Data Article

Data for the modelling of the future power system with a high share of variable renewable energy

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**Abstract**

Energy and power system models have become necessary tools that provide challenges and technical and economic solutions for integrating high shares of Variable Renewable Energy. Models are focused on analysing strategies of power systems to achieve their decarbonisation targets. The data presented in this paper includes the model algorithm, inputs, equations, modelling assumptions, supplementary materials, and results of the simulations supporting the research article titled “Facing the high share of variable renewable energy in the power system: flexibility and stability requirements”. The analysis is based on data from the system operator of one of the European Union member states (Spain). The developed models have been validated against real-world data from the European Union’s Ten Year Network Development Plan (2022-2031).

**Keywords:** Renewable energies, Spain, Power system model, Power generation, Inertia

**Abbreviations:** CC, Combined-cycle power plants; CIL, Critical Inertia Level; CR, Cogeneration and non-renewable waste; DG, Distributed Generation; ENTSO-E, European Network of Transmission System Operators for Electricity; ENTSO-G, European Network of Transmission System Operators for Gas; ERCOT, Electric Reliability Council of Texas; EU, European Union; GCA, Global Climate Action; LCOE, Levelized Cost of Electricity; LIR, Rotational Inertia Lost in a Contingency; PHS, Pumped Hydro Storage; PV, Photovoltaic; REE, Spanish Electricity System Operator (Red eléctrica de España); ROCOF, Rate of Change of Frequency; ST, Sustainable Transition; TR, Renewable thermal and other renewables; TS, Solar thermal; TSI, Total System Inertia; TYNDP, Ten Year Network Development Plan; VBA, Visual Basic for Applications; VRE, Variable Renewable Energy.

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model allows making projections and calculations to obtain the power generation of each technology, the international interconnections, inertia, emissions, system costs and flexibility requirements of new technologies. These data can be used for energy policy development or decision making on power capacity and the balancing needs of the future power system.

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Specifications Table

| Subject | Renewable Energy, Sustainability, and the Environment |
|---------|------------------------------------------------------|
| Specific subject area | Power system modelling |
| Type of data | Table |
| | Raw data |
| | Equation |
| | Figure |
| | Chart |
| How the data were acquired | Historical and literature data were used for model parameters, and equations were developed from the latter and modelling rules. Modelled data were obtained by applying model parameter values, installed capacities of power system technologies and interconnections to the equations |
| Data format | Raw |
| | Analysed |
| | Filtered |
| Description of data collection | Data collection was based on the input data and parameters needed to design a power system model that allows obtaining power generation based on flexibility and stability restrictions to make future scenarios. |

1. Historical data were obtained from the transmission system operator (TSO) of the Spanish Power System “Red Eléctrica de España” (REE).
2. For the modelling, literature data were used as well as installed capacities provided by the Ten-Year Network Development Plan (TYNDP) of the European Network of Transmission System Operators for Electricity (ENTSO-E).
3. Visual Basic for Applications (VBA) was used for the development of the rule-based power system model. The data obtained are for different scenarios: 2017, Sustainable Transition (ST)-2030, ST-2040, Distributed Generation (DG)-2030, DG-2040, and Global Climate Action (GCA-2040).

Data source location
Country: Spain
Primary dataset: “Red Eléctrica de España”, table “Generation mix (MW)” from 01 January 2017 to 31 December 2017.
Link: https://demanda.ree.es/visiona/peninsula/demanda/tablas/2017-01-01/2

Data accessibility
Repository name: HARVARD Dataverse
Data identification number: 10.7910/DVN/R2IVYN
Direct link to the dataset: https://doi.org/10.7910/DVN/R2IVYN [A1]

Related research article
K. Guerra, P. Haro, R. E. Gutiérrez, A. Gómez-Barea, Facing the high share of variable renewable energy in the power system: flexibility and stability requirements, Appl. Energy. 310 (2022) 118561
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Value of the Data

• These data are useful for the modelling of future power systems. These data include inputs, equations and parameters that can be used to design and represent the behaviour of the electricity system. The data also provide insights into the possibility of achieving the decarbonisation targets considered by national and international organisations.
• These data are useful for representing the challenges of integrating high shares of variable renewable energy (VRE; wind and solar) in the power system as they enrich and expand flexibility and stability parameters that have not been addressed in previous studies.
• These data include flexibility parameters of generation technologies and grid stability (inertia) that limit the generation of renewable energies. Therefore, the use and modelling from these parameters would allow obtaining the curtailment of VRE and the requirement of synchronous technologies (e.g., combined cycle).
• Researchers, stakeholders and policy-makers can use the model algorithm to explore future scenarios of other power systems with different VRE shares, interconnections, and power generation mix. Therefore, this manuscript provides the research community with modelling characteristics to obtain power generation, emissions, costs, inertia, curtailment, and synchronous generation requirements at an hourly resolution.
• The model reflects the need to ensure a stable and reliable supply rather than optimising power generation. Therefore, the results of the modelling could also be used by the research community to compare with other simulation and optimisation studies (Spain is used as a case study).
• Further studies could use these data to analyse power technologies that might support the increasing penetration of VRE, provide inertia to the grid to ensure stability and achieve the decarbonisation targets. For example, these data might be used to assess the role of energy storage systems that could help to reduce curtailment and increase flexibility in the power system.

1. Data Description

The research paper linked to this data models the integration of high shares VRE into the power system considering flexibility and stability constraints. The model is called Future Renewable Energy Performance into the Power System (FEPPS), and the parameters and variables used to analyse future scenarios are provided in Table 1. The extended flowchart of the model can be seen in Appendix 1, and the selected European Union (EU) member state to carry out the simulations was Spain.

Fig. 1. shows the flowchart of the model with its main characteristics.

1.1. Methodology data

1.1.1. Demand, VRE, solar thermal, and hydro

The historical demand function was calculated according to the hourly demand data and the minimum demand of the year. Later, it allows calculating the projected demand. The final demand is obtained by discounting the interconnections. For VRE, solar thermal, and hydro the historical function is obtained from the historical installed capacity and power output. From that function and a new installed capacity, the available power is calculated. The equations that allow obtaining the variables are shown in Table 2.
Table 1
Parameters and variables used in the model.

| Symbol | Unit | Parameter |
|--------|------|-----------|
| D      | MW   | Historical power demand |
| D_{mn} | MW   | Minimum historical demand |
| C_w    | MW   | Installed wind capacity (historical) |
| C_pv   | MW   | Installed photovoltaic capacity (historical) |
| C_ts   | MW   | Installed solar thermal capacity (historical) |
| P_{st} | MW   | Nominal power of a solar thermal power plant |
| C_hy   | MW   | Installed hydropower capacity (historical) |
| C_phs  | MW   | Installed PHS capacity (historical) |
| E_{phy} | %  | Pumping efficiency |
| E_{bhy} | %  | PHS discharge efficiency |
| P_{hyd} | MW   | Nominal power of a hydropower plant |
| P_{w}  | MW   | Wind power output (historical) |
| P_{pv} | MW   | Photovoltaic power output (historical) |
| P_{ts} | MW   | Solar thermal power output (historical) |
| P_{hy} | MW   | Hydropower output (historical) |
| I_{fs} | MW   | Historical import capacity of the interconnection with France |
| I_{fe} | MW   | Historical export capacity of the interconnection with France |
| I_{p}  | MW   | Historical export and import capacities of the interconnection with Portugal |
| I_{mi} | MW   | Historical import capacity of the interconnection with Morocco |
| I_{me} | MW   | Historical export capacity of the interconnection with Morocco |
| I_{be} | MW   | Historical interconnection capacity with the Balearic Islands (and between them) |
| P_{I_f} | MW   | Historical imported power - Interconnection with France |
| P_{I_P} | MW   | Historical imported power - Interconnection with Portugal |
| P_{I_A} | MW   | Historical imported power - Interconnection with Andorra |
| P_{I_M} | MW   | Historical imported power - Interconnection with Morocco |
| N_{I_f} | MW   | Historical exported power - Interconnection with France |
| N_{I_P} | MW   | Historical exported power - Interconnection with Portugal |
| N_{I_A} | MW   | Historical exported power - Interconnection with Andorra |
| N_{I_M} | MW   | Historical exported power - Interconnection with Morocco |
| E_{B}  | MW   | Historical exported power - Interconnection with the Balearic Islands |
| i_b    | %    | Historical contribution of the Peninsula to the Balearic Islands in covering demand |
| I_{pm} | MW   | Limit of the Peninsula power output with Mallorca |
| C_{cr} | MW   | Installed Cogeneration and non-renewable waste (CR) capacity (historical) |
| P_{cr} | MW   | Nominal power of a CR power plant |
| P_{Dh} | MW   | Maximum CR power output (historical) |
| P_{Nh} | MW   | Minimum CR power output (historical) |
| R_{Dh} | %/C_T per hour | Maximum CR ramp-down rate (historical) |
| R_{Uh} | %/C_T per hour | Maximum CR ramp-up rate (historical) |
| C_{tr} | MW   | Installed renewable thermal and other renewables (TR) capacity (historical) |
| P_{tr} | MW   | Nominal power of a TR power plant |
| P_{Dh} | MW   | Maximum TR power output (historical) |
| P_{Nh} | MW   | Minimum TR power output (historical) |
| R_{Dh} | %/C_T per hour | Maximum TR ramp-down rate (historical) |
| R_{Uh} | %/C_T per hour | Maximum TR ramp-up rate (historical) |
| C_{n}  | MW   | Installed nuclear capacity (historical) |
| n_{h}  | Integer | Historical number of nuclear power plants in a year |
| P_{th} | MW   | Nominal power of a nuclear power plant |
| P_{m}  | MW   | Minimum theoretical load of a nuclear power plant |
| R_{th} | %/P_T per hour | Theoretical ramp rate of a nuclear power plant |
| P_{Mh} | MW   | Maximum nuclear power output (historical) |
| P_{m}  | %/C_T or MW   | Minimum nuclear power output (historical) |
| R_{Dh} | %/C_T or MW per hour | Maximum nuclear ramp-down rate (historical) |
| R_{Uh} | %/C_T or MW per hour | Maximum nuclear ramp-up rate (historical) |
| C_{c}  | MW   | Installed coal capacity (historical) |

