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Two smart energy management models for the Spanish electricity system

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A B S T R A C T

This paper evaluates two smart energy management models for the Spanish electricity system in terms of power consumption savings, CO_2 emissions, and dependence upon primary energy from abroad. We compare a baseline scenario with two alternatives. The first model entails the reduction of the power demand through energy savings measures, smart meters, and self-supply. The second model entails the application of all measures included in first scenario, plus measures oriented to electric vehicles. For each model a sensitivity analysis was performed. Results show that both models can result in reductions of peak loads, CO_2 emissions, and energy dependence.

1. Introduction and overview

Implementation of a smart power grid could facilitate the integration of all users connected to it (producers, consumers, and "prosumers" or producer-consumers, as described in Crispim et al., 2014), to ensure efficient and sustainable electricity supply, with reduced power losses, lower emissions, greater reliability, and security of supply (EU, 2012a). Smart grids also allow greater involvement of the final consumer, who thus becomes the lead manager of the energy consumed (Vijayapriya and Kothari, 2011). Smart grids contribute substantially to the transition" toward a more decentralized and sustainable energy system. In this regard, a smart grid is a socio-technical network characterized by the active management of both information and energy flows to control practices of distributed generation, storage, consumption, and flexible demand (Wolsink, 2012).

The main characteristics of smart grids are: (1) capacity to satisfy demand on a distributed basis without the need for new and large infrastructures; (2) capacity to integrate a large number of technologies and energy sources; (3) real-time communication to improve the consumer's negotiation position (such as price and energy type); (4) creation of new markets; (5) improvement in the quality of supply; (6) resistance to natural disasters; and, (7) lesser impact on the environment (El-hawary, 2014).

A smart-grid network facilitates communication between consumers, managers, generators, and enables self-supply and self-consumption by the "prosumer" (producer and consumer). However, the development of smart grids must overcome barriers related to the structure and regulation of the electricity market. Cambini et al. (2016) concluded that the keys to developing smart grids are: (1) lower market concentration in the electricity distribution sector; (2) the use of incentive-based regulatory schemes; and, (3) the adoption of innovation-stimulus mechanisms.

Utilities play an essential role in the implementation of an intelligent energy management system based on energy saving, improved energy management, self-supply, and electro-mobility. To a large extent, these companies will implement the various measures proposed.

Smart systems for energy management requires substantial investment and in-depth information on the energy system, the environment, the economy, and society.

This paper compares a baseline case with two alternative models (named as 3S and 3S + EV) to calculate the extent to which alternative power management methods can improve the electrical system in terms of demand management, power consumption savings, reduced CO_2 emissions, and reduced dependence on primary energy from abroad. Impacts on customer prices are also provided. The "3S" model entails the reduction of power demand through energy-saving and efficiency measures and self-supply. The "3S + EV" model requires the application of all measures included in the 3S model, plus the electro-mobility measures oriented to electric vehicles (EVs). For each model, a sensitivity analysis was performed.

The data used for the model calculations, including those for fuel consumption in transportation, come from the Spanish Ministry of Industry, Energy and Tourism, the Institute for Energy Diversification and Saving (IDAE) and Red Eléctrica Española (REE). Fuel prices were from the National Commission for Markets and Competition. Details are given in the Dataset section.

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Compared with the baseline case, the results obtained for the 3S model show that it may reduce total power generation needed (up to 12%) and electricity consumption (up to 14%). The CO_2 emissions avoided would amount to a conservative 27% reduction. The findings for the 3S + EV model show an increase in power generation and electricity consumption (6% and 4% higher compared with the baseline case, respectively) because of the introduction of the EVs. CO_2 emissions were reduced by up to 5%, compared with the baseline case. Primary energy dependence could be reduced by 16% (3S) and 2% (3S + EV) over the baseline under conservative assumptions.

In line with the available literature, this paper provides results that could enhance the evaluation of smart energy management models (Basso et al., 2013). The contribution is also derived from the policy recommendations, including stimulus mechanisms (Cambini et al., 2016) and the inclusion of smart meters and EVs as part of a comprehensive approach (Malvik et al., 2013; Mwasilu et al., 2014; Naus et al., 2014; and Bager and Mundaca, 2015).

Regarding distributed electricity, this research contributes to the literature due to its relevance not only for Spain but also for other countries where self-supply is legally allowed, such as in Australia, Belgium, Brazil, Canada, Chile, China, Columbia, Denmark, Finland, France, Germany, Israel, Italy, Japan, Mexico, Sweden, Switzerland, the Netherlands, the United Kingdom, and the United States (International Energy Agency, 2016; Cadena, 2007; Cadena et al., 2009).

This paper provides additional information to Spanish authorities by quantifying the effects of energy efficiency and decarbonization (García and Román, 2014). The period analyzed also allows evaluation of the Spanish Horizon Commitments for 2020 and 2050 (EC, 2010; EU, 2011). Spanish commitments for 2020 call for lowering final energy consumption by a cumulative 185,802 GWh for 2014–2020, increasing the share of renewable energy sources (RES) up to 20% for final energy, and reducing greenhouse gas (GHG) emissions by up to 20% from 1990 levels (57.5 CO_2 Mt) (EU, 2012b; Spanish Ministry of Industry, 2014b; EU, 2009b; Spanish National GHG Inventory, 2017).

The paper is organized into seven sections. Following this introduction, Section 2 addresses the topic of smart grids within the Spanish electricity system. Section 3 describes the methodological approach. Section 4 details the dataset used. Section 5 offers results, which are discussed in Section 6. Section 7 summarizes the main conclusions and provides policy recommendations.

2. Smart grid within the Spanish electricity system

Since 1997, with the liberalization of the Spanish electricity market (Spanish Parliament, 1997), utilities have experienced important changes. First, electricity utilities were forced to separate their generation, distribution, and marketing businesses. Subsequently, the services offered to their customers were diversified. Some new services consist of programs to improve the efficiency of electricity consumption. Through these programs, the utilities have become advisers to their clients and offer them services of management, control, and installation of new equipment for energy efficiency improvement, mainly in homes and businesses. At the same time, utilities have begun to provide management services traditionally been offered by energy service companies. In the field of EVs, utilities are developing projects that include the installation of charging points for electro-mobility. In Spain, the utilities also offer their services as charging managers.

Second, new services oriented to the self-supply of electricity have emerged as a new line of business for the Spanish utilities. Pioneering examples include the utility company Iberdrola, through its Smart solar program and the electricity marketing company Fenie Energia, which offers its customers equipment for self-supply of electricity.

From a technical perspective, smart grids typically include three elements: (1) smart meters; (2) the generation of distributed electricity; and (3) energy storage.

Smart meters are an essential element (Naus et al., 2014) and their contribution improves when consumers utilize the information they provide (Bager and Mundaca, 2015). Of course, there is room for authorities to help consumers by providing information they can use to improve energy management and adjust habits. In the case of Spain, the majority of small consumers (using less than 15 kV of installed capacity), for which the use of smart meters is mandatory by the end of 2018, rent their meters. For these consumers, the rollout of smart meters has been done through the electricity distribution companies, which recover their investment by charging a small rent included in the bill. The cost per smart meter for consumptions of less than 15 kV is about € 90 per unit. Smart meters have also facilitated remote management by these companies. The Spanish government has not subsidized the purchase of smart meters. It is anticipated that all 15 kV consumers in Spain will have been fitted with smart meters by the end of 2018 (Spanish Industry Ministry, 2007). Large electricity consumers have to acquire smart meters directly, which allows them to benefit from dynamic pricing (discussed in Annex 1) and manage their electricity bills.

