Energy 258 (2022) 124743

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

A novel approach to represent the energy system in integrated assessment models

Gonzalo Parrado-Hernando [a,*], Pfeifer Antun [b], Frechoso Fernando [c], Miguel González Luis Javier [a], Duić Neven [b]

[a] Department of System Engineering and Automation, School of Industrial Engineering, University of Valladolid, Spain
[b] Department of Energy, Power Engineering and Environment Faculty of Mechanical Engineering and Naval Architecture University of Zagreb, Zagreb, Croatia
[c] Department of Electrical Engineering, School of Industrial Engineering, University of Valladolid, Spain

ARTICLE INFO

Keywords:
100% renewable System
PNIEC
NECP
Spain
EnergyPLAN
MEDEAS

ABSTRACT

The Spanish national energy and climate plan (PNIEC) has recently been published, leading the worldwide task of climate change mitigation towards a net zero-carbon economy by 2050. The objective scenario of the PNIEC expects to reach a renewable share in the power system of 74% by 2030. In this context, three contributions are developed: i) providing an analysis of how Spain is facing the energy transition; ii) conceptualizing the link between an hourly energy model (EnergyPLAN) and a yearly integrated assessment model (MEDEAS); and iii) proposing a transparent policy agenda for the Spanish benchmarking in line with the official report. The results clarify the decreasing role such technologies as the combined heat and power facilities, as well as the pressure of biomass in Spain. Coherency in translating common variables in the energy chain of IAMs to the energy model is effectively reflected in the tables as an output of the research. Positive conclusions are found for Spain. The commitment of 74% might well be completed and the Spanish economy could run with a 100% renewable energy system by 2050, with requirements of sixteen and six times more installed capacity of solar-PV and wind onshore, respectively, by 2050 related to 2017.

1. Introduction

The updated report from the Intergovernmental Panel on Climate Change (IPCC) point to unprecedented situations worldwide. Currently, observed climate patterns have not been seen for at least several thousand years. This provides a warning of extreme conditions for human life beyond the average global temperature increase of 1.5 °C [1]. Given the threat, the European Union (EU) is funding an energy transition at two levels, according to the geopolitical risks and priorities (Fig. 1 in Ref. [2]): first, business opportunities (e.g., boosting renewables) for countries in the Spain-Finland corridor; second, increasing the security of the supply chain facilities through reinforcing pipelines and reaching agreements for the supply of fossil fuels in Eastern Europe and Ireland. Signing climate change agreements is therefore necessary and Spain did so for the Paris Agreements in 2017 (date of entry into force), undertaking commitments to reduce the levels of greenhouse gas (GHG) emissions [3], as well as for its national energy and climate plan (NECP, PNIEC in Spanish) which supposes a detailed official pathway to 2030 [4]. In addition, the recent war between Russia and Ukraine may likely drive the acceleration of decarbonization plans in Europe.

Most of Spain's gross CO_2-equivalent emissions (76%) in 2017 came from the energy sector. Sorted in descending order they are: Transport, Commercial & Public services, Industry, Households, and lastly Agriculture. These are the potential sectors to decarbonize this country. An additional 8% of total emissions from non-energy industrial processes are positively affected by structural changes in their chain of value.

A regulatory framework of the power sector in Spain has been proactively removing barriers for renewables and new agents from 1980 onwards (Fig. 1 in Ref. [5]). Three regulatory periods concerning renewables have been identified, from strong feed-in-tariffs (before 2007), through support halt (between 2007 and 2015) and, finally, to a stable renewable remuneration regulatory framework (since 2015) [6]. In Ref. [5], it is highlighted that renewables have displaced the conventional technology – and especially the combined cycle gas turbines

* Corresponding author. Research Group on Energy, Economy and System Dynamics, School of Industrial Engineering, University of Valladolid, Paseo del Cauce s/n, 47011 Valladolid, Spain.
E-mail addresses: gonzalo.parrado@uva.es (G. Parrado-Hernando), Antun.Pfeifer@fsb.hr (P. Antun), frechoso@eii.uva.es (F. Fernando), ljmiguel@eii.uva.es (M.G. Luis Javier), Neven.Duic@fsb.hr (D. Neven).

https://doi.org/10.1016/j.energy.2022.124743
Received 25 December 2021; Received in revised form 1 July 2022; Accepted 2 July 2022
Available online 15 July 2022

(CCGTs) – away from profitable shares of generation, but they have even been used to partially alleviate the fast ramps required at some hours to follow the demand. This has been understood as a risk on the energy security of Spain.

Public and Academic institutions have supported governments in dealing with the energy transition. In addition to the aforementioned NECP, the Commission of Experts in Energy Transitions highlighted the use of renewable primary energy and electrification of transport as key measures to decarbonize 26% of the final energy consumption by 2030 and to reduce 80–95% of GHG emissions by 2050, related 2006 [7]. In the research work of Bonilla et al. [8], curtailment and costs are both hourly minimized to provide an optimal free-carbon mix (with respect to 1990). The 100% of renewable mix (no carbon capture storage) is based on 23.9% of solar-PV, 45.8% of wind and 18.57% of concentrated solar power (CSP, 324.2 GW of total installed capacity). However, the optimal case of 100% CO_2 emissions reduction in 2050 (with regard to the year 1990) delivered 238.96 TWh of curtailment (75.4% of the electricity demand, 316.55 TWh in Table 2) and a high imbalance in the international exchange (75.68 TWh of electricity exports as opposed to 0.0 TWh of imports) remained even with such as optimal solution. This is mainly caused by the lack of any cross-sectoral options and the assumption, for the analysis, of constant properties in the energy system (only the power sector is analysed). The conclusions are in line with a previous paper in which the extreme role of storage and interconnectivity were also brought to light [9]. Three strategies for the Spanish electricity sector have been evaluated to fulfil the goals ordered by the European Commission: i) integration with the European power network, ii) investments to the renewable sources; and iii) competitiveness in the electricity market. Positive effects in the economy as a whole and concerning business opportunities are found in all the three scenarios [10].

In order to avoid undesirable levels of curtailment and the major roles of technologies being fixed to bilateral national agreements, the advice from the current literature studying the transition, under the concept of *smart energy system*, is to allow more flexible management by introducing technologies based on sector coupling (power-to-heat, synthetic fuels, electric vehicles) and by facilitating an advanced framework to exchange energies between suppliers, carriers and final sectors in a sustainable and structured step-by-step planning [11]. The goal of these approaches is to take advantage of the overproduction of renewable energy.

By reviewing flexibility technologies for a *smart* energy system, Spain hopes to build up 6 GW of electrolysers in a first phase (2020–2024), and 40 GW by 2030 (producing of 10 million tonnes of green hydrogen) [12]. Hydrogen as an energy carrier is immature today but it is being studied for sector-coupling (power-to-gas) through an innovative numerical model of a co-electrolyser system with heat recovery to produce synthetic gas and to effectively (79%, second-law efficiency) substitute fossil fuels in high-temperature processes (operating range between 600 and 850 Celsius) [13]. The scenario proposes the decommission of fossil fuels and nuclear power, while promoting renewables (wind, solar-PV and solar CSP); where seasonal hydrogen storage would be required to balance, on an hourly basis, the first half of the year's deficit with the second half's surplus [14]. The authors estimate a potential of green hydrogen – from renewable sources – of 2.55% the natural gas demand by 2030 (7.27 TWh, 75% of electricity-to-hydrogen efficiency) in storage. Load control, geographic diversity, flexible back-up facilities, storage and curtailment are crucial and mature options to accommodate variable generation [15]. Power-to-Heat can be used as demand-side management to direct control or to regulate price-based programmes [16]. Stress of materials regarding operating temperatures is highlighted for future developments. In addition, grid expansion has been considered as an acceptable option to manage the variability of renewables in Europe and Asia [17], Portugal [18], and Morocco [19]. The EU goal of the interconnection ratio[1] for Spain is 15% by 2030, far away from the current value (6%) [20,21]. Additionally, technical – active and reactive power, wind speed and irradiation intensity – and non-technical – optimal number of substations, transformers, voltage regulators, switches, buses, and other power equipment – constraints that require more discussion in the results [22].

From among the existing energy models existing in literature [23], EnergyPLAN is one of the most widely recognised hourly simulation tools running on this framework. This is due to the wide and free Academic use in many countries and regions. In 2015, there were 91 articles in which EnergyPLAN is applied for different purposes (Table 2 in Ref. [24]), most concerning the integration of renewables (45), but also for specific technologies, positively adding flexibility into the power system, such as biomass usage (2) or transmission lines (3). Publications can be found after 2015, linking approaches to test powerful algorithms from the MATLAB Toolbox [25], object-oriented codes in Java [26] and Python [27], mainly developed to increase the assessment of this model by implementing optimization algorithms. The last publication along these lines is a framework of hard-linking between TIMES (generation expansion), EnergyPLAN (optimization of operation), MEDUSA (unit commitment & economic dispatch model, operating constraints) and MOEA (multi-objective evolutionary algorithm for long-term energy planning optimization), has been formalized for Poland [28]. However, further work into a different insight has been mentioned in the aforementioned declaration-of-intent paper, when the authors says *'Lastly, top-down equilibrium models have shown significant sensitivity when analysing the integration of RES and potentially need to be enhanced as a part of integrated mixed models'* [11]. This is exportable to integrated assessment models (IAMs) and economy-energy-environment modelling in general, models which are very present in IPCC reports that usually cover the entire world, as well as such sub-systems as the human economy, non-human ecosystems, and the availability of mineral resources.

Over the preceding decade, four challenges have been stated for energy modelling: First, uncertainty and transparency in models; second, the complexity and optimization across scales; third, how to capture the human dimension; and finally, how to solve details in time and space resolution in optimization and simulation models so as to better capture the variability of renewables, especially technologies under the category *variable renewable energy supply* (VRES, which groups wind, solar-PV, tidal, wave and run-of-river hydropower) [29]. The problem is greater in IAMs, since they have traditionally paid attention, on a yearly basis, to the general dynamics and feedbacks among them. However, there is increasing pressure in this field to represent hourly impacts of VRES, given the large expected role of these technologies in decarbonization pathways ([30,31]). This pressure has stimulated new approaches from time-slices, through time aggregation, and even hard-linking of two or more software programmes. In Ref. [32], the authors suggest aggregations from at least 8 h of resolution in data and advise against approaches based on time slices. The hour would therefore be acceptable for energy calculations at the national planning level.

Economically, the subsidies applied to wind and solar technologies and programmes of carbon abatement costs have had uncertain effects among producers and consumers in Spain. In Ref. [33], the average cost of reducing 1 ton of CO_2 is found to be between 411€ and 1944€ by promoting solar energy, and between 82€ and 276€ by promoting onshore wind. The effect of renewables displacing conventional power plants towards worse positions in the merit order curve has been contextualized for Spain [34]. To facilitate the aggregation of small units participating in the market, the authors recommend separating the balance of energy products and capacities, reducing both lead times of intra-day market and the minimum bid size. Regarding the Spanish

[1] The interconnection ratio is computed as the sum of the import capacities divided by the installed generation capcity.

market, four rules have been modelled to show the behaviour of different regulations with hourly resolution [35]. The results show that the feed-in-tariff and the priority dispatch rule would lead to higher VRES penetration and lower GHG emissions, as well as lower demand costs when negative prices are present in the market. On the technological side, an hourly analysis [36] has evaluated the optimal[2] integration of onshore wind, solar-PV, and solar CSP capacities in order to reach EU-2030 objectives. Table 5 in this reference shows a capacity ratio of solar-PV/wind equal to 5.5229 and solar-PV/CSP equal to 1.0734, so as to optimize the power system according to the EU-2030 scenario, falling within the assumed backup (3 TWh) and surplus (3.3 TWh) of electricity.

Households are usually the agent of the market from which companies of the electricity market look for profitability via price regulation, the *"losers"* in the words of [37]. Consumers are generally located as individual points in the lowest voltage level of the distribution grid. Nonetheless, the situation could change for regions where energy communities agree to act as demand aggregators to the market, a legal figure recently introduced in Spain. Democratization could be led by such active instruments as renewable cooperatives to reduce the deficit of liberalization and increase the awareness of society about energy [38]. In finances, the distributed ledger technology (DTL) based on crowdfunding has reported reductions in the levelized cost of energy (LCOE) of rooftop PV projects and the democratization[3] of the energy industry with the entrance of smaller investors [39].

Promises of a fair transition for households is not yet clear; indeed, some authors have stated the situation is more complex [37]. On the negative side, there is evidence of a decarbonization paradox, i.e., increasing residential electricity prices while the apparent benefits to society are hoped for with the penetration of renewables, as well as the displacement of the labour force with non-transferability skills. On the positive side, zero-carbon technologies would be beneficial for health, and they are also labour intensive (especially wind, geothermal and bioenergy), thus boosting employment and facilitating income for the working class.

Energy intensity is a widely used indicator of efficiency, which is calculated as the ratio between gross inland energy consumption (GIEC) and gross domestic product (GDP). In the literature of IAMs, energy intensities are commonly employed to dynamize the final energy balance (FEB) [40], which summarizes the exchange from primary to final energy consumption. On the supply side, all the technologies should be represented by both models and IAMs are familiar with a broad set of them [41].

In this research, a detailed analysis of Spanish data improves the representation of this country in the energy community, especially for EnergyPLAN's modellers, but it may be also useful to other planning models. The configuration of inputs from several public datasets are homogenized when introduced into EnergyPLAN, so the calibration has filtered outliers and shown imbalances. It also clearly represents the behaviour of energy flows, which is of special interest in the relationship between CHP units and the heating system to deliver reliable potentials of power-to-heat usage in scenarios; and a way to include hydrogen values in balances, an essential energy carrier for decarbonization scenarios.

Finally, the policy agenda is integrated within the process to generate the scenario in a transparent way. It includes plausible values to the discussion of the Spanish energy transition, considering mainstream such reports as the PNIEC. As result of it, a feasible 100% renewable scenario of designed targets and goals is delivered for 2017, 2030, and 2050. The level of detail achieved by the method is shown throughout Section 3. Structural changes in the energy consumption, feasibility of mature and immature technologies, and the potential loads of hydrogen and biomass resources in the system, are part of the discussion in section 4.

1.1. Contributions and hypothesis

The proposed framework (section 2.1) has been conceptualized from the IAM perspective, i.e., how the inputs of EnergyPLAN are calculated to easily exchange information with these, usually, yearly models, laying the foundation for future works between both. Section 2.2 explains the series of equations that harmonizes both sides of the modelling, whose connections are validated by the calibration process of the case study.

