Document de treball de l'IEB 2016/4

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Energy Sustainability

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treball de l'IEB

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The **Chair of Energy Sustainability of the University of Barcelona-IEB** is funded by the following enterprises ACS, CEPSA, CLH, Enagas, Endesa, FCC Energia, HC Energia, Gas Natural Fenosa, and Repsol) through FUNSEAM (Foundation for Energy and Environmental Sustainability).

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ABSTRACT: Although electricity losses constitute an important, but inevitable, amount of wasted resources (and a share that has to be funded), they remain one of the lesser known parts of an electricity system, and this despite the fact that the decisions of generators, transmission and distribution system operators and consumers all impact on them. In this paper we analyse the effects of such losses from two perspectives: from that of consumption or outflows and from that of generation or inflows. Given that end-user consumption varies across the day, consumption has direct implications for electricity losses. Indeed, demand-side management policies seek to encourage consumers to use less energy during peak hours and to reduce network congestion. At the same time, from the perspective of generation, the recent growth in distributed generation has modified the traditional, unidirectional, downward flows in electricity systems. This affects losses as energy is produced in the lower voltage network, which is closer to points of consumption. In this paper we evaluate the impact of consumption patterns and different generation technologies on energy losses. To do so, we draw on data from a real electricity system with a high level of renewable penetration, namely, that of Spain between 2011 and 2013. To the best of our knowledge, this is the first paper to analyse the real impact of consumption and the effect of each generation technology on energy losses, offering an opportunity to evaluate the potential benefits of demand-side management policies and distributed generation. Based on our results, we make a number of regulatory recommendations aimed at exploiting to the full these potential benefits. Our results should serve as a baseline for countries that are in the early stages of implementing these policies.

JEL Codes: L51, L94

Keywords: Regulation, networks, energy losses, distributed generation

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1 Introduction

An electricity system serves to transport energy to consumption points, given that generation plants are not always sited close to homes and industries. To guarantee the success of the system, four essential activities have to be successfully managed: generation, transmission, distribution and retailing. Traditionally, electricity is generated in large-scale plants located near raw materials, or reservoirs in the case of hydropower. Economies of scale are critical in the generation stage before the energy can be sent to points of consumption via a transmission network comprising high-voltage lines. In recent years, a number of new, small generation plants have been connected to the distribution grid, which are known as distributed generation (DG) (Ackermann et al., 2001). To distribute the electricity among consumers, low-voltage (LV) distribution lines are used to transport power to meters. Finally, retailing is responsible for billing.

Owing to certain physical phenomena, electricity systems always yield less than 100%, with some energy being lost as it flows through the system's components: lines, electric transformers, etc. This means that when a consumer i wants to consume q_i units of energy (UoE) as recorded by their meter, $(q_i + \delta_i)$ UoE have to be produced by a generation plant, given that δ_i UoE are lost in the grids. In the aggregate, Q represents total meter consumption (Eq. 1) and Q_L is the meter consumption with the losses incurred (Eq. 2):

$$Q = \sum_i q_i \quad (1)$$

$$Q_L = \sum_i (q_i + \delta_i) = \sum_i q_{il} \quad (2)$$

Cross country comparisons of electricity losses are far from straightforward, because, among other reasons, regulatory definitions vary; consumption from the meter (or fraud) may or may not be considered as an energy loss; and heterogeneous levels of voltages are operated by the transmission system operators (TSOs) and the distribution system operators (DSOs) (ERGEG, 2008). In Spain, losses in 2012 represented 8.90% of the energy injected in the grid (generation and imports), resulting in an annual cost of 1,160 M¹ for the Spanish electricity system, which has to be borne by the final electricity consumers. To put this figure in context, total loss levels published in the World Bank Database² for other countries in the same year were 7.92% in the United Kingdom, 3.94% in Germany, 6.74% in France, 5.40% in Austria, 6.29% in the United States of America and 5.06% in Australia.

The mechanism via which energy losses affect the retail price is illustrated in Figure 1. First, based on the characteristics of the formation of the electricity wholesale price (WP), losses exert an upward pressure on total demand, so that the D curve is displaced upwards to D_L . Second, real hourly demand might differ from that estimated on the day-ahead wholesale market, which means additional adjustment costs are incurred. Third, when losses are (totally or partially) borne by the end-users, three possible mechanisms can be applied: the regular network tariff (as in France, Sweden, Norway, etc.), a special tariff (as in Austria, Poland, etc.) or other specific mechanisms (Italy, Portugal, United Kingdom and Spain) (ERGEG, 2008). In the end, regardless of the mechanism, when the losses are borne by the end-users, the amount they pay ($q_{il} \cdot p_{il}$) and the consumer surplus are both affected (ENTSO-E, 2014). In the period 2011-2013, losses in Spain represented between 1.47 and

¹Annual cost of losses is calculated by multiplying hourly losses of energy by the MWh hourly price. Costs of CO2 emissions and energy savings targets are not included. This is the same methodology adopted herein to calculate loss costs.

²Source: World Bank Database - *Electric power transmission and distribution losses (% of output)*. <http://data.worldbank.org/indicator/EG.ELC.LOSS.ZS> (last consulted on 15 September, 2015).

5.19% of the retail price of electricity³.

Figure 1: General loss impacts on the retail market price.

Note: D is the aggregate demand curve of consumers at the meter (without losses); D_L is the same curve taking losses into consideration; S is the aggregate supply curve of generation; d and s are the demand and supply curve for a consumer i ; q_i is the individual consumption at the meter (without losses); q_{il} is the individual meter consumption with losses; p_{il} is the price associated with q_{il} ; Q is the aggregation of q_i ; Q_L is the aggregation of q_{il} ; P is the wholesale price associated with Q ; P_L is the wholesale price associated with Q_L .

The implementation of policies that modify electricity flows, on the demand and supply side, could have an impact on losses. In Spain, as in other European countries, they include, for example, the massive introduction of intelligent meter systems (or smart meters) to promote the active participation of consumers in the electricity supply market via the use of innovative pricing formulas, and the promotion of electricity generation from renewable energy sources (RES-E), which in most cases has been implemented in conjunction with a priority dispatch for generation from promoted technologies (European Directive 2009/72/EC).

On the demand side (energy outflows), the impact of consumers on losses is unequal, depending on the voltage of the network where consumers are connected and how peaked their demand profile is (Shaw et al., 2009). The role of the DSO regarding consumers is passive since the unbundling of activities (European Directive 1996/92/EC), while the possibilities of modifying peak demand profiles are restricted to specific technological solutions, such as smart meters, which can provide consumers with clearer price signals that might in turn modify their behaviour. In this line, European Directive 2012/27/EC, requires network tariffs and regulation improvements to support dynamic pricing for demand response by final consumers, such as time-of-use tariffs, critical peak-pricing, real time pricing and peak time rebates.

On the supply side (energy inflows) and in response to the 2020 European Strategy, the

³These are average costs and vary with the level of voltage where consumers are connected and the tariff scheme being implemented. In general, the lowest costs are associated with the heaviest consumers connected to the highest voltage grids.

share of energy produced by RES-E in Europe (EU28) has increased from 14.32% in 2004 to 25.37% in 2013. This change has been accompanied by the installation of new small RES-E plants connected directly to DSO networks (DG) and located close to the points of consumption. This had had a significant impact on most electricity systems. For instance, in Spain, a quarter of the country's total generation between 2011 and 2013 was produced directly by plants connected to this network. These changes have modified traditional unidirectional flows from transmission to distribution, and a series of technical and operational problems have arisen in relation to their geographical dispersion, predictability, the flexibility of the remaining generation, the correlation between production and consumption profiles, and the extent to which the network can absorb the imbalances between them.

Although intuition tells us that a higher share of generation in close proximity to consumers would reduce energy losses and grid congestion, as the energy would have to travel over shorter distances, DG plants are not always properly sited close to the main points of consumption, their production is not always dispatchable⁴ and the smaller plants are often operated and fully controlled by their owners (Eurelectric, 2013a). As a result, DG production might not coincide with demand requirements. A number of authors, including Quezada et al. (2006) and Marinopoulos et al. (2011), report losses follow a U-shape trajectory as function of the DG penetration in the networks⁵, which means they tend to fall at low levels of DG capacity, but increase after a given level is reached. The Spanish regulatory framework⁶ provides for the free location of electricity generation, which has resulted in the heterogeneous establishment of DG capacity throughout the country's grid.