Distributed generation capacity also plays an important role in smart-grid design, as losses of electricity traveling through the grid are reduced when production is located closer to production. Self-supply avoids generation by conventional power plants and allows consumers to draw power directly from their own equipment (Naus et al., 2014). Both the 3S and 3S + EV models incorporate self-supply of electricity by consumers with their own PV power equipment, where the unused energy is fed into the grid. When the consumers do not generate electricity, they take it from the grid. This system does not require network expansion because it uses the available grid. The only exception is the need for low-voltage networks extension to add charging points for EVs considered in the 3S + EV model. The expansion necessary would be approximately 1700 km, with a cost in the region of €100 M (CYPE Ingenieros, n.d.).

The Spanish legal framework on electricity self-supply contemplates that some of the electricity produced is self-consumed, some is stored, and the rest is fed into the electrical network. Regarding the part that is fed into the network, and to avoid bottlenecks, the Spanish legislation allows the connection of installations of less than 100 kW to distribution networks of 1 kV (Spanish Industry Ministry, 2011a,b). The legislation assumes that the energy produced is consumed by users close to the installation and does not affect the medium- and high-voltage connection nodes.

Power storage systems are becoming essential elements of smart grids and energy management. If as assume that EVs are parked 95% of the time, their batteries could be made into a storage system known as vehicle-to-grid (V2G) (Malvik et al., 2013; Mwasilu et al., 2014). EVs could be used to serve peak loads, improve grid regulation, or facilitate the generation of electricity by RES that are intermittent (wind or photovoltaic). Nevertheless, EVs also increase overall electricity demand. It is generally not assumed that EVs are used for energy arbitrage in the network. The energy accumulated in the batteries of the vehicles will be used directly for the movement of the vehicle itself in substitution of petroleum derivatives.

Regarding the Spanish regulatory framework, the models considered in this paper fully achieve the requirements laid down by the Spanish legal framework and in force by Law 24/2013, Articles 6 and 9, RD 647/2011 and RD 900/2015 (Spanish Parliament, 2011, 2015). In light of this, no regulatory adaptations are required to facilitate the deployment of smart energy management. It is also expected that the EU legal framework will reinforce measures that are in line with models we propose (European Commission, 2016).

3. Specification of the models

3.1. Elements of the models

We compare the reference baseline case with two models for smart

Table 1
Main items to be considered.
Source: Own elaboration

Data And Model	
Input data	Annual energy consumption model
• Electricity consumption per month • Peak electricity demand per month • Electricity from renewable energy sources (RES) • Emissions factor CO_2 • Monthly CO_2 emissions • Daily/hourly CO_2 emissions in peak summer and winter months • Daily/hourly electricity generated in peak summer and winter months • Monthly transmission grid losses • Monthly distribution grid losses • Fuel consumption and emissions for transport • Fuel consumption for electricity transport	• Monthly/hourly electricity generation profile • Monthly/hourly electricity distribution profile • Monthly transmission grid losses • Monthly distribution grid losses • Monthly diesel/gasoline/biofuel consumption in transport sector • Monthly/hourly CO_2 emissions profile
Baseline scenario	
Outputs (monthly/hourly/annual) • Electricity balance • Primary energy and CO2 balance (Electrical System) • Primary energy and CO2 balance (Transport sector)	
Smart energy management system (SEMS)	
Definition: 3S MODEL POWER DEMAND REDUCTION • Active savings measures in electricity demand • Smart metering • Self-consumption (photovoltaic) • Smart management	**Definition: 3S + EV MODEL** POWER DEMAND REDUCTION • Active savings measures in electricity demand • Smart metering • Self-consumption (photovoltaic) • Smart management DEMAND INCREASING • Electromobility
Outputs (monthly/hourly/annual) • Self-consumption energy • Electricity balance • Primary energy and CO_2 balance (Electrical System) • Energy (electricity and primary) and CO_2emission savings	**Outputs** (monthly/hourly/annual) • Self-consumption energy • Electricity • Primary energy and CO_2 balance (Electrical System) • Primary energy and CO_2 balance (transport sector) • Energy (electricity and primary) and CO2emission savings (electricity and transport sector)

energy management.

The models incorporate: (1) smart meters and energy management; (2) the electricity self-supply capacity (the inclusion of photovoltaic energy was explained in section 2); and, (3) energy storage to improve load management and facilitate V2G. Energy savings are achieved by jointly applying other measures, such as the implementation of actions to reduce usage, the incorporation of equipment with higher energy efficiency, and the energy rehabilitation of buildings. Among the measures aimed at improving efficiency in the residential sector are rational lighting, cooling, and heating systems; double glazing of windows; and solar-heated water for household use (Tolón-Becerra et al., 2013; Alcántara et al., 2010). To develop these and other actions, the National Energy Efficiency Fund (Spanish Parliament, 2014; Spanish Industry Ministry, 2014a) was created with financial aid from the European Regional Development Fund (ERDF) and annual economic contributions from electricity, gas, petroleum products and equity traders, as well as funding from the Government of Spain.

Table 1 outlines the 3S model. In the upper right section of the outline, power generation and consumption for the baseline case are shown. The baseline provides the following outputs: monthly and hourly electricity generation distribution profiles, monthly transmission and distribution grid losses, and monthly diesel, gasoline, and biofuel consumption in the transportation sector. This information is obtained from the input data shown in the upper left section of the outline, i.e., the monthly distribution per hour of electricity consumption, electricity generated, fuel consumption in transport and CO_2 emissions. The bottom of Table 1 illustrates the elements of the 3S and 3S + EV models.

The lower box to the left defines a 3S model entailing smart meters and energy management, and self-supply. Energy management systems permit changing the hourly demand to distribute it more evenly throughout the day, thus avoiding spikes. Self-supply reduces generation needs as well as losses in the transmission and distribution of electricity.

The 3S model also includes self-supply of electricity with net consumption balance. When consumers self-supply, their unused energy is fed into the grid. Alternatively, if consumers do not generate electricity, they receive it from the grid.

In Table 1, in the lower box to the right, the 3S + EV model is defined, which requires the application of all measures included in model 3S, plus the electrification of land vehicles that are currently diesel or gasoline consumers. This model assumes that EVs do not feed the stored energy into the grid but use it only for their own operation (comparable to vehicles using petroleum derivatives). Although the increase in electro-mobility may increase power consumption, it could also produce other results. The synergies between solar photovoltaics and EVs was explored by Nunes et al. (2015). The potential benefits are to reduce energy costs to the user, reduce the peak load on the network, improve energy management of the power grid, and reduce CO_2 emissions (Hong et al., 2012).

At the bottom of Table 1, the results to be obtained for the 3S and 3S + EV models are listed respectively. By comparing the outputs from the 3S and 3S + EV models with the baseline case outputs, we can estimate the impact on electricity usage, energy resource mix, power losses, and, CO_2 emissions.

3.2. Methodology for calculating electricity demand

The methodology used to calculate the final electricity demand associated with the 3S and 3S + EV models is based on the annual electricity activity matrix T_1 in Eq (1) in Annex 1. It is a 24 × 12 (hours x months) matrix representing hourly activity for each month of 2013. Based on our data sources (described in Section 5), daily variations range from −1% to 1.5% of the average. This is because the impact of energy efficiency improvements will vary between work days and weekend days. In the expressions in capital letters mean matrix and in the lower case letters mean scalars. Each of the models is associated with a new activity matrix that incorporates key assumptions.

4. Dataset

Most of the data used for the calculations were provided by the Spanish Ministry of Industry, Energy and Tourism, the Institute for Energy Diversification and Saving (IDAE) and Red Eléctrica Española (REE). Transmission, distribution, and monthly and hourly electricity generation data measured in TWh were taken from the REE (REE, 2013a) (REE, 2013b) and (REE, 2013c). Data on fuel consumption in transportation came from the Spanish Ministry of Industry, Energy and Tourism (Spanish Industry Ministry, 2013). The fuel prices considered in the analysis of cost impacts were obtained from the National Commission for Markets and Competition (NCMC, 2014a; 2014b). Table A4 in Annex 2 shows the descriptive statistics.