2. Methods

2.1. General approach

The conceptualization (Fig. 1) developed in this section allows the connection between energy models, like those of EnergyPLAN, and IAMs like MEDEAS [42]. Biophysical constraints to energy availability; mineral and energy return to energy investments (dynamic EROI) for the transition, potential mineral and energy scarcities, climate change damages and a detailed economic system are determinant characteristics that make MEDEAS of interest and have been selected for our research.

The energy module of MEDEAS is represented on the left, while the EnergyPLAN is on the right. Some of the variables of the IAM MEDEAS may be endogenous (e.g., energy intensity), while other are exogenous (e.g., energy policies). On the other hand, given the large uncertainty in the climate change impacts, hourly normalized profiles exogenously adequate the energy model to the specific regional conditions of both generation and demand sides. Consistency is provided when moving from one model to the other over the chain *IAM – EnergyPLAN inputs – EnergyPLAN outputs – IAM*.

The improvement of the energy system over time from a traditional to a *smart* operation is modelled with different regulation parameters of EnergyPLAN. These are the priorities in the critical excess of electricity production (CEEP) regulation, the level of back-up,[4] and the parameters of flexibility options (e.g., V2G and transmission infrastructure).

The final energy balance (FEB) must be consistent with the meaning of the inputs in EnergyPLAN, which strongly relies on what is covered by the hourly model (figure A1). Statistical differences, changes in stocks, energy transformations, and imports/exports of fossil fuels are usually part of the national FEBs, but EnergyPLAN does not cover them. Consequently, this lack of agreement needs to be solved with additional information to balance fossil fuels in primary energies when calibrating and comparing results.

The outputs of EnergyPLAN could contribute to the IAM in two ways. Hourly results can provide feedback to annual feasibility indicators (EnergyPLAN's warnings[5]). Capacities may be boosted or not according

[2] In this article, 'optimal' means the VRES configuration by which both backup generation and critical excess of electricity production (CEEP) are minimized for the whole year (8760 h).

[3] Democratization in the context of electriciy markets refers to the permission of customers to move beyond simply consuming energy to become participants in the production (so-called prosumers).

[4] Back-up refers to units able to add stability in the power network by running every time at certain capacity.

[5] Five warnings of interest for this research may arise in EnergyPLAN: i)*"Critical Excess"* appears if the excess of electricity is not able to operate; ii) *"Grid Stab.Problem"* if the production of electricity does not meet the regulation parameters; iii) *"PP/Import problem"* if there is no enough capacity to meet the electricity demand (if so, the model consider the rest as imports); iv) *"Syn/biogas shortage"* appears when demand exceeds the supply on an annual basis; and v) *"V2G connection too small"* is displayed if charging infrastructure is not sufficient to supply the demand of electric vehicles.

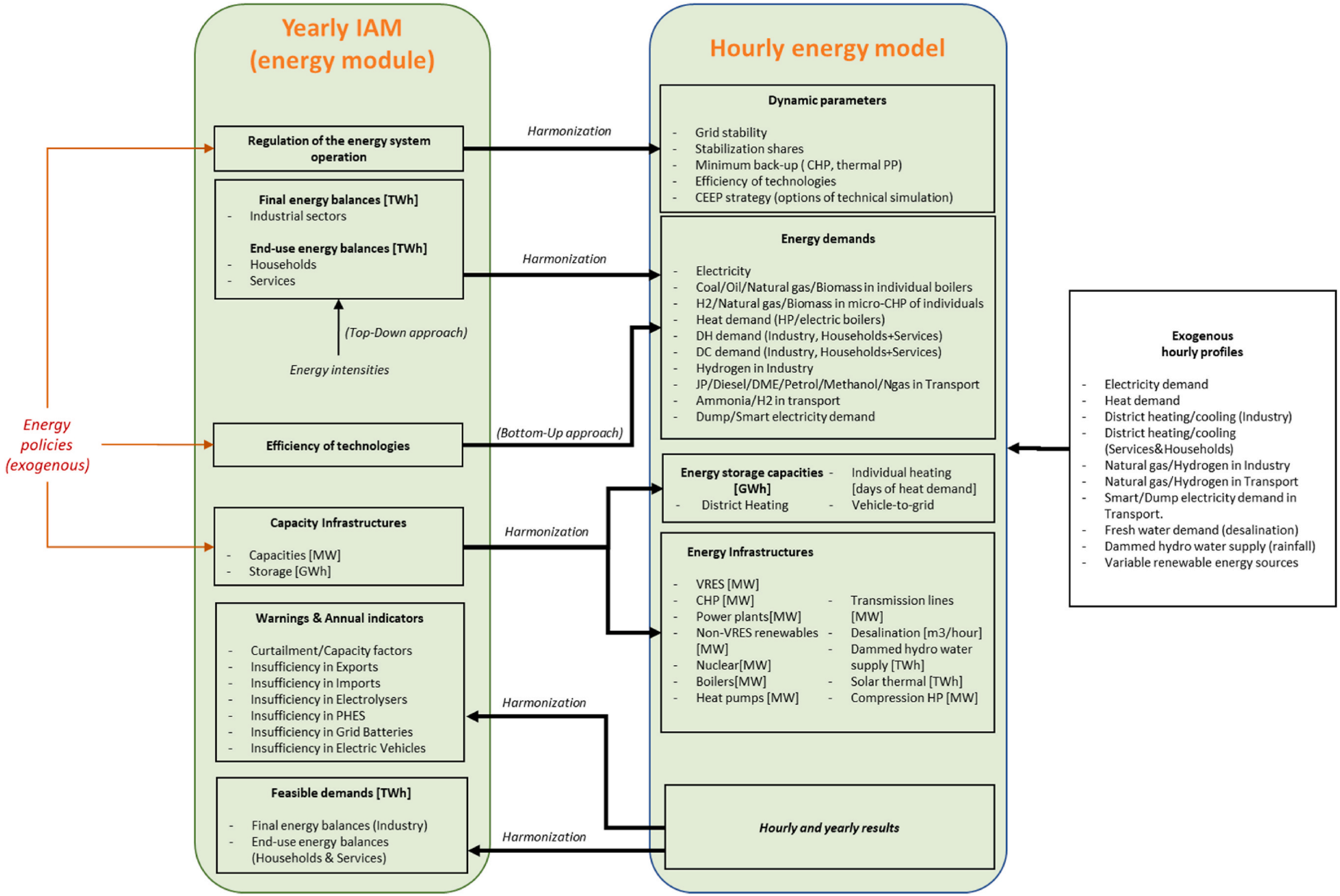


Fig. 1. Overview of the approach for hard-linking between the annual-step MEDEAS and hourly-step EnergyPLAN.

to different financial and policy criteria derived from curtailment (critical excess, variation in the capacity factor of generating units) and congestion in matching supply and demand, while the FEB could be updated to maintain the consistency across results. Additionally, visualization would be able to reflect hourly aspects of the system such as residual load duration curves or daily windows of the energy dispatch.

2.2. Approximation to the Spanish case

As mentioned above, at least two advances for linking EnergyPLAN are present in the literature, a toolbox in Matlab [25] and a code in Python [27]; however, the hard-linking needs further work, since the Spanish IAM is written in Vensim – systems dynamics software – and the programming routines calling external code are not available yet. In their absence, the enabling mechanisms that the IAM should have inside to materialize the conceptualization proposed above should be implemented.

The procedure to simulate scenarios is summarized in Fig. 2. Once calibration is finished, the scenarios are estimated in two consecutive steps, simulating the influence of an IAM. First, the energy intensities per sector and fuel in the FEB of the national energy accounts (IDAE structure) and their evolution (through Eq. (1)) are assumed. How energy intensities would actually evolve over time involves the dynamics of efficiency, economic production, energy scarcities, and other topics very present in the IAM field [40]. Once the energy intensities have been applied to the FEB, a second step considers energy policies to substitute fuels. When substitution implies changes in technology, the difference between efficiencies is considered, e.g., boilers by heat pumps or diesel by electric vehicles. –The tools to apply the substitution are set out in Table 1.

Policy of district heating is estimated from a percentage of the space and water heating in group 2.

CHP generation (electricity and heat) is linked with the whole energy consumption of the sectors (after fuel substitutions), related to the reference year. For instance, electricity generation by CHP technology decreases by 20% in group 3 when the total energy consumption of this group faces a reduction of the same quantity.

Capacity of CHP units is unfolded according to the variation in the total energy consumption of the sector, with the exception of *Refineries* (related to the oil consumption) *Activity related Transport* (related to the total consumption of all transport sectors), *Other Services* (related to the total consumption in *Commercial, Services and Public Administration*), and *Other Sectors not specified* (related to the total consumption of *Agriculture, Fishing and others*).

Table 1
Implementation of the substitution policies with two columns: references to Appendix A on the left and the explanation of the measures on the right.

Table A. 4	Equations and parameters to estimate inputs of Transport in EnergyPLAN.
Table A. 5	Efficiencies of policy substitution among fuels in Transport (MPGe, Milles Per Gallon equivalent).
Table A. 6	Parameters to electrify individual heating (heat pumps and electric boilers). Solar thermal and hydrogen (TWh) directly substituted the consumption in final energy balances. A percentage covering space demand in individuals is introduced for the policy of heat pumps. In a similar way, solar-thermal is included in a percentage to cover each traditional fuel (coal, oil, natural gas, and biomass).

Table 2
Percentage of error for different variables in the calibration process (basis year, 2017), related to the real value.

Wind power generation	0.02
Solar-PV power generation	−0.01
Solar-CSP power generation	−0.04
Dam hydropower generation	0.02
Nuclear generation	−0.01
CHP + Waste power generation	−0.01
Electricity generation in thermal plants	2.12
Consumption of coal in power plants	0.5
Consumption of oil in power plants	−0.07
Consumption of natural gas in power plants	0.72
Consumption of biomass in power plants	−0.17
Primary energy consumption – coal	0.43
Primary energy consumption – oil	0.12
Primary energy consumption – natural gas	1.26
Primary energy consumption – biomass	−1.11
Total primary energy consumption	0.35
Corrected CO2-emissions (IEA)	6.05
Share of renewables in primary energy	0.03
Share of renewables in electricity generation	−0.78
Production of renewable electricity	−0.16
Electricity generated from coal in power plants	−10.21
Electricity generated from oil in power plants	−5.46
Electricity generated from natural gas in power plants	16.03
Electricity generated from biomass in power plants	−0.17

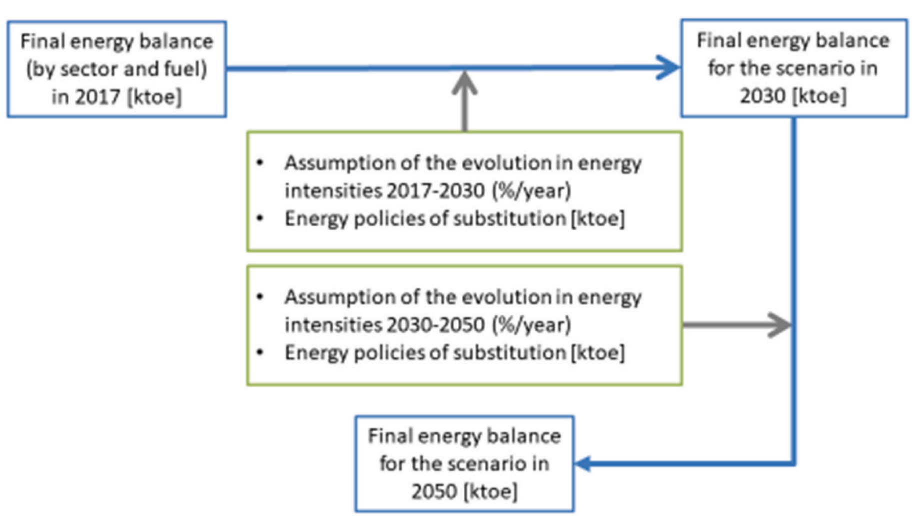


Fig. 2. How scenarios for energy consumption are built in this article, based on national final energy balance, assumption in the energy intensity by sector and fuel, and energy policies of substitution.

$$value_t = value_{t-1} \cdot (1 + EI)^t \quad (1)$$

After running the scenario with EnergyPLAN, the FEBs are recalibrated to solve a few gaps in, e.g., the fuel consumption in boilers.

A set of three data sources has been necessary to develop the methods. First, the national energy accounts specify the energy balances by sector and fuel. These data are freely accessible tables annually published by official institutions such as the Institute of Energy Savings and Diversification (IDAE, Spanish acronym) [43], or such European organizations as Eurostats [44]. The correspondence of sectors and fuels between the IDAE and Eurostats is summarized in table A.1 and table A.2 (appendix A) as the data of the FEBs reflect different aggregation. For instance, *International aviation* and *Other transport* in the IDAE definitions are both aggregated as *Not elsewhere specified (other)*.

Second, the power system operator provides real data – 10 min of resolution – from which hourly profiles of power generating technologies and electricity demand are created, as well as hourly prices of electricity (ESIOS [45]). On the heat side, consumption and hourly distributions of heating and cooling demands were gathered from the Heat Roadmap Europe project [46] and from the database of the EnergyPLAN project itself [47], and district grids [48]. Heat pumps (IDAE, IEA), biomass potential (Eurostats, IDAE) and installed capacities (IRENA, Eurostats, IDAE, REE) are compared to better represent the energy system. Other parameters of less importance were retained from a previous study with EnergyPLAN for Spain in the context of the Heat Roadmap project.

Finally, data from compounded by reports, articles, and model databases (the EnergyPLAN database is available in Ref. [47]) to, e.g., transfer information between technologies and energies. The techno-economic potential and quality of the biogas [49] and biodiesel [50] production, the vehicle fleet [51], the efficiency of the mining sector [52], the average efficiency of Spanish boilers [53], solar thermal generation [54], transport & distribution losses in the power system [55], and the efficiency in the hydrogen generation [56].

A comparison across sources is carried out to check possible outliers and unjustified differences as part of the validation process. It is surprising that emissions on *Households* were much lower than *Commercial & Public Services* in 2017, while they have similar consumptions. The reason behind this is the fact that the fuels consumed in *Households* are less intensive in CO2-equivalent emissions.

IDAE and Eurostats revealed high statistical differences in the consumption of some fuels (114% for *Anthracite*, −201% for *Other bituminous coal*, 18% for *coke oven coke*, 22% for *fuel oil* and −6% for *pure biodiesels*) and such sectors as *Iron & Steel* (*Coking coal* and *Hard coal, Anthracite and Aggregated*). Sharing a common framework to report data in European countries would avoid imbalances. The authors suggest Eurostats as the reference for all the European countries and official institutes to carefully process data about coal products in the *Iron & Steel* sector, *fuel oil* and *pure biodiesel*.