(continued on next page)
Table 1 (continued)

| Symbol | Unit | Variable |
|--------|------|----------|
| \( c_h \) | Integer | Historical number of coal power plants in a year |
| \( P_e \) | MW | Nominal power of a coal power plant |
| \( P_{m_{it}} \) | % | Minimum theoretical load of a coal power plant |
| \( R_{ct} \) | % per hour | Theoretical ramp rate of a coal power plant |
| \( PM_{lh} \) | MW | Maximum coal power output (historical) |
| \( PM_{lh} \) | % of MW | Minimum coal power output (historical) |
| \( RD_{lh} \) | % or MW per hour | Maximum coal ramp-down rate (historical) |
| \( RL_{lh} \) | % or MW per hour | Maximum coal ramp-up rate (historical) |
| \( C_{cc} \) | MW | Installed combined-cycle (CC) capacity (historical flexible and inflexible) |
| \( c_{cc} \) | Integer | Historical number of CC power plants in a year |
| \( P_{m_{it}} \) | % of CC | Theoretical minimum load of a CC power plant |
| \( R_{cc} \) | % of CC per hour | Theoretical ramp rate of a CC power plant |
| \( PM_{lh} \) | CC | Maximum CC power output (historical) |
| \( PM_{lh} \) | % of CC or MW | Minimum CC power output (historical) |
| \( RD_{cc} \) | % of CC or MW per hour | Maximum CC ramp-down rate (historical) |
| \( RL_{cc} \) | % of CC or MW per hour | Maximum CC ramp-up rate (historical) |
| \( n_{1w} \) | % | First level of wind curtailment |
| \( n_{2w} \) | % | Second level of wind curtailment |
| \( n_{3w} \) | % | Third level of wind curtailment |
| \( n_{1p} \) | % | First level of photovoltaic curtailment |
| \( n_{2p} \) | % | Second level of photovoltaic curtailment |
| \( n_{3p} \) | % | Third level of photovoltaic curtailment |
| \( n_{2h} \) | % | Hydropower reduction level |
| \( n_{2s} \) | % | Curtailment level of solar thermal |
| \( n_i \) | s | Average rotational inertia constant for nuclear |
| \( c_i \) | s | Average rotational inertia constant for coal |
| \( c_{cc} \) | s | Average rotational inertia constant for combined-cycle |
| \( h_{tr} \) | s | Average rotational inertia constant for hydropower and PHS |
| \( c_{tr} \) | s | Average rotational inertia constant for CR |
| \( tr_{t} \) | s | Average rotational inertia constant for TR |
| \( tso_{t} \) | s | Average rotational inertia constant for solar thermal |
| \( if_{i} \) | s | Average rotational inertia constant for PNI |
| \( i_{p} \) | s | Average rotational inertia constant for PNI |
| \( im_{i} \) | s | Average rotational inertia constant for PNI |
| \( f_{eh} \) | - | Emission factor for hot-start of flexible CC |
| \( f_{ct} \) | - | Emission factor for constant-operation of flexible CC |
| \( tss \) | min | Fraction of start-up time where power is not yet fed into the grid (\( t_0 \rightarrow t_f \)) |
| \( ttm \) | min | Minutes in an hour (60) |

Symbol | Unit | Variable |
|--------|------|----------|
| \( ND_{et} \) | MW | New minimum demand |
| \( PD \) | MW | Projected initial demand |
| \( f_{h} \) | - | Historical demand function |
| \( PD_{f} \) | MW | Projected final demand |
| \( D_{e} \) | MW | Initial net load |
| \( Comp \) | MW | Load to adjust to match demand |
| \( f_{w} \) | - | Wind projection function |
| \( f_{pr} \) | - | Photovoltaic projection function |
| \( f_{ts} \) | - | Solar thermal projection function |
| \( f_{hy} \) | - | Hydropower projection function |
| \( NC_{w} \) | MW | New installed wind capacity |
| \( NC_{p} \) | MW | New installed photovoltaic capacity |
| \( NC_{s} \) | MW | New installed solar thermal capacity |
| \( NC_{hy} \) | MW | New installed hydropower capacity |
| \( NP_{w} \) | MW | Wind power available |
| \( NP_{p} \) | MW | Photovoltaic power available |
| \( NP_{s} \) | MW | Solar thermal power available |
| \( NP_{hy} \) | MW | Hydropower available |
| \( NP_{hy} \) | MW | Annual average of \( NP_{hy} \) |

(continued on next page)
Table 1 (continued)

| Symbol | Type      | Description                                                                 |
|--------|-----------|-----------------------------------------------------------------------------|
| $NP_W$ | MW        | Wind power output (final)                                                  |
| $NP_{PV}$ | MW    | Photovoltaic power output (final)                                          |
| $NP_{ST}$ | MW    | Solar thermal power output (final)                                         |
| $NP_{H}$ | MW     | Hydropower output (final)                                                  |
| $t_{32}$ | Integer | Number of solar thermal power plants for each hour                         |
| $NIC_{ji}$ | MW | New import interconnection capacity with France                             |
| $NIC_{je}$ | MW | New export interconnection capacity with France                            |
| $NIC_{pi}$ | MW   | New import interconnection capacity with Portugal                          |
| $NIC_{pe}$ | MW  | New export interconnection capacity with Portugal                          |
| $NIC_{sm}$ | MW  | New import interconnection capacity with Morocco                           |
| $NIC_{se}$ | MW  | New export interconnection capacity with Morocco                           |
| $NIC_{ci}$ | MW  | New interconnection capacity with the Balearic Islands (and between them) |
| $NI_{B}$ | %      | New contribution of the Peninsula to the Balearic Islands in covering demand |
| $NPI_{if}$ | MW   | New import power - interconnection with France                             |
| $NNI_{if}$ | MW   | New export power - interconnection with France                             |
| $NPI_{pj}$ | MW   | New import power - interconnection with Portugal                            |
| $NNI_{pj}$ | MW   | New export power - interconnection with Portugal                            |
| $NPI_{ln}$ | MW | New import power - interconnection with Morocco                            |
| $NNI_{ln}$ | MW | New export power - interconnection with Morocco                            |
| $NEB$ | MW    | New export power - interconnection with the Balearic Islands               |
| $PIB$ | MW    | Import balance of international interconnections                           |
| $NIB$ | MW    | Export balance of international interconnections                            |
| $NC_{cr}$ | MW | New installed CR capacity                                                  |
| $P_{mi_{cr}}$ | MW | Minimum CR power output                                                    |
| $RD_{cr}$ | MW per hour | CR ramp-down rate limit                                                  |
| $RU_{cr}$ | MW per hour | CR ramp-up rate limit                                                    |
| $NP_{r}$ | MW | CR power output (final)                                                   |
| $cr_{f}$ | Integer | Number of CR power plants for each hour                                   |
| $PM_{cr}$ | MW | Maximum CR power output                                                   |
| $NC_{tr}$ | MW | New installed TR capacity                                                 |
| $P_{mi_{tr}}$ | MW | Minimum TR power output                                                  |
| $RD_{tr}$ | MW per hour | TR ramp-down rate limit                                                   |
| $RU_{tr}$ | MW per hour | TR ramp-up rate limit                                                    |
| $NP_{r}$ | MW | TR power output (final)                                                   |
| $tr_{f}$ | Integer | Number of TR power plants for each hour                                   |
| $PM_{tr}$ | MW | Maximum TR power output                                                  |
| $n$ | Integer | Number of nuclear power plants assumed for a future year                   |
| $NC_{n}$ | MW | New installed nuclear capacity                                             |
| $PM_{n}$ | MW | Maximum nuclear power                                                     |
| $RD_{n}$ | % of $NC_{n}$ or MW per hour | Nuclear ramp-down rate limit                                |
| $RU_{n}$ | % of $NC_{n}$ or MW per hour | Nuclear ramp-up rate limit                                      |
| $P_{mi_{n}}$ | % of $NC_{n}$ or MW | Minimum nuclear power                                                   |
| $nu_{2}$ | Integer | Final number of nuclear power plants for each hour                         |
| $NP_{nu}$ | MW | Nuclear power output (final)                                              |
| $nu$ | Integer | Initial number of nuclear power plants for each hour                       |
| $nu_{0}$ | Integer | Code variables that allow obtaining $nu_{2}$                              |
| $co_{2}$ | Integer | Number of coal power plants assumed for a future year                      |
| $NC_{c}$ | MW    | New installed coal capacity                                               |
| $PM_{c}$ | MW | Maximum coal load                                                        |
| $RD_{c}$ | % of $NC_{c}$ or MW per hour | Coal ramp-down rate limit                                |
| $RU_{c}$ | % of $NC_{c}$ or MW per hour | Coal ramp-up rate limit                                      |
| $P_{mi_{c}}$ | % of $NC_{c}$ or MW | Minimum coal load                                                       |
| $co_{0}$ | Integer | Final number of coal power plants for each hour                            |
| $NP_{co}$ | MW | Coal power output (final)                                                 |
| $co_{0}$ | Integer | Initial number of coal power plants for each hour                         |
| $co_{0}$ | Integer | Code variables that allow obtaining $co_{2}$                              |

