U_t * I_t \tag{14}$$

where P_t is the active power, Q_t is the reactive power, U_t is the voltage and I_t the current. To simplify, we consider $Q_t = 0$ and then $S_t \equiv P_t$. Therefore, electricity losses (Equation (15)):

$$LT_t = I_t^2 * R \tag{15}$$

where R is the impedance. Combining both Equations (14) and (15), and including all constant parameters into k (Equation (16)):

$$LT_t = \left[\frac{P_t}{\sqrt{3} * U_t}\right]^2 * R = P_t^2 * \left[\frac{R}{3 * U_t^2}\right] = P_t^2 * k \tag{16}$$

Therefore, Marginal Loss Factors (MLF_t) might be calculated as (Equation (17)):

$$MLF_t = \frac{\partial LT_t}{\partial P_t} = 2 * P_t * k \tag{17}$$

Finally, flows between two pair of nodes ($F_t^{i,j}$) can be somehow calculated[20] as the difference between MLF_t^i and MLF_t^j (Equation (18)):

$$F_t^{i,j} = MLF_t^i - MLF_t^j = 2 * k * \left(P_t^i - P_t^j\right) \tag{18}$$

In our dataset we are including each transmission line twice [21], then $F_t^{i,j}$ is either positive, negative or zero. Then, we only consider $F_t^{i,j} \geq 0$ and if $F_t^{i,j} < 0 \rightarrow F_t^{i,j} = 0$.

$F_t^{i,j} \geq 0$ implies that $MLF_t^i > MLF_t^j$. In other words, there is a surplus of generation at i node or/and a deficit of generation in j. Therefore, $F_t^{i,j}$ comes always from the i source node to the j destination node. This implies that if more energy is injected in i source node - where there is already a surplus of generation - this energy should travel through the transmission lines to find consumption and the impact on flows is expected to be positive. Regarding the j destination node, arguments are the opposite to i and if more energy is injected in j destination node - where there is deficit of generation - this energy does not need to travel from the source node i and $F_t^{i,j}$ reduces.

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[20] *Note:* $F_t^{i,j}$ in Equation (18) is not represented in MWh. However, this is not relevant in our analysis because we calculate elasticities and only need $\partial F_t^{i,j}/F_t^{i,j}$ (see Equations 5 and 6). Moreover, it is not necessary calculating k because it is constant for each pair of nodes during all the period of time.

[21] In the first observation, i is the source node and j the destination. Vice-versa, in the second.

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