Part of the calibration process is focused on providing regional meanings for inputs, so a few notes from the analysis are highlighted concerning the calibration. CHP and district heating and cooling have been thoroughly studied. Large CHP units (>10 MW) are mostly used in three industrial sectors (Food, Beverages & Tobacco, Chemical & Petrochemical, and Paper, Pulp & Printing), presenting a roughly constant hourly distribution of generation over the historical period. This is caused by having a high priority for CHP in the electricity market, after Nuclear and renewables.

Industrial processes are probably the trickiest sectors to be decarbonized. First, approximately 45% of carbon emissions come from feedstock so they cannot be avoided by a change in fuels but by substituting the processes. Second, roughly a 35% of these emissions come from burning fossil fuels in high-temperature processes, and nowadays alternative fuels are still not competitive in costs. Third, the high integration in the chain of industrial lines suppose that any change to one part must be accompanied by modifications to other parts of that same process. And fourth, the industrial facilities have long lifetimes (higher than 50 years), so rebuilds or retrofits assume additional costs [57].

Heat excess in high-temperature processes (<500 °C), as in a steam cracking furnace in ethylene production is used to make high-pressure steam to drive turbines and compressors in the next stages of the production chain. These industrial processes represent a 47% of total heat demand in 2017. CHP and heat demand should be planned together, since they are highly integrated, limiting the potential of district heating. In EnergyPLAN-Spain, heat and power generations in CHP units are proportional to the energy consumption of these groups related to the reference year (2017).

These units are placed in specific industries, delivering electricity when the productive systems are running. Recent energy policy [58] is oriented to the decommissioning of subsidies and giving priority to the electricity market. Delivering electricity from CHP, *Primary metals* (24%), *Paper and pulp* (20%), *Chemicals* (20%), and *Refineries* (14%) were the most important industries in 2017. On the other hand, district heating has been disregarded in calibration since there was only 0.54 TWh of heating and 0.30 TWh of cooling generation, mostly in the tertiary sector (44% of the district heating capacity installed). The outcome is that CHP and DH grids are disconnected in Spain.

Research on the desalination in Spain has proposed scenarios for different water sources and crops in the agricultural sector [59]. However, the lack of available data at both hourly (production and water demand) and yearly (capacity of desalination plants) levels persuaded to us to consider this option in this work.

In line with the abovementioned regional characteristics, the following meanings have been used for the inputs of EnergyPLAN-Spain in order to calibrate with regard to the reference year (2017):

- Individual heating and cooling: Residential, Commercial, Public sector and Services.
- DH heating and cooling: Residential and Services (future scenarios).
- CHP-Group 2: Residential, Commerce, Services and Public Administration heating processes.
- CHP-Group 3: Industry heating processes (all industrial sectors).

In order to assess which VRES should be promoted in the energy transition, a calibrated model has been developed using the historical data from 2017. Experiments have been carried out on this base situation. The exercise promotes one technology, while the others stay constant to show the capacity at which the CEEP reaches 2% of the electricity demand. The results revealed different behavioural patterns for each technology. Onshore wind emerged as the more integrable source (up to a maximum of 49,000 MW), followed by solar-PV (max. 27,000 MW), and then solar CSP (max. 21,000 MW). Combining different technologies, the optimal capacity ratio of onshore wind divided by solar-PV was found to be 1.86, by which the CEEP increases more slowly, i.e., the configuration that produces less variability. It was used to extrapolate those renewables to 2030 and 2050.

The authors highlight the fact that the ratio is a technical indicator derived from the real hourly distributions of solar-PV and wind. However, it is a decision that is only partially discussed, since the economic and social aspects fall outside the scope of this study. Nevertheless, some points are discussed to clarify the situation of this ratio for Spain. First, the global-average LCOE of these technologies have experienced continued declines over the last decade, utility-scale solar photovoltaics being the most surprising with a fall of 85%, followed by onshore wind (56%), which remains the cheapest renewable to produce electricity (39 $/MWh) [60]. This aspect implies that, economically, the ratio may strongly decrease in favour of the new solar capacity in Spain, a sunny region. Second, there is geographical information system (GIS) research to estimate the potential of floating offshore wind power in Galicia [61] and wind, solar, and biomass energy in Southern Spain [62]. However, a major contribution of GIS research to the entire national territory has still to be carried out specifically for Spain, perhaps following the work of Ryberg et al. [63]. Finally, the greater the flexibility is that included in the system, the more flexible the ratio will be. Examples of different ratios from the literature are as follows: PNIEC delivers 1.29 in the 2030-objective scenario; the optimized ratio is 1.86 in 2030 and 1.91 in 2050 (100% renewable system) in Table 3 in Ref. [8]. The duck curve might be a plausible reason to have ratios greater than 1 (more wind than solar), i.e., an unavoidable amount of potential curtailment in the middle of the day. Increasing the capacity of solar-PV would mean to boosting this effect, so larger flexible generators with higher ramp capacities would be required in the mix [64].

Calibration followed the schedule stated by Huang et al. (Fig. 1 in Ref. [65]). This model has three inputs for thermal power plants (PP). The capacity of PP fuelled by biomass is placed in PP1-condensing mode; while PP fuelled by coal, oil or natural gas are rendered in PP2[6] (fossil fuels), the rest of the CHP capacity remaining in PP1[7]-back pressure mode operation (biomass). Two sectors (*Residential* and *Commercial & public services*) are analysed by end use in concordance with the final energy balances from the same source, IDAE (table A.2). Calibration is satisfied when the differences between the real and calculated values are below 2.5%. These relative percentages of error are set out in Table 2. It was not possible to reduce the difference in the corrected CO2-emissions due to differences in the emission factors. Along the same lines, the differences in the electricity generated by fossil fuels could not be better fitted because of the lack of disaggregation in the model, even though the entire electricity generation and consumption of these fuels looked good in the calibration results. The emissions and electricity generated by fossil fuels in power plants should therefore be assessed with caution.

The contribution of CHP is decommissioned by 2030, and municipal waste by 2050, to reflect the current Spanish energy policy on these units. Boilers are less necessary in 2050 because of the promotion of heat pumps and district grids.

Hydrogen has been highlighted as a necessary energy vector for the transition. The policies proposed in the next section show the increasing capacities of this technology, from 0 MW in 2017–2540 MW by 2030, and 20,000 MW by 2050. This trend is in line with the official roadmap for hydrogen in this country [12], but more conservative since the official report foresees 4000 MW by 2030. The heavy load of hydrogen is placed in the last year (2050), joining industrial demand for this energy vector with its related technology (electrolysers, H_2 storage, and so on), presumably mature as of 2030. Thus, the CEEP strategy in cases of CEEP >0 is considered to first increase CO_2 hydrogenation whenever possible and then to curtail it.

Finally, the evolution of the energy system towards a smart management of the dispatch between the supply and demand sides is considered thanks to the options EnergyPLAN includes for the technical simulation, which are summarized in table A3.

3. 100% renewable energy system for Spain

Based on the methodology proposed in the previous section and assuming some hypotheses and policies, a feasible scenario of 100% renewable energy for Spain is now proposed.

The values used for energy intensities are detailed in table A.7 (industry), figure A.2 (transport), figure A.3 (various, which represented ~3.5% of the total final energy demand in 2017), figure A.4 (residential), and figure A.5 (commercial & public services), including the references to the data sources.

[6] According to the EnergyPLAN's documentation, PP2 refers to thermal power plants operating only in condensing mode, so delivering only electricity.

[7] PP1 in EnergyPLAN refers to combined heat and power (CHP). This technology may operate either in back-pressure mode (delivering heat and electricity) or in condensing mode (delivering electricity). In EnergyPLAN-Spain, these units are mostly located on industrial heating grids.

The hypothesis applied for the substitution policies are written in Table 3 (2017–2030) and Table 4 (2030–2050), embodying the policy output of this work as a result of summarizing what measures are more present in the decarbonization pathways.

With the proposed configuration of policies, the results of the model show that the total decarbonization of the energy sector is achieved by 2050 through a strategic combination based on a strong electrification and the use of biomass and hydrogen-based products. The results in 2030 and 2050 are shown together to easily compare both simulations related to the calibration year (2017).

The evolution of constant and negative energy intensities implies either efficiency improvements or loss of production, or a combination of both, causing a smooth depletion in consumption over time. Consequently, the total primary energy consumption shows lower values until 2050, which means around 50% less than 2017 (Fig. 3). Technology substitution positively influences the roadmap towards decarbonization. For instance, heat pumps are more efficient than boilers fuelled with natural gas or coal. A similar situation occurs when diesel/gasoline vehicles are substituted by electric vehicles. Following the discussion, increasing energy efficiency targets from 24.2% (2020) to 39.5% (2030) were revealed in the introduction section [66]. The residential and industrial sectors, but not only these, have been highlighted as drivers for reducing the final energy consumption by 27–30% by 2030 [20].

Any decarbonization pathway should check the availability of biomass. Fig. 4 shows that the level of biomass consumption does not reach the maximum potential any year. In fact, it is lower in 2050 with respect to 2030; this is partially due to the general declining trend and a good equilibrium in policies. In 2050, the level is close to the maximum potential estimated in 2011.

Renewables are notably present on the supply side of the energy system (figure B1). Between both years, the renewable electricity production positively increases by roughly 4.5 times. In terms of primary energy (EnergyPLAN indicator), the renewable share in 2050 increases more than 6.5 times in relation to 2017 (figure A1). Variable renewable supply covers 64.5% and 95.6% of the electricity generation in 2030 and 2050, respectively. This situation is reached by building a huge bulk of capacities (Fig. 5), as well as flexibility options to manage the extreme variability coming from wind and solar power technologies. The most prominent options are storage systems, including electric vehicles. Since 2017, Spain would require around 16 times more solar-PV capacity, two times more solar CSP, and six times more wind power plants to compete with the decarbonization pathway. The decommission of all nuclear and large CHP units could be completed in 2030.

A remarkable behaviour of fuels in the power sector can be seen in figure B2. Coal could already be eliminated by 2030; however, natural gas and oil would be required to cover the peaks of demand, facing possible shutdowns in the demand side even when keeping the other facilities, such as electric vehicles, pumping hydropower and so on, in mind. The same values of natural gas and oil consumption are due to how the capacities and the fuel distribution tab were defined in EnergyPLAN (only two groups of back-up power plants were available). The operation would completely change by 2050, and a great amount of new renewable generation would reduce the dependency on biomass, while also allowing for the decommissioning of oil. The entrance of synthetic gas (18%) to cover those peaks of demand would achieve carbon neutrality in the power sector.

The CEEP in the scenario is zero to avoid any breakdown voltage and consequent power outage [67]. However, the last regulation strategy for CEEP is curtailment, an interesting value to evaluate the general performance of the system. Curtailment has therefore been calculated as an indicator (percentage of the electricity demand, Fig. 6). It is shown that a curtailment of 1.34% is reached in 2030 and 2.80% in 2050. These levels remain far below the maximum of 5% for the VRES production for both years (0%, 1.92%, and 2.37%, respectively) suggested in some studies, so as not to not saturate the regulation [68,69]. The electricity demand increases by almost 45% by 2050 (related to 2017), something which is

Table 3
The policies applied in the period 2017–2030.

INDUSTRY
- **Biofuels:** 100% substitution of LPG, diesel and fuel oil in **Construction**, **Wood & Wood products**, and **Other industries.**
- **Biomass:** 100% substitution of coal in **Food, Beverages & Tobacco**, **Non-metallic minerals** and **Non-ferrous metals.**

TRANSPORT
- **Strategic measure: road transport** is 20% electrified through 5,640,817 electric vehicles (smart charge) and 50% by **rail transport** (dump charge).
- **Electrification:** 100% of **rail transport** (dump charge).
- **Biofuels:** 100% substitution of gasoline and diesel in **Other transport.**
- **Biofuels:** 15% substitution of diesel in **Domestic navigation.**
- **Biofuels:** 10% substitution of gasoline and diesel in **Road transport.**

RESIDENTIAL & SERVICES
- **Biomass:** 100% substitution of coal and fuel oil in Space and Water heating in the **Commercial & Public services and Residential sectors.**
- **Electrification:** 100% of fossil fuels for cooking by electric boilers in the **Residential sector.**
- **Solar thermal:** 15% of natural gas, LPG, and diesel for space and water heating are covered by solar thermal in the **Residential sector.**
- **District heating (group 2):** 10% of the space and water heating is allocated in the **Commercial & Public services and Residential sectors.**
- **Heat pumps:** 90% of the remaining space heating demand is covered by heat pumps (the rest by electric boilers) in the **Residential sector.**

VARIOUS
- **Biofuels:** 100% of coal is substituted in the entire **Various sectors.**
- **Biofuels:** 100% of LPG, petrol and fuel oil are substituted in the entire **Various sectors.**
- **Biofuels:** 10% of diesel is substituted in the entire **Various sectors.**

POWER SYSTEM
- **Decommission:** 0 MW of **CHP** (cogeneration) in 2030.
- **Decommission:** 0 MW of **Nuclear** power plants in 2030.
- **Efficiency improvement:** + 5% of generation in **VRES** power plants.
- **Efficiency improvement:** from 27% to 31% in power plants fuelled with **biomass** in 2030.
- **Capacity development:** capacity of 2000 MW for power plants fuelled with **biomass** in 2030.
- **Capacity development:** capacity of 5000 MW (20 GWh) of **Electric storage** in 2030.
- **Capacity development:** capacity of 10,000 MW for **PHES** (pump hydropower energy storage) in 2030.
- **Capacity development:** capacity of 5000 MW for **International interconnection** in 2030.

HEAT SYSTEM
- **Fuel share: Boilers** are only fuelled with biomass.

HYDROGEN:
- Capacity development: 2540 MW (20 GWh) of Electrolysers in 2030.
- Hydrogen production: 100% of the 16,67 TWh/year of hydrogen consumption estimated for the Industrial sectors in 2017 is covered by electrolysers in 2030.

BIOGAS:
- **Development:** the production of biogas is increased up to 10 TWh/year in 2030.

Table 4
The policies applied in the period 2030–2050 (with respect to 2030).

INDUSTRY
- Biomass: 100% substitution of coal in Chemicals & Petrochemical and Iron & Steel.
- Electrofuel-Synthetic gas: 100% substitution of oil and natural gas in all industrial sectors with the exception of Non-metallic minerals.
- Electrofuel-Synthetic gas: 100% substitution of hydrogen in all the industrial sectors.
- Electrification: 100% substitution of the remaining oil by electricity in Non-metallic minerals.