(continued on next page)
Table 1 (continued)

| Symbol | Definition |
|--------|------------|
| NC<sub>ph</sub> | New installed PHS capacity |
| L<sub>ph</sub> | PHS installed capacity limit |
| L<sub>by</sub> | PHS availability limit |
| Compst | Load available for storage |
| F<sub>ph</sub> | Pumping factor |
| Comp<sub>P1</sub> | Excess load pending reduction (does not meet the condition L<sub>by</sub>) |
| Comp<sub>P2</sub> | Unsupplied power demand (before PHS) |
| St<sub>y</sub> | Cumulative storage load (unlimited) |
| St<sub>1</sub> | Storage load up to its limit |
| St<sub>2</sub>, St<sub>22</sub> | Code variables that allow obtaining St<sub>y2</sub> |
| St<sub>23</sub>, St<sub>24</sub> | |
| St<sub>25</sub> | Load that remains in storage after charges and discharges |
| Comp<sub>P1r</sub> | Unsupplied power demand (after PHS) |
| Comp<sub>P2r</sub> | Excess load pending reduction (could not be stored) |
| F<sub>r</sub> | Final load in storage |
| P<sub>r</sub> | Variable that allows obtaining the PHS power output |
| P<sub>ph</sub> | PHS power output (final) |
| Comp<sub>pb</sub> | Total load to adjust after PHS |
| hy<sub>x</sub> | Final number of PHS power plants for each hour |
| NC<sub>c0</sub> | New installed inflexible CC capacity |
| RD<sub>c0</sub> | Inflexible CC ramp-down rate limit |
| RU<sub>c0</sub> | Inflexible CC ramp-up rate limit |
| Pmi<sub>c0</sub> | Minimum inflexible CC power output |
| NC<sub>c1</sub> | New installed flexible CC capacity |
| NP<sub>c0</sub> | Inflexible CC power output |
| NP<sub>c</sub> | Variable that allows obtaining NP<sub>c1</sub> |
| NP<sub>c1</sub> | Flexible CC power output |
| NP<sub>c2</sub> | Flexible CC power output (after inertia constraints) |
| cc<sub>2</sub> | Final number of CC (flexible + inflexible) power plants for each hour |
| NP<sub>c2</sub> | CC power output (flexible + inflexible) |
| NC<sub>cC</sub> | New installed CC capacity (flexible + inflexible) |
| c<sub>n</sub> | Average rotational inertia contribution for nuclear |
| c<sub>c</sub> | Average rotational inertia contribution for coal |
| c<sub>cC</sub> | Average rotational inertia contribution for combined-cycle |
| c<sub>by</sub> | Average rotational inertia contribution for hydropower and PHS |
| c<sub>CR</sub> | Average rotational inertia contribution for CR |
| c<sub>TR</sub> | Average rotational inertia contribution for TR |
| c<sub>TS</sub> | Average rotational inertia contribution for TS |
| c<sub>EF</sub> | Average rotational inertia contribution for NPI<sub>F</sub> |
| c<sub>I</sub> | Average rotational inertia contribution for NPI<sub>I</sub> |
| c<sub>I</sub> | Average rotational inertia contribution for NPI<sub>In</sub> |
| TSI | Total system inertia |
| ΔP | Power lost in the largest system contingency |
| NF | Nominal system frequency |
| ROCOF | Rate of change of frequency |
| LIR | Rotational inertia lost in ΔP contingency |
| CIL | Critical inertia level |
| V<sub>f</sub> | Inertia variation |
| Eo | Start emissions (flexible CC) |
| So | Emissions of the fraction of start-up time where power is not yet fed into the grid (t<sub>0</sub>→t<sub>1</sub>) for the 2nd criteria |
| Sto | Stop emissions of (flexible CC) |
| 1st Criteria | Start and stop emissions |
| Pi | Production of each power plant when the power output increases |
| Et | Emission in constant operation (flexible CC) |
| Eh | Emission when the power output increases |
| Es | Emissions of the fraction of start-up time where power is not yet fed into the grid (t<sub>0</sub>→t<sub>1</sub>) for the 2nd criteria |

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Table 1 (continued)

| Criteria       | (tCO₂ eq/h) | Description                                                                 |
|----------------|-------------|------------------------------------------------------------------------------|
| 2nd Criteria   |             | Increase in power output, constant operation and start emissions             |
| Pd             | MW          | Production of each power plant when the power output decreases or when the   |
|                |             | number of plants is constant in the previous or next hour.                  |
| Ec             |             | Emissions in constant operation for the 3rd criteria                        |
| Ep             |             | Stop emissions for values that increased previously for the 3rd criteria    |
| El             |             | Stop emissions for values that decreased previously for the 3rd criteria    |
| 3rd Criteria   |             | Decrease in power output, constant operation and stop emissions              |
| 4th Criteria   |             | Constant operation emissions not previously contemplated                     |
| Ei             |             | Emissions for values that have decreased and increase in the next hour        |
| Eg             |             | Stop emissions for values that increased previously for the 5th criteria     |
| Ef             |             | Stop emissions for values that decreased previously for the 5th criteria     |
| Ep             |             | Emissions from each plant to calculate Ev                                   |
| Ev             |             | Stop emissions for values that have previously started                       |
| 5th Criteria   |             | Decrease in power output and stop emissions not previously contemplated      |
| 6th Criteria   |             | Constant operation emissions when the next value increases                   |

**Code counters**

| j, l, b, k, a | - | Hour counter (j). Counters every 24 hours (l, b). Day counters in the year (k, a) |
| Hours        | h | Number of hours in the year minus one                                         |
| Hoursc       | h | Number of hours in the year                                                  |

Fig. 1. Flowchart of the model. The extended flowchart of the model can be seen in Appendix 1. Modified from [1]
Table 2
Demand, VRE, solar thermal and hydro variables.

| Variables | Eq. | No |
|-----------|-----|----|
| Historical demand function | $f_h = \frac{P}{PD}$ | (1) |
| Projected initial demand (MW) | $PD = f_{ih} \cdot N_{Dih}$ | (2) |
| Projected final demand (MW) | $PD_1 = PD - PIB - NIB - NEB$ | (3) |
| Initial net load (MW) | $D_h = PD_1 - (NP_{hv} + NP_{hv} + NP_{h} + NP_{h} + NP_{h})$ | (4) |
| Wind projection function | $f_w = \frac{f_{ih} \cdot C}{P_{w}}$ | (5) |
| Solar PV projection function | $f_{pv} = \frac{f_{ph} \cdot N_{pv}}{N_{pv}}$ | (6) |
| Solar thermal projection function | $f_{ts} = \frac{f_{ph} \cdot N_{ts}}{N_{ps}}$ | (7) |
| Wind power available (MW) | $NP_{w} = f_{ph} \cdot N_{w}$ | (8) |
| Solar PV power available (MW) | $NP_{pv} = f_{ph} \cdot N_{pv}$ | (9) |
| Solar thermal power available (MW) | $NP_{ts} = f_{ph} \cdot N_{ts}$ | (10) |
| Number of TS power plants for each hour | $t_{s} = \frac{NP_{ps}}{t_{ph}}$ | (11) |
| Hydropower available (MW)$^a$ | $NP_{hy} = f_{ph} \cdot (1 - F_{ph})$ | (12) |
| Pumping factor$^a$ | $F_{ph} = \frac{0.047 \cdot N_{ph}}{C_{ph}}$ | (13) |
| Hydropower projection function | $f_{hy} = \frac{NP_{hy}}{C_{ph}}$ | (14) |
| Hydropower available (MW)$^b$ | $NP_{hy} = f_{ph} \cdot N_{hy}$ | (15) |

$^a$ Consumption by pumping represented 4.7% of the total annual hydropower generation in 2017. This percentage is assumed as the share of the PHS, which is modelled separately. Therefore, to obtain the available hydro (before making any projection), the new pumping factor (which depends on the installed capacity) is discounted from the historical power output.

$^b$ The same variable is used as it is recalculated according to the projection function.

Table 3
Balance of historical international interconnection exchanges in Spain (2017) [2].

| Interconnection | Import (GWh) | % | Export (GWh) | % |
|-----------------|--------------|---|--------------|---|
| France          | 15561        | 65.6 | 3094        | 21.2 |
| Portugal        | 8190         | 34.5 | 5505        | 37.7 |
| Andorra         | 0            | 0   | 233         | 1.6 |
| Morocco         | 8            | 0.03| 5756        | 39.5 |

Table 4
Import and export power of International Interconnections.

| Variable                      | Eq.                          | No |
|-------------------------------|------------------------------|----|
| New import power with France (MW) | $NP_{if} = \frac{P_{if}}{C_{ph}} \cdot N_{CI_{i}}$ | (15) |
| New export power with France (MW) | $NN_{if} = \frac{P_{if}}{C_{ph}} \cdot N_{CI_{f}}$ | (16) |
| New import power with Portugal (MW) | $NP_{ip} = \frac{P_{ip}}{C_{ph}} \cdot N_{CI_{ip}}$ | (17) |
| New export power with Portugal (MW) | $NN_{ip} = \frac{P_{ip}}{C_{ph}} \cdot N_{CI_{ip}}$ | (18) |
| New import power with Morocco (MW) | $NP_{im} = \frac{P_{im}}{C_{ph}} \cdot N_{CI_{mi}}$ | (19) |
| New export power with Morocco (MW) | $NN_{im} = \frac{P_{im}}{C_{ph}} \cdot N_{CI_{im}}$ | (20) |
| Import balance (MW) | $PIB = NP_{if} + NP_{ip} + Pla + NPI_{m}$ | (21) |
| Export balance (MW) | $NEB = NN_{if} + NN_{ip} + NLa + NNI_{m}$ | (22) |
| New export with the Balearic Islands (MW) | $NEB = \frac{609}{8}$ | (23) |

1.1.2. International interconnections

REE provides the total annual energy (GWh) for each interconnection, i.e., the historical import balance (positive values) and export balance (negative values). Therefore, a participation percentage for 2017 was obtained for each interconnection [2]). With these percentages, the power of the time series was decoupled. Table 3 shows the participation percentage of each international interconnection by 2017.

The equations to calculate the new power of imports and exports of each international interconnection and the balances are shown in Table 4.
1.1.3. Conventional power generation

Table 5 provides the equations to calculate the limits of minimum and maximum power output, ramp rates and the number of power plants of each hour of renewable thermal and other renewables (TR), cogeneration and non-renewable waste (CR). It also shows the equations to calculate the nominal power of a typical plant and the new installed capacities for coal and nuclear. With the historical installed capacity, the nominal power of a typical plant, the historical minimum power output (%) and the minimum theoretical load (%), through linear regression, we obtain the equation to find the minimum load percentage and its value in MW to apply in the model. The equation to find the maximum ramp rates for each technology (in share) is obtained through linear regressions. In this way, with the new installed capacity, the maximum ramp up and down rates in MW can be found.

For 2017, the model identifies the maximum number of power plants each day to limit the minimum coal and nuclear loads. The model establishes one limit for nuclear and three limits for coal. Therefore, the maximum number of coal power plants participating in the day is divided by three. The result and its multiples are defined as the final number of power plants, limiting the minimum loads for that day. For example, if the maximum number is 12 (initial number), dividing by three, the result is 4 and the multiples 8 and 12. Therefore, 4, 8, and 12 are the new limits. If the initial number of plants in an hour of that day is 6, the final number of plants for that hour will be 8 since it must be adjusted to the new upper limit, and the minimum load will be limited to 910 MW (see Table 6). The equations to calculate the variables of the combined-cycle are also provided.