Table 2
Evaluation of CO_2 emissions in Spanish generation system in 2013 (model 3S).
Source: Own elaboration

	Baseline scenario		3S_1 Model				3S_2 Model			
			TWh		Mt CO_2		TWh		Mt CO_2	
	TWh	Mt CO_2	Medium	Optimal	Medium	Optimal	Medium	Optimal	Medium	Optimal
Nuclear	56.4	0.0	38.0	56.0	0.0	0.0	37.0	56.0	0.0	0.0
Coal	39.8	38.0	27.0	0.0	25.5	0.0	26.0	0.0	25.5	0.0
Natural gas	25.4	9.5	17.0	25.0	6.5	9.5	17.0	24.0	6.0	9.0
Renewable	112.8	0.0	123.0	123.0	0.0	0.0	123.0	123.0	0.0	0.0
Co-generation	32.0	12.0	32.0	32.0	12.0	12.0	32.0	32.0	12.0	12.0
TOTAL	**266.4**	**59.5**	**236.0**	**236.0**	**44.0**	**21.5**	**235.0**	**235.0**	**43.5**	**21.0**

Under climate conventions, namely the Kyoto Protocol and the recent Paris Agreement, targets are set, and accounting is performed with precision. At the same time, Spanish national inventory reports estimate uncertainties about emissions levels at 4.5% for power generation and 5.5% for road transport. Therefore, we rounded the reported emissions measured in Mt CO_2 equivalent to only three significant digits for our analysis.

The baseline case is defined for the Spanish electricity system in 2013. To obtain a meaningful analysis, it is essential to prove that this year is representative. For this purpose, we use the normalized working day and annual temperature. This coefficient was calculated by the REE and eliminates distortions in electricity demand due to the effects of extreme weather or leap years. In 2013, this ratio was - 0.1% (REE, 2016). The higher the value in absolute terms, the less representative it is for the year chosen. In the previous five years, the values were 0.4% (2012), −0.9% (2011), 0.4% (2010), 0.2% (2009) and 0.2% (2008). After 2013, the values were 0.7% (2016), 0.3% (2015), and −1.0% (2014). Therefore, we consider data for 2013 to be reasonably representative for the Spanish case.

The power generation system for self-supply considered in our analysis is a solar photovoltaic (PV) system. This choice is based on the fact that Spain has elevated solar resources, consistent with the 2011–2020 Renewable Energy Plan (Institute for Energy Diversification and Saving, 2010) establishing 38.1% electricity renewable sources by 2020. The numerous annual sunshine hours in Spain ensures a role for solar thermal technology (for the generation of electricity and heating) and photovoltaic technology. An installed PV capacity of 5600 MW is assumed, which is equivalent to 15% of 2013 peak load (July). To obtain results, we have simulated the operation of a standard PV system that considers the monthly power profiles for winter and summer and the energy produced per hour.

The 3S model is defined from the data on electricity transmission during peak load months (maximum electricity transmission in one hour on a given day). This value corresponds to maximum electrical power requirements from the generation system and, measures the impact of 3S on total electricity generation. Specifically, January 2013 was the peak month for winter and July for summer. We take into account the time profile of power for these months and apply the appropriate profile for all winter and summer months. Table A3 in Annex 2 shows the monthly peak loads for 2013. The winter month profile shows the peak load at 21:00 h corresponding to January, February, March, November, and December. The remaining months are the summer profile.

The value of the emission factors considered in this paper was taken from the Spanish Renewable Energy Plan 2005–2010 (Institute for Energy Diversification and Saving, 2005) and is in line with the European Commission Decision 2007/589/EC (REE, 2013b). Emission factors are measured in t CO_2/GWh and t CO_2/ktoe depending on the resource.

5. Results

This section presents the results of our comparison between the baseline case and the 3S and 3S + EV models. Detailed information of the distribution factors assumed (see F_{ah} and F_d in Annex 1) is shown in Table A1. Assumed CO_2 emissions factors are detailed in Table A2. Once the values of the variables included models 3S and 3S + EV are estimated, they are compared with those of the baseline allowing us to estimate impact EVs on energy and emissions.

5.1. Results from the comparison between the baseline case and the 3S model

Electricity consumption in Spain in 2013 (the baseline case) amounted to 223.5 TWh, while the total electricity supply rose to 266.4 TWh emitting 59.5 Mt CO_2 (REE, 2013b). Of the total electricity generated, 42.4% came from renewable sources, mainly wind (20.2% of total generation) and hydropower (15.5%). The remaining electricity was generated by nuclear (21.2%), cogeneration (12.0%), coal-powered (14.9%), and natural gas combined cycle plants (9.5%).

Results from the 3S model imply that total electrical demand would be 191.4 TWh (14% below the baseline case), with 9.8 TWh from self-supply, and 181.6 TWh from the grid. As a result of all these measures, the demand for electricity from the grid would be reduced by 18.7% (41.9 TWh) relative to the baseline case.

For the sensitivity analysis, we defined two sub-models. The first (3S-1) considers a 5% reduction in peak load. For the transmission and distribution losses, the reduction would be 2%. A second option (3S-2) would show a reduction of 10% for peak load and 10% for losses.

In the case of sub-model 3S-1, electricity generation would reach 236.5 TWh (11.2% lower than in the baseline case). After deducting self-supply, the generation need would be 226.7 TWh. Regarding the electricity generation structure, shown in Table 2, RES increase their share from the baseline case, reaching the Spanish commitment for Horizon 2020 (EC, 2010).

Regarding sub-model 3S-2, electricity generation would be 11.8% less than in the baseline. Considering self-supply, generation would amount to 15.5% less than in the baseline. Regarding the energy resource mix, shown in Table 2, this amount implies an increase of ten percentage points from the baseline case. This is mainly due to the net increase of self-supply by solar PV 9.8 TWh and the reduction of electricity generation, losses, and peaks.

Table 2 also shows the primary resource mix for the baseline case and the 3S model. To estimate this mix for each of the sub-models, resource profiles have been considered. It is assumed that the "Medium" profile corresponds to the structure of the current mix in Spain for nuclear technologies, coal and natural gas. The profile assumed as "Optimal" corresponds to a mix that minimizes CO_2 emissions. In this case, the use of coal by thermal plants is not included, as it

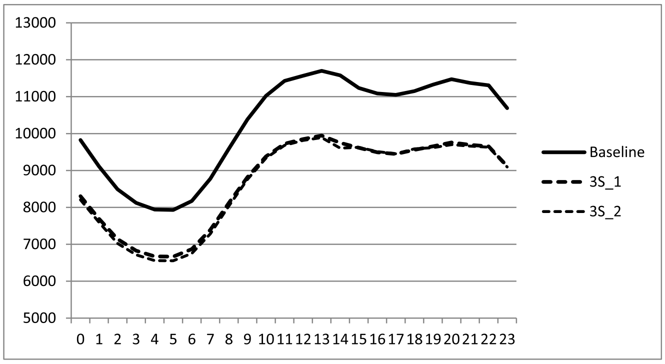

Fig. 1. Electrical Demand in transport times baseline scenario, and 3S_2, 3S_1 scenarios (GWh).
Source: Own elaboration

is replaced by nuclear and renewable technologies as non-producers of CO_2, while the cogeneration and combined cycles remain, as they are more efficient and cleaner than the coal plants operating in Spain. The baseline case is assumed to be the worst case in terms of emissions. For sub-model 3S-1, results for primary energy savings would be in the range of 15.6% and 26.1% of the baseline. In the case of sub-model 3S-2, the reduction varies between 16.3% and 26.8% of the baseline. In the models considered, the contribution of RES in the electricity generation structure is higher, which is in line with Horizon 2020.