TRANSPORT
- Strategic measure: reduction of 93% in Domestic and international aviation.
- Electrofuel-JetFuel: 100% substitution of kerosene in Domestic and international aviation.
- Biofuels: 100% substitution of oil in Domestic and international navigation.
- Electrofuel-Methanol: 20,35% substitution of gasoline in road and domestic aviation transport.
- Electrofuel-Methanol: 100% substitution of natural gas in road transport.
- Electrification: 50% substitution of gasoline in road transport.
- Electrofuel-DME: 19,31% substitution of diesel in road transport.
- Electricity: 50% substitution of diesel in road transport.
- Electrofuel-DME: 100% substitution of LPG in road transport.

RESIDENTIAL & SERVICES
- **Solar thermal**: 20% substitution of natural gas, GLP, petrol and diesel in boilers for space and water heating in the **Commercial & Public services and Residential sectors.**
- **District heating (group 2):** 10% of space and water heating in the **Commercial & Public services and Residential sectors.**

POWER SYSTEM
- **Repowering:** the installed capacity of **dam hydropower** plants grows up to 20,000 MW in 2050.
- **Capacity Development:** 20,000 MW (40 GWh) of **electrolsyers** in 2050.
- **Capacity Development:** 25,000 MW (100 GWh) of electric **grid storage** in 2050.

HEAT SYSTEM
- Capacity Development: 2000 MW of boilers in the Commercial & Public services and Residential sectors in 2050.
- Capacity Decommission: 624 MW of industrial boilers (Industry) in 2050.

expected, given the efforts to electrify the economic sectors.

Some indicators save information about the hours when an insufficient electricity in the system arises (Table 5). If the technology reaches the maximum capacity, the hour is accounted as *insufficiency*. The crucial role of PHES can be concluded from the hourly results of 2030, a role led by the electrolysers in 2050. The charging mode of electric vehicles could face a problem in 2030, while curtailment and exports of electricity would not imply a great challenge.

The panorama in the transport sector would radically change in fuels and modes of mobility (figure B.3). Rain transport could be totally electrified up to 7.36% of transport in 2050. Meanwhile, air transport would experiment a reduction of 93% (Table 4), mainly explained by the effective measure to perpetuate this sector with kerosene by 2030, and synthetic liquids by 2050 (perhaps using the traditional oil pipelines). In

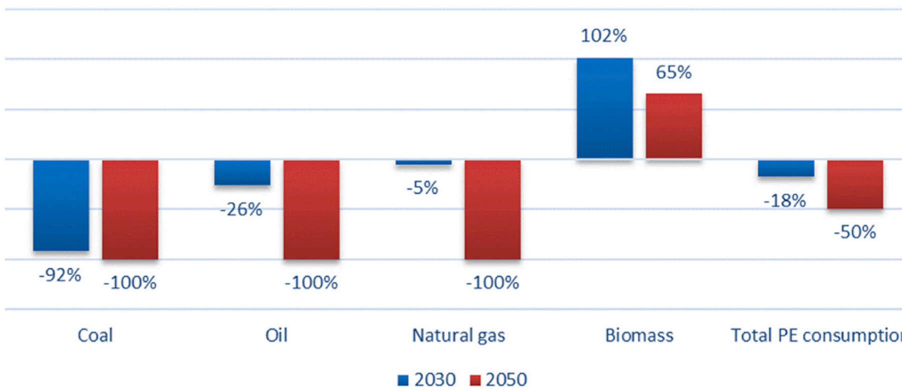


Fig. 3. Primary energy consumption of fossil fuels and biomass estimated for Spain in 2030 and 2050 (related to 2017).

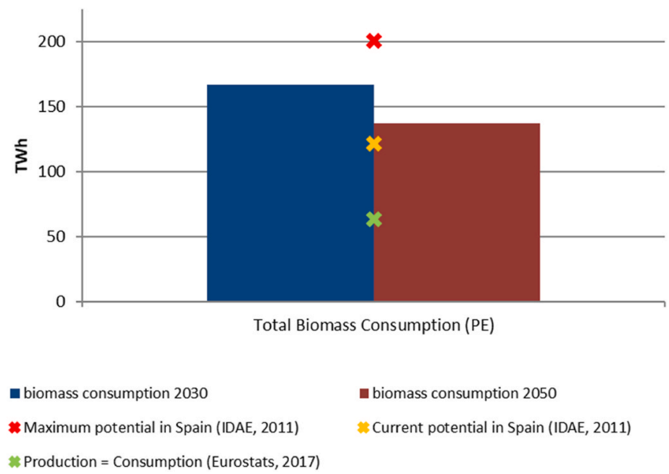


Fig. 4. Biomass consumption in 2030 and 2050. The three levels estimated by different studies are marked by crosses (red for the maximum potential, orange for the potential in 2011, and production of biomass in 2017).

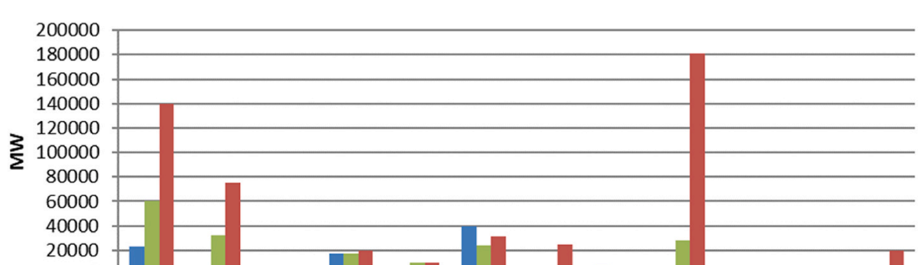
order to allow more time for research into modern fuels, the policy is applied in the period 2030–2050, instead of the previous one. Finally, biofuels are employed in sectors where substituting fossil fuels will be tricky, such as marine navigation and agriculture (farm machinery). From among all the flexibility options, electric vehicles is the most boosted, close to 30 million would be running by 2050 (almost 33 million vehicles formed the motor vehicle park in 2017).

The fuel pattern in the tertiary sector and households is very different over the various simulations (figure B.4). It would suffer a deep structural change from fossil to renewable shares when electrification is assumed to be not applicable. These sectors decrease by 7% and 10% by 2030, and 31% and 34% by 2050, respectively.

District heating was residual in the base year, so the promotion of heat pumps has been evaluated as the best option for Spain. A double effect is reflected here. On the one hand, we have the improvement in the global efficiency of the heating system due to the replacement of old heating devices by heat pumps, and on the other hand, some additional flexibility and demand of electricity in the power sector (sector coupling).

In general, Spanish industry would evolve towards a less energy intensive production. It faces great challenges to reduce by 19% its final energy consumption by 2030, and 42% by 2050 (related to 2017, figure B.5 and figure B.6, respectively). In addition, although the decarbonization of Industry could be technically possible, some considerations are discussed in the next section.

The agriculture sector could be completely decarbonized by 2050 (figure B.7). In this case, the energy intensities would reduce to half the entire consumption of final energy. Biofuels are fostered to substitute the presence of fossil fuels in heavy vehicles by 2030. In the following years, the machinery of this sector would be progressively electrified for, e.g., irrigation and non-heavy tasks. In this sector, the use of biomass products would remain to help in specific heavy processes.



	Wind	Solar-PV	Solar-CSP	Dam Hydro power	PHES	PP	Electricity storage - Grid	Transmission capacity	EV (V2G connection)	Boilers 2	Boilers 3	Electrolisers
2017	23132	4687	2304	17032	3329	39322	0	5800	0	281	2930	0
2030	60000	32308	5000	17032	10000	23900	5000	5000	27862	1000	1851	2540
2050	140000	75385	5000	20000	10000	31400	25000	5000	181120	2000	624	20000

Fig. 5. Capacities of renewables and flexibility technologies for the three years of simulation. Values in megawatts.

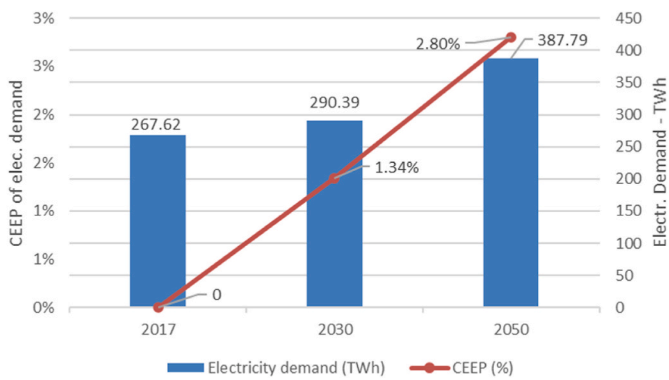


Fig. 6. Critical excess of electricity production (curtailment) as a percentage of the electricity demand (TWh) for the three years of simulation.

Table 5
Annual hours of curtailment and insufficiency of flexibility options for simulations of 2030 and 2050, in relative terms (8784 hours).

	2030	2050
Hours with VRES >0 (curtailment)	4.41%	6.34%
Insufficiency Exports	1.74%	5.33%
Insufficiency Imports	0%	0%
Insufficiency Electrolysers	0%	10.83%
Insufficiency in PHES	17.24%	8.86%
Insufficiency in Electric Batteries of Grid (charge)	4.78%	0.08%
Insufficiency in Electric Batteries of Grid (discharge)	0%	0%
Insufficiency in G2V (charge EV)	0%	0%
Insufficiency in V2G (discharge EV)	0%	0%

4. Discussion

The findings are further debated throughout this section. The literature review revealed how Spain is currently in line with the international scope of climate change legislation. Its geo-localization brings business opportunities.

Biomass has been employed to decarbonize a relevant part of the system, set to reach 163 TWh in 2030 and 137 TWh in 2050. In terms of sustainability (Fig. 1 in Ref. [70]), agricultural products to produce bioethanol and biodiesel should be avoided so as to maintain a strong food security, good quality of available clean water and low production costs (excluding subsidies and grants) in the region. Advancement in technology and rising costs of fossil fuels would soon make waste from agriculture and industry, non-food crops, and lignocellulose feedstock (most of the potential from forests) profitable in the emerging framework for a circular, bioeconomic European market [71]. Geographically, the Spanish coast is 7905 km long, so a third generation of biofuels from algae may increase the potential of renewable feedstock. However, 99% of algae is water and obtaining biomass requires processes which are currently only in a conceptual stage. In short, the second generation seems to be the most mature and promising renewable feedstock in Spain.

The cherry on the cake of the transition is a set of hydrogen-based products (around 17 TWh by 2030 and 70 TWh by 2050). The PNIEC did not promote the facilities of electrolysers (only a minor reference). However, the results suggest that Spain should start by installing in-situ industrial electrolysers (and 20 GWh of storage) where processes do already require hydrogen, thus creating an actual bench on which to test this technology. Then, hydrogen and biomass products would increase in relevance to supply heavy transport and machinery. In addition, related to the last paragraph, biomass and hydrogen may create synergies thanks to some gasification and biological conversion processes [72]. Of these, those with an acceptable global warming potential (GWP, t able 8 in Ref. [72]) are biomass gasification (M8, GWP equal to 3.54 in average) and electrolysis based on biomass (M11, 2.70), as compared to the higher climate impact of alcoholic waste reforming (M7, 9.55) or the lower impact of electrolysis based on wind (M12, 1.08).

The potential for improvement in efficiency may not totally justify the depletion for some economic sectors showed in the scenario. Degrowth mitigation pathways were referenced in the last IPCC report, opening up a new branch of decarbonization policies in the economy [73]. However, the literature that is running the concept of *'decoupling'* between energy and the economy could define a similar energy pathway with a low economic growth [74]. In comparison with the objective scenario of PNIEC (2030), the scenario differs in terms of final energy by −16% in Industry, +5% in Residential, −0% in Transport, and +29% in services and other sectors. Globally, the figure is +0.43%, very close to the official report. Differences in Industry and Services are explained by the different assumptions. For example, PNIEC (f igure. 4.1) delivers 18.7% of investments to Services and Residential sectors, while 3.2% to Industry. In contrast, the historical energy intensities (2017–2030) applied in our study shows higher improvements for industries, especially in Paper, Pulp & Printing (−5.29%/year), Chemical & Petrochemical (−3.27) and Transport Equipment (−3.17).

More uncertainty is implicit in 2050. In order to be conservative, the same intensities have been considered. Other biophysical reasons may cause restrictions or *limits to growth* in the energy consumption. On the one hand, the European Union has warned about barriers in the material global market of critical raw materials, especially in the so-called light and heavy rare earth elements, very present in electronics and machinery [75]. On the other hand, the peak of fossil fuels leads to economically and politically unextractable resources [76], which could in turn lead to protective measures in the regions of origin, while Spain does not have any significant amount of these resources.

The integration of batteries into the Spanish electricity system does not seem likely to occur in the short term. A recent publication concludes that, to fully electrify the island of the Canary Islands, 9.73 GWh of pumped storage (607 MW) and 5.82 GWh Lithium-ion battery system (2.3 GW) would be required [77]. The difficulty of deploying such batteries becomes clear when comparing the results with the value of 8.09 GWh coming from the forecast made by Wood Mackenzie for Spain in 2031 (89 GWh for Europe) [78]. However, this rate of deployment may be even under discussion. The International Energy Agency (IEA) is very concerned about the plans to promote storage technologies, stating that they could be above the limits of mineral extraction such as lithium, cobalt, nickel, manganese, graphite and copper [79].

The development of technologies and the availability of materials for the future e-mobility in road transport are still very high. The highest risk falls on the construction of traction motors due to the requirements of neodymium, dysprosium, praseodymium and boron. Furthermore, the assembly step for Li-ion batteries and fuel cells have bottlenecks in the supply chain [75]. To summarize, the conclusion of the study is the necessity for high capacity storage in a well-connected future power system and technologies that can support the decarbonization of the transport sector at the same time; however, this strategic policy would have similar levels in benefit and risks.

Electricity penetrates every sector, becoming the first energy carrier of the Spanish system. In comparison to the results here presented, the PNIEC (objective scenario, 2030) delivers 12.5% lower electrification and 6% higher renewable penetration in the final energy demand. The presence of electrification and biofuels in Transport is 9% higher in PNIEC, with 5 million electric vehicles (vs 4.7 in our results). EVs enabling smart charge and discharge may be shown as electric storage, which helps to make the match between supply and demand (2.61 TWh by 2030 and 18.75 TWh by 2050) and requirements of thermal power plants smoother. The differences with the PNIEC's installed capacities are related to the flexibility test performed, based on conditions in 2017: +19.2% of wind, −17.5% of solar-PV, and −31.5% of solar CSP.