The minimum load data for nuclear and coal to which the generation must be adjusted are shown in Table 6.

1.1.4. Pumped hydro storage (PHS)

Spain has recorded the lowest hydropower production in October 2017 since 1990 monthly records, followed by November [3]. The annual average of the hourly hydropower available (2017) was 1966 MW, and the average production for October and November (1195 MW) represents 60.8% of the annual average. Therefore, the availability limit was calculated according to Eq. (1):

\[ L_{HY} = \left( \bar{N}_{HY} \cdot 24h \cdot 0.608 \right) \]

This limit shows the value of hydropower generated in a day, below which it is assumed that pumping will not be available for the following day due to low generation. In this way, if hydropower generation does not exceed the limit, pumping will not be available for the next day. It should be noted that this limit has been set because Spain has both pure and mixed PHS, and mixed PHS depends on weather conditions.

The monthly average production of hydropower obtained from the hourly data reported in REE (once the pumping has been discounted) can be seen in Table 7.

After PHS participates, the model allows the calculation of the excess load pending reduction (Comp_{2p}), which cannot be used for pumping (because it does not meet the limit) and must be reduced by other sources. It also determines the unsupplied power demand (Comp_{1p}). Finally, the model calculates the total load to adjust Comp_{pb} (pending to cover or reduce) after this technology participates. The equations used to calculate the variables of pumped hydro storage (PHS) can be seen in Table 8.


Table 5
TR, CR, nuclear and inflexible CC variables.

| Variables | Eq. | No |
|-----------|-----|----|
| Maximum TR\(^1\) power output (MW) | \(PM_{tr} = \frac{NC_r \cdot PM_{th}}{C_{tr}}\) | (24) |
| Number of TR power plants for each hour | \(n_{tr} = \frac{PM_{tr}}{C_{tr}}\) | (25) |
| Minimum TR power output (MW) | \(PM_{l_{tr}} = \frac{NC_r \cdot PM_{th}}{C_{tr}}\) | (26) |
| TR ramp-down rate limit (MW per hour) | \(RD_{tr} = RD_{trc}(\%) \cdot NC_r\) | (27) |
| TR ramp-up rate limit (MW per hour) | \(RU_{tr} = RU_{trc}(\%) \cdot NC_r\) | (28) |
| Maximum CR power output (MW) | \(PM_{tr} = \frac{NC_r \cdot PM_{th}}{C_{tr}}\) | (29) |
| Number of CR power plants for each hour | \(n_{cr} = \frac{PM_{cr}}{C_{cr}}\) | (30) |
| Minimum CR power output (MW) | \(PM_{l_{cr}} = \frac{NC_r \cdot PM_{th}}{C_{cr}}\) | (31) |
| CR ramp-down rate limit (MW per hour) | \(RD_{cr} = RD_{crc}(\%) \cdot NC_c\) | (32) |
| CR ramp-up rate limit (MW per hour) | \(RU_{cr} = RU_{cr}(\%) \cdot NC_c\) | (33) |
| Nominal power of a nuclear power plant | \(P_n = \frac{NC_n}{n_{nu}}\) | (34) |
| New installed nuclear capacity (MW) | \(NC_a = P_n \cdot n\) | (35) |
| Maximum nuclear load (MW) | \(PM_n = \frac{NC_n \cdot PM_{th}}{C_{nu}}\) | (36) |
| Nuclear ramp-down rate limit (%\(NC_n\) per hour) | \(RD_n(\%) = (-0.0021 \cdot NC_n) + 19.145\) | (37) |
| Nuclear ramp-up rate limit (%\(NC_n\) per hour) | \(RU_n(\%) = (-0.0021 \cdot NC_n) + 19.166\) | (38) |
| Nuclear ramp-down rate limit (MW per hour) | \(RD_n = RD_{n_{trc}}(\%) \cdot NC_n\) | (39) |
| Nuclear ramp-up rate limit (MW per hour) | \(RU_n = RU_{n_{trc}}(\%) \cdot NC_n\) | (40) |
| Minimum nuclear load (%) | %\(PM_{ln}\) = \((-0.0005 \cdot NC_n) + 75.468\) | (41) |
| Minimum nuclear load (MW) | \(PM_{ln} = NC_n \cdot %PM_{ln}\) | (42) |
| Initial number of nuclear power plants for each hour | \(nu = \frac{NC_n}{n_{nu}}\) | (43) |
| Final number of nuclear power plants for each hour | \(nu2\) Redimensión | (44) |
| Nominal power of a coal power plant (MW) | \(P_c = \frac{NC_c}{n_{cc}}\) | (45) |
| New installed coal capacity (MW) | \(NC_c = P_c \cdot c\) | (46) |
| Maximum coal load (MW) | \(PM_c = \frac{NC_c \cdot PM_{th}}{C_{cc}}\) | (47) |
| Coal ramp-down rate limit (%\(NC_c\) per hour) | \(RD_c(\%) = (-0.0079 \cdot NC_c) + 92.895\) | (48) |
| Coal ramp-up rate limit (%\(NC_c\) per hour) | \(RU_c(\%) = (-0.0084 \cdot NC_c) + 93.099\) | (49) |
| Coal ramp-down rate limit (MW per hour) | \(RD_c = RD_{c_{trc}}(\%) \cdot NC_c\) | (50) |
| Coal ramp-up rate limit (MW per hour) | \(RU_c = RU_{c_{trc}}(\%) \cdot NC_c\) | (51) |
| Minimum nuclear load (%) | %\(PM_{ln}\) = \((-0.0005 \cdot NC_n) + 75.468\) | (52) |
| Minimum nuclear load (MW) | \(PM_{ln} = NC_n \cdot %PM_{ln}\) | (53) |
| Initial number of coal power plants for each hour | \(co = \frac{NC_c}{n_{cc}}\) | (54) |
| Final number of coal power plants for each hour | \(co2\) Redimensión | (55) |
| New installed inflexible CC capacity (MW) | \(NC_{c_{co}} = PM_{c_{co}} \cdot C_{c_{co}}\) | (48) |
| Nominal power of a CC power plant (MW) | \(P_{cc} = \frac{PM_{c_{co}}}{C_{c_{co}}}\) | (49) |
| Inflexible CC ramp-down rate limit (% \(\%NC_{co}\) per hour) | \(RD_{c_{co}} = (-0.0099 \cdot NC_{co} + 105.15\) | (50) |
| Inflexible CC ramp-up rate limit (% \(\%NC_{co}\) per hour) | \(RU_{c_{co}} = (-0.0099 \cdot NC_{co} + 105.17\) | (51) |
| Inflexible CC ramp-down rate limit (MW per hour) | \(RD_{c_{co}} = RD_{c_{co}}(\%) \cdot NC_{co}\) | (52) |
| Inflexible CC ramp-up rate limit (MW per hour) | \(RU_{c_{co}} = RU_{c_{co}}(\%) \cdot NC_{co}\) | (53) |
| Minimum inflexible CC power output (%) | %\(PM_{c_{co}}\) = \((-0.0016 \cdot NC_{co}) + 40.807\) | (54) |
| Minimum inflexible CC power output (MW) | \(PM_{c_{co}} = NC_{co} \cdot %PM_{c_{co}}\) | (55) |
| New installed CC capacity (flexible + inflexible) (MW) | \(NC_{cc} = NC_{cc} + NC_{c_{cc}}\) | (56) |
| Final number of CC (flexible + inflexible) power plants for each hour | \(cc2 = \frac{PM_{c_{co}} + PM_{th}}{C_{hc}}\) | (57) |
| CC power output (flexible + inflexible) (MW) | \(NP_{cc} = (NP_{c_{co}} + NP_{c_{cc}})\) | (59) |
| New installed CC capacity (flexible + inflexible) (MW) | \(NC_{cc} = NC_{cc} + NC_{c_{cc}}\) | (60) |
| Flexible CC power output (after inertia constraints) (MW) | \(NP_{cc} = NP_{c_{co}}(\text{resize}) - NP_{c_{co}}\) | (61) |

\(^a\) includes biogas, biomass, marine, and geothermal.
Table 6
Minimum nuclear load according to the number of power plants (MW).

| $n$ | $Pmi_{in}$ | $c$ | $Pmi_{inc}$ | $c$ | $Pmi_{inc}$ | $c$ | $Pmi_{inc}$ | $c$ |
|-----|------------|-----|-------------|-----|-------------|-----|-------------|-----|
| 0   | 0          | 0   | 0           | 8   | 910         | 16  | 1217        | 24  |
| 1   | 762        | 1   | 147         | 9   | 981         | 17  | 1213        | 25  |
| 2   | 1514       | 2   | 284         | 10  | 1043        | 18  | 1200        | 26  |
| 3   | 2255       | 3   | 412         | 11  | 1096        | 19  | 1777        | -   |
| 4   | 2987       | 4   | 530         | 12  | 1139        | 20  | 1145        | -   |
| 5   | 3707       | 5   | 639         | 13  | 1172        | 21  | 1103        | -   |
| 6   | 4418       | 6   | 739         | 14  | 1197        | 22  | 1052        | -   |
| 7   | 5118       | 7   | 829         | 15  | 1212        | 23  | 992         | -   |

Table 7
Average hourly data of hydropower available-2017.

| Months | $NH_{hy}(MW)$ |
|--------|---------------|
| Jan    | 2701          |
| Feb    | 2594          |
| Mar    | 3341          |
| Apr    | 2312          |
| May    | 2335          |
| Jun    | 2016          |
| Jul    | 1436          |
| Aug    | 1317          |
| Sep    | 1564          |
| Oct    | 1077          |
| Nov    | 1311          |
| Dec    | 1627          |

Table 8
PHS variables.

| Variables                                      | Eq.                                      |
|------------------------------------------------|------------------------------------------|
| New installed PHS capacity                    | $NC_{phy} = \frac{C_{hy} \cdot NC_{phs}}{\gamma_w}$ (62) |
| PHS installed capacity limit                  | $L_{phs} = NC_{phs}$ (63)                |
| Load available for storage                    | $Compst (\text{resize})$ (64)            |
| Final load in storage                         | $f_{hy} = St_{v2} \frac{(N_{hy1}+N_{phs})}{h_{nor}}$ (65) |
| Final number of PHS power plants for each hour| $hy_2 = \frac{N_{hy1}+N_{phs}}{h_{nor}}$ (66) |

Table 9
Power system mix for France and Portugal considered for future scenarios [4,5].

| Percentage (%) | Nuclear | Combined-cycle | Wind | Solar | Hydro | Cogeneration and waste | Renewable thermal | Coal |
|----------------|---------|----------------|------|-------|-------|------------------------|-------------------|------|
| France         | 51      | 8              | 19   | 7     | 12    | 0                      | 3                 | 0    |
| Portugal       | 0       | 31             | 27   | 8     | 16    | 10                     | 8                 | 48   |
| Morocco        | 0       | 0              | 20   | 20    | 12    | 0                      | 0                 | 48   |

a TYNDP does not specify the share of participation of solar photovoltaic and solar thermal separately. Therefore, it has been assumed that 20% of the total share corresponds to solar thermal for the two countries.

b It has been assumed that 4% is for solar thermal.

c Reported as thermal, assumed as coal.