The potential consequences, problems and benefits to be derived from the active participation of consumers (smart meters) and the widespread penetration of DG have called the current DSO regulatory framework into question. In this regard, CEER (2015) proposes various ideas that need to be considered in the future. For example, in the case of consumption and smart meters, future tariffs should aim at encouraging consumers to reduce peak demand as a lever for increasing the efficiency of electricity systems. Moreover, tariffs should give clear economic signals, enable DSOs to recover their costs and be compatible with retail competition. In the case of generation, DG has increased the complexity of flows in the distribution grids and with them the challenges for their efficient management. Hence, it has been proposed that the relationship between the TSO and the DSO needs to evolve by adopting a number of principles: a whole system approach, greater coordination, a greater exchange of data, greater flexibility and a fairer cost sharing strategy. Moreover, as the interaction between, and communication with, consumers and producers increases, the DSO should take on a range of new activities and responsibilities. Here, smart grid investments seem to represent a key facilitator (Farhangi, 2010).

To the best of our knowledge, no previous studies have empirically assessed (ex-post) the determinants of losses on transmission and distribution from the demand and supply side in a whole real electricity system. We have selected Spain because, among the five biggest economies of Europe, it had the highest share of RES-E⁷ in 2013: 36.39%. In this study we, first, estimate the impact of consumption on losses, which allows us to quantify the poten-

⁴*Dispatchable sources* are technologies whose output can be adjusted or turned on/off on request. This is not the case of photovoltaic systems, where for a third of the day they do not produce, or small wind plants.

⁵*Level of DG penetration in a network* is the share of energy generated by DG in an area with respect to total consumption.

⁶Royal Decree 54/1997.

⁷From 2004 to 2013, the five biggest economies in Europe increased their RES-E share of energy production from 9.40 to 25.59% in Germany, 3.54 to 13.85% in the UK, 13.79 to 16.87% in France, 16.09 to 31.30% in Italy, and 18.98 to 36.39% in Spain. Source: Eurostat Database - *Short Assessment of Renewable Energy Sources* (% of electricity generation from all sources). <http://ec.europa.eu/eurostat/web/energy/data/shares> (last consulted on 24 September, 2015).

tial loss reductions of policies devoted to smoothing the consumption demand profile due to lower levels of grid congestion. Second, we estimate the costs and the short/long-run effects on losses for each power generation technology. An interesting comparison is conducted between DG technologies (wind, solar and CHP) installed during the last decade in Spain and all other traditional base sources (nuclear, coal, combined cycle), in which we evaluate their differences in terms of losses along with their economic costs and benefits. This allows us to make a contribution to the scarce literature examining economy-wide aspects of DG (Allan et al., 2015). Our results should be useful for regulators and policymakers in countries with a low penetration of RES-E, or that are in an earlier stage in the implementation of DG, in order that they might take better advantage of their potential. Indeed, today, the distribution network is used for quite a different purpose to that for which it was employed two decades ago.

In this paper, Section 2 provides an overview of the related academic literature. The European regulatory framework of losses and the Spanish case are explained in Section 3, including definitions and characteristics. The model and empirical strategy are described in Section 4 and, in Section 5 the results of the estimations are presented from the perspective of the outflow (consumption) and inflow (generation). Losses are quantified in terms of flows and economic cost. Finally, Section 6 includes conclusions, policy implications and regulatory recommendations.

2 Related Literature

The literature examining electricity losses can be classified according to the scope of the policy on either the demand or supply sides. This review section is organised according to this focus and on the impact of policies oriented at modifying either consumer or TSO/DSO behaviour.

In the case of demand policies impacting consumer behaviour (energy outflows), demand side management (DSM) is seen to play a key role. The main target of DSM is to shift demand from peak to off-peak periods so as to obtain a better performance from the infrastructure, avoid the congestion problems affecting certain nodes⁸, adapt demand to the capacity of generation at each moment in time and reduce losses. DSM calls on various techniques: load limiters, load-interruptible programs, time-of-use pricing and smart metering (Strbac, 2008). Information and communication technology (ICT) is a major facilitator of the implementation of DSM. The impact of DSM on losses has been estimated by Shaw et al. (2009) and Cronenberg et al. (2012).

First, Shaw et al. (2009) simulate potential loss reductions by changing the shape of the demand profile for Electricity Network West (ENW), one of the 14 distribution network operators in Great Britain. The study focuses on domestic consumers that present a strongly peaked demand profile, as they pay a single flat rate for each unit of consumption, irrespective of the time period. As the variable component of losses depends on the square of current, this could be reduced if the peak load is delayed to off-peak periods. They use a spreadsheet model that combines network power flow and loss data with consumption profiles and report total loss reductions of up to 1.4%, depending on the peak reduction and when this delay is allocated. Second, Cronenberg et al. (2012) simulate potential loss reductions from active demand (AD) programs aimed at reducing domestic peak loads in Spain, Germany, Italy and Belgium projected to 2020. They consider a constant and linear rate of losses and monetize the loss reductions from an aggregate perspective by multiplying the simulated results by the average hourly price of electricity. In Spain, total loss reductions

⁸A *node* represents the physical location in a transmission or distribution network where energy is injected by generators (inflows) or withdrawn by consumers (outflows).

range between 1.2 and 4.81%, depending on the scenario considered, with the highest values coinciding with the combination of two effects: a 35% reduction in peak load and a 20% reduction in overall consumption.

Consumption out of the meter produces non-technical losses (NTLs), which have consequences for total electricity demand, the quality of supply, the system's total income, etc. NTLs have traditionally been a problem in developing countries; however, in the context of the present economic crisis they have become problematic in the developed world, too. Depuru et al. (2011) describe how such factors as unemployment, the straitened finances of consumers and rising electricity prices can increase NTLs. Among the policies proposed to alleviate these losses and their economic consequences we find subsidies to low-income consumers, thorough audits of electricity consumption at the distribution level, stricter law enforcement and smart metering. In Spain, unemployment has reached record levels during the crisis which strongly suggests that these losses should not be ignored. As Smith (2004) has noted, while NTLs cannot be precisely computed, they can at least be estimated, though this falls outside the scope of this paper.

In short, studies on the demand side report that demand policies have a significant and positive effect on both losses in transmission and distribution. However, Shaw et al. (2009) and Cronenberg et al. (2012) constitute simulations and ex-ante studies; moreover, they do not analyse the impact of each generation source covering the peak demand profile.

In the case of supply policies affecting TSO and DSO behaviour (energy inflows), the penetration of DG has given rise to an academic debate about its consequences for losses. Due to the mathematical complexity of this area, two different approaches, providing similar outcomes, are reviewed here. In the first, Quezada et al. (2006), Marinopoulos et al. (2011) and Hung et al. (2013) estimate the impact of losses for a simple electricity feeder⁹. In the second, Delfanti et al. (2013) use a probabilistic approach to consider a larger electricity system.

Taking the simple feeder approach, Quezada et al. (2006) compute annual energy loss variations with different levels of penetration and concentration of DG in a radial line. They conclude that not all technologies have the same effect on losses. For instance, photovoltaic (PV) energy presents a higher correlation with consumption and a lower impact on losses, while wind power is more random, does not match as well with consumption and, consequently, has a worse impact on losses. Marinopoulos et al. (2011) evaluate loss reductions with a dispersed PV penetration using stochastic processes for load time-varying and PV generation in a feeder located in a city in northern Greece. Their results are in line with those of Quezada et al. (2006): losses follow a U-shape trajectory with the degree of PV penetration. The best solution is a uniform distribution of plants across a feeder, although this is extremely difficult to achieve in reality. Finally, Hung et al. (2013) identify the best locations, optimal sizes and power factors of DG units at various locations in order to minimize power losses. Among their results, it is interesting to highlight that dispatchable DG units perform better than non-dispatchable units in terms of loss impact and voltage profile enhancement.

A different approach is adopted by Delfanti et al. (2013), in which they use a Monte Carlo process to estimate loss evolution with DG penetration. They consider ten DG rated powers from 0.5 to 10 MW and estimate the probability of loss variations for each case. They find loss reductions are nearly always achieved for low levels of DG penetration. A higher DG penetration level raises the likelihood of increasing and reducing losses, which mainly depends on the specific characteristics of each case: the DG production profile, its correlation

⁹An *electricity feeder* is a medium-voltage (MV) power line extending from a distribution substation to the transformers used for reducing the supply to LV, i.e., the voltage used by domestic consumers.

with the demand profile, the presence of reverse flows, load locations, etc. An additional solution for potentially reducing losses for high DG penetration levels is network reconfiguration, which involves opening and closing switches in the distribution grid in response to flow changes (Lueken et al., 2012).