The results support policies that look at the Iberian region as a decentralized grid with 5000 MW of international interconnections (Spain-Portugal, mainly) in 2030 and 2050. However, the European

Union foresees 15% of connection by 2030, so additional profit could fall on the side of Spain if it generates cheaper electricity. Traditionally, French nuclear has been dominant in the market; however, the situation could change in a renewable-dominant system.[8]

Nowadays, the number of energy communities in Spain is increasing. However, the composite behavior in the grid is indistinguishable from an individual self-consumption, due to the fact that most of them do not have accumulation installed (a reason could be the high prices of these technologies). Because of the sizing factor, a set of grouped consumers or *prosumers* can produce with a higher performance (mostly photovoltaic generation). So, despite it is a decentralizing measure, the energy communities do not have the potential to manage the intermittency of generation and demand, at least for now. The communities do not expect the Spanish government promotes their creation since, and according to the Spanish public organism called CNMC (National Markets and Competition Commission), the installation of self-consumption is advancing above the official forecasts in between 9 and 14 GW, in comparison to the 2030 goal. The information can be read on page 113 of [80], where the photovoltaic production of 5.6 GW with 1500 equivalent hours per year under the self-consumption category would be reached by 2025.

As mentioned above, agriculture represented 12% of GHG emissions in 2017. Non-energy-related mitigation measures for livestock, forests and crops have been proposed to reach 28% of the annual abatement of tCO_2e, with a reference social cost of 40 €/tCO_2e [81]. The technological changes such as advanced irrigation and treatment of manure, can provide natural fertilizer without high amounts of energy being involved in the process. Investments in the agriculture sector should be focused on electrifying, while modernizing the means of production.

The demand of hydrogen as industrial feedstock in 2017 could be totally *green* in 2030, and provide, along with synthetic gas, 27% of the final energy by 2050. In the last year, 50% would be satisfied with electricity and the rest with renewables (mainly biomass products). Among industrial activities, cement, steel, ammonia, and ethylene have been identified as those for which cost is the decisive consideration in production (all of them) and global trade (except cement). Developed countries producing such zero-carbon products thanks to protective measures could have an advantage over developing countries, which require greater efforts with respect to climate change commitments due to their historical low-intensive economy. In this way, international cooperation and diplomacy should be intensified in this future regulated sector, intensifying international agreements to promote a fair transition. A deeper modelling of industrial processes involving production and the use of hydrogen (whole chain of value added) is needed to achieve a better resolution of the impacts of specific policies over the transition.

Finally, congestion has been detected in a mature technology, i.e., pump hydropower (17.24% of the hours in 2030) and a new one, i.e., electrolysers (10.83% of the hours in 2050). This would suggest the need for further analysis of these configurations in greater detail, modelling the power flow analysis and economic costs over a dynamic simulation.

5. Conclusions

Spain, as part of the European Union’s singing of the and Paris Agreement needs a decarbonized economy with a coherent pathway. Time is crucial, so this article has analysed the efforts facing three reference years: the year of calibration (2017), the year of the NECP (2030), and the long-term scenario (2050).

The literature review and the analysis of the reference year (2017) identifies the energy sector as the major sector responsible for the CO_2 equivalent emissions in this country (76%) and the most polluting economic sectors (44% by Transport). A brief legislative and policy review shows the necessary flexibility in the institutions to adapt the regulation of the system with the new technologies available in the market. Furthermore, CHP and DH grids are found to be disconnected when they should be further developed to give a higher power-to-heat capacity, especially in the tertiary sector and households for both cooling and heating demands. However, the analysis seems to point to a very slow development in the history of this technology, so CHP would suppose a wrong strategy as we would be facing the energy transition in a business-*as*-usual pathway.

A conceptualization for linking an hourly energy model (EnergyPLAN) with a yearly integrated assessment model is shared to point towards a new line of research in both fields. A transparent method is proposed and validated to deliver consistent results while allowing policy measures (exogenously or endogenously introduced) in a case of study. The proposed scenario delivers a share of renewable contribution is quite similar to the NECP’s objective scenario by 2030. The results show that Spain can take place a total net decarbonization of the energy system by 2050, with difficulties at some hours and materials.

Further research should clearly be focused on two paths. On the one hand, IAMs usually capture the evolution of energy intensities which means that many topics in other areas (demography, economy, resources, and climate, among others) should be running together in the model to deliver holistic results, and therefore an improved assessment about the whole system. On the other hand, the power flow analysis could be carried out to improve the assessment of insufficiencies in the power grid, as well as other features such as the quality (voltage, frequency) in the power lines and substations.

Author contributions

Gonzalo Parrado-Hernando: Conceptualization, Methodology, Formal analysis, Writing – original draft, Visualization, Writing – review & editing. Antun Pfeifer: Writing – review & editing, Supervision, Neven Duić: Supervision, Fernando Frechoso-Escudero: Writing – review & editing, Supervision, Luis Javier Miguel González: Supervision

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgments

This work has been supported by MODESLOW (Modelling and Simulation of scenarios towards a LOW-carbon transition: The Spanish case), a project funded under the Spanish National Research, Development and Innovation Program (Ministry of Economy and Competitiveness of Spain, ref. ECO2017-85110-R). Finally, some authors are members of the Network called MENTES (project reference RED2018-102794), funded by the Ministry of Science and Innovation.

[8] Variable renewable technologies (VRES) have a lower levelized cost of electricity (LCOE) in comparison to nuclear. Nonetheless, there are uncertain costs of flexibility the system could compute to VRES, which has been summarized into metrics such as the value-adjusted LCOE (VALCOE) [87].

Appendix A

The material here presented is part of the article. This appendix sets out the following information:

- a Sankey diagram to show the differences in the conceptualization of EnergyPLAN in comparison with the structure of the energy balances;
- which sectors and fuels are considered in the analysis;
- the options and regulation parameters modified in EnergyPLAN for the calibration year (2017), 2030 and 2050;
- the values of the energy intensities applied from one year of simulation to the next;
- the values applied in the energy balances to substitute one fuel for another (policies of substitution).

This appendix is therefore necessary to understand and follow the explanations in the body of the paper.

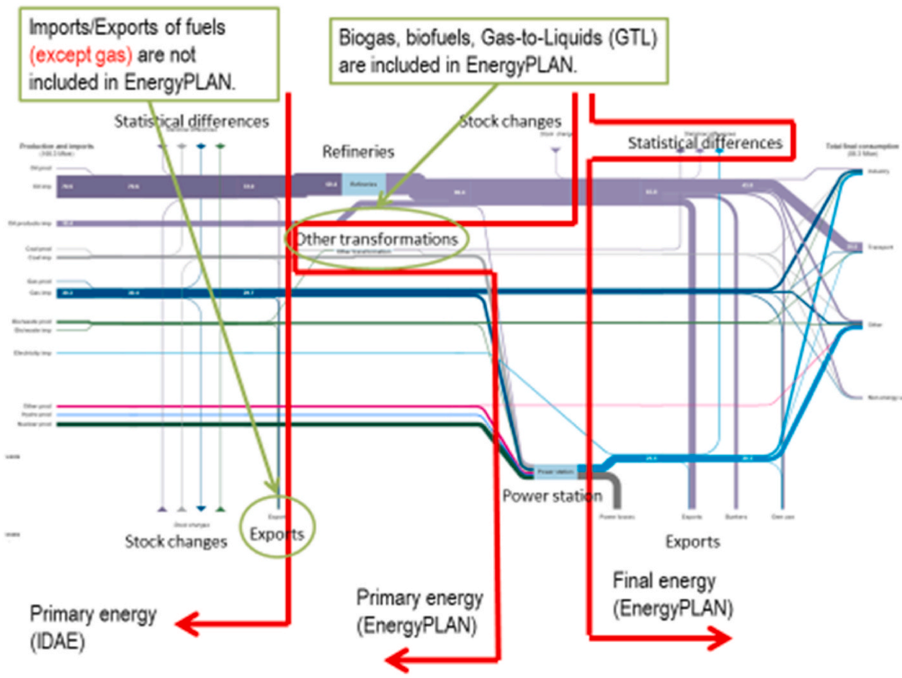


Fig. A. 1. Sankey diagram of the Spanish energy flows in 2018. Different criteria between national energy accounts (IDAE source) and EnergyPLAN are shown in terms of primary and final energy. Source: International Energy Agency (IEA).

Sectors and fuels in the Spanish energy accounts

Table A. 1
Correspondence of sectors and fuels between final energy balance on Spanish energy accounts (IDAE, left) and Eurostats data in 2017 (Eurostat's codes between square brackets, right).

Sectors	
Industry	Mining & Quarring (non-energy) [FC_IND_MQ_E]
	Food, Beverages & Tobacco [FC_IND_FBT_E]
	Textile & Leather [FC_IND_TL_E]
	Paper, Pulp & Printing [FC_IND_PPP_E]
	Chemical & Petrochemical [FC_IND_CPC_E]
	Non-metallic Minerals [FC_IND_NMM_E]
	Iron & Steel [FC_IND_IS_E]
	Non-ferrous metals [FC_IND_NFM_E]
	Machinery [FC_IND_MAC_E]
	Transport equipment [FC_IND_TE_E]
	Construction [FC_IND_CON_E]
	Wood & Wood products [FC_IND_WP_E]
	Other Industries [FC_IND_NSP_E]
Transport	Road [FC_TRA_ROAD_E]
	Rail [FC_TRA_RAIL_E]
	Domestic navigation [FC_TRA_DNAVI_E]
	Domestic aviation [FC_TRA_DAVI_E]
	International aviation [part of FC_TRA_NSP_E]
	Pipeline transport [FC_TRA_PIPE_E]
	Other transport [part of FC_TRA_NSP_E]
Residential and Services	Commercial & public services [FC_OTH_CP_E]
	Residential/Households [FC_OTH_HH_E]
Various	Agriculture [part of FC_OTH_AF_E]

(*continued on next page*)

Table A. 1 (*continued*)

Sectors	
	Fishing [FC_OTH_FISH_E]
	Other sectors not specified [part of FC_OTH_AF_E (forestry) and FC_OTH_NSP_E]
FUELS	
Coal	Hard coal, Anthracite and Aggregated [C0110, C0129, C0210, C0220, C0330]
	Coking coal [C0121, C0311]
	Gas coke and blast furnace [C0350 + C0371]
	Coal tar [C0340]
Oil products	LPG (O4630)
	Gasoline [O4652XR5210B, O4651, O4653].
	Kerosene [O4661XR5230B, O4669]
	Diesel [O4671XR5220B]
	Fuel oil [O4680]
	Petroleum coke [O4694]
	Other oil products [O4500, O4640, O4699]
Natural gas	Natural gas [G3000]
	Other gases [C0360]
Waste	Industrial non-renewable waste (W6100)
	Municipal non-renewable waste (W6220)
Renewables	Solar thermal [RA410]
	Geothermal [RA200]
	Biomass [R5110-5150_W6000RI]
	Biogas [R5300]
	Biofuels [R5210P, R5210B, R5220P, R5220B, R5230P, R5230B]
	Municipal renewable waste [W6210]
	Charcoal [R5160]
Electricity	Electricity [E7000]

Table A. 2
Disaggregation of residential sector and Commercial & public services by fuel and end use category.

	Fuels	End uses
Residential sector	Electricity	Space Heating
	Natural gas	Water Heating (ACS)
	Coal	Cooling
	LPG	Cooking
	Diesel	Illumination & electronics
	Fuel oil	
	Solar thermal	
	Biomass	
	Geothermal	
	Biofuels	
	Charcoal	
Commercial & public services	LPG	Water Heating (ACS)
	Petrol	Space Heating
	Diesel	Process Heating
	Fuel oil	Space Cooling
	Natural gas	Process Cooling
	Waste Non-Renewable	Electronics & Illumination
	Solar thermal	
	Geothermal	
	Biomass	
	Biogas	
	Biofuels	
	Waste Renewable	
	Electricity	

Parameters for policies based on both substitution and technological change.

Table A. 3
Options selected in the technical simulation of EnergyPLAN for the three years simulated.

	2017	2030	2050
Technical Simulation Strategy	Balancing heat demands	Balancing both heat and electricity demands	Balancing both heat and electricity demands
Individual Heat Pump Simulation	Individual Heat Pumps and Electric Boilers seek to utilise only Critical Excess Production	Individual Heat Pumps and Electric Boilers seek to utilise all electricity export	Individual Heat Pumps and Electric Boilers seek to utilise all electricity export
V2G regulation	V2G seek to balance only Critical Excess and Power Plant production	V2G seek to balance Power Plants and all electricity import and export	V2G seek to balance Power Plants and all electricity import and export
Rockbed storage regulation	Rockbed storage seek to balance only Critical Excess and Power Plant production	Rockbed storage seek to balance Power Plants and all electricity import and export	Rockbed storage seek to balance Power Plants and all electricity import and export
Priorities in balancing electricity	1 – Pumped Hydro 2 – Vehicle to grid	1 – Pumped Hydro 2 – Vehicle to grid	1 – Vehicle to grid 2 – Pumped Hydro

(*continued on next page*)

Table A. 3 (*continued*)

	2017	2030	2050
	3 – Rockbed storage	3 – Rockbed storage	3 – Rockbed storage
Minimum stabilization share in power generation	0.3	0.3	0.0

Table A. 4
Parameters to estimate the electricity demand and related relevant variables in the electric-vehicle policy. Values of Spain for 2030 and 2050 scenarios are shown as example.

	2030	2050
Usage EV [km/year]	14,000	14,000
Elec. Consum. EV [kWh/100 km]	14	14
Elect. Smart EnergyPLAN [TWh]	Total electricity demand of road transport in FEB = 9.22	Total electricity demand of road transport in FEB = 59.97
Electric storage by vehicle [KWh]	48	60
Number of electric vehicles (EV)	Elect. Smart EnergyPLAN [KWh] *100/(Usage EV [km/year]* Elec. Consum. EV [kWh/100 km]) = 4,706,408	Elect. Smart EnergyPLAN (KWh) *100/(Usage EV (km/year)* Elec. Consum. EV (kWh/100 km)) = 30,594,669
Max. Share of cars during peak demand	**0.2**	**0.2**
Capacity of battery to grid connection [MW] [82]	7.4 [KW/EV] * 0.8 [80% of chargers in parking] * Number of electric vehicles * 0.001 [MW/kW] = 27,862	7.4 [KW/EV] *0.8* Number of electric vehicles * 0.001 [MW/kW] = 181,120
Capacity of grid to battery connection [MW] [82]	(7.4 * 0.8 + 3.1) [kW/EV] * Number of electric vehicles* 0.001 [MW/kW] = 42,452	(7.4 * 0.8 + 3.1) [kW/EV] * Number of electric vehicles* 0.001 [MW/kW] = 275,964
Share of parked cars grid connected	0.7	0.7
Efficiency (grid-to-battery)	0.9	0.9
Battery storage capacity [GWh]	Electric storage by vehicle [GWh] * Number of electric vehicles = 226	Electric storage by vehicle [GWh] * Number of electric vehicles = 1836

Table A. 5
Efficiencies of vehicles in Transport. Parameters to be transferred among fuels in energy policies of substitution.