1.1.5. Inertia

The contribution (%) of each technology for France and Portugal was obtained from TYNDP (see Table 9) [4]. The rotational inertia constant is obtained through a weighted average (considering the inertia constants) (see Eq. (2)).

$$\text{Average rotational inertia constant for } NPI_f = \left( \% N \cdot n_i \right) + \left( \% C \cdot c_i \right) + \left( \% CC \cdot cc_i \right) + \left( \% HY \cdot hy_i \right) + \left( \% TS \cdot ts0_i \right) + \left( \% CR \cdot cr_i \right) + \left( \% TR \cdot tr_i \right)$$ (2)

The inertia contribution of power plants is calculated using the equations presented in Table 10, which consider the final number of plants, the inertia constant by type of generator, and the power plants' nominal power.
Table 10
Average rotational inertia contribution by technology (MW·s).

| Variables       | Eq.                   | No. |
|-----------------|-----------------------|-----|
| Nuclear         | $c_{in} = n_{w} \cdot n_{i} \cdot P_{n}$ | (67) |
| Coal            | $c_{i} = c_{o2} \cdot c_{i} \cdot P_{c}$ | (68) |
| CC              | $c_{i} = c_{cc} \cdot c_{i} \cdot P_{cc}$ | (69) |
| Hydro and PHS   | $c_{i} = c_{hy} \cdot c_{i} \cdot P_{hyd}$ | (70) |
| CR              | $c_{i} = c_{cr} \cdot c_{i} \cdot P_{cr}$ | (71) |
| TR              | $c_{i} = c_{tr} \cdot c_{i} \cdot P_{tr}$ | (72) |
| TS              | $c_{i} = c_{ts} \cdot c_{i} \cdot P_{ts}$ | (73) |
| NPI_f           | $c_{i} = NPI_{f} \cdot c_{i}$ | (74) |
| NPI_P           | $c_{i} = NPI_{P} \cdot c_{i}$ | (75) |
| NPI_m           | $c_{i} = NPI_{m} \cdot c_{i}$ | (76) |

The total system inertia (TSI) was calculated according to Eq. (3) and the critical inertia level (CIL) according to Eq. (4) used in Johnson et al. [6] where $\Delta P_{MW}$ represents the power lost in the greatest contingency. In Continental Europe, being an interconnected system, the regulatory contingency or reference incident (which represents the loss of the two largest generating facilities) is 3000 MW [7].

$$TSL = c_{i} \cdot c_{i} + c_{i} \cdot c_{i} + c_{i} \cdot c_{i} + c_{i} \cdot c_{i} + c_{i} \cdot c_{i}$$

$$CIL = \frac{\Delta P}{2 \cdot ROCOF \cdot NF + (LIR)}$$

LIR refers to the rotational inertia lost in this contingency. That is equal to (MVA·H). MVA refers to the apparent power capacity representing the largest contingency, and H is the inertia constant for these plants. In ERCOT, the largest contingency is represented by two nuclear power plants. The apparent power capacity of the two nuclear power plants (2750 MW) was 460.69 MVA. Therefore, for a power capacity of 3000 MW, the apparent power capacity is assumed to be 502.57 MVA. The inertia constant of these power plants has a value of 4.07. ROCOF is the Rate of Change of Frequency and NF is the nominal frequency of the power system (50 Hz).

According to Eq. (5) and Eq. (6), the inertia variation and the increase in the combined-cycle, respectively, are calculated.

$$V_i = CIL - TSI$$

$$NPI_{cc} = (NPI_{cc0} + NPI_{cc1}) + \left(\frac{V_i}{CIL}\right)$$

1.1.6. CO₂ emissions (mode of operation of the CC)

The criteria for calculating the flexible combined-cycle CO₂ emissions according to the mode of operation are:

- 1st Criteria “Start and stop emissions”: Start of operation from 0, which includes hot start (with an emission factor of 0.59 tCO₂ / MWh) and the emissions of the fraction of start-up time where power is not yet fed into the grid ($t_0 \rightarrow t_1$). This fraction added to these hours will be proportional to $t_0$ until $t_1$, which is 12 min. Emissions from stops (up to 0) are also considered with a proportional time of 12 min.
- 2nd Criteria “Increase in power output, constant operation and start emissions”: If there is power in the previous hour, the hourly power corresponding to each plant is calculated assuming an exact division of the power output for the number of plants. Subsequently, the emission of these plants in constant operation (0.37 tCO₂/MWh) is calculated. The emission of the hot start and the fraction of start-up time are also calculated according to 1st criteria.
- 3rd Criteria “Decrease in power output, constant operation and stop emissions”: If there is power in the previous hour and the power is reduced, the power corresponding to each plant and the emission in constant operation is calculated (0.37 tCO₂ / MWh). This criterion includes the emission of stops with the proportion explained in the 1st criteria.
- 4th Criteria "Constant operation emissions not previously contemplated".
- 5th Criteria "Decrease in power output and stop emissions not previously contemplated": fourth criteria do not contemplate the hours in which the number of power plants has decreased and in the subsequent hour increase. This criteria also considers the emissions of the stops. In this case, three criteria are considered for the stops: stops when in the previous hour the number of power plants is maintained or had fallen; when in the previous hour the number of power plants had increased; and when in the previous hour the power plants had started to operate.
- 6th Criteria "Constant operation emissions when the next value increases".

The flowchart of these criteria can be seen in Appendix 2.

1.2. Results data

1.2.1. Parameters and variables for 2017 and future scenarios
The historical installed capacities of 2017 are shown in Table 11 and parameters for nuclear, coal and combined-cycle in Table 12.

Table 11
Historical installed capacity of 2017 (GW).

| Technology         | Installed capacity |
|--------------------|-------------------|
| Wind               | 22.922            |
| Solar PV           | 4.439             |
| Solar Thermal      | 2.304             |
| Nuclear            | 7.117             |
| Coal               | 9.536             |
| Combined-cycle     | 21.856            |
| Hydro              | 17.03             |
| PHS                | 3.329             |
| CR                 | 6.277             |
| TR                 | 0.975             |

Table 12
Parameters of 2017 for nuclear, coal and combined-cycle.

| Parameters                             | Nuclear | Coal | CC    | CR    | TR |
|----------------------------------------|---------|------|-------|-------|----|
| Maximum load (MW)                      | 7114    | 8727 | 17 054| 4078  | 492|
| Minimum load (MW)                      | 5118    | 772  | 511   | 2562  | 261|
| Minimum load (% of Installed capacity) | 72.19   | 8.10 | 2     | -     | -  |
| Ramp-down rate limit (MW)              | 294     | 1681 | 1736  | 262   | 52 |
| Ramp-down rate limit (% of installed capacity per hour) | 4.13 | 17.63 | 12.71 | 4.17 | 5.33 |
| Ramp-up rate limit (MW)                | 285     | 1195 | 1680  | 261   | 46 |
| Ramp-up rate limit (% of installed capacity per hour) | 4.00 | 12.53 | 12.30 | 4.16 | 4.72 |
| Number of power plants                 | 7       | 26   | 48    | -     | -  |

The values assumed\(^1\) or calculated (as input\(^2\) or as a result\(^3\)) for the model are presented in Table 13. Theoretical\(^4\) values are also shown. For CR and TR with 2017 installed capacities, the same historical\(^5\) values were obtained.

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\(^1\) Assumed: assumed value used as input of the model.
\(^2\) Calculated values before being used as inputs to the model, based on theoretical and historical reference values.
\(^3\) Calculated (as a result): value obtained because of the model.
\(^4\) Theoretical: value found in the literature, used as input.
\(^5\) Historical: actual values of the reference year.
Table 13
Values used or calculated in the model with historical data.

| Variables                                           | Nuclear | Coal | Inflexible CC | CR | TR | Flexible CC |
|-----------------------------------------------------|---------|------|---------------|----|----|-------------|
| New installed capacity (MW)                         | 7117\(^a\) | 9536\(^a\) | 13 654\(^\text{b}\) | 6277\(^\text{b}\) | 975\(^\text{b}\) | 8202\(^\text{c}\) |
| Maximum load (MW)                                   | 7114\(^a\) | 8727\(^a\) | 9334\(^\text{b}\) | 4078\(^\text{b}\) | 492\(^\text{b}\) | 5607\(^\text{c}\) |
| Minimum load (MW)                                   | 5118\(^\text{a}\) | 753\(^\text{a}\) | 2589\(^\text{a}\) | 2562\(^\text{a}\) | 261\(^\text{a}\) | - |
| Minimum load (% of Installed capacity)              | 71.91\(^a\) | 7.90\(^a\) | 18.96\(^a\) | - | - | - |
| Ramp-down rate limit (MW)                           | 299\(^a\) | 1675\(^a\) | 1740\(^a\) | 262\(^a\) | 52\(^a\) | - |
| Ramp-down rate limit (% of installed capacity per hour) | 4.20\(^a\) | 17.56\(^a\) | 12.74\(^a\) | 4.17\(^a\) | 5.33\(^a\) | - |
| Ramp-up rate limit (MW)                             | 300\(^a\) | 1239\(^a\) | 1743\(^a\) | 261\(^a\) | 46\(^a\) | - |
| Ramp-up rate limit (% of installed capacity per hour) | 4.22\(^a\) | 13.00\(^a\) | 12.76\(^a\) | 4.16\(^a\) | 4.72\(^a\) | - |
| Number of power plants assumed for a future year    | 7\(^\text{b}\) | 26\(^\text{b}\) | - | - | - | - |
| Nominal power of a power plant (MW)                 | 1017\(^a\) | 367\(^a\) | 520\(^a\) | 7.93\(^d\) | 7.93\(^d\) | - |
| Minimum theoretical load (% of nominal power)      | 75\(^\text{d}\) | 40\(^\text{d}\) | 40\(^\text{d}\) | - | - | - |
| Theoretical ramp rate (% of nominal power per hour) | 17\(^e\) | 90\(^e\) | 100\(^e\) | - | - | - |

\(^a\) Calculated (as input),
\(^b\) Assumed,
\(^c\) Calculated (as a result),
\(^d\) Avg. obtained from [8],
\(^e\) Theoretical (avr. obtained from [9]),
\(^f\) Theoretical (values obtained from [10]),
\(^g\) Theoretical (value obtained from [11])

The variables used for hydro and PHS and solar thermal are presented in Table 14.