Strbac et al. (2007) point to the importance of well-located DG plants coinciding with peak-demand consumption to improve losses, which depends on technology, size, network topology, etc. The same generation technology in different locations might have the opposite impact on losses. For instance, micro CHP production in the UK is better correlated with the winter peak load (5:30 pm) than is PV.

In the case of regulatory strategies, many regulators around the world have implemented incentive-based schemes to promote efficiency improvements in natural monopoly activities (TSO/DSO) since 1990s. In addition to quality service improvements, loss reductions have been another performance target. In traditional electricity systems, DSOs can decide whether to apply specific strategies to reduce losses in their infrastructure, such as strengthening or reconfiguring networks to reduce congestion, installing low-loss level transformers, etc. Moreover, within a single country, each DSO has its own specific characteristics, so that incentive-based regulation is a general solution for all. In the UK, as in Spain, the quality of service and network energy losses are individually considered, separately incentivized and affects revenues of each DSO (Jamasb and Pollitt, 2007). Jamasb et al. (2012) estimated the marginal cost of improving quality in the UK DSO companies between 1995 and 2003. With respect to losses, the estimated average marginal cost was 2.4 pence per KWh, while the regulator's incentive or reward was 4.8 pence. However, this improvement was not equal across all companies because some were insufficiently incentivized and not all of them adopted the same strategies to reduce losses. Hence, incentives need to be well designed to make significant reductions in losses.

The significant increase in DG penetration in recent years has modified the traditional top-down approach to energy. Flows are becoming increasingly unpredictable and this is having consequences for local congestion, voltage and system security. In general, DG curtailment and feed-in management rules are not in the hands of DSOs. Moreover, the TSO is not monitoring distribution network conditions, which means that the DSO must react to DG actions and the operation of the distribution grids is becoming more complex. In this new context, an active distribution system management¹⁰ is proposed to ensure the better integration of DG/RES-E in the DSO. The idea is to provide the DSO with the tools for the maintenance of network stability by means of ICT solutions (Eurelectric, 2013a). Other recommendations include the establishment of mechanisms to compensate the DSO for their increasing CAPEX and OPEX due to the presence of DG by paying special attention to their impact on losses, the implementation of local signals to promote DG contribution to peak demand such as differentiated use-of-system (UoS) charges for DG, the promotion of DG to provide ancillary services to help DSOs operate their networks, etc. (Frías et al., 2009).

Our research is closely related to the above literature, and seeks to estimate the contribution of the consumption profile and generation technologies to losses. In the next section we present the Spain's current regulatory framework of losses within the broader European Union context. However, note that a study of the efficiency of regulator laws at the TSO and DSO loss levels is beyond the scope of this paper because this would require a longer period of time to achieve robust conclusions.

¹⁰The *Active distribution system management* is based in the interaction between planning, access and operational timeframes. It is based in the continuous monitoring of distribution network parameters to act over DG and consumers (Eurelectric, 2013a).

3 Regulatory framework of losses

European Directive 1996/92/EC concerning internal electricity markets establishes the rules for the unbundling of generation, transmission (i.e., transport on high-voltage grids) and distribution (i.e., transport on medium/low-voltage grids to consumers) activities. Below we discuss the main regulatory issues concerning losses in Europe and in Spain.

3.1 Regulation in Europe

In general, two complementary mechanisms are employed in determining how the costs associated with energy losses should be borne by generators and consumers in Europe. First, *zonal pricing* or *market splitting* uses the same market-based mechanisms as those used in the nodal price¹¹, but rather than setting an energy price for each node, a common price is fixed for the nodes located in a given area. This mechanism also takes into consideration the internodal congestion between regions or even between entire countries. It is employed in Italy, Nordel (Denmark, Finland, Iceland, Norway and Sweden) and MIBEL (Spain and Portugal). Second, *single energy pricing* sets the same price at the nodes in a given country or area and the effects of losses and constraints are addressed by employing other methods. For example, agents internalize losses in the prices that they bid, employing additional mechanisms such as corrective factors in supply-side bids or in the sums of energy produced. Constraint management mechanisms such as re-dispatch, countertrading and capacity auctions address problem of congestion. This mechanism is used in many European countries (Pérez-Arriaga, 2014).

Energy to cover all losses needs to be procured and, here, there are two possible courses of action. In some European countries, including Austria, Belgium, Switzerland, France, Poland, Sweden, Denmark and Germany, the TSOs and DSOs are responsible for the procurement of this energy, in others, such as Spain, Greece and Portugal, this energy is procured by the suppliers, who have to inject their own energy to offset the losses associated with end-user consumption. The two mechanisms have advantages and disadvantages, but in both instances energy has to be procured using non-discriminatory, transparent and market-based procedures (ERGEG (2008); Eurelectric (2013b)).

The components of transmission and distribution losses are not the same, which in turn affects the regulatory mechanisms employed to improve efficiency. For instance, NTLs are mostly, or even exclusively, present in distribution, whereas transmission losses are affected by major external factors, including the availability of natural resources, the outcome of generation and consumption auctions, etc. When TSOs or DSOs procure energy for losses, there is an additional incentive if the loss rates funded by tariffs are capped, given that the surplus represents an extra operating cost for them. An additional, complementary mechanism is the establishment of rewards (or penalties) if losses are below (or above) previously fixed reference values (ERGEG, 2008).

When a TSO has to purchase energy to cover losses, Eurelectric (2008) suggests it should be allowed to pass through the associated costs. Similarly, Ofgem in the UK removed all financial incentives associated with losses in transmission, arguing that it had little control over them (Ofgem, 2015). The German and Spanish TSOs, likewise, are offered no financial incentives in relation to losses.

¹¹ *Nodal price* is also referred to as the *spot price* or *locational marginal price*. The system fixes different energy prices at each node on the basis of the effects of consumer and producer decisions on congestion, grid constraints and losses. In the case of generation, the production of electricity at some distance from consumption means lower nodal prices than a production closer to consumption in a city. In the case of demand, the consumption of electricity in a generating area incurs lower nodal prices because this energy suffers low levels of loss. Among others, this system is used in Chile, New Zealand, New England, New Jersey and California.

In the case of DSOs, several schemes are employed. For example, in the UK, Ofgem establishes an annual percentage of electricity losses and so operators receive a reward/penalty linked to a set of performance indicators. Additionally, losses might be considered as operational cost reductions in investment remunerations (Ofgem, 2015). In Spain, the incentive mechanism to reduce losses is based only on a reward (or penalty) with respect to past data. In Germany, there are no financial incentives to minimize losses and the TSOs and DSOs are able to recover costs when purchasing energy. However, a benchmark has been fixed to ensure that energy is purchased efficiently. However, changes are expected in this regard in the future (Ecofys, 2013).

3.2 Regulation in Spain

In Spain, the electricity network is divided in two sections according to voltage: a voltage higher than or equal to 220kV¹² is considered transmission and is owned and operated by the TSO¹³, the Red Eléctrica de España (REE). The system operator (SO) operates the transmission network and seeks to guarantee the system's security and continuity of supply (REE, 2014). The rest of the network is considered as being of distribution, and is owned and operated by several DSOs. Although in Spain there are almost 350 registered DSOs (Ministry of Industry, 2015), five cover most of the territory (Endesa, Gas Natural Fenosa, Iberdrola, EDP and Eon).

In the Spanish transposition of European Directive 1996/92/EC¹⁴, the distribution of electricity is defined as a regulated activity with proper levels of quality and losses. Consequently, the regulatory framework in 1997 established a common DSO remuneration to be shared between all the DSOs, without considering individual improvements in efficiency or the geographical specifics of the area covered by each. In 2008, a reference network model (RNM)¹⁵ was introduced to better approach the performance of the different DSO networks, and individual loss reduction incentives were established between $\pm 1\%$ the remuneration of the previous year. The cost of energy wasted was valued at the hourly market price. In the following year¹⁶, it was increased until $\pm 2\%$ of the previous year's income and zonal loss coefficients are considered to better capture the specifics of the area covered by each DSO. Finally, in 2013¹⁷ it was modified again and the reference loss levels were fixed as values based on the figures for several previous years. This incentive scheme is similar to the one used in the UK, but it is capped at $+1\%$ and -2% of the allowed revenue. In Section 5, we calculate the economic costs of losses following the same methodology.

To quantify the DSO incentive in 2011-2013 period according to the current regulatory scheme, the annual maximum incentive reward for losses among all the DSOs stands at about 40 M€, while the annual average cost of losses in distribution is 945 M€¹⁸. In trans-

¹²This is a general classification because the Spanish TSO also owns and operates an electricity grid of less than 220kV in the Balearic and Canary Islands. However, this paper limits its study to Continental Spain.