	Efficiency (MPGe)
Petrol	52.3 [83]
Diesel	42.9 [84]
GLP	35.0 [85]
EV	133.0 [86]

Table A. 6
Efficiencies of heat-generation devices in Individuals. Parameters to be transferred between boilers and heat pumps in energy policies of substitution. Values were assumed by expertise.

Technology	Final energy	Efficiency [%]
Boiler	Coal	75.23%
	Oil	83.60%
	Natural gas	87.40%
	Electricity	100%
Heat Pump	Demand = Policy [%] * space demand of individual	350% (COP)

Energy intensities.

Table A. 7
Efficiencies of heat-generation devices in Individuals. Parameters to be transferred between boilers and heat pumps in energy policies of substitution. Values were assumed by expertise.

Industrial sectors	Energy intensity 2017–2030 [%/year]	Energy intensity 2030–2050 [%/year]
Mining & Quarrying (non-energy)	−2.00	−2.00
Food, Beverages & Tobacco	−2.47	−2.47
Textile & Leather	0.00	0.00
Paper, Pulp & Printing	−5.29	−5.29
Chemical & Petrochemical	−3.27	−3.27
Non-metallic Minerals	−0.25	−0.25
Iron & Steel	−1.92	−1.92
Non-ferrous metals	−0.84	−0.84

(*continued on next page*)

Table A. 7 (*continued*)

Industrial sectors	Energy intensity 2017–2030 [%/year]	Energy intensity 2030–2050 [%/year]
Machinery	−0.01	−0.01
Transport equipment	−3.17	−3.17
Construction	−0.50	−0.50
Wood & Wood products	−0.50	−0.50
Other Industries	−0.50	−0.50

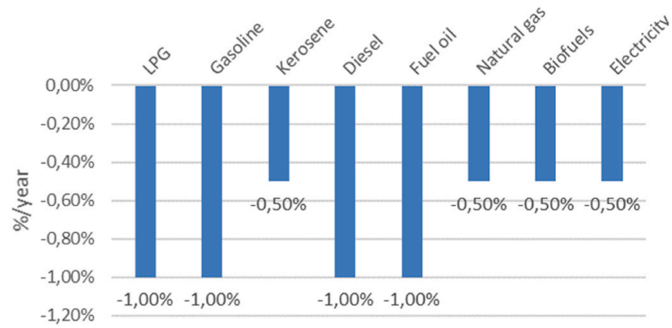


Fig. A. 2. Energy intensities for Transport sectors from 2017 to 2030. The evolution from 2030 to 2050 was conservative for all sectors with a value of −0.01%. The rest of fuels were included as 0.00%.

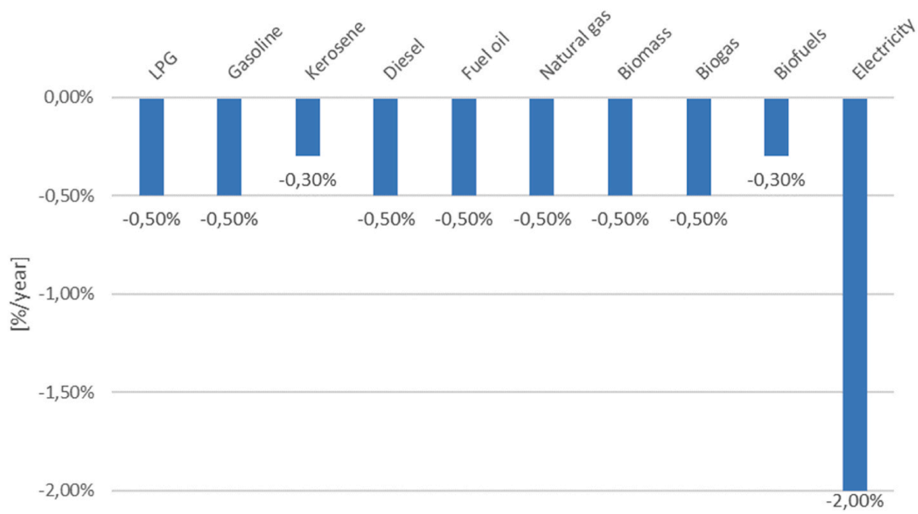


Fig. A. 3. Energy intensities for Various sectors from 2017 to 2050. The rest of fuels were included as 0.00%.

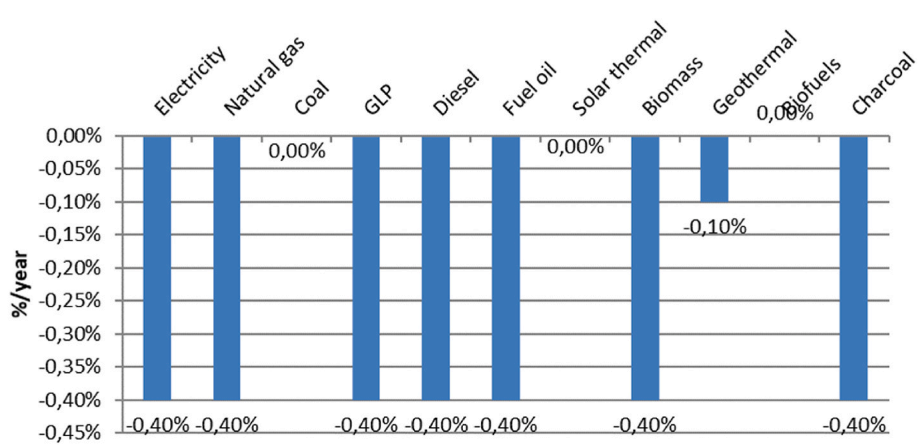


Fig. A. 4. Energy intensities for Residential sector from 2017 to 2050. The rest of fuels were included as 0.00%.

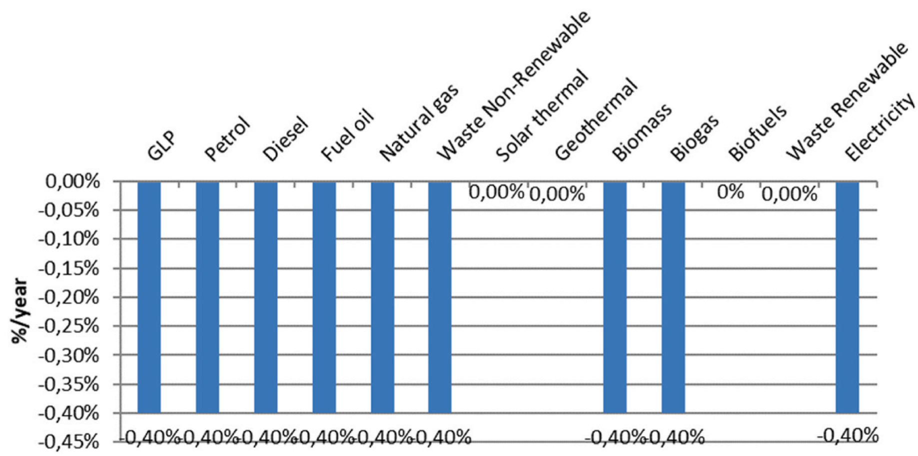


Fig. A. 5. Energy intensities for Commercial & Public services from 2017 to 2050. The rest of fuels were included as 0.00%.

Appendix B

The material here presented is part of the article. This appendix shows results from the analysis for 2017, 2030, and 2050.

- General results of interest.
- Results concerning the economic sectors. It also includes information about the energy prices when using hydrogen in Industry in a profitable way.

This appendix is therefore necessary to understand and follow the explanations in the body of the paper.

General results

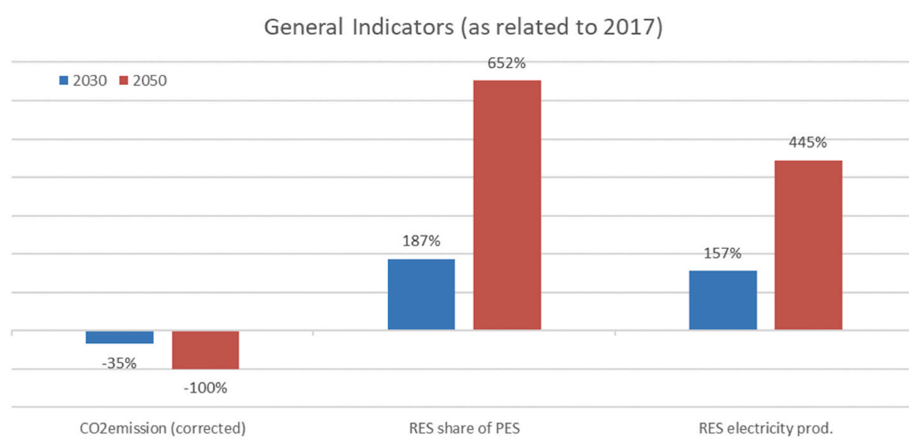


Fig. B. 1. General indicators relative to 2017 (base year of calibration). Corrected CO2 emissions, share of renewables in primary energy supply, share of renewables in electricity generation, and renewable electricity generation.

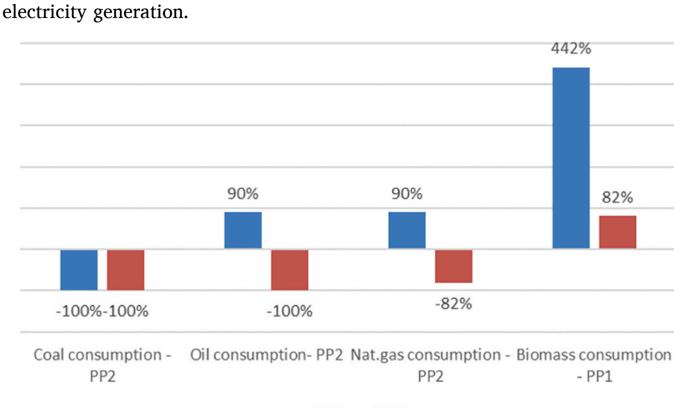


Fig. B. 2. Fuel consumption in thermal power plants by 2030 and 2050, related to 2017.

Sectorial results

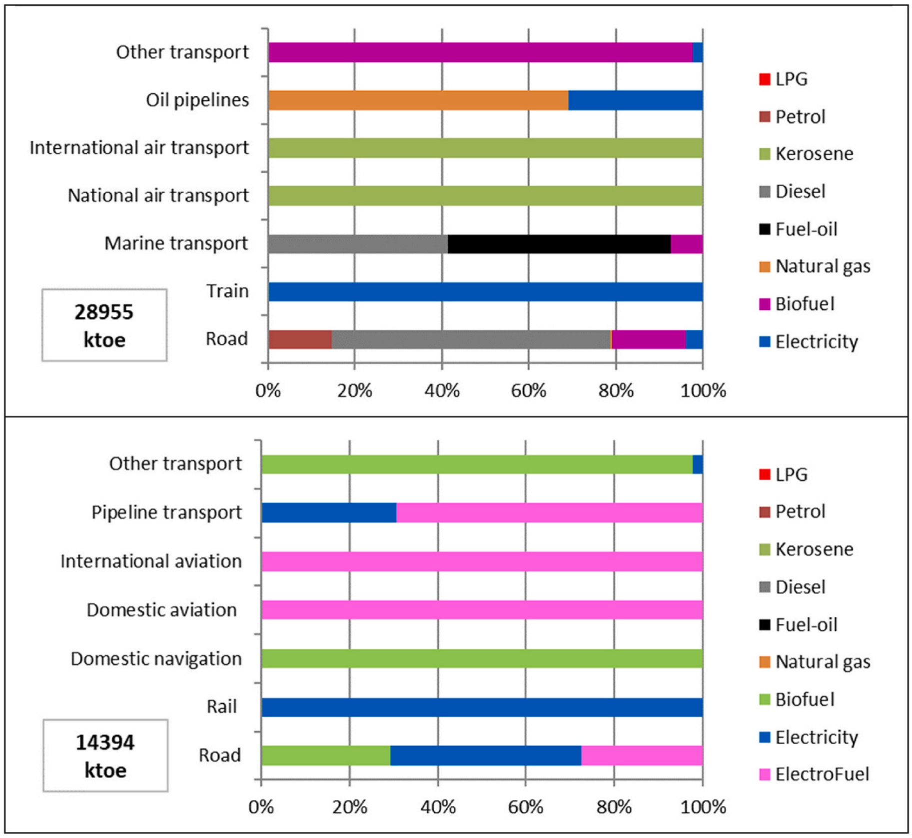


Fig. B. 3. Shares of fuels in Transport sectors, 2030 (top) and 2050 (bottom). Total energy consumption of Transport is shown.