Table 14
Values of hydro and solar thermal used or calculated in the model with historical data.

| Variables                                               | Nuclear |
|---------------------------------------------------------|---------|
| New installed hydropower capacity (MW)                  | 17 030\(^a\) |
| New installed PHS capacity (MW)                         | 3329\(^b\) |
| Annual average of hydropower available (MW)             | 1966\(^b\) |
| PHS installed capacity limit (MW)                       | 3329\(^b\) |
| PHS availability limit (MWh/day)                        | 28 685\(^b\) |
| Pumping efficiency (%)                                  | 85\(^a\) |
| PHS discharge efficiency (%)                            | 85\(^a\) |
| Pumping factor (%)                                      | 0.048\(^b\) |
| Nominal power of a hydropower plant                     | 14.6\(^c\) |
| Nominal power of a solar thermal power plant            | 45.2\(^d\) |

\(^a\) Assumed (pure and mixed power plants),
\(^b\) Calculated (as input),
\(^c\) Average obtained from [12],
\(^d\) Average obtained from [13].

Table 15 shows the required curtailment of wind and photovoltaic for system stability for different levels of ROCOF for the 2017 scenario.

In Fig. 2, it can be seen how the CIL decreases with the increase in ROCOF.

The values of the variables used in the model for the sustainable transition ST-2030 scenario are in Table 16. These variables are calculated as input, assumed, theoretical values or calculated due to the model.

The variables used for hydro and PHS and solar thermal for ST-2030 can be seen in Table 17. To project and model the 2040 scenario, the model requires a new installed capacity for all technologies, except for the combined-cycle, which will be obtained. Therefore, we tried to
Table 15
Required curtailment for system stability for different levels of ROCOF (2017).

| CIL (MW-s) | ROCOF (Hz/s) | Wind curtailment (GWh) | PV Curtailment (GWh) | Power grid failure (GWh) |
|------------|--------------|-----------------------|---------------------|-------------------------|
| 152045     | 0.5          | 42341                 | 7010                | 69494                   |
| 127045     | 0.6          | 40776                 | 5973                | 28115                   |
| 109188     | 0.7          | 33858                 | 2723                | 7577                    |
| 95795      | 0.8          | 21018                 | 576                 | 1264                    |
| 85379      | 0.9          | 9457                  | 69                  | 133                     |
| 77045      | 1            | 3670                  | 1                   | 6                       |
| 70227      | 1.1          | 1303                  | 0                   | 0                       |
| 64545      | 1.2          | 425                   | 0                   | 0                       |
| 59738      | 1.3          | 114                   | 0                   | 0                       |
| 55617      | 1.4          | 26                    | 0                   | 0                       |
| 52045      | 1.5          | 1                     | 0                   | 0                       |
| 48920      | 1.6          | 0                     | 0                   | 0                       |

Fig. 2. Critical inertia level (CIL) VS Rate of change of frequency (ROCOF) in the model (GWs).

Table 16
Values used or calculated in the model by ST-2030.

| Variables                              | Nuclear | Coal | Inflexible CC | CR | TR | Flexible CC |
|----------------------------------------|---------|------|---------------|----|----|-------------|
| New installed capacity (MW)            | 7117a   | 4768a| 13654a        | 8500b| 2550b| 21959c      |
| Maximum load (MW)                      | 7114a   | 4364a| 9334a         | 5522a| 1286b| 15011c      |
| Minimum load (MW)                      | 5118a   | 1172a| 2589a         | 3469a| 682a | -            |
| Minimum load (% of Installed capacity) | 71.91a  | 24.59a| 18.96a        | -   | -   | -            |
| Ramp-down rate limit (MW)              | 299c    | 2633c| 1740c         | 355c | 136c | -            |
| Ramp-down rate limit (% of installed capacity per hour) | 4.20c | 55.23c| 12.74c | 4.17c | 5.33c | -           |
| Ramp-up rate limit (MW)                | 300c    | 2529c| 1743c         | 353c | 120c | -            |
| Ramp-up rate limit (% of installed capacity per hour) | 4.22c | 53.05c| 12.76c | 4.16c | 4.72c | -           |
| Number of power plants assumed for a future year | 7b | 13b | - | - | - |

a Calculated (as input).
b Assumed.
c Calculated (as a result).

approximate our data to the data provided by the TYNDP 2018 from ENTSO (ENTSO-E, ENTSO-G) for the Sustainable Transition ST-2040 scenario, as can be seen in Table 18.

The demand for DG-2030 was 293676 GWh, 317688 for DG-2040 and 290439 GWh for GCA-2040, approximating to TYNDP values. Table 19 provides the installed capacities of the rest of the technologies.

1.2.2. PHS generation and histograms of power output 2017- ST-2030

Fig. 3. shows the hydropower production, as well as the PHS limit, which is 28 685 MWh for 2017. We also assume that PHS pumps water with an efficiency of 85% [14].
Table 17
Values of hydro and solar thermal used or calculated in the model by ST-2030.

| Variables | Nuclear |
|-----------|---------|
| New installed hydropower capacity (MW) | 23 050\(^a\) |
| New installed PHS capacity (MW) | 8280\(^b\) |
| Annual average of hydropower available (MW) | 2463\(^b\) |
| PHS installed capacity limit (MW) | 8280\(^b\) |
| PHS availability limit (MWh/day) | 35 941\(^b\) |
| Pumping efficiency (%) | 85\(^a\) |
| PHS discharge efficiency (%) | 85\(^a\) |
| Pumping factor (%) | 0.018\(^b\) |
| Nominal power of a hydropower plant (MW) | 14.6\(^c\) |
| Nominal power of a solar thermal power plant (MW) | 45.2\(^d\) |

\(^a\) Assumed, 
\(^b\) Calculated (as input), 
\(^c\) Average obtained from [12], 
\(^d\) Average obtained from [13].

Table 18
Model Installed capacity for ST-2040.

| Technology | TYNDP Installed capacity (ST-2040) (MW) | MODEL Installed capacity (2040) (MW) |
|------------|----------------------------------------|-------------------------------------|
| Wind       | 39 561                                 | 39 561                              |
| Solar PV   | 51 394                                 | 51 394                              |
| Solar Thermal | 3363                               | 3363                                |
| Nuclear    | 3100                                   | 3050\(^a\)                          |
| Coal       | 0                                      | 0                                   |
| Combined-cycle | 24 560                        | 48 340\(^b\)                      |
| Hydro      | 23 050                                 | 23 050                              |
| PHS        | 8280                                   | 8280                                |
| CR         | 8500                                   | 8500                                |
| TR         | 2550                                   | 2550                                |
| Demand     | 282 705                                | 282 682\(^c\)                      |
| France (import) | 9000                           | 9000                                 |
| France (export) | 9000                         | 9000                                 |
| Portugal (import) | 4000                           | 4000                                 |
| Portugal (export) | 4700                           | 4700                                 |
| Morocco (import) | 1500                           | 1500                                 |
| Morocco (export) | 1500                           | 1500                                 |
| Balearic Islands | 927                                | 927                                  |

\(^a\) Approximate value to the TYDNP, obtained in the model with 3 nuclear power plants. 
\(^b\) Calculated (as a result). 
\(^c\) Approximated value to the TYDNP, obtained in the model with a ND\(_m\) of 20955 MW.

Table 19
Installed capacities for DG-2030-2040 and GCA-2040.

| Technology | Installed capacityDG-2030 (MW) | Installed capacityDG-2040 (MW) | Installed capacityGCA-2040 (MW) |
|------------|-------------------------------|-------------------------------|-------------------------------|
| Nuclear    | 7117                          | 3050\(^a\)                    | 3050\(^a\)                    |
| Coal       | 734                           | 0                             | 0                             |
| Solar Thermal | 2304\(^a\)                   | 2304\(^a\)                   | 3363\(^b\)                   |
| Hydro      | 23 050\(^b\)                 | 23 050\(^b\)                 | 24 920\(^b\)                 |
| PHS        | 8280\(^b\)                   | 8280\(^b\)                   | 10 150\(^b\)                 |
| CR         | 8500\(^b\)                   | 8500\(^b\)                   | 8500\(^b\)                   |
| TR         | 2550\(^b\)                   | 2550\(^b\)                   | 2550\(^b\)                   |

\(^a\) Approximated value to the TYDNP. 
\(^b\) Value taken from TYNDP.
Fig. 3. Hydropower generation (2017) and PHS availability limit.

Fig. 4. Histogram of combined-cycle power output 2017 (MW).

Fig. 5. Power generation from the PHS (model with historical data (MWh)).

Regarding combined-cycle (CC) the histogram of the power output is shown in Fig. 4. The power generation of the pumped hydro storage (PHS) in the simulation with historical data can be seen in Fig. 5.

Fig. 6 shows the frequency histogram of the power output for the modelled technologies compared to the historical data.
Fig. 6. Frequency Histograms of the historical and modelled power output (model with historical data).
Fig. 7 shows the PHS generation obtained in the sustainable transition ST-2030 scenario.