¹³Within the Third Energy Package, the Spanish TSO was organized in accordance with the Full Ownership Unbundling (OU) scheme. This model requires full independence of the transmission owner and operator from any company that generates, produces or supplies electricity. The scheme is also used in other EU countries such as the UK, Germany and Italy (European Directive 2009/72/EC).

¹⁴Law 54/1997 and Royal Decree 2819/1998.

¹⁵A *reference network model* (RNM) is a large-scale distribution network tool, which is able to define an optimal distribution grid using geographical location and electrical data from the TSO, DSO and consumers. Geographical constraints can also be considered in the simulations (Royal Decree 222/2008).

¹⁶Complementary Technical Instruction 2524/2009.

¹⁷Royal Decree 1048/2013.

¹⁸Annual income among all DSOs is about 4,000M€, so 1% represents 40 M€. The annual cost of losses in distribution was 915 M€ in 2011, 980 M€ in 2012 and 940 M€ in 2013.

mission, the average annual cost of losses is 188 M€¹⁹.

In 1997, the generation sources were separately classified in two main groups: first, installations of 50 MW or less installed capacity that used RES-E, combined heat and power plants (CHP) or waste; and, second, all other technologies: nuclear, coal, combined cycle, etc. This facilitated the implementation of several promotion schemes for the sources in the first group. In the period 2011-2013, RES-E plants already produced 40% of total generation. Figure (2) shows that 90% of consumption has been achieved in the distribution networks, which implies a gap between generation and consumption. In our estimations, we also analyse whether the impact of consumption is similar in respect of transmission and distribution.

Figure 2: Share of total generation and consumption at TSO and DSOs in Spain (2011-2013).

Source: Own elaboration from REE (2014) and Ministry of Industry (2015).

Table 1 summarizes the characteristics and operation of each generation technology in Spain. This is relevant because their respective impacts on losses is related to where and when they produce. Although solar and CHP mostly generate to distribution, we expect indirect effects on transmission losses because they might displace other sources.

In Spain, DG curtailment and feed-in management rules can only be implemented by the SO, independently of whether they are connected to transmission or distribution²⁰. Today, this regulatory scenario is being questioned in order to facilitate the emergence of a more active DSO (CNE, 2012a). Finally, Table 2 summarizes the incentives for all agents involved in the electricity system in order to provide a better understanding of the impact of losses on decision making.

¹⁹The annual cost of losses in transmission is 215 M€ in 2011, 180 M€ in 2012 and 170 M€ in 2013.

²⁰In Spain, RES-E plants are only required to have a generation control centre as an interlocutor with the SO if they have more than 10MW of installed power.

Table 1: Characteristics and operation of generation sources (inflows) (2011-2013).

Technol.	Role in the hourly balancing of energy	Network level where generates
N_t	Used as a base source.	Transmission
CO_t, CC_t	Used as a base source after Nuclear.	Transmission
H_t	Mainly hydropower flowing. SO can modulate its production by the connection/disconnection of groups.	Most large flow-hydro plants inject in transmission. The rest in distribution.
W_t	Production depends on climate. SO can modulate its production by the connection/disconnection of big plants.	More than 45% of energy is injected in distribution. The rest in transmission.
SOL_t	Production during sun hours. At evening peak only thermosolar plants.	About 80% of energy is injected in distribution. The rest in transmission.
PG_t	Basically used to cover high peak hours.	Transmission
I_t	Used to cover peaks periods.	Transmission
CHP_t	Its production curve is flat over the whole day.	Almost 85% is injected in distribution.

Note: N_t is nuclear, CO_t is coal, CC_t is combined cycle, H_t is hydropower, W_t is wind, SOL_t is solar, PG_t is pumping generation, I_t are imports and CHP_t is combined heat and power.

Source: Based on CNMC (2013).

Table 2: Behaviour of agents at each stage with regard to losses in Spain (2011-2013).

Agent	Market Structure	Economic loss incentives
Generator	Liberalized activity	Losses are not considered when location and daily generation bid auctions are decided upon. However, both variables have an impact on TSO and DSO losses depending on distance to loads and when produce. A common UoS charges of 0.5€/MWh are applied to generation since 2011. Non-optimal decisions at this stage might imply greater losses and higher costs of losses for all end-consumers.
TSO	Regulated activity	Losses are not a key performance indicator in the regulation scheme. However, when investments are supposed to solve congestions problems, losses might be indirectly affected.
DSO	Regulated activity	In contrast with the TSO, losses are a key performance indicator in the regulatory scheme (incentive equal to $\pm 1\%$ of the year's remuneration). Investments, network operation and fight against consumption out of the meter are useful instruments. It is important to highlight that decisions taken by generators, TSO and consumers might affect their level of losses and worsen their performance indicators.
Consumer	Liberalized activity	Consumers can choose the voltage at the meter point. The higher the voltage, the less they pay to cover losses. However, this means funding an expensive own electricity infrastructure to reduce the voltage. Consumers are simply price takers of losses, although if a consumer decides to consume out of the meter, these losses are socialized among the rest. To avoid this perverse behaviour, efficient regulatory incentives and punishments are necessary.

Source: Based on the Spanish regulatory framework.

4 Data and Empirical Strategy

In this section, we present the empirical strategy and the data used to characterise losses in the Spanish Electricity System. In general, such losses can be defined by Eq. (3):

$$L_t = f(flow_t) \quad (3)$$

At a more disaggregated level, losses can be analysed in terms of the nature of their flow, i.e., as outflows and inflows, as in Eq. (4). The former, analogous to the demand-side approach, takes into account consumption and exports, while the latter, analogous to the supply-side approach, considers all sources of generation and imports in the electricity system. Eqs. (5) and (6) break the outflows and inflows down into their respective components.

$$L_t = f(Outflow_t; Inflow_t) \quad (4)$$

$$Outflow_t = C_t + E_t + PC_t \quad (5)$$

$$Inflow_t = \sum_k GEN_{kt} + I_t \quad (6)$$

with: $k = [N, CC, CO, H, PG, SOL, W, CHP]$

End-user consumption (domestic and industrial) is represented by C_t in Eq. (5). PC_t represents the pumping consumption needed to have subsequent pumping generation (PG_t). In Eq. (6), the technologies included are as follows: N nuclear; CC combined cycle; CO coal; H hydropower; PG pumping generation; SOL photovoltaic and thermosolar; W wind; and CHP combined heat and power. International exchanges of energy are made between continental Spain and other countries (Andorra, France, Portugal and Morocco). Depending on the direction of this flow, I_t represents the energy imports entering Spain, E_t the country's exports. Flows through the electrical submarine interconnection from the Spanish Peninsula to the Balearic Islands, in operation since August 2012²¹, are also included in I_t and E_t .

In our regressions, we estimate separately losses in transmission (L_{Tt}) and losses in distribution (L_{Dt}), according to the network where these losses are produced²². It should be borne in mind that losses are inversely proportional to the voltage, and the average level of losses in transmission (L_{Tt}) is consequently smaller than that in distribution (L_{Dt}). The accuracy is higher in transmission because of the widespread use of continuous meters. In distribution, small end-user consumption should be partially estimated with predetermined and known in-advance loss profiles (ERGE, 2008). In Spain, smart meter installation is still not fully completed, the deadline being 2018²³. This affects consumers with a LV connection and a contracted power rating less than (or equal to) 50 kW whose consumption profile is currently estimated by patterns based on a representative panel of consumers²⁴. These LV consumers represent 40% of total demand used in the calculation of losses in distribution (L_{Dt}) (CNE, 2012b). The difference between the final real consumption with losses (C_t) and predicted consumption (C_t^p) including consumers that do not have hourly or smart meters, plus NTL, is considered Energy Close (EC_t), which might be positive or negative²⁵ depending on its construction, as shown in Eq. (7).

$$EC_t = (C_t - C_t^p) + NTL_t \quad (7)$$

²¹The *Romulo Project* comprises a High Voltage Direct Current (HVDC) link of ± 150 kV (2x200MW) between Sagunto (Valencia) and Calvia (Mallorca).

²²The methodology used in this paper is defined in *Operating procedure 5.0 for determining transmission losses and calculation of loss coefficients per node* published in BOE on 03/07/1999, Royal Decree 1048/2013 and Technical Complementary Instruction 2524/2009.

²³Order IET/290/2012.

²⁴Royal Decree 1110/2007.

²⁵In the EC, 39% of observations are negative. However, the average value is positive: 380.88.