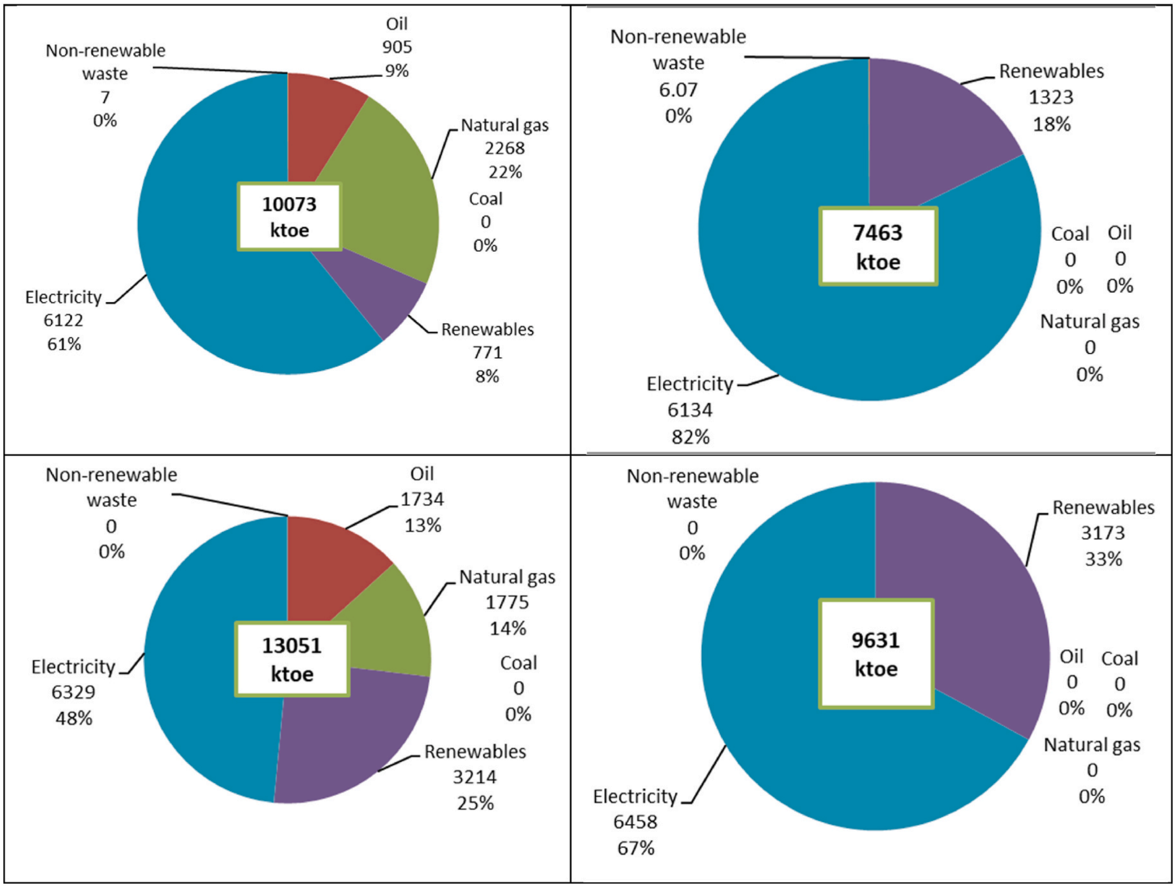


Fig. B. 4. Contribution of fuels in the energy consumption of Commercial & Public Services (top), and Households (bottom), 2030 (left) and 2050 (rigth). Units in ktoe.

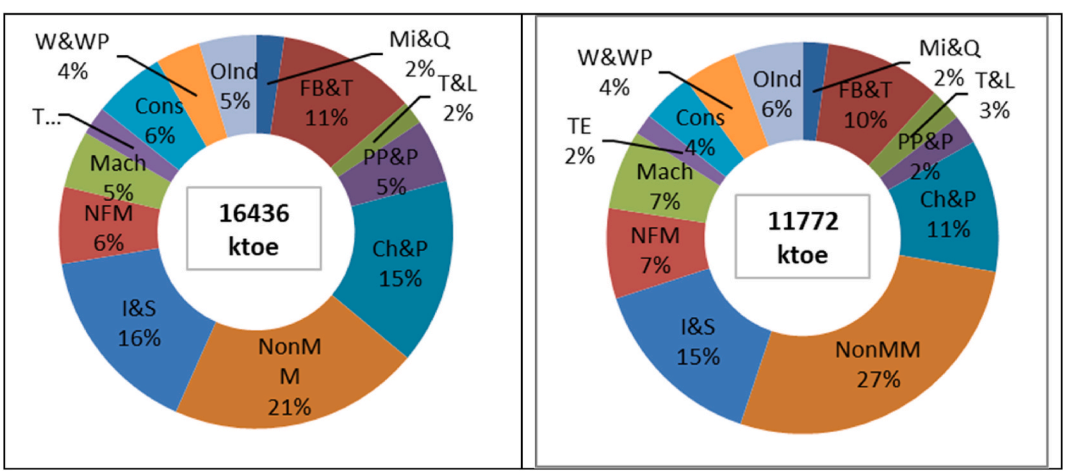


Fig. B. 5. Structure of energy consumption in Spanish industries, 2030 (left) and 2050 (right). Total energy consumption of Industry is shown in the middle of donuts. Mi&Q = Mining & Quarrying (non-energy); FB&T = Food, Beverages & Tobacco; T&L = Textile and Leather; PP&P=Paper, Pulp & Printing, Ch&P=Chemical & Petrochemical; NonMM = Non-metallic Minerals; I&S = Iron & Steel; NFM =Non-ferrous metals; Mach = Machinery; TW = Transport equipment; Cons = Construction; W&Wp = Wood & Wood products; OiInd = Other industries.

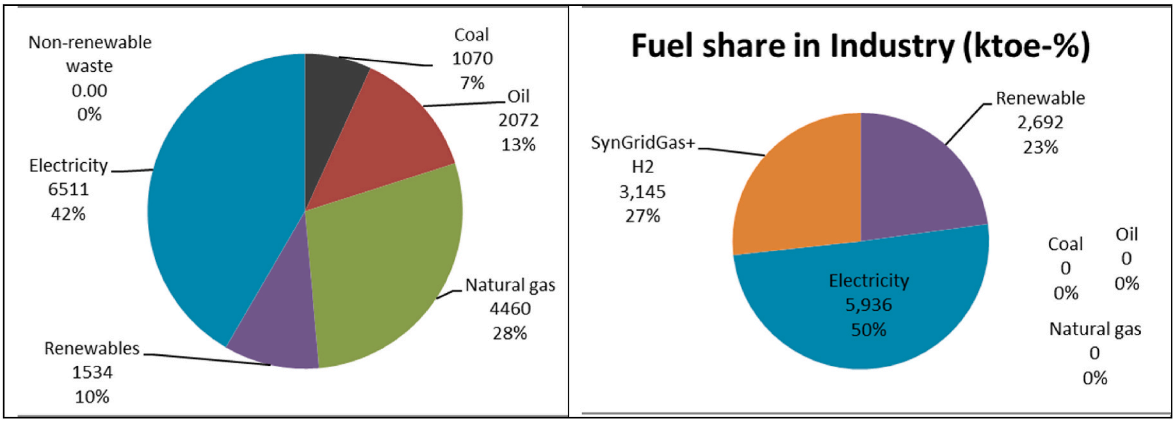


Fig. B. 6. Percentage of final energy consumption in Industry, 2030 (left) and 2050 (right). Values are in ktoe.

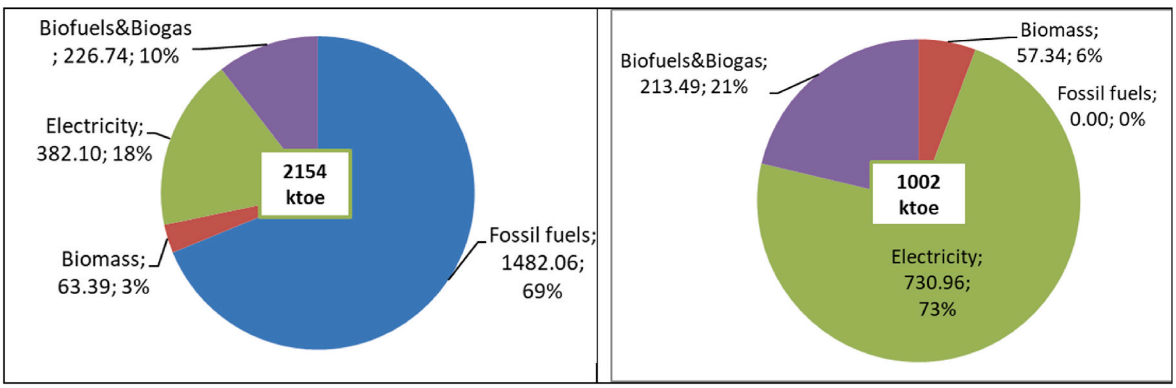


Fig. B. 7. Structure of energy consumption for Agriculture in Spain, 2030 (left) and 2050 (right). Values are in ktoe.

References

[1] IPCC, "Summary for Policymakers. In: Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental Panel on climate change; 2021. https://doi.org/10.1017/9781009157896.001.

[2] Mata Pérez M de la E, Scholten D, Smith Stegen K. The multi-speed energy transition in Europe: opportunities and challenges for EU energy security. Energy Strateg. Rev. 2019;26(August). https://doi.org/10.1016/j.esr.2019.100415.

[3] Directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Off. J. 2009;011: 39–85. Chapter 15, http://data.europa.eu/eli/dir/2009/28/oj [Online]. Available: .

[4] Ministerio para la Transición Ecológica y el Reto Demográfico (MITERD), "Integrated National Energy and Climate Plan 2021-2030 of Spain (English draft version)," 2021, [Online]. Available: https://energy.ec.europa.eu/system/files/2019-06/ec_courtesy_translation_es_necp_0.pdf.

[5] Bianco V, Driha OM, Sevilla-Jiménez M. Effects of renewables deployment in the Spanish electricity generation sector. Util Pol 2019;56:72–81. https://doi.org/10.1016/j.jup.2018.11.001. no. October 2017.

[6] Ciarreta A, Pizarro-Irizar C, Zarraga A. Renewable energy regulation and structural breaks: an empirical analysis of Spanish electricity price volatility. Energy Econ 2020;88:104749. https://doi.org/10.1016/j.eneco.2020.104749. , Jul.

[7] Comisión de Expertos de Transición Energética. Análisis y propuestas para la descarbonización. 2018 [Online]. Available: http://www6.mityc.es/aplicaciones/transicionenergetica/informe_cexpertos_20180402_veditado.pdf.

[8] J. Bonilla, J. Blanco, E. Zarza, and D. C. Alarcón-Padilla, "Feasibility and practical limits of full decarbonization of the electricity market with renewable energy: application to the Spanish power sector," Energy, vol. 239, 2022, doi: 10.1016/j.energy.2021.122437.

[9] Parrado-Hernando G, Miguel-González LJ, Frechoso-Escudero F. Analysis of the variable renewable energy in the Spanish power system based on kernel probabilistic distributions. Dyna 2021;96(2):179–85. https://doi.org/10.6036/9892.

[10] Langarita R, Duarte R, Hewings G, Sánchez-Chóliz J. Testing European goals for the Spanish electricity system using a disaggregated CGE model. Energy 2019;179: 1288–301. https://doi.org/10.1016/j.energy.2019.04.175.

[11] Lund H, Thellufsen JZ, Østergaard PA, Sorknæs P, Skov IR, Mathiesen BV. EnergyPLAN – advanced analysis of smart energy systems. Smart Energy 2021;1: 100007. https://doi.org/10.1016/j.segy.2021.100007.

[12] Ministerio para la Transición Ecológica y el Reto Demográfico (MITERD), "Hoja de ruta del hidrógeno: una apuesta por el hidrógeno renovable. 2020 [Online]. Available: https://www.miteco.gob.es/images/es/hojarutahidrogenorenovable_tcm30-525000.PDF. Madrid.

[13] Ancona MA, et al. Thermal integration of a high-temperature co-electrolyzer and experimental methanator for Power-to-Gas energy storage system. Energy Convers Manag 2019;186:140–55. https://doi.org/10.1016/j.enconman.2019.02.057. March.

[14] Brey JJ. Use of hydrogen as a seasonal energy storage system to manage renewable power deployment in Spain by 2030. Int J Hydrogen Energy 2021;46(33): 17447–57. https://doi.org/10.1016/j.ijhydene.2020.04.089.

[15] Kroposki B. Integrating high levels of variable renewable energy into electric power systems. J. Mod. Power Syst. Clean Energy 2017;5(6):831–7. https://doi.org/10.1007/s40565-017-0339-3.

[16] Gjorgievski VZ, Markovska N, Abazi A, Duić N. The potential of power-to-heat demand response to improve the flexibility of the energy system: an empirical review. Renew Sustain Energy Rev September 2020;138:2021. https://doi.org/10.1016/j.rser.2020.110489.

[17] European Commission. Optimal paths for electricity interconnections between central Asia and Europe. 2020. https://doi.org/10.2760/95740.

[18] Graça Gomes J, Medeiros Pinto J, Xu H, Zhao C, Hashim H. Modeling and planning of the electricity energy system with a high share of renewable supply for Portugal. Energy 2020;211. https://doi.org/10.1016/j.energy.2020.118713.

[19] Boulakhbar M, et al. Towards a large-scale integration of renewable energies in Morocco. J Energy Storage 2020;32(August):101806. https://doi.org/10.1016/j.est.2020.101806.

[20] European Commission. Towards a sustainable and integrated Europe. Report of the Commission Expert Group on electricity interconnection targets; 2017 [Online]. Available: https://ec.europa.eu/energy/sites/ener/files/documents/report_of_the_commission_expert_group_on_electricity_interconnection_targets.pdf.

[21] L. M. Abadie and J. M. Chamorro, "Evaluation of a cross-border electricity interconnection: the case of Spain-France," Energy, vol. 233, 2021, doi: 10.1016/j.energy.2021.121177.

[22] Verma MK, Mukherjee V, Yadav VK, Ghosh S. Constraints for effective distribution network expansion planning: an ample review. Int. J. Syst. Assur. Eng. Manag. 2020;11(3):531–46. https://doi.org/10.1007/s13198-020-00969-w.