The 3S model also contributes to smoothing the load curve. As a result of the proposed energy consumption improvements (reduction of the peak load, improved energy efficiency, time consumption and re-distribution to reduce transmission and distribution losses), the curve flattens, demonstrating the energy need. Fig. 1 shows the annual hourly demands for energy transmission.

The peak loads (produced at 21:00. hours) in sub-models, 3S-2 and 3S-1, are reduced by 15.5% and 15.0%, respectively, compared to the baseline. Similarly, the minimum peaks are also reduced by 17.4% and 15.9%, respectively, in both scenarios. It is also observed how the difference between the maximum and minimum hourly consumption is reduced as well (11.5% and 13.0% respectively). As a result of this optimization, peak power generation is also lower.

Emissions avoided would range from between 26.1% and 64.7% compared with the baseline. Table 2 provides the detailed results. For the sub-model 3S-1, the reductions are 26.1% and 63.9%, while for the sub-model 3S-2, these are 26.9% and 64.7%. With a resource mix that minimized emissions coal powered plants could be closed.

5.2. Results from the comparison between baseline case and the 3S + EV model

The 3S + EV model includes an increased use of EVs. This assumption implies that 10% of all fossil fuels (gasoline and diesel) used in road transport are replaced by electricity, thus affecting total electricity demand. Compared to hydrogen vehicles, which may require an entirely new infrastructure, the advantage of EVs is seen as largely making use of existing electricity delivery infrastructure. Deployment of charging stations is the most usual measure to promote the use of EVs carried out by the main urban authorities funding by the Spanish Ministry of Industry, Tourism and Trade through the Institute for Diversification and Energy Saving (IDAE). This figure matches the target set for 2020 in Spain (Institute for Energy Diversification and Saving, 2011). It also considers that 93% of vehicles correspond to trickle charge (usually an overnight charge) and 7% faster charge (daytime). This assumption is consistent with the forecasts of the Spanish Government, based on the "Plan Movele" (Institute for Energy Diversification and Saving, 2014b). Currently, there are 761 charging points in Spain, of which only four are fast charging (Institute for Energy Diversification and Saving, 2014b). Regarding the number of EVs, there were 377 registered in 2011, 484 in 2012 (Motor Passion, 2014); in 2013, this number had grown to 1149 (Foro coches eléctricos, 2014). These statistics are a far cry from the 2.5 million vehicles target by H 2020 (Institute for Energy Diversification and Saving, 2011).

A higher use of EV in 3S + EV model would increase electricity requirements over 17.8% compared with the baseline case. The implementation of measures to achieve the 3S + EV model would be 3.4% higher than in the baseline case (231.1 TWh). Table 3 shows that RES reach a 9.1% increase in electricity generation from the baseline.

The electrification of road transportation would reduce the consumption of petroleum products by 10%, increase the share of renewable energies in the transport sector, and reduce CO_2 emissions, as will be shown later. The reduction of 10% of oil consumption in road transport would be equivalent to the consumption of around 4.4 million conventional tourism vehicles IDAE (2017a). As for renewable energy, in the baseline case, 7.0% was from biofuels (mainly biodiesel). By including EVs, the use of biofuel is maintained, but the renewable fraction of electricity is added, which means that RES would provide about 10.8% of total transport consumption (45.0 TWh).

Table 3 shows the resource mix in the baseline case and the 3S + EV model. For sub-model 3S + EV-1 saving in primary energy would vary in a range from 1.9% to 6.7% when comparing with the baseline case. For sub-model 3S + EV-2 savings would vary in a range from 2.3% to

Table 3
Evaluation of CO_2 emissions in Spanish generation system and transport in 2013 (model 3S + EV).

	Baseline scenario		3S + EV_1 Scenario				3S + EV_2 Scenario			
			TWh		Mt CO_2		TWh		Mt CO_2	
	TWh	Mt CO_2	Medium	Optimal	Medium	Optimal	Medium	Optimal	Medium	Optimal
Nuclear	56.3	0.0	59.0	56.0	0.0	0.0	58.0	56.0	0.0	0.0
Coal	39.7	38.0	42.0	0.0	40.0	0.0	41.0	0.0	39.5	0.0
Natural gas	25.4	9.5	27.0	71.0	10.0	26.5	26.0	69.0	10.0	26.0
Renewable	112.7	0.0	123.0	123.0	0.0	0.0	123.0	123.0	0.0	0.0
Co-generation	32.0	12.0	32.0	32.0	12.0	12.0	32.0	32.0	12.0	12.0
TOTAL ELECTRICITY (*)	**266.4**	**59.5**	**282.0**	**282.0**	**62.0**	**38.5**	**280.0**	**280.0**	**61.5**	**38.0**
ELECTRICITY without transport	**266.4**	**59.5**	**239.0**	**238.0**	**52.5**	**32.5**	**237.0**	**237.0**	**52.0**	**32.0**
Diesel	293.0	77.5	293.0	264.0	69.5	69.5	293.0	264.0	70.0	70.0
Gasoline	54.0	13.5	54.0	49.0	12.0	12.0	54.0	49.0	12.0	12.0
Biofuel	26.0	0.0	26.0	26.0	0.0	0.0	26.0	26.0	0.0	0.0
Electricity			44.0	43.0	9.5	6.0	43.0	44.0	9.5	6.0
TOTAL TRANSPORT	373.0	91.0	417.0	382.0	91.0	87.5	417.0	382.0	91.5	88.0
TOTAL Mt CO_2		**150.2**			**143.5**	**120.0**			**143.5**	**120.0**

(*) Includes electricity consumption in transport sector.

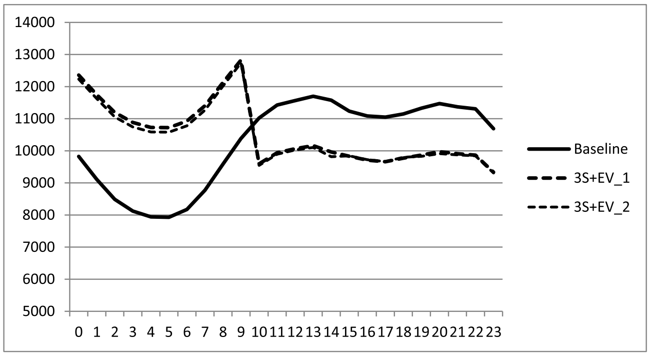

Fig. 2. Generation and consumption of electricity in 2013 h and 3S + EV (GWh). Source: Own elaboration (REE, 2013a).

7.1%. The use of electricity in the transport sector would reduce the consumption of diesel and gasoline by 35 TWh. The overall balance of the process is shown in Table 3. To avoid double accounting, the electricity consumption used for transportation, which was already included in the electricity generation, was excluded here.

Fig. 2 represents the change in the power generation profile associated with the 3S + EV scenario. This same Figure shows the effect of EVs, which greatly increases the night time power demand. In the baseline case, during the off-peak (night), a minimal consumption is reached, with 7.9 TWh being consumed at 05.00 h. Nonetheless, by considering the EV peaks in the 3S + EV-1 and 3S + EV-2 scenarios, these values vary from 12.8 TWh and 12.7 TWh (09.00 h), respectively. This new peak load is 10.2% higher than in the baseline. In Fig. 2, the jump observed in consumption between night and daytime hours is because the model assumes that 93% of the charging of the vehicles is made from 00:00 h to 09:00 h, due to the lower cost of energy. Alternatively, if there is a uniform 24-hour recharge, the peak is reduced to 1.0% and 1.5%, respectively, which is slightly below the current peak consumption.