Before defining the equations, we analyse which variables should be included in both the transmission (L_{Tt}) and distribution (L_{Dt}) estimations. With respect to outflows, exports (E_t) are only used in transmission because 99.99% of the exported energy uses transmission. Likewise, Pumping Consumption (PC_t) is fully associated with transmission, and so it is not included in distribution (L_{Dt}). Imports (I_t) are included in both transmission (L_{Tt}) and distribution (L_{Dt}) because 90% of consumption is in distribution.

Losses are expected to follow a dynamic process over time. By definition, losses are proportional to consumption, with the latter having an inertial component (the consumption of one hour being highly correlated to that of the previous hour). Therefore, to capture the dynamic process of losses properly, we include the lagged endogenous variable as an additional explanatory variable (L_{Tt-1} and L_{Dt-1}).

Adhering to the dual perspective of outflows and inflows (see Eqs. (5) and (6)), the analysis of the impact on losses is performed in two groups of estimations: first, the impact of outflows (consumption) as described Eqs. (8) and (9); and, second, the impact of inflows (generation) as described in Eqs. (10) and (11). In both cases, the equations are estimated using the endogenous variable measured in MWh ($i=M$) and in € ($i=C$). As EC_t^i directly affects losses, it is measured in the same units as losses when it is included in the following equations:

$$\Delta L_{Tt}^i = \beta_0 + \beta_1 \Delta L_{Tt-1}^i + \beta_2 \Delta EC_t^i + \beta_3 \Delta C_t + \beta_4 \Delta E_t + \beta_5 \Delta PC_t + \beta_6 PEAK_t + \beta_7 DOW_{it} + \beta_8 FES_t + \beta_9 MONTH_t + \beta_{10} YEAR_t + \varepsilon_t \quad (8)$$

$$\Delta L_{Dt}^i = \beta_0 + \beta_1 \Delta L_{Dt-1}^i + \beta_2 \Delta EC_t^i + \beta_3 \Delta C_t + \beta_4 PEAK_t + \beta_5 DOW_{it} + \beta_6 FES_t + \beta_7 MONTH_t + \beta_8 YEAR_t + \varepsilon_t \quad (9)$$

$$\begin{aligned} \Delta L_{Tt}^i = & \beta_0 + \beta_1 L_{Tt-1}^i + \beta_2 \Delta EC_t^i + \beta_3 \Delta N_t + \beta_4 \Delta CC_t + \beta_5 \Delta CO_t + \beta_6 \Delta H_t + \\ & + \beta_7 \Delta PG_t + \beta_8 \Delta SOL_t + \beta_9 \Delta W_t + \beta_{10} \Delta CHP_t + \beta_{11} \Delta I_t + \\ & + \beta_{12} DOW_{it} + \beta_{13} FES_t + \beta_{14} MONTH_t + \beta_{15} YEAR_t + \varepsilon_t \end{aligned} \quad (10)$$

$$\begin{aligned} \Delta L_{Dt}^i = & \beta_0 + \beta_1 L_{Dt-1}^i + \beta_2 \Delta EC_t^i + \beta_3 \Delta N_t + \beta_4 \Delta CC_t + \beta_5 \Delta CO_t + \beta_6 \Delta H_t + \\ & + \beta_7 \Delta PG_t + \beta_8 \Delta SOL_t + \beta_9 \Delta W_t + \beta_{10} \Delta CHP_t + \beta_{11} \Delta I_t + \\ & + \beta_{12} DOW_{it} + \beta_{13} FES_t + \beta_{14} MONTH_t + \beta_{15} YEAR_t + \varepsilon_t \end{aligned} \quad (11)$$

As electricity demand varies during the day, a temporary variable is included in the out-flow models (Eqs. (8) and (9)) to distinguish the highest demand hours ($PEAK_t=1$) from the rest. This classification is used for a share of LV consumers in Spain with two period-meters²⁶.

In all equations, seasonality is controlled using a set of variables: DOW_t for the day of the week²⁷; $FES_t = 1$ for weekday holidays and 0 otherwise; $MONTH_t$ and $YEAR_t$ capture the long-term seasonality.

²⁶This price discrimination scheme corresponds to 2.0DHA and 2.1DHA tariffs in Spain. Consumption during the peak period (from 12pm to 10pm) has a higher price with respect to rest of the day or off-peak period.

²⁷In DOW_t , one value is used for everyday of the week: 0=Sunday, 1=Monday, 2=Tuesday (...) through to 6=Saturday. We discard using a unique dummy for all working days because EC_t does not follow common patterns for all working days.

We use an hourly dataset from 2011 to 2013. Our geographical area is continental Spain, except for the Balearic and Canary Islands, which have been excluded because their electricity systems could bias our results. Data used comes from REE (2014), where monthly settlement reports²⁸ are published including hourly information for all agents in the electricity system: generators, end-consumers, TSO, DSOs, energy marketers, etc. If we compare our research with previous studies, our approach could be considered more accurate because we use the hourly level of losses in transmission and distribution, and the corresponding hourly price of electricity to calculate the consequent cost. In Table 3 we present the descriptive statistics of the variables used in the previous equations. While losses are quantified in MWh when ($i = M$) and in € when ($i = C$), the rest of variables are all measured in MWh.

Table 3: Statistical summary of hourly variables (in € and MWh).

Variable	N	mean	Std.Deviation	min	max
Losses in Transmission (L_{Tt}^M)	26,304	446.25	102.14	11.81	991.20
Losses in Distribution (L_{Dt}^M)	26,304	2,274.70	1,262.47	-3,395.26	7,785.20
Losses in Transmission (L_{Tt}^C)	26,304	21,453.70	9,803.34	0	84,164.33
Losses in Distribution (L_{Dt}^C)	26,304	108,020.3	76,090.23	-228,840.6	572,448
Energy Close (EC_t)	26,304	380.88	1,268.94	-5,492.29	6,123.43
Nuclear (N_t)	26,304	6,379.79	825.78	3,291.23	7,524.35
Combined Cycle (CC_t)	26,304	4,206.00	2,477.80	295.09	15,982.49
Coal (CO_t)	26,304	4882.38	2,252.26	-99.34	10,074.73
Hydro (H_t)	26,304	3,436.32	1,942.61	467.65	11,021.73
Pumping Generation (PG_t)	26,304	257.25	351.37	-3.07	1,951.55
Solar (SOL_t)	26,304	1,239.28	1,496.41	0	5,565.68
Wind (W_t)	26,304	5,497.38	3,174.46	70.40	16,671.59
Combined Head and Power (CHP_t)	26,304	4,232.95	565.77	2,595.66	5,506.65
Imports (I_t)	26,304	648.53	536.71	0	3,089.74
Consumption (C_t)	26,304	28,184.98	5,082.955	14,095.6	42,941.02
Pumping Consumption (PC_t)	26,304	578.4314	807.5924	0.751	4,092.00
Exports (E_t)	26,304	1,641.47	692.91	27.26	4,172.76
Peak ($PEAK_t$)	26,304	0.417	0.493	0	1

Source: own elaboration.

Having described the variables, we evaluate the stationarity of the time series variables used in this paper. Firstly, we perform the augmented Dickey-Fuller (ADF) test (Dickey and Fuller, 1979) under the null hypothesis of a unit root and, secondly, the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) tests (Kwiatkowski, et al., 1992) under the null hypothesis of stationary. For the ADF, we reject the null hypothesis of a unit root for both levels and differences. However, for the KPSS, we reject the null hypothesis of stationarity in levels but not in differences. Both tests, therefore, confirm that our series are stationary in differences, so we estimate the models in differences. In the next section, the results of the estimations are presented and discussed.

5 Results

In this section we present the results of the estimations performed on the equations described in the previous section. Losses are estimated from two perspectives: outflow (consumption and exports) and inflow (generation and imports). Finally, an additional post-estimation analysis is performed with the outflow results.

²⁸In Spain, there are five monthly settlements depending on the time elapsed since the last day of the month. The one used in this paper is C5, the most definitive report, which is published after 11 months. In May 2011 we use the C6 settlement, which is also available. For further details see the Resolution of the Ministry of Industry (28/07/2008) published in BOE on 31/07/2008: *General procedures for SO settlements*.

Table 4: Augmented Dickey-Fuller and Kwiatkowski-Phillips-Schmidt-Shin test.