![Fig. 7. Power generation from the PHS by ST-2030 (MWh).](image)

Fig. 8 shows the frequency histogram of the power output for the modelled technologies by ST-2030.

![Fig. 8. Frequency Histograms of the modelled power output by ST-2030.](image)
1.2.3. **Power generation and curtailment for ST-2040, DG-2030, DG-2040 and GCA-2040**

The results for the ST-2040 scenario are shown in Table 20.

**Table 20**
Annual energy generation by technology ST-2040.

| Technology          | Power generation of the model without curtailment (for flexibility and stability) (GWh) | Power generation of the model with curtailment (ROCOF 1) (GWh) |
|---------------------|------------------------------------------------------------------------------------------|---------------------------------------------------------------|
| Wind                | 81 370                                                                                    | 47 267                                                       |
| Solar PV            | 98 184                                                                                    | 52 412                                                       |
| Solar Thermal       |                                                                                         | 7410                                                         |
| Nuclear             | 18 520                                                                                    | 18 520                                                       |
| Coal                | 0                                                                                        | 0                                                            |
| Combined-cycle      | 48 077                                                                                    | 67 804                                                       |
| Hydro               | 23 051[^a]                                                                               | 21 119                                                       |
| PHS                 | -                                                                                        | 1475                                                         |
| CR                  | 37 653                                                                                    | 37 653                                                       |
| TR                  | 7789                                                                                      | 7789                                                         |
| PHS consumption     | -2126                                                                                    | -2126                                                        |
| Balearic Islands    | -1480                                                                                    | -1480                                                        |
| International Interconnections Balance | 24 837                                                                                 | 24 837                                                       |
| Total generation balance (TG) or Final demand | 282 682                                                                                 | 282 682                                                       |

[^a]: Hydro + PHS

The curtailment results for ST-2040 are shown in Table 21.

**Table 21**
Annual curtailment for ST-2040.

| Technology          | Curtailment required by inflexible operation (GWh) | Curtailment required for stability (ROCOF 1 Hz/s) (GWh) | Total Curtailment (GWh) | Curtailment [%][^a] |
|---------------------|-----------------------------------------------------|--------------------------------------------------------|-------------------------|---------------------|
| Wind                | 17 205                                               | 16898                                                  | 34 103                  | 21                  |
| Solar PV            | 35 232                                               | 2830                                                   | 38 061                  | 39                  |
| Solar Thermal       | 300                                                  | 0                                                      | 300                     | 4                   |
| Hydro               | 458                                                  | 0                                                      | 458                     | 2                   |

[^a]: Curtailment percentage of the availability of renewable generation.
The power output results for DG-2030, DG-2040 and GCA-2040 scenarios are provided in Table 22.

### Table 22
Annual energy generation by technology, DG-2030, DG and GCA-2040.

| Technology          | Scenario DG-2030 (GWh) | Scenario DG-2040 (GWh) | Scenario GCA-2040 (GWh) |
|---------------------|------------------------|------------------------|-------------------------|
| Wind                | 46 890                 | 52 452                 | 56 790                  |
| Solar PV            | 51 838                 | 66 509                 | 55 452                  |
| Solar Thermal       | 5261                   | 5249                   | 7327                    |
| Nuclear             | 45 975                 | 22 064                 | 15 745                  |
| Coal                | 2406                   | 0                      | 0                       |
| Combined-cycle      | 52 839                 | 79 733                 | 67 666                  |
| Hydro               | 21 493                 | 21 479                 | 22 048                  |
| PHS                 | 1986                   | 1917                   | 1570                    |
| CR                  | 39 296                 | 39 421                 | 35 658                  |
| TR                  | 8211                   | 8196                   | 7208                    |
| PHS consumption     | -2792                  | -2689                  | -2277                   |
| Balearic Islands    | -1480                  | -1480                  | -1480                   |
| International Interconnections Balance | 21 760 | 24 837 | 24 837 |
| Total generation balance (TG) or Final demand | 293 676 | 317 688 | 290 439 |

The curtailment results for DG and GCA scenarios are shown in Table 23.

### Table 23
Annual curtailment for DG-2030, DG-2040 and GCA-2040.

| Technology          | DG-2030 (ROCOF 1) (GWh) | DG-2040 (ROCOF 1.2) (GWh) | GCA-2040 (ROCOF 1.2) (GWh) |
|---------------------|-------------------------|--------------------------|---------------------------|
| Wind                | 16 872                  | 26                       | 29                        | 48 104 | 46 |
| Solar PV            | 31 177                  | 38                       | 44                        | 80 098 | 59 |
| Solar Thermal       | 22                      | 0.4                      | 1                         | 383    | 5  |
| Hydro               | 84                      | 0.4                      | 0.5                       | 572    | 3  |

* Percentage of curtailment of the availability of renewable generation.

Table 24 shows the required curtailment for each technology by ST-2030-2040 due to system stability. It also contains the power grid failures.

#### 1.2.4. CO₂ emissions

The results by technology for 2017, ST-2030 and ST-2040 obtained using Red Eléctrica de España (REE) methodology are shown in Table 25.

The emissions obtained by technology for 2017 and the base scenarios ST-2030-2040 can be seen in Table 26. It also provides the emissions obtained for the CC after applying the mode of operation for 2030 and 2040.
Table 24
Required curtailment of VRE due to system stability for different ROCOF levels (ST-2030-2040).

| CIL (MW.s) | ROCOF (Hz/s) | Wind curtailment 2030 (GWh) | PV Curtailment 2030 (GWh) | Power grid failure 2030 (GWh) | Wind curtailment 2040 (GWh) | PV Curtailment 2040 (GWh) | Power grid failure 2040 (GWh) |
|------------|--------------|-----------------------------|---------------------------|-------------------------------|-----------------------------|--------------------------|-------------------------------|
| 152045     | 0.5          | 46 011                      | 38 066                    | 39 674                        | 55 573                      | 44 640                   | 39 077                        |
| 127045     | 0.6          | 41 518                      | 29 577                    | 12 173                        | 50 286                      | 33 827                   | 11 851                        |
| 109188     | 0.7          | 32 861                      | 14 887                    | 2473                          | 41 897                      | 21 822                   | 2307                          |
| 95795      | 0.8          | 22 573                      | 6699                      | 233                           | 32 130                      | 12 514                   | 225                           |
| 85379      | 0.9          | 13 649                      | 2475                      | 8                             | 23 684                      | 6319                     | 3                             |
| 77045      | 1            | 7512                        | 793                       | 0                             | 16 898                      | 2830                     | 0                             |
| 70227      | 1.1          | 3980                        | 242                       | 0                             | 11 665                      | 1148                     | 0                             |
| 64545      | 1.2          | 2181                        | 60                        | 0                             | 7930                        | 426                      | 0                             |
| 59738      | 1.3          | 1213                        | 6                         | 0                             | 5297                        | 144                      | 0                             |
| 55617      | 1.4          | 652                         | 0                         | 0                             | 3526                        | 37                      | 0                             |
| 52045      | 1.5          | 337                         | 0                         | 0                             | 2326                        | 6                       | 0                             |
| 48920      | 1.6          | 166                         | 0                         | 0                             | 1530                        | 0.6                     | 0                             |
| 46163      | 1.7          | 82                          | 0                         | 0                             | 1029                        | 0                       | 0                             |
| 43712      | 1.8          | 35                          | 0                         | 0                             | 705                         | 0                       | 0                             |
| 41519      | 1.9          | 12                          | 0                         | 0                             | 488                         | 0                       | 0                             |
| 39545      | 2            | 4                           | 0                         | 0                             | 341                         | 0                       | 0                             |
| 37760      | 2.1          | 3                           | 0                         | 0                             | 240                         | 0                       | 0                             |
| 36136      | 2.2          | 2                           | 0                         | 0                             | 170                         | 0                       | 0                             |
| 34654      | 2.3          | 22                          | 0                         | 0                             | 120                         | 0                       | 0                             |
| 33295      | 2.4          | 1                           | 0                         | 0                             | 85                          | 0                       | 0                             |
| 32045      | 2.5          | 0.5                         | 0                         | 0                             | 62                          | 0                       | 0                             |
| 30892      | 2.6          | 0.1                         | 0                         | 0                             | 44                          | 0                       | 0                             |
| 29823      | 2.7          | 0                           | 0                         | 0                             | 31                          | 0                       | 0                             |
| 28831      | 2.8          | 0                           | 0                         | 0                             | 20                          | 0                       | 0                             |
| 27908      | 2.9          | 0                           | 0                         | 0                             | 11                          | 0                       | 0                             |
| 21045      | 3            | 0                           | 0                         | 0                             | 4                           | 0                       | 0                             |
| 26239      | 3.1          | 0                           | 0                         | 0                             | 0.5                         | 0                       | 0                             |
| 25483      | 3.2          | 0                           | 0                         | 0                             | 0                           | 0                       | 0                             |

Table 25
Emissions by technology for the model and TYNDP ST-2030-2040 (Mt CO₂/year).

| Scenario           | Coal    | Combined-cycle | CR  |
|--------------------|---------|----------------|-----|
| Historical 2017    | 40.6    | 12.6           | 8.7 |
| Model 2017         | 37.2    | 10.7           | 10.0|
| Model 2030         | 9.2     | 16.0           | 11.0|
| TYNDP 2030         | 6.8     | 16.1           | 10.8|
| Model 2040         | 0       | 25.1           | 10.5|
| TYNDP 2040         | 0       | 17.7           | 10.8|

Table 26
CO₂eq emissions by technology for 2017, ST-2030 and ST-2040 (kt of CO₂ eq.).

| Technology           | 2017   | ST-2030a | ST 2040b |
|----------------------|--------|----------|----------|
| Nuclear              | 1338   | 948      | 407      |
| Wind                 | 458    | 448      | 473      |
| Solar PV             | 313    | 1890     | 2096     |
| Solar Thermal        | 106    | 104      | 148      |
| Biomass              | 123    | 225      | 241      |
| Biogas               | 274    | 97       | 92       |
| Marine               | -      | 4        | 3        |
| Geothermal           | -      | 17       | 16       |
| Hydro (impoundment)  | 252    | 309      | 306      |
| Hydro diversion      | 8      | 11       | 10       |
| PHS                  | 0.1    | 2        | 2        |

a Emissions for the CC are 16977 kt.
b Emissions for the CC are 26641 kt.
Table 27 shows the TSI, the total emissions, and the emission factors (weighted average) when decreasing the ROCOF for 2017, ST and DG 2030.