The balance of CO_2 emissions, as shown in Table 3, indicates that emissions from the road transportation sector would be reduced, when compared with the baseline case, by between 3.3% and 3.8%, respectively, in the 3S + EV-1 and 3S + scenarios EV-2. The CO_2 emissions associated with the demand for EVs have been calculated based on the resource mix. For the 3S + EV-1 and 3S + EV-2 model, the emissions would be reduced by between 4.5% and 20.1%.

6. Discussion

The results, as shown in Table 4, indicate that the 3S scenario would yield an electricity consumption saving of 14.4%, this represents a 32.1 TWh consumption reduction from 2013 (223.5 TWh). Taking into account the impact of self-supply, electricity from the grid would decrease in 19.0% compared with the baseline case. Furthermore, the power generation structure would experience significant change. However, the uncertainty affecting electricity demand could vary by a range from −1.0% to 1.5%.

The presence of RES in the resource mix would increase by 1.1–9.5% by 2013, raising its relative weight in the structure of electricity generation from 42.3% to 51.8% in 2013, and 52.2%, according to the minimum or maximum level of compliance (3S model). Along with this, cogenerated power plants would represent 11.3%–13.6%. Nuclear, coal, and natural gas would reduce their weight in the resource mix from 45.6% to 34.6% and 34.2% in the 3S stage. These energy savings, together with the modification of the generation structure would reduce CO_2 emissions. Tables 5 and 6 show how these results could contribute to meeting Horizon 2020 commitments.

The inclusion of EVs in the analysis for the 3S + EV scenario would reduce the consumption of electricity as well as petroleum products. In the 3S + EV scenario, the electricity generation structure is slightly modified. Renewable energy goes from 42.5% to 43.5% and 43.7%, CHP moves from 11.6% to 11.3%, while the rest reduce their contribution from 45.6% to 45.2%–44.8%, compared to baseline. The CO_2 emissions avoided in the medium scenario would decrease between 7 and 30 million tons, and between 754 and 31 million tons in an optimal scenario. Tables 7 and 8 show how these results could contribute to meeting Horizon 2020 commitments.

As for reducing the need for primary power, in a 3S scenario, the variation ranges from 14.4 to 50.7 TWh. The 3S + EV reduction would vary between 17.6 and 54.1 TWh, whereas, the total primary energy consumption in 2013 was 1408 TWh (Institute for Energy Diversification and Saving, 2014a). Spain would have reduced the

Table 5
Linked between 3S model and energy savings commitments for 2020.
Source: Own elaboration

	Baseline	3S_1		3S_2	
		Medium	Optimal	Medium	Optimal
Energy (TWh)	386.1	326.0	285.5	323.3	282.6
Energy Savings (TWh)		60.1	100.6	62.8	103.5
% Achieved the objective of energy savings		32.4%	54.2%	33.8%	55.7%

Table 6
Linked between 3S scenarios and CO_2 commitment in 2020.
Source: Own elaboration

	Baseline	3S_1		3S_2	
		Medium	Optimal	Medium	Optimal
Emissions ($MtCO_2$)	59.5	44.0	21.5	43.5	21.0
Avoided Emissions ($MtCO_2$)		15.5	38.0	16.0	38.5
% Achieved the objective of reducing CO_2 emissions		28.9%	70.9%	29.8%	71.8%

Table 4
Major results.
Source: Own elaboration

Changes vs baseline scenario	3S				3S + EV			
	3S_1		3S_2		3SV + EV_1		3SV + EV_2	
	Medium	Optimal	Medium	Optimal	Medium	Optimal	Medium	Optimal
Savings in power generation	11.2%	11.2%	11.8%	11.8%	−5.9%	−5.9%	−2.2%	−2.2%
Savings in electricity consumption	14.4%	14.4%	14.4%	14.4%	−3.5%	−3.5%	−3.5%	−3.5%
Increased share of RES	8.7%	8.7%	8.7%	8.7%	7.1%	7.1%	7.1%	7.1%
Reducing demand peak	15.0%	15.0%	15.5%	15.5%	−9.0%	−9.0%	−9.0%	−9.0%
Reducing primary energy use	15.5%	26.0%	16.3%	26.8%	1.9%	6.7%	2.3%	7.1%
CO_2 emissions avoided	26.1%	63.9%	26.9%	64.7%	4.5%	20.1%	4.5%	20.1%

Table 7
Linked between 3S + EV scenarios and energy savings commitments for 2020.
Source: Own elaboration

	Baseline	3S + EV_1		3S + EV_2	
		Medium	Optimal	Medium	Optimal
Energy (TWh)	759.1	745	708	51	705
Energy Savings (TWh)		14	51	18	54
% Achieved the objective of energy savings		7.8%	27.3%	9.5%	29.1%

consumption of total primary energy by between 1.0% and 3.8%. The contribution of renewable energy in 2013 was 14% compared to the primary energy consumption (Institute for Energy Diversification and Saving, 2014a). Considering the new scenarios analyzed, this contribution would range between 14.0% and 16.0%. Moreover, the share of renewable energies in the transport sector would increase from the current 7.0%–12.0%.

These savings in consumption of total primary energy would contribute to fulfilling the commitment established by the European Union (EU, 2012b), whereby each of the Member States utility companies (or distributors or retailers of energy) save 1.5% per year of all energy sold. The impacts described above (the primary energy savings, the emissions avoided, the changes in power generation and the greater share of renewable energies) also incorporate improved demand management and softening electricity consumption peaks. In the 3S scenario, a 15.5% reduction in consumption is achieved in the annual peak hours (21:00 h). Regarding the results obtained for the 3S + EV scenario, they differ significantly due to an EV charging system that is more consumption intensive at night. For this reason, the new energy peak is 10.2% higher than the baseline. Vehicle recharging is calculated between 00:00 h to 09:00 h due to the lower cost of energy. In the case of there being a uniform recharge throughout a 24-hour period, the peak would be reduced by 1% compared to the current situation.

Smart energy management requires investment. López-Peña et al. (2012) provide interesting data on the cost of a variety of investments aimed at reducing power consumption and producing savings.

For the 3S model, essential investments are estimated at €21,600 M. For the 3S + EV model, the necessary investments would reach €24,000 M. Considering only the 2013 cost of energy for an average consumer, these investments would generate annual savings of up to €3593 M for 3S and €7463 M for 3S + EV, which allow cost recovery periods of six and three years, respectively. Part of these investments corresponds to smart meters which the utility companies are required to install for power supplies contracting up to 15 kW before 31 December 2018 (Spanish Industry Ministry, 2007). Investments in self-supply and EVs are, for the most part, borne by citizens and SMEs. Companies operating the generation, transmission, and distribution infrastructures will be responsible for financing the investments in system management, electricity storage, and the smart grid. Therefore, a variety of stakeholders are involved in the development of this new architecture of the Spanish energy system, with the public administration playing an important role in the promotion, coordination, regulation, and facilitation of these efforts. Other associated benefits would be the employment impact linked with the development of PV and EVs and the energy efficiency improvement or pollutant emissions avoided due to EVs. Equally important is the saving due to reduced purchases of fossil fuels from abroad. Spain has an 83% dependency on these fuels (Eurostat, 2013).

Table 8
Linked between 3S + EV scenarios and CO_2 commitment in 2020.
Source: Own elaboration

	Baseline	3S + EV_1		3S + EV_2	
		Medium	Optimal	Medium	Optimal
Emissions ($MtCO_2$)	150.2	143.5	120.0	143.5	120.0
Avoided Emissions ($MtCO_2$)		6.7	30.2	6.7	30.2
% Achieved the objective of reducing CO_2 emissions		12.5%	56.3%	12.5%	56.3%

Finally, the proposed Smart grid systems would impact on the final price of electricity for consumers. This final price in Spain is determined by two components: (1) a variable component that depends on the actual consumption of electricity and which is determined in the electricity market generated for each hour of the day; and (2) a fixed component established by the regulator to finance the fixed costs of the electricity delivery system. Two taxes are added to both components, the special tax on electricity and VAT. For a domestic consumer, the variable component of the final price represents, on average, 28% of their total bill - taxes included (Spanish Industry Ministry, 2017). The value of this component varies for each hour of the day depending mainly on the technologies that generate electricity at that time of day. In general, both the technologies that use RES and nuclear plants offer the electricity generated at a sale price of €0/MWh. This is because the Spanish spot electricity market utilizes marginal-cost pricing. As a consequence, the electricity offered by the generating plants will be remunerated with the final price that results from the auction held for each hour of the day.