Variable	ADF Test	ADF Test	KPSS Test	KPSS Test
	Levels	Differences	Levels	Differences
Losses in Transmission (L_{Tt}^M)	-12.962***	-30.036***	17.10***	0.002700
Losses in Distribution (L_{Dt}^M)	-11.407***	-28.359***	8.74***	0.000197
Losses in Transmission (L_{Tt}^C)	-11.981***	-30.033***	20.2***	0.000282
Losses in Distribution (L_{Dt}^C)	-12.743***	-29.005***	10.80***	0.000160
Energy Close (EC_t)	-9.967***	-30.251***	5.91***	0.000188
Nuclear (N_t)	-5.107***	-37.508***	79.10***	0.029000
Combined Cycle (CC_t)	-17.951***	-25.044***	12.60***	0.000615
Coal (CO_t)	-10.885***	-22.995***	91.40***	0.003520
Hydro (H_t)	-4.762***	-31.778***	154.00***	0.000565
Pumping Generation (PG_t)	-17.868***	-35.526***	5.03***	0.000121
Solar (SOL_t)	-9.225***	-31.468***	6.43***	0.000432
Wind (W_t)	-14.435***	-26.669***	12.00***	0.004250
Combined Head and Power (CHP_t)	-15.887***	-30.354***	40.60***	0.000421
Imports (I_t)	-13.039***	-31.873***	11.60***	0.000212
Consumption (C_t)	-18.271***	-29.836***	1.98***	0.000439
Pumping Consumption (PC_t)	-13.969***	-94.650***	12.50***	0.000240
Exports (E_t)	-12.627***	-31.182***	31.00***	0.000227

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

As explained, the inclusion of the lagged endogenous variable as a regressor seeks to capture the dynamic loss process. However, this might cause an endogeneity problem because the residuals are correlated with this lagged variable. To avoid any potential bias that might arise when using the least squares method in the presence of lagged dependent variables, estimations are performed using maximum likelihood estimators.

Before analysing the estimations, it is important that we clarify the sign of the coefficients associated with each outflow (or inflow). On the one hand, a positive sign associated with the flow outcomes (MWh) in columns (1) and (2) of Tables 5 and 7 implies a higher level of losses for an additional MWh consumed (or generated), while a negative sign implies a lower level. Although this might seem irrational, such an outcome is technically feasible when one flow displaces others in a real electricity system. On the other hand, a positive sign associated with the cost outcomes (€) in columns (3) and (4) implies a higher cost of losses caused by an additional MWh consumed (or generated). However, a negative coefficient in this case does not necessarily mean a saving because of the presence of the hourly price: a technology that has its main impact during periods of low demand might present positive coefficients for flows but negative coefficients for costs. In such circumstances, we consider absolute values for the economic cost. Finally, when both the flow and cost coefficients are negative, this is deemed to be a cost saving.

5.1 Loss analysis from the outflow perspective

Table 5 shows the results of the loss estimations from the outflow perspective (Eqs. (8) and (9)). In columns (1) and (2), the endogenous variables are flows measured in MWh ($i = M$), while in columns (3) and (4), the endogenous variables are costs measured in € ($i = C$). All the associated coefficients are significant. An interesting result is the economic cost of the energy loss for each additional MWh consumed because it shows that the cost of distribution losses (9.077€) is much higher than those of transmission (1.641€).

To understand better the coefficients in Table 5, we calculate the short- and long-run marginal economic effects on losses²⁹ in Table 6. In the short-run, the consumption marginal effect on distribution (0.00840%) is also higher than that of transmission (0.00765%). The

²⁹Transmission and distribution short and long-run marginal effects for each outflow are calculated as β_{oi}/L_T^i and β_{oi}/L_D^i , and $[\beta_{oi}/(1 - \beta_1)]/L_T^i$ and $[\beta_{oi}/(1 - \beta_1)]/L_D^i$, respectively. It is useful to compare impacts on transmission and distribution for each outflow.

Table 5: Consumption flows (outflows) impact on losses.

	$i = M$ (in MWh)		$i = C$ (in €)	
	ΔL_{Tt}^i	ΔL_{Dt}^i	ΔL_{Tt}^i	ΔL_{Dt}^i
	(1)	(2)	(3)	(4)
$\Delta(L_{Tt-1}^i)$	-0.0473*** (-18.11)		0.0772*** (23.41)	
$\Delta(L_{Dt-1}^i)$		-0.0725*** (-59.15)		0.137*** (63.24)
ΔC_t^i	0.0179*** (124.24)	0.116*** (475.59)	1.641*** (147.70)	9.077*** (314.32)
ΔEC_t^i	0.0243*** (88.50)	0.995*** (1356.05)	0.0269*** (84.28)	1.002*** (953.92)
ΔE_t^i	0.00443*** (7.32)		-0.760*** (-17.68)	
ΔPC_t^i	0.0127*** (19.66)		-0.428*** (-8.50)	
PEAK=1	10.67*** (26.80)	10.66*** (7.70)	921.7*** (26.66)	2496.9*** (19.40)
Constant	-4.749*** (-6.93)	-4.527 (-1.79)	-368.9*** (-6.28)	-944.9*** (-4.30)
sigma				
Constant	31.92*** (669.40)	86.66*** (1274.97)	2405.4*** (459.33)	8158.3*** (692.78)
<i>Seasonality</i>	Y	Y	Y	Y
<i>Year</i>	Y	Y	Y	Y
<i>Month</i>	Y	Y	Y	Y
<i>Fes</i>	Y	Y	Y	Y
<i>Dow</i>	Y	Y	Y	Y
Observations	26303	26303	26303	26303
R^2				

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Note: L_{Tt}^i and L_{Dt}^i are losses on transmission and distribution.

Table 6: Marginal economic effects on losses (outflows) (%).

	Short-run		Long-run	
	ΔL_{Tt}^C	ΔL_{Dt}^C	ΔL_{Tt}^C	ΔL_{Dt}^C
	(1)	(2)	(3)	(4)
$\Delta \bar{C}_t$	0.00765	0.00840	0.00829	0.00973
$\Delta \bar{PC}_t$	-0.00199	-	-0.00216	-
$\Delta \bar{E}_t$	-0.00354	-	-0.00384	-
$\Delta \bar{PEAK}_t$	4.29602	2.31155	4.65517	2.67744

Note: L_{Tt}^i and L_{Dt}^i are losses on transmission and distribution.

peak dummy variable captures the extra losses that occur during the peak period. In the short-run, they represent an additional 4.30% and 2.31% of the average hourly cost of losses in transmission and distribution, respectively. If we quantify these losses in economic terms, their total cost is 12.48 M€/year³⁰, equivalent to 1.10% of the total annual cost of losses.

In the long-run, the consumption marginal effects on distribution (0.00973%) and on transmission (0.00829%) are slightly higher than the corresponding short-run effects. Extra losses in the peak period correspond to an additional 4.66 and 2.68% of the average hourly cost of

³⁰These savings are calculated from the average hourly cost of losses and their potential reduction during the *peak period* of each day (10 hours): $365 \cdot 21,454 \cdot 10 \cdot (4.30\%) + 365 \cdot 108,020 \cdot 10 \cdot (2.31\%) = 12.48$ M€/year. We have not considered the carbon emissions avoided or other externalities.

losses in transmission and distribution, respectively. Their total cost is 14.2 M€, which represents the maximum potential economic savings from DSM policies aimed at fully smoothing the demand profile curve.

Using the same methodology, but for the coefficients in columns (1) and (2) in Table 6, we obtain the potential savings in terms of flows of energy lost in MWh when applying the same DSM policies. In the long-run, they represent 0.31% of the total energy lost in MWh. These results are similar to those reported by Shaw et al. (2009). Pumping consumption is analysed in the next section together with pumping generation.

5.2 Loss analysis from the inflow perspective

In this subsection we present the results of the estimations performed from the inflow perspective (Eqs. (10) and (11)). In columns (1) and (2) of Table 7, the endogenous variables are measured in MWh ($i = M$), while in columns (3) and (4), the endogenous variables are costs measured in € ($i = C$). All associated coefficients are significant.

In Table 7, the coefficients in column (3) show the economic cost of losses in transmission for each additional MWh generated. In the case of DG sources, the economic cost of losses in transmission for each additional MWh produced is -0.082€ for solar, 1.221€ for wind and 0.858€ for CHP³¹. These impacts are smaller than those associated with the base sources: 1.743€ for nuclear, 1.638€ for combined cycle, 2.414€ for coal and 2.658€ for hydro.

With respect to the impact of each additional MWh generated on distribution (see column (4)), the impacts of both solar (4.986€) and wind (4.696€) sources are smaller than those of the base sources: nuclear (8.946€), combined cycle (10.18€) and coal (9.678€). In the case of hydro (8.700), the cost is higher than that of solar and wind power, but lower than those of combined cycle and coal. In contrast, the impact of CHP (14.67€) is higher than that of the rest of DG. The intuition for CHP is the presence of the U-shape trajectory for losses in distribution, as proposed by Quezada et al. (2006) and Marinopoulos et al. (2011), given that its production is not proportionally generated to the voltage of the grid in distribution³² and its hourly production profile is not well-correlated with the consumption profile. Although solar production is also not generated proportionally to the voltage of distribution, the U-shape trajectory for losses is not noticed because its total production is 60% smaller than that of CHP³³. However, the future expansion of solar power might affect the corresponding losses, depending on the resultant voltage of injection.