**Table 27**
Inertia and emission factor results for 2017, ST and DG-2030.

|                      | 2017     | ST-2030 (no restrictions) | ST-2030 (ROCOF 1.2 Hz/s) | ST-2030 (ROCOF 1 Hz/s) | ST-2030 (ROCOF 1 Hz/s) | DG-2030 (no restrictions) | DG-2030 (ROCOF 1.2 Hz/s) | DG-2030 (ROCOF 1 Hz/s) | DG-2030 (ROCOF 1 Hz/s) |
|----------------------|----------|---------------------------|--------------------------|------------------------|------------------------|---------------------------|--------------------------|------------------------|------------------------|
| TSI (GWs)            | 747 732  | 717 348                   | 728 483                  | 758 621                | 763 708                | 770 997                   | 796 558                  |                       |                       |
| Total Emissions (Mt CO₂) | 60.9     | 38.1                      | 38.9                     | 41.2                   | 36.0                   | 36.6                      | 38.5                     |                       |                       |
| Medium emission factor (kgCO₂/MWh) | 241      | 144                       | 148                      | 157                    | 131                    | 133                       | 141                      |                       |                       |

**Table 28** shows the TSI, the increase in total emissions, and the emission factors (weighted average) when by 2040.

**Table 28**
Inertia and emission factor results for ST, DG and GCA-2040.

|                      | ST-2040 (no restr.) | ST-2040 (1.2 Hz/s) | ST-2040 (1 Hz/s) | DG-2040 (no restr.) | DG-2040 (1.2 Hz/s) | DG-2040 (1 Hz/s) | DG-2040 (1 Hz/s) | GCA-2040 (no restr.) | GCA-2040 (1.2 Hz/s) | GCA-2040 (1 Hz/s) | GCA-2040 (1 Hz/s) |
|----------------------|---------------------|-------------------|-----------------|---------------------|-------------------|-----------------|-----------------|-------------------|-------------------|-----------------|-----------------|
| TSI (GWs)            | 641 077             | 682 471           | 739 121         | 756 020             | 778 532           | 817 131         | 590 014         | 651 478           | 719 985           |                 |                 |
| Total Emissions (Mt CO₂) | 33.5     | 36.7               | 41              | 42.5                | 44.2              | 47              | 30.6            | 35.4              | 40.4              |                 |                 |
| Medium emission factor (kg CO₂/MWh) | 129      | 142               | 159             | 145                 | 150               | 160             | 115             | 134               | 153               |                 |                 |

1.2.5. Levelized cost of electricity (LCOE)

**Table 29** shows the LCOE data used to calculate system costs. LCOE input depends on the capacity factor resulting from each scenario.
Table 29
Input LCOE for all scenarios considered in the study.

| Scenario                        | Full load hours (capacity factor %) | Input LCOE (€/MWh) |
|---------------------------------|-------------------------------------|--------------------|
| 2017 Wind (no restrictions)     | 2053 (23%)                          | 79                 |
| 2017 PV (no restrictions)       | 1760 (20%)                          | 68                 |
| 2017 Coal                       | 4199 (47%)                          | 65                 |
| 2017 Nuclear                    | 8547 (98%)                          | 45                 |
| 2017 CC (no restrictions)       | 1264 (14%)                          | 136                |
| 2017 Wind (1.1 Hz/s)            | 1996 (23%)                          | 79                 |
| 2017 PV (1.1 Hz/s)              | 1760 (20%)                          | 68                 |
| 2017 CC (1.1 Hz/s)              | 1324 (14%)                          | 133                |
| ST 2030 Wind (1.2 Hz/s)         | 1618 (18%)                          | 79                 |
| ST 2030 PV (1.2 Hz/s)           | 1200 (14%)                          | 75                 |
| ST 2030 Coal                    | 2022 (23%)                          | 99                 |
| ST 2030 Nuclear                 | 6054 (69%)                          | 60                 |
| ST 2030 CC (1.2 Hz/s)           | 1046 (12%)                          | 147                |
| ST 2030 Wind (no restrictions)  | 1688 (19%)                          | 75                 |
| ST 2030 PV (no restrictions)    | 1202 (14%)                          | 75                 |
| ST 2030 CC (no restrictions)    | 983 (11%)                           | 148                |
| ST 2030 Wind (1 Hz/s)           | 1446 (17%)                          | 88                 |
| ST 2030 CC (1 Hz/s)             | 1182 (13%)                          | 76                 |
| ST 2030 CC (1 Hz/s)             | 1217 (14%)                          | 139                |
| DG 2030 Wind (1.2 Hz/s)         | 1636 (19%)                          | 77                 |
| DG 2030 PV (1.2 Hz/s)           | 1127 (13%)                          | 80                 |
| DG 2030 Coal                    | 3280 (37%)                          | 73                 |
| DG 2030 Nuclear                 | 6460 (74%)                          | 57                 |
| DG 2030 CC (1.2 Hz/s)           | 1069 (12%)                          | 147                |
| DG 2030 Wind (no restrictions)  | 1680 (19%)                          | 75                 |
| DG 2030 PV (no restrictions)    | 1129 (13%)                          | 79                 |
| DG 2030 CC (no restrictions)    | 1036 (12%)                          | 148                |
| DG 2030 Wind (1 Hz/s)           | 1513 (17%)                          | 84                 |
| DG 2030 PV (1 Hz/s)             | 1099 (13%)                          | 82                 |
| DG 2030 CC (1 Hz/s)             | 1184 (14%)                          | 140                |
| ST 2040 Wind (1.2 Hz/s)         | 1422 (16%)                          | 89                 |
| ST 2040 PV (1.2 Hz/s)           | 1067 (12%)                          | 84                 |
| ST 2040 Coal                    | 0                                  | 0                  |
| ST 2040 Nuclear                 | 6072 (69%)                          | 60                 |
| ST 2040 CC (1.2 Hz/s)           | 1167 (13%)                          | 141                |
| ST 2040 Wind (no restrictions)  | 1622 (19%)                          | 78                 |
| ST 2040 PV (no restrictions)    | 1075 (12%)                          | 83                 |
| ST 2040 CC (no restrictions)    | 995 (11%)                           | 148                |
| ST 2040 Wind (1 Hz/s)           | 1195 (14%)                          | 106                |
| ST 2040 PV (1 Hz/s)             | 1020 (12%)                          | 88                 |
| ST 2040 CC (1 Hz/s)             | 1403 (16%)                          | 128                |
| DG 2040 Wind (1.2 Hz/s)         | 1573 (18%)                          | 80                 |
| DG 2040 PV (1.2 Hz/s)           | 1052 (12%)                          | 85                 |
| DG 2040 Coal                    | 0                                  | 0                  |
| DG 2040 Nuclear                 | 7234 (83%)                          | 52                 |
| DG 2040 CC (1.2 Hz/s)           | 1259 (14%)                          | 136                |
| DG 2040 Wind (no restrictions)  | 1668 (19%)                          | 76                 |
| DG 2040 PV (no restrictions)    | 1068 (12%)                          | 84                 |
| DG 2040 CC (no restrictions)    | 1180 (13%)                          | 140                |
| DG 2040 Wind (1 Hz/s)           | 1464 (17%)                          | 86                 |
| DG 2040 PV (1 Hz/s)             | 994 (11%)                           | 90                 |
| DG 2040 CC (1 Hz/s)             | 1395 (16%)                          | 129                |
| GCA 2040 Wind (1.2 Hz/s)        | 1285 (15%)                          | 99                 |
| GCA 2040 PV (1.2 Hz/s)          | 784 (9%)                            | 114                |
| GCA 2040 Coal                   | 0                                  | 0                  |
| GCA 2040 Nuclear                | 5162 (59%)                          | 68                 |
| GCA 2040 CC (1.2 Hz/s)          | 1012 (12%)                          | 148                |
| GCA 2040 Wind (no restrictions) | 1502 (17%)                          | 84                 |
| GCA 2040 PV (no restrictions)   | 801 (9%)                            | 112                |
| GCA 2040 CC (no restrictions)   | 783 (9%)                            | 155                |
| GCA 2040 Wind (1 Hz/s)          | 1114 (13%)                          | 114                |
| GCA 2040 PV (1 Hz/s)            | 720 (8%)                            | 125                |
| GCA 2040 CC (1 Hz/s)            | 1272 (15%)                          | 136                |
Table 30 shows the total costs and the LCOE (weighted average) when going from the scenario without inertia constraints to the restricted ones for 2017 and ST and DG 2030.

|                | 2017 | ST-2030 (no restrictions) | ST-2030 (ROCOF 1.2 Hz/s) | ST-2030 (ROCOF 1 Hz/s) | ST-2030 (ROCOF 1 Hz/s) | Total Costs (Me) | Medium LCOE (€/MWh) |
|----------------|------|----------------------------|---------------------------|-------------------------|-------------------------|------------------|---------------------|
| Total Costs    | 16 612 | 20 235                     | 20 562                    | 21 081                  | 21 761                  | 21 975           | 22 394              |
| Medium LCOE    | 68     | 77                         | 78                        | 80                      | 79                      | 79               | 81                  |

Table 31 shows the total costs and the LCOE (weighted average) when going from the scenario without inertia constraints to the restricted ones for ST, DG and GCA 2040.

|                | ST-2040 (no rest.) | ST-2040 (1.2 Hz/s) | Total Costs (Me) | Medium LCOE (€/MWh) |
|----------------|---------------------|--------------------|------------------|---------------------|
| Total Costs    | 21 762              | 22 621             | 24 171           | 25 503              |
| Medium LCOE    | 83                  | 86                 | 89               | 84                  |

Table 32 shows the maximum and minimum LCOE and the frequency of values greater than € 85/MWh for each scenario.

| Scenario                  | Frequency in the impacted area (> 85 €/MWh) | Maximum annual LCOE (€/MWh) | Minimum annual LCOE (€/MWh) | Annual frequency (> 85 €/MWh) |
|---------------------------|---------------------------------------------|-----------------------------|-----------------------------|-------------------------------|
| ST 2030 No restrictions   | 41 (3%)                                     | 104                         