For the base year considered in this research, 2013, the average market price of electricity in Spain was €44.26/MWh (OMIE, 2017). Considering the increase in the use of RES and applying the market operation described above to scenarios 3S and 3S + EV, the market price would be reduced to €18.33/MWh (for 3S) and €24.04/MWh (for 3S + EV). This means a reduction in the market price of 58.6% and 45.7%. For a typical domestic consumer, the systems proposed would allow annual savings of 16.4% for 3S and 12.8% for 3S + EV. The effect of the dynamic tariffs on the scenario 3S + EV was not evaluated due to the lack of available information on the total electricity consumption of a household with EV.

7. Conclusions

The results obtained show that the self-supply of electricity and the improvement of energy management are interesting lines of business that Spanish utilities can offer to their customers. As part of a smart-energy system, these services contribute to the decarbonization of the Spanish economy by reducing the demand for electricity, the risk of electricity disruption, the emission of other air pollutants, and the external dependence for primary energy.

The deployment of smart-grid systems is relevant because of the reduction of the peak power. A proposal such as the one considered in this paper also increases the share of RES in the Spanish electricity matrix, so the CO_2 emissions could decrease as well, enhancing the quality of air, mainly, but not only, in urban zones. The deployment of EVs is also relevant from a perspective of noise and urban air pollution due to the reduction of pollutants such as particulate matter (PM 10 and PM 2.5), NOx, HC, and CO.

Taking the Spanish power system data for 2013 as the baseline case, two comparison models identified as 3S (smart grid, smart city, and smart metering) and 3S + EV (which adds EV to 3S) are defined. Each comparison is associated with a low compliance level (a 5% reduction in peak power load and a 2% reduction in transmission losses) and a maximum one (10% and 10%, respectively).

Both comparison models and the two compliance levels are defined from objectives established in official documents from the EU authorities and those of Spain. Consequently, these are realistic and credible scenarios. However, we might be cautious with the findings due to uncertainty concerning electricity demand behaviour. In any case, based on the available historical data, the level of uncertainty varies from −1.0% to 1.5% and considered acceptable.

Our findings suggest that the two smart energy systems considered could help the Spanish authorities to meet their international commitments, particularly those established by the EU legal framework. All the same, given the limited use of electric cars in Spain to date, the 3S + EV model is more elusive than the 3S. The results show a remarkable improvement in the decarbonization process in the Spanish economy. Equally interesting are the results from the primary energy dependence perspective, as they would be reduced by 16% (3S) and 2% (3S + EV) under conservative assumptions. The 3S model (mostly due to the low adoption of EVs), would result in annual savings of around €3600 M.

The Spanish legal framework in force since 2013 is oriented to (1) correct electricity demand management; (2) higher quality of the electricity supply; (3) expand recharging systems of EVs; and (4) self-electricity consumption. We identify three main barriers acting as limits against the two smart energy systems assessed in the paper. The main barriers are (1) the lack of a legal regulatory framework for smart grids and options to enhance electricity demand management; and (2) the fear by consumers that the information that they share about their energy consumption will be misused by the energy service companies, as indicated by FUTURED (2016).

To overcome these barriers, some measures were recently brought into force, namely promoting the acquisition of efficient vehicles through the "Programa de Incentivos para los Vehículos Eficientes" (PIVE) and promoting energy efficiency efforts with funding by the Fondo Nacional de Eficiencia Energética (IDAE, 2017b).

We further recommend strengthening intelligent electrical demand management by enforcing compliance with the ISO 50.001 standard as well as the expanded use of information communication technologies (ICTs) in grids and meters, for them to become smart grids and smart meters. These are necessary steps toward smart cities. We recommend mandatory use of smart metering for all customers, not just those consuming under 15 kV. We agree with previous research that found room for authorities to help consumers in managing information from smart meters. We also recommend guaranteeing the confidentiality of the consumption data provided by consumers to energy service companies. These data should only be used to improve demand management. Expanded adoption of EVs should be promoted to achieve air quality goals.

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Annex 1

First, the expression [1] defines annual consumption (C_1) deducting transmission and distribution losses for the baseline case (matrix P_1) from T_1. The total electricity saving for this scenario is distributed among the hours of each day of the month. Specifically, the reduced demand is expected to be 10%. This value is considered realistic if one considers that the 2011–2020 Action Plan for Energy Saving and Efficiency (Institute for Energy Diversification and Saving, 2011) foresees a 26.5% reduction in energy consumption for the period 2010–2020. A monthly schedule for this energy saving is implemented through factor F_{ah} defined as a 24 × 1 vector on Table A1 in Annex 2.

$$\begin{pmatrix} c_{11}^1 & c_{12}^1 & \cdots & c_{112}^1 \\ c_{21}^1 & c_{22}^1 & \cdots & c_{212}^1 \\ \vdots & \vdots & \ddots & \vdots \\ c_{241}^1 & c_{242}^1 & \cdots & c_{2412}^1 \end{pmatrix} = \begin{pmatrix} t_{11}^1 & t_{12}^1 & \cdots & t_{112}^1 \\ t_{21}^1 & t_{22}^1 & \cdots & t_{212}^1 \\ \vdots & \vdots & \ddots & \vdots \\ t_{241}^1 & t_{242}^1 & \cdots & t_{2412}^1 \end{pmatrix} - \begin{pmatrix} p_{11}^1 & p_{12}^1 & \cdots & p_{112}^1 \\ p_{21}^1 & p_{22}^1 & \cdots & p_{212}^1 \\ \vdots & \vdots & \ddots & \vdots \\ p_{241}^1 & p_{242}^1 & \cdots & p_{2412}^1 \end{pmatrix}$$

$$C_1 = T_1 - P_1 \tag{1}$$

c_{ij}^1 being the energy consumption of hour i (hereafter i = 1, …,24) for j the month of the baseline case, t_{ij}^1transmitted energy and $p_{ij}^1$the power losses due to transmission and distribution per hour i in month j.

The matrix $\widehat{F_{ah}}$ in Eq (2) is a 24 × 24 matrix constructed from the diagonalization of the vector F_{ah}. The new consumption matrix C_2 is obtained in Eq (2) by deducting the matrix $\widehat{F_{ah}}$ from the Identity matrix (I) and multiplying by the C_1 matrix. The C_2 matrix represents the energy consumption after the implementation of savings measures.

$$\begin{pmatrix} c_{11}^2 & c_{12}^2 & \cdots & c_{112}^2 \\ c_{21}^2 & c_{22}^2 & \cdots & c_{212}^2 \\ \vdots & \vdots & \ddots & \vdots \\ c_{241}^2 & c_{242}^2 & \cdots & c_{2412}^2 \end{pmatrix} = \left(\begin{pmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{pmatrix} - \begin{pmatrix} f_{ah1} & 0 & \cdots & 0 \\ 0 & f_{ah2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & f_{ah24} \end{pmatrix} \right) * \begin{pmatrix} c_{11}^1 & c_{12}^1 & \cdots & c_{112}^1 \\ c_{21}^1 & c_{22}^1 & \cdots & c_{212}^1 \\ \vdots & \vdots & \ddots & \vdots \\ c_{241}^1 & c_{242}^1 & \cdots & c_{2412}^1 \end{pmatrix}$$

$$C_2 = \left(I - \widehat{F_{ah}}\right) * C_1 \tag{2}$$

where, after applying saving measures, c_{ij}^2 represents energy consumption, I is the identity matrix and $f_{ahj}$is a coefficient of energy saved per hour i in month j.