Considering both the costs of losses in transmission and distribution, an additional MWh produced by nuclear has a total loss cost of 10.689€, compared to 4.904€ in the case of solar, 5.917€ for wind and 15.528€ for CHP. These results show the potential benefits for consumer welfare of wind and solar energy generation as the total losses are smaller than the rest of the mix. As we see in the next section, the level of CHP losses might be reduced if its production could be lowered during periods of low demand. These results differ from

³¹Following the same reasoning as in the previous section, when coefficients in flows in columns (1) or (2) have positive coefficients and coefficients in columns (3) or (4) are negative, we consider the last in absolute values.

³²For CHP, the 111,343 GWh generated in the 2011-2013 period are disproportionately generated by grid voltage (V) at distribution: 0.46% for $V < 1\text{kV}$; 26.52% for $1 \leq V < 36\text{kV}$; 35.38% for $36 \leq V < 72.5\text{kV}$; 20.89% for $72.5 \leq V < 145\text{kV}$ and 16.75% for $V > 72.5\text{kV}$. The 144,603 GWh generated by wind in the same period are proportionate: 0.89% for $V < 1\text{kV}$; 4.01% for $1 \leq V < 36\text{kV}$; 13.16% for $36 \leq V < 72.5\text{kV}$; 28.00% for $72.5 \leq V < 145\text{kV}$ and 53.94% for $V > 72.5\text{kV}$ (CNMC, 2013).

³³For solar, the 32,597 GWh (2011-2013) are disproportionately generated as follows: 25.05% for $V < 1\text{kV}$; 37.31% for $1 \leq V < 36\text{kV}$; 11.79% for $36 \leq V < 72.5\text{kV}$; 6.02% for $72.5 \leq V < 145\text{kV}$ and 19.84% for $V > 72.5\text{kV}$. This technology comprises many small plants connected to the LV grid (CNMC, 2013).

Table 7: Generation flows (inflows) impact on losses.

	$i = M$ (in MWh)		$i = C$ (in €)	
	ΔL_{Tt}^i (1)	ΔL_{Dt}^i (2)	ΔL_{Tt}^i (3)	ΔL_{Dt}^i (4)
$\Delta(L_{Tt-1}^i)$	-0.111*** (-43.53)		0.0285*** (8.08)	
$\Delta(L_{Dt-1}^i)$		0.103*** (106.05)		0.103*** (41.31)
ΔEC_t^i	0.00240*** (9.28)	0.872*** (1244.99)	-0.0121*** (-34.82)	0.815*** (669.19)
ΔN_t^i	0.0149** (3.03)	0.0943*** (4.88)	1.743*** (4.45)	8.946*** (4.47)
ΔCC_t	0.0114*** (28.45)	0.108*** (97.67)	1.638*** (55.37)	10.18*** (97.22)
ΔCO_t	0.0231*** (27.88)	0.125*** (52.23)	2.414*** (36.61)	9.678*** (37.53)
ΔH_t	0.0335*** (75.79)	0.0974*** (82.03)	2.658*** (77.02)	8.919*** (68.76)
ΔPG_t	0.0160*** (15.81)	0.133*** (50.41)	3.358*** (43.61)	17.56*** (64.05)
ΔSOL_t	-0.00124** (-3.13)	0.107*** (88.89)	-0.082* (-2.12)	4.986*** (33.93)
ΔW_t	0.0204*** (45.09)	0.0901*** (58.04)	1.221*** (31.08)	4.696*** (31.42)
ΔCHP_t	0.00698*** (6.92)	0.400*** (150.03)	-0.858*** (-11.52)	14.67*** (56.50)
ΔI_t	0.0311*** (46.71)	0.0841*** (53.54)	2.985*** (58.46)	10.12*** (56.90)
Constant	-0.408 (-0.69)	-0.618 (-0.26)	11.94 (0.21)	100.3 (0.44)
sigma				
Constant	30.22*** (696.97)	76.39*** (1478.61)	2416.9*** (450.39)	8865.9*** (656.48)
<i>Seasonality</i>	Y	Y	Y	Y
<i>Year</i>	Y	Y	Y	Y
<i>Month</i>	Y	Y	Y	Y
<i>Fes</i>	Y	Y	Y	Y
<i>Dow</i>	Y	Y	Y	Y
Observations	26303	26303	26303	26303
R^2				

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Note: L_{Tt}^i and L_{Dt}^i are losses on transmission and distribution.

those reported by Strbac et al. (2007), who find the micro CHP is able to reduce losses by up to 40% in rural and 33% in urban areas of the UK, because its production is highly correlated with the electricity profile demand. In Spain, the installed capacity of micro CHP³⁴ is residual, which means the two results are not directly comparable.

³⁴On September 2013, the installed capacity of CHP plants with less than or equal to 1MW of power (also known as micro CHP) was below 200 MW, which barely amounts to 2.1% of the total CHP installed capacity in Spain (IDAE, 2014).

As for pumping generation technology, the prerequisite for generation is pumping consumption. Consequently, we need to add 0.428€ from losses in pumping consumption (Table 5) to the 3.358€ of losses in transmission and 17.56€ in distribution (Table 7). Hence, for a consumer connected to distribution, the total cost in terms of losses of consumption from pumping generation would be 21.346€. This generation technology is almost exclusively used during hours of maximum demand, consequently the losses are produced at the highest hourly price, which greatly penalizes their costs in terms of the efficiency of the system.

As with the previous set of results, to understand better the coefficients in Table 7, we calculate the short- and long-run marginal effects on losses (see Table 8). In the case of the short-run marginal economic effects on transmission and distribution losses (columns (1) and (2) in Table 8), pumping generation in transmission (0.01565%) and distribution (0.01626%) has the highest effects. In transmission losses, solar has the smallest (and even negative effect) on losses (-0.00038%), which is more than 20 times smaller than the effect of base sources (nuclear or combined cycle). The negative sign or effect seems to indicate that during hours of solar generation, the flows from other technologies are displaced. In terms of distribution, wind (0.00435%) and also solar (0.00462%) present the smallest effects on losses, being almost half those of the base sources. This points to the benefits of generating in distribution, i.e., close to points of consumption. However, CHP represents a special case (0.01358%), with more than 85% of production being generated at distribution. In the long-run (columns (3) and (4)), the coefficients do not vary greatly, because the lag coefficients are quite small.

Table 8: Marginal economic effects on losses (inflows) (%).

	Short-run		Long-run	
	ΔL_{Tt}^C	ΔL_{Dt}^C	ΔL_{Tt}^C	ΔL_{Dt}^C
	(1)	(2)	(3)	(4)
$\Delta \overline{N_t}$	0.00812	0.00828	0.00836	0.00924
$\Delta \overline{CC_t}$	0.00763	0.00943	0.00786	0.01051
$\Delta \overline{CO_t}$	0.01125	0.00896	0.01158	0.00999
$\Delta \overline{H_t}$	0.01239	0.00826	0.01276	0.00921
$\Delta \overline{PG_t}$	0.01565	0.01626	0.01611	0.01813
$\Delta \overline{SOL_t}$	-0.00038	0.00462	-0.00039	0.00515
$\Delta \overline{W_t}$	0.00569	0.00435	0.00586	0.00485
$\Delta \overline{CHP_t}$	-0.00400	0.01358	-0.00412	0.01515
$\Delta \overline{I_t}$	0.01391	0.00937	0.01432	0.01045

Note: L_{Tt}^i and L_{Dt}^i are losses on transmission and distribution.

In general, from the inflow analysis, it can be seen that nuclear performs as a source base with a small impact on losses. When technologies cover a greater share of the peak demand, their impact on losses increases proportionally. In the case of DG, its impact on both transmission and distribution is smaller than the impact of all other sources. This is not the case for CHP in distribution where we deduce the U-shape trajectory attributable to the disproportionate amounts of energy injected by network voltage and an incorrect correlation between its production and the demand profile. In the extreme case, the impact of imports and pumping generation are highest, confirming that a peaked demand profile has major consequences for losses.

5.3 Additional post-estimation analysis

In this section, we use the results reported above for inflows (Table 7) to calculate the hourly price effect³⁵. This allows us to identify the time of day when the losses in each source are at their highest. The largest coefficients suggest that losses occur mainly during the highest hourly price periods (or during the highest total demand periods). In contrast, the lowest coefficients are associated with periods of low demand. The results are presented in Table 9.