[23] Ringkjøb H-KK, Haugan PM, Solbrekke IM. A review of modelling tools for energy and electricity systems with large shares of variable renewables. Renew Sustain Energy Rev Dec. 2018;96(August):440–59. https://doi.org/10.1016/j.rser.2018.08.002.
[24] Østergaard PA. Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations. Appl Energy Sep. 2015;154:921–33. https://doi.org/10.1016/j.apenergy.2015.05.086.
[25] Cabrera P, Lund H, Thellufsen JZ, Sorknæs P. The MATLAB Toolbox for EnergyPLAN: a tool to extend energy planning studies. Sci Comput Program 2020;191:102405. https://doi.org/10.1016/j.scico.2020.102405.
[26] Mahbub MS, Cozzini M, Østergaard PA, Alberti F. Combining multi-objective evolutionary algorithms and descriptive analytical modelling in energy scenario design. Appl Energy 2016;164:140–51. https://doi.org/10.1016/j.apenergy.2015.11.042.
[27] Prina MG, et al. Multi-objective optimization algorithm coupled to EnergyPLAN software: the EPLANopt model. Energy 2018;149:213–21. https://doi.org/10.1016/j.energy.2018.02.050.
[28] A. Wyrwa, W. Suwała, M. Pluta, M. Raczyński, J. Zyśk, and S. Tokarski, "A new approach for coupling the short- and long-term planning models to design a pathway to carbon neutrality in a coal-based power system," Energy, vol. 239, 2022, doi: 10.1016/j.energy.2021.122438.
[29] Pfenninger S, Hawkes A, Keirstead J. Energy systems modeling for twenty-first century energy challenges. Renew Sustain Energy Rev Dec. 2014;33:74–86. https://doi.org/10.1016/j.rser.2014.02.003.
[30] Hoevenaars EJ, Crawford CA. Implications of temporal resolution for modeling renewables-based power systems. Renew Energy 2012;41:285–93. https://doi.org/10.1016/j.renene.2011.11.013.
[31] Bistline JET. The importance of temporal resolution in modeling deep decarbonization of the electric power sector. Environ Res Lett 2021;16(8). https://doi.org/10.1088/1748-9326/ac10df.
[32] Shirizadeh B, Quirion P. Do multi-sector energy system optimization models need hourly temporal resolution? A case study with an investment and dispatch model applied to France. Appl Energy 2022;305:117951. https://doi.org/10.1016/j.apenergy.2021.117951. October 2021.
[33] Abrell J, Kosch M, Rausch S. Carbon abatement with renewables: evaluating wind and solar subsidies in Germany and Spain. J. Public Econ. Jul. 2019;169:172–202. https://doi.org/10.1016/j.jpubeco.2018.11.007.
[34] Fernandes C, Frías P, Reneses J. Participation of intermittent renewable generators in balancing mechanisms: a closer look into the Spanish market design. Renew Energy 2016;89:305–16. https://doi.org/10.1016/j.renene.2015.12.037. Jul.
[35] Chaves-Avila JP, Banez-Chicharro F, Ramos A. Impact of support schemes and market rules on renewable electricity generation and system operation: the Spanish case. IET Renew Power Gener 2017;11(3):238–44. https://doi.org/10.1049/iet-rpg.2016.0246. Jul.
[36] Gómez-Calvet R, Martínez-Duart JM, Serrano-Calle S. Current state and optimal development of the renewable electricity generation mix in Spain. Renew Energy 2019;135:1108–1120, Jul. https://doi.org/10.1016/j.renene.2018.12.072.
[37] Monyei CG, Sovacool BK, Brown MA, Jenkins KEH, Viriri S, Li Y. Justice, poverty, and electricity decarbonization. Electr J 2019;32(1):47–51. https://doi.org/10.1016/j.tej.2019.01.005.
[38] Capellán-Pérez I, Campos-Celador Á, Terés-Zubiaga J. Renewable Energy Cooperatives as an instrument towards the energy transition in Spain. Energy Pol 2018;123(August):215–29. https://doi.org/10.1016/j.enpol.2018.08.064.
[39] Halden U, Cali U, Dynge MF, Stekli J, Bai L. DLT-based equity crowdfunding on the techno-economic feasibility of solar energy investments. Sol Energy 2021;227 (August):137–50. https://doi.org/10.1016/j.solener.2021.08.067.
[40] de Blas I, Miguel LJ, Capellán-Pérez I. Modelling of sectoral energy demand through energy intensities in MEDEAS integrated assessment model. Energy Strateg. Rev. 2019;26. https://doi.org/10.1016/j.esr.2019.100419. September 2018.
[41] Pietzcker RC, et al. System integration of wind and solar power in integrated assessment models: a cross-model evaluation of new approaches. Energy Econ 2017;64:583–99. https://doi.org/10.1016/j.eneco.2016.11.018. 2017.
[42] Capellán-Pérez I, et al. MEDEAS: a new modeling framework integrating global biophysical and socioeconomic constraints. Energy Environ Sci 2020;13(3): 986–1017. https://doi.org/10.1039/c9ee02627d.
[43] Instituto para la Diversificación y Ahorro de la Energía, "Balance del Consumo de energía final. http://sieeweb.idae.es/consumofinal/bal.asp?txt=2017&tipbal=t. [Accessed 11 May 2021]. accessed.
[44] Eurostat. Energy balances. https://ec.europa.eu/eurostat/web/energy/data/energy-balances. [Accessed 11 May 2021]. accessed.
[45] Eléctrica de España Red. Base de datos ESIOS. https://www.esios.ree.es/es. [Accessed 11 May 2021]. accessed.
[46] Heat Roadmap Europe, "Profiles and Baselines for heating and cooling energy demands in 2015 for EU28 countries. 2015. https://heatroadmap.eu/heating-and-cooling-energy-demand-profiles/. [Accessed 11 May 2021]. accessed.
[47] Lund H, Thellufsen JZ. EnergyPLAN | Advanced energy systems analysis computer model. 2020. https://www.energyplan.eu/. [Accessed 11 May 2021]. accessed.
[48] Asociación de Empresas de Redes de Calor y Frío (ADHAC). Censo de Redes de Calor y frío. 2017. https://www.adhac.es/portalsSrvcs/publicaciones/archivos/10_Presentacion-Censo-de-Redes-2017.pdf. [Accessed 11 May 2021]. accessed.
[49] Shafiei M, Kabir MM, Zilouei H, Sárvári Horváth I, Karimi K. Techno-economical study of biogas production improved by steam explosion pretreatment. Bioresour Technol 2013;148:53–60. https://doi.org/10.1016/j.biortech.2013.08.111.
[50] Muzio J, Hilbert J. Análisis de Emisiones de la Producción de Biodiesel a partir de Soja en Argentina. INTA; 2008. p. 1–3 [Online]. Available: https://inta.gob.ar/sites/default/files/script-tmp-bc-inf-05-08_analisis_emisiones_produccion_biodiesel.pdf.
[51] Dirección General de Tráfico. Anuario estadístico general. 2017. Accessed: May 11, 2021. [Online]. Available: https://www.dgt.es/export/sites/web-DGT/.galleries/downloads/dgt-en-cifras/publicaciones/Anuario_Estadistico_General/Anuario-estadistico-general-2017.pdf.
[52] Awuah-Offei K. Energy efficiency in mining: a review with emphasis on the role of operators in loading and hauling operations. J Clean Prod 2016;117:89–97. https://doi.org/10.1016/j.jclepro.2016.01.035.
[53] Olmedo Torre N, Farrerons Vidal O, Prieto Urbano A. Análisis comparativo de la eficiencia energética en calderas para viviendas. 2015. p. 24 [Online]. Available: http://upcommons.upc.edu/bitstream/handle/2117/79552/An%E1lisis+comparativo+de+la+eficiencia+energ%E9tica+en+calderas+para+viviendas.pdf;jsessionid=043233DA6824C7A7B5800D87203FF1BC?sequence=1.
[54] ASIT. Informe Mercado 2017 Energía Solar Térmica en España. 2017 [Online]. Available: https://www.solarthermalworld.org/sites/default/files/news/file/2018-03-06/asit_informe_mercado_st_2017.pdf.
[55] Castilla Gallego E. Modelo de pérdidas eléctricas en el transporte y la distribución del Sistema Eléctrico Español. (Trabajo Fin de Grado Inédito). Universidad de Sevilla; 2019.
[56] Simpson AP, Lutz AE. Exergy analysis of hydrogen production via steam methane reforming. Int J Hydrogen Energy 2007;32(18):4811–20. https://doi.org/10.1016/j.ijhydene.2007.08.025.
[57] de Pee A, Pinner D, Roelofsen O, Somers K, Speelman E, Witteveen M. Decarbonization of industrial sectors: the next frontier. McKinsey & Company; 2018 [Online]. Available: https://www.mckinsey.com/~/media/mckinsey/business functions/sustainability/our insights/how industry can move toward a low carbon future/decarbonization-of-industrial-sectors-the-next-frontier.pdf.
[58] Oficial del Estado Boletín. Real Decreto-ley 23/2020, de 23 de junio, por el que se aprueban medidas en materia de energía y en otros ámbitos para la reactivación económica. BOE-A-2020-6621; 2020. Accessed: May 11, 2021. [Online]. Available: https://www.boe.es/eli/es/rdl/2020/06/23/23.
[59] Martin-Gorriz B, Soto-García M, Martínez-Alvarez V. Energy and greenhouse-gas emissions in irrigated agriculture of SE (southeast) Spain. Effects of alternative water supply scenarios. Energy 2014;77:478–88. https://doi.org/10.1016/j.energy.2014.09.031.
[60] IRENA Renewable Cost Database. Renewable power generation costs in 2020. Int. Renew. Energy Agency; 2020. p. 160 [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_2018.pdf.
[61] Castro-Santos L, Lamas-Galdo MI, Filgueira-Vizoso A. Managing the oceans: site selection of a floating offshore wind farm based on GIS spatial analysis. Mar Pol 2020;113:103803. https://doi.org/10.1016/j.marpol.2019.103803. May 2019.
[62] Díaz-Cuevas P, Domínguez-Bravo J, Prieto-Campos A. Integrating MCDM and GIS for renewable energy spatial models: assessing the individual and combined potential for wind, solar and biomass energy in Southern Spain. Clean Technol Environ Policy 2019;21(9):1855–69. https://doi.org/10.1007/s10098-019-01754-5.
[63] Ryberg DS, Robinius M, Stolten D. Evaluating land eligibility constraints of renewable energy sources in Europe. Energies 2018;11(5):1–19. https://doi.org/10.3390/en11051246.
[64] Hou Q, Zhang N, Du E, Miao M, Peng F, Kang C. Probabilistic duck curve in high PV penetration power system: concept, modeling, and empirical analysis in China. Appl Energy 2019;242:205–15. https://doi.org/10.1016/j.apenergy.2019.03.067. November 2018.
[65] Huang J, Purvins A. Validation of a Europe-wide electricity system model for techno-economic analysis. Int J Electr Power Energy Syst 2020;123(May):106292. https://doi.org/10.1016/j.ijepes.2020.106292.
[66] Malinauskaite J, Jouhara H, Egilegor B, Al-Mansour F, Ahmad L, Pusnik M. Energy efficiency in the industrial sector in the EU, Slovenia, and Spain. Energy 2020;208: 118398. https://doi.org/10.1016/j.energy.2020.118398.
[67] Tahir MF, Haoyong C, Khan A, Javed MS, Laraik NA, Mehmood K. Optimizing size of variable renewable energy sources by incorporating energy storage and demand response. IEEE Access 2019;7:103115–26. https://doi.org/10.1109/ACCESS.2019.2929297.
[68] Pfeifer A, Krajačić G, Ljubas D, Duić N. Increasing the integration of solar photovoltaics in energy mix on the road to low emissions energy system – economic and environmental implications. Renew Energy 2019;143:1310–7. https://doi.org/10.1016/j.renene.2019.05.080.
[69] Komušanac I, Ćosić B, Duić N. Impact of high penetration of wind and solar PV generation on the country power system load: the case study of Croatia. Appl Energy 2016;184:1470–82. https://doi.org/10.1016/j.apenergy.2016.06.099.
[70] Kargbo H, Harris JS, Phan AN. 'Drop-in' fuel production from biomass: critical review on techno-economic feasibility and sustainability. Renew Sustain Energy Rev 2021;135:110168. https://doi.org/10.1016/j.rser.2020.110168. , no. December 2019.
[71] Koytsoumpa EI, Magiri – Skouloudi D, Karellas S, Kakaras E. Bioenergy with carbon capture and utilization: a review on the potential deployment towards a European circular bioeconomy. Renew Sustain Energy Rev 2021;152(August):111641. https://doi.org/10.1016/j.rser.2021.111641.
[72] Ji M, Wang J. Review and comparison of various hydrogen production methods based on costs and life cycle impact assessment indicators. Int J Hydrogen Energy 2021;46(78):38612–35. https://doi.org/10.1016/j.ijhydene.2021.09.142.
[73] Keyßer LT, Lenzen M. 1.5 °C degrowth scenarios suggest the need for new mitigation pathways. Nat Commun 2021;12(1):1–16. https://doi.org/10.1038/s41467-021-22884-9.

[74] García-Gusano D, Suárez-Botero J, Dufour J. Long-term modelling and assessment of the energy-economy decoupling in Spain. Energy 2018;151:455–66. https://doi.org/10.1016/j.energy.2018.03.102.
[75] European Commission. Critical materials for strategic technologies and sectors in the EU - a foresight study. 2020. https://doi.org/10.2873/58081.
[76] Welsby D, Price J, Pye S, Ekins P. Unextractable fossil fuels in a 1.5 °C world. Nature 2021;597(7875):230–4. https://doi.org/10.1038/s41586-021-03821-8.
[77] Berna-Escriche C, Vargas-Salgado C, Alfonso-Solar D, Escrivá-Castells A. Can a fully renewable system with storage cost-effectively cover the total demand of a big scale standalone grid? Analysis of three scenarios applied to the Grand Canary Island, Spain by 2040. J Energy Storage 2022;52. https://doi.org/10.1016/j.est.2022.104774. February.
[78] Darmani A. Europe's grid-scale energy storage capacity will expand 20-fold by 2031," *11 April*. Wood Mackenzie; 2022.
[79] IEA. The role of critical minerals in clean energy transitions. 2021. https://doi.org/10.1787/f262b91c-en.
[80] CNMC. Memoria justificativa de la propuesta de resolución de la Comisión Nacional de los Mercados y la Competencia por la que se establecen los valores de los peajes de acceso a las redes de transporte y distribución de electricidad para el año 2022. 2022 [Online]. Available: https://www.cnmc.es/sites/default/files/editor_contenidos/Energia/Consulta Publica/02_RAP_DE_013_21 Memoria de la Resolucion de peajes.pdf.
[81] Albiac J, Kahil T, Notivol E, Calvo E. Agriculture and climate change: potential for mitigation in Spain. Sci Total Environ 2017;592:495–502. https://doi.org/10.1016/j.scitotenv.2017.03.110.
[82] Dixon J, Bell K. Electric vehicles: battery capacity, charger power, access to charging and the impacts on distribution networks. eTransportation 2020;4:100059. https://doi.org/10.1016/j.etran.2020.100059.
[83] WhatCar. Catalogue of cars - seat leon. https://www.whatcar.com/make/seat/leon/hatchback/deals. [Accessed 18 May 2021]. accessed.
[84] US Department of Energy. Catalogue of cars - chevrolet cruze. 2018. https://www.fueleconomy.gov/feg/Find.do?action=sbs&id=39328. [Accessed 18 May 2021]. accessed.
[85] Motorway. Catalogue of LPG cars. https://motorway.co.uk/guides/lpg-cars. [Accessed 18 May 2021]. accessed.
[86] CarAndDriver. Catalogue of electric cars - hyundai ioniq EV. 2020. https://www.caranddriver.com/news/a29740868/2020-hyundai-ioniq-range-mpge/. [Accessed 18 May 2021]. accessed.
[87] Doluweera G. Using system levelized cost, levelized avoided cost and value-adjusted levelized cost to evaluate electricity generation technologies. Can. Energy Res. Inst.; 2020. p. 1–6. no. April.