The self-supply matrix (A) is subtracted from C_2 to obtain the final energy consumption C_3 in Eq (3).

$$\begin{pmatrix} c_{11}^3 & c_{12}^3 & \cdots & c_{112}^3 \\ c_{21}^3 & c_{22}^3 & \cdots & c_{212}^3 \\ \vdots & \vdots & \ddots & \vdots \\ c_{241}^3 & c_{242}^3 & \cdots & c_{2412}^3 \end{pmatrix} = \begin{pmatrix} c_{11}^2 & c_{12}^2 & \cdots & c_{112}^2 \\ c_{21}^2 & c_{22}^2 & \cdots & c_{212}^2 \\ \vdots & \vdots & \ddots & \vdots \\ c_{241}^2 & c_{242}^2 & \cdots & c_{2412}^2 \end{pmatrix} - \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{112} \\ a_{21} & a_{22} & \cdots & a_{212} \\ \vdots & \vdots & \ddots & \vdots \\ a_{241} & a_{242} & \cdots & a_{2412} \end{pmatrix}$$

$$C_3 = C_2 - A \tag{3}$$

c_{ij}^3 being energy consumption and a_{ij}self-powered energy per hour i in month j respectively.

Energy management systems allow us to distribute electricity more evenly across the hours/days, due to smart meters, which permit consumers to manage their consumption and power storage systems or self-supply of electricity using photovoltaic (PV) (Wolsink, 2012; Bager and Mundaca, 2015). This distribution is carried out by the F_d factor that is a vector (24 × 1) described in Table A1.

Expression [4] allows us to obtain matrix C_4 (24 × 12) in which the consumption is redistributed by multiplying F_d by C_3', the latter is a (1 × 12) vector in which every element is calculated as the sum of each column of the C_3 matrix. Finally, the new T_2 matrix is calculated by adding the new C_4 matrix to the transmission and the distribution power losses of the baseline case (matrix P_2).

$$\begin{pmatrix} c_{11}^4 & c_{12}^4 & \cdots & c_{112}^4 \\ c_{21}^4 & c_{22}^4 & \cdots & c_{212}^4 \\ \vdots & \vdots & \ddots & \vdots \\ c_{241}^4 & c_{242}^4 & \cdots & c_{2412}^4 \end{pmatrix} = \begin{pmatrix} f_{d1} \\ f_{d2} \\ \vdots \\ f_{d24} \end{pmatrix} * \begin{pmatrix} \sum c_{i1}^3 & \sum c_{i2}^3 & \cdots & \sum c_{i12}^3 \end{pmatrix}$$

$$C_4 = F_d * C'_3 \tag{4}$$

where c_{ij}^4 shows energy consumption per hour i in month j and f_{di} new energy distribution from a smart system corresponding to scenario 3S per hour i. For the 3S scenario, a new T_2 matrix has been calculated in Eq (5).

$$\begin{pmatrix} t_{11}^2 & t_{12}^2 & \cdots & t_{112}^2 \\ t_{21}^2 & t_{22}^2 & \cdots & t_{212}^2 \\ \vdots & \vdots & \ddots & \vdots \\ t_{241}^2 & t_{242}^2 & \cdots & t_{2412}^2 \end{pmatrix} = \begin{pmatrix} c_{11}^4 & c_{12}^4 & \cdots & c_{112}^4 \\ c_{21}^4 & c_{22}^4 & \cdots & c_{212}^4 \\ \vdots & \vdots & \ddots & \vdots \\ c_{241}^4 & c_{242}^4 & \cdots & c_{2412}^4 \end{pmatrix} + \begin{pmatrix} p_{11}^2 & p_{12}^2 & \cdots & p_{112}^2 \\ p_{21}^2 & p_{22}^2 & \cdots & p_{212}^2 \\ \vdots & \vdots & \ddots & \vdots \\ p_{241}^2 & p_{242}^2 & \cdots & p_{2412}^2 \end{pmatrix}$$

$$T_2 = C_4 + P_2 \tag{5}$$

t_{ij}^2 being energy transmitted and p_{ij}^1power losses due to transport and distribution in scenario 3S per hour i in month j.

The sum of the elements for each of the T_2 columns represents the monthly consumption of energy transmitted. The sum of the 12 values obtained matches the total annual transmission energy consumption (e_t). To calculate the total energy consumed in distribution, (g) must be added to the consumption of generation (e_g) and the imported-exported power balance ($e_{imp\text{-}exp}$), as shown in Eq (6).

$$g = e_t + e_g + e_{imp+\exp} \tag{6}$$

This allows us to calculate the final electricity demand associated with the 3S system.

For the sensitivity analysis, the demand shows a minimum and a maximum. The targets set by the EU (EU, 2009a; 2012a), related to a reduction in peak power (between 5 and 10%) and a reduction of transmission and distribution power losses (between 2 and 10%), have been taken into account. Since these objectives have been formulated in terms of maximum and minimum values for each of the scenarios analyzed in this paper, 3S and 3S + EV have established two levels of compliance. This allows a sensitivity analysis to be performed, which enriches the results. The minimum level is associated with achieving a 5% reduction in peak power and a 2% reduction in transmission losses, while for the maximum level, the reduction has been calculated at 10% in peak power and a 10% reduction in transmission losses.

To calculate the final power demand that corresponds to the other smart system considered in this paper, 3S + EV, a target penetration of EVs is added to the above calculations. To be realistic, this objective has been defined following the 2050 Energy Roadmap (EU, 2011). From this document, Spanish authorities established a 10% replacement target for gasoline and diesel fuel in favor of electricity by 2020 (Institute for Energy Diversification and Saving, 2011).

The electricity demand associated with the 3S + EV scenario, that is C_5 in Eq (7), has been calculated by adding to the final demand for the 3S scenario (C_4), the energy demand associated with a greater use of EVs (V_E matrix in Eq (7)). It has been calculated that 97% of all EV recharging is performed in the time slot from 00:00 h to 9:00 h because that is when power costs are lower.

A specific comment on dynamic tariffs is here recommended. In 2011, a specific tariff for EV recharging was adopted in Spain to provide an incentive for adoption of EVs. The tariff was modified in 2014 when a dynamic tariff system was implemented (Spanish Industry Ministry, 2011a, 2014c and 2015), so any EV users could enjoy specific tariff for EVs jointly with dynamic tariffs. Although benefits of dynamic tariffs have been analyzed (Faruqui and Sergici, 2010; Faruqui et al., 2010; Buryk et al., 2015), they have not acted as a spur for EVs in Spain until now. Regarding 2017 and for the period from 1:00 to 7:00 h the final electricity price for EV users was 98% lower than for a standard user, while during the period from 13:00 to 23:00 h it was 41% higher. If average annual prices (2015 and 2016) are considered for a standard user, these were 120.84 €/MWh and 102.61 €/MWh, while for EVs they were 98.81 €/MWh and 82.63 €/MWh, respectively (ESIOS, 2017; OMIE, 2017). Despite these difference in prices by the end of 2015, the number of EVs in Spain was 6,000, the total number of vehicles being more than 22 million, while in Norway, for example, the total number of EVs was 71,000 with a total fleet of 2.5 million vehicles (Deloitte, 2017). Due to the dynamic tariffs allowing the optimization of the loading times of the EVs this should have favoured the penetration of such vehicles in Spain. However, some barriers seem to have hindered this so far. These barriers include the current high price of EVs, limited incentives for potential buyers, user mistrust and a lack of recharging points. Overcoming these barriers, together with the specific tariff for charging and the dynamic tariffs, allow us to be optimistic about the penetration of EVs in Spain in the coming years. Although this would be interesting, a modelling of the choice of the optimum recharge period using the dynamic tariffs system exceeds the purpose of this research but should be taken into account for future analysis.