Table 9: Inflow hourly price effect on L_{Tt} and L_{Dt} in €/MWh.

	ΔL_{Tt} (1)	ΔL_{Dt} (2)
$\Delta \overline{N_t}$	116.99	94.87
$\Delta \overline{CC_t}$	143.68	94.28
$\Delta \overline{CO_t}$	104.51	77.43
$\Delta \overline{H_t}$	79.36	91.57
$\Delta \overline{PG_t}$	209.87	132.06
$\Delta \overline{SOL_t}$	66.26	46.60
$\Delta \overline{W_t}$	59.87	52.12
$\Delta \overline{CHP_t}$	-122.95	36.69
$\Delta \overline{I_t}$	95.98	120.36
<i>t</i> statistics in parentheses		
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$		

Pumping generation of transmission (209.87) and distribution (132.06) obviously present the highest values as this technology is mostly used to cover the hours of peak demand, when prices are at their highest. The most interesting results are obtained when comparing base sources and DG in distribution. Solar (46.60), wind (52.12) and CHP (36.69) have much smaller effects than nuclear (94.87), combined cycle (94.28) and coal (77.43). This might suggest that the losses produced by DG mainly occur during periods of lower demand (when the hourly price is lowest) because energy needs to travel further in the distribution grids until it finds a consumption point. These are the consequences of a non-dispatchable DG connected, and potential loss reductions if DSOs would be able to manage them³⁶ and improve their correlation with demand. These results are in line with those reported by Hung et al. (2013) and appear to demonstrate the potential benefits of a more dispatchable DG source.

6 Conclusions and regulatory recommendations

In this study we have analysed the impact of each outflow (consumption) and inflow source (generation) on electricity losses in Spain. As outlined in the introduction, such losses are an intrinsic part of energy flows in any electricity system and they affect both the producer and consumer surplus. Our analysis has involved a quantification of the marginal effect on losses in MWh and € from an additional MWh consumed or produced.

³⁵For each l source, the *hourly price effect* is estimated by the division of two coefficients: β_{lC}/β_{lM} , where β_{lC} is in columns (3) and (4) of Table 7, and β_{lM} in columns (1) and (2). Consequently, the price's hourly effect is measured in €/MWh.

³⁶In the case of solar power, energy is very difficult to manage. It is divided between *photovoltaic cells* whose production might be managed by the use of batteries, and *concentrated solar steam power stations* that use radiation to heat a fluid and generate electricity, the production of which is a little more than that from cells (Pérez-Arriaga, 2014).

In terms of outflow, we estimated the average cost of losses produced by an additional MWh consumed in transmission (1.641€) and distribution (9.077€), when considering the peak effect separately. In the Spanish regulatory scheme, these costs are borne by consumers in the retail market. The highest loss cost in distribution shows that policies designed to improve the system's efficiency should be focused at the grid level, where all LV end-consumers are connected. Thus, the use of DG to inject energy as close as possible to the point of consumption seems to be an appropriate policy, since losses are directly proportional to the distance separating generation plants from consumers.

A key finding to emerge from this study are the maximum potential economic savings in relation to losses that can be achieved by reducing network congestion via the implementation of DSM policies, such as the use of smart meters. This allows single or flat rate tariffs to be replaced by time-of-use tariffs and, thus, to smooth the aggregate demand profile. On average and in the long-run, the maximum cost savings associated with this policy would represent 1.25% of the annual cost of losses, i.e., a total of 14.2M€ per year (3.6M€ in transmission and 10.6M€ in distribution). These results are in line with other ex-ante studies (Shaw et al. (2009) and Cronenberg et al. (2012)) and show that the incentives to reduce losses are not great enough to encourage DSOs to finance DSM policies³⁷. To put these findings into the context of consumer charges, the potential 1.25% cut in losses due to less network congestion represents an average of 0.08€ per MWh consumed by LV consumers ($T < 1\text{kV}$) and less than 0.01€ per MWh for all other consumers connected to the transmission grid. However, if a smoother demand profile could be achieved, generation plants might operate differently to the way in which they are currently running, which would have an additional (positive or negative) impact on losses.

In terms of inflow, we have analysed short- and long-run marginal effects on losses. The key finding to emerge here is that the impact of each technology varies in a real electricity system. Two circumstances account for these differences: the timing of generation (during peak or off-peak periods) and the specific grid level (transmission or distribution). As for the effects of DG on the distribution of losses, we find that while the marginal cost of an additional MWh generated by solar and wind power is lower than the cost of all base sources, the opposite is the case for CHP. We conclude that CHP generation has a U-shaped impact on distribution losses, given that the injection of CHP production is not proportional to the grid voltage and in periods of low demand there might be insufficient local load to absorb its production and energy has to travel further along LV lines. Spain's CHP installations are composed mainly of industrial plants (with a smooth generation profile), while micro CHP plants are largely residual due to their poor economic viability (González-Pino et al., 2014). However, future technological developments and cost reductions might change this situation, and the market might be able to exploit the potential benefits identified by Strbac et al. (2007).

Our results suggest that an increase in solar and wind capacity would reduce energy losses; however, at the limit, we find that this might produce a U-shaped effect (as reported above in the case of CHP) and actually increase their respective contribution to losses. Hence, there is a need to analyse first the changes in the demand profile due to the introduction of smart meters. If the correlation between demand and the generation of solar power changes in the future, the scope for the installation of increased solar capacity might also change.

The high cost of the losses associated with pumping generation plants is a direct consequence of the period of time during which this technology operates. Plants are able to start

³⁷In Spain, it is estimated that more than 27 million smart meters, together with the corresponding infrastructure, have to be installed. However, it is very difficult to completely flatten the demand profile given that some consumption, such as lighting, cannot be delayed to off-peak periods.

up and shut down in a matter of minutes, which makes them ideal for coping with the variability in RES-E production and for keeping the electricity system balanced. Pumping consumption occurs mainly during periods of low demand when there is a surplus of generation. As a result, the average cost of losses associated with an additional MWh consumed is small (0.428€) compared to that of the end-user consumption cost (1.641€). Pumping generation plants operate primarily during periods of peak demand, which results in a high average loss cost associated with the production of an additional MWh (20.98€). In the future, the increased penetration of RES-E might increase the variability of the total generation, and in this scenario pumping is expected to gain in importance (Eurelectric, 2015). However, the higher loss costs might counter the lower costs of solar and wind power, thus determining the overall efficiency of the electricity system.

Our results highlight the need to improve the relationship between TSOs and DSOs in order to consider a whole system approach with greater coordination, exchange of data and use of flexibility (CEER, 2015). In Spain's current regulatory framework as in other countries, DG is controlled by the SOs³⁸ and small plants are often fully operated and controlled by their owners. The passive role currently being adopted by DSOs will have to change in the future. In this way, Eurelectric (2013a) proposes to become DSOs as real system operators; a better monitoring of MV and LV distribution network parameters to act over DG and consumers; review the grid access regimes including priority and guaranteed grid access for renewables; enable the creation of new system services at distribution level, etc.

In the light of the inflow results, and adopting a broad system perspective, Spain's current regulatory scheme, in which suppliers purchase the energy required to cover losses that are, in turn, borne by consumers, needs to be subjected to a careful analysis to determine whether it remains valid. In the meantime, there is obvious room for improvement. Two potential areas for action are i) the substitution of constant UoS charges in electricity production for differentiated charges that take into consideration impact on energy losses; and ii) the implementation of locational marginal prices in order that the costs of losses could be shared between generators and consumers. For instance, this might involve defining different areas in Spain in order to differentiate between low and high demand (and production) sites. In the long-run, this could serve as an efficient signal for locating new generator plants based on the efficiency of the whole system.

Future empirical studies of the economics of electricity losses could usefully focus on the impact on CO₂ emissions, examining those attributable to each generation technology. In the case of outflows, the methodology proposed herein could be reapplied following the introduction of smart meters in order that the impact of current DSM policies on losses might be verified. Other potential lines of investigation include using these models to forecast the impact of charging electric vehicles during off-peak hours, or estimating the impact of losses on the wholesale price market (auctions) because of the greater demand for energy.

³⁸In Spain, RES-E are monitored and controlled by a "Control Centre of Renewable Energies" (CECRE) operated by the TSO. Its objective is to integrate the maximum amount of generation from renewable energy sources into the electricity system under secure conditions. However, only wind farms of over 10 MW are connected to this control centre (REE, 2015).

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