The new profile of consumed and transmitted energy is obtained on a monthly schedule distributed profile as in Eq (7) and Eq (8). In this scenario, the total energy produced will be calculated as follows:

$$\begin{pmatrix} c_{11}^5 & c_{12}^5 & \cdots & c_{112}^5 \\ c_{21}^5 & c_{22}^5 & \cdots & c_{212}^5 \\ \vdots & \vdots & \cdots & \vdots \\ c_{241}^5 & c_{242}^5 & \cdots & c_{2412}^5 \end{pmatrix} = \begin{pmatrix} c_{11}^4 & c_{12}^4 & \cdots & c_{112}^4 \\ c_{21}^4 & c_{22}^4 & \cdots & c_{212}^4 \\ \vdots & \vdots & \cdots & \vdots \\ c_{241}^4 & c_{242}^4 & \cdots & c_{2412}^4 \end{pmatrix} + \begin{pmatrix} v_{11} & v_{12} & \cdots & v_{112} \\ v_{21} & v_{22} & \cdots & v_{212} \\ \vdots & \vdots & \cdots & \vdots \\ v_{241} & v_{242} & \cdots & v_{2412} \end{pmatrix}$$

$$C_5 = C_4 + V_E \tag{7}$$

being c_{ij}^5 energy consumption and v_{ij}energy used by EVs in scenario 3S + V.

$$\begin{pmatrix} t_{11}^3 & t_{12}^3 & \cdots & t_{112}^3 \\ t_{21}^3 & t_{22}^3 & \cdots & t_{212}^3 \\ \vdots & \vdots & \cdots & \vdots \\ t_{241}^3 & t_{242}^3 & \cdots & t_{2412}^3 \end{pmatrix} = \begin{pmatrix} c_{11}^5 & c_{12}^5 & \cdots & c_{112}^5 \\ c_{21}^5 & c_{22}^5 & \cdots & c_{212}^5 \\ \vdots & \vdots & \cdots & \vdots \\ c_{241}^5 & c_{242}^5 & \cdots & c_{2412}^5 \end{pmatrix} + \begin{pmatrix} p_{11}^3 & p_{12}^3 & \cdots & p_{112}^3 \\ p_{21}^3 & p_{22}^3 & \cdots & p_{212}^3 \\ \vdots & \vdots & \cdots & \vdots \\ p_{241}^3 & p_{242}^3 & \cdots & p_{2412}^3 \end{pmatrix}$$

$$T_3 = C_5 + P_3 \tag{8}$$

where t_{ij}^3 shows transmitted energy and p_{ij}^5 power losses derived from transport and distribution under scenario 3S + V.

For the sensitivity analysis, demand shows a minimum and a maximum level. The targets set by the EU (EU, 2009a; 2012a), related to a reduction in peak power (between 5 and 10%) and a reduction of transmission and distribution losses (between 2 and 10%), have been taken into account. Since these objectives have been formulated in terms of maximum and minimum values, for each of the scenarios in this paper, two levels of compliance were analyzed. The minimum level in both scenarios, 3S-1 and 3S + EV-1, is associated with achieving a 5% reduction in peak power and a 2% reduction in transmission losses. The maximum level in both scenarios, 3S-2 and 3S + EV-2, are related with a reduction of 10% in peak power and in transmission losses.

Once the final demands for 3S and 3S + EV have been calculated, as well as the minimum and maximum compliance levels for the scenarios, the CO_2 emissions avoided can then be estimated. These emissions are calculated from the emission factor for each technology and fuel (see Table A2 in the Annexe 2).

The analytical results will provide information on, i) electricity generated and consumed; ii) renewable energy generated and consumed (TWh and % on total); iii) primary energy used for electricity generation; iv) total primary energy consumed; v) peak hourly electric power; vi) CO_2 emitted and avoided; and, vii) avoided primary energy cost (M €).

Annex 2

Table A.1
Detailed information of the distribution factors (F_{ah} and F_d).

Hour day	F_{ah}	F_d			
		MEDIUM		OPTIMAL	
		Winter	Summer	Winter	Summer
1	7.0%	4.1%	3.8%	4.3%	3.7%
2	7.0%	3.8%	3.6%	3.9%	3.4%
3	7.0%	3.6%	3.3%	3.8%	3.0%
4	7.0%	3.4%	3.2%	3.6%	2.9%
5	7.0%	3.4%	3.1%	3.6%	2.8%
6	7.0%	3.4%	3.0%	3.6%	2.8%
7	7.0%	3.5%	3.1%	3.8%	2.9%
8	7.0%	3.9%	3.2%	4.2%	3.0%
9	11.1%	4.3%	3.6%	4.4%	3.4%
10	11.1%	4.3%	4.1%	4.3%	4.1%
11	11.1%	4.5%	4.5%	4.4%	4.6%
12	11.1%	4.6%	4.7%	4.5%	4.8%
13	11.1%	4.5%	4.9%	4.4%	5.0%
14	11.1%	4.6%	4.9%	4.5%	4.9%
15	11.1%	4.5%	4.8%	4.5%	4.7%
16	11.1%	4.3%	4.8%	4.3%	4.9%
17	11.1%	4.2%	4.8%	4.2%	4.9%
18	11.1%	4.2%	4.8%	4.1%	4.9%
19	11.1%	4.3%	4.8%	4.2%	5.0%
20	11.1%	4.6%	4.6%	4.4%	4.8%
21	11.1%	4.7%	4.7%	4.4%	4.9%
22	11.1%	4.7%	4.6%	4.4%	4.8%
23	11.1%	4.5%	4.7%	4.2%	5.0%

24	11.1%	4.2%	4.5%	4.0%	4.6%

Winter: November, December, January February and March.
Summer: April, May, June, July, August, September, October.
Source: Own elaboration from REE (2013a).

Table A.2
CO_2 emissions factors.

	t CO_2/GWh	t CO_2/ktoe
Central thermal coal (efficiency 36.1%)	961	
Gas natural combined cycle	372	
Hydropower	0	
Wind	0	
Biomass	Neutral	
Biogas	Neutral	
Photovoltaic	0	
Thermal solar power	0	
Gasoline		2,8
Diesel		3

Source: IDAE (2005).

Table A.3
Total monthly peak demand and transmission

	Transmission energy (GWh)	Peak	
		MWh	hour/day month
JANUARY	22,553	39,787	21 h - 22/01
FEBRUARY	20,549	39,963	21 h - 27/02
MARCH	21,209	38,322	21 h - 04/03
APRIL	19,437	34,838	13 h - 09/04
MAY	19,439	32,651	13 h - 29/05
JUNE	19,140	34,826	14 h - 14/06
JULY	21,637	37,399	14 h - 10/07
AUGUST	20,604	36,446	14 h - 02/08
SEPTEMBER	19,665	34,848	14 h - 04/09
OCTOBER	19,878	34,281	14 h - 03/10
NOVEMBER	20,518	39,742	21 h - 28/11
DECEMBER	21,685	39,424	21 h - 02/12

Source: REE, 2013b.

Table A.4
Descriptive statistics

	Data		
	Monthly electric power transmisioned per hour	Monthly electric power losses per hour	Monthly energy consumed by transport per hour
Observations	288,00	288,00	288,00
Maximin	1106,83	15,41	24,77
Minimum	626,30	6,97	1,16
Average	855,26	11,06	10,36
Standard deviation	121,97	2,11	10,83
Asymmetry coefficient	−0,29	0,10	0,35
Kurtosis	−1,02	−0,99	−1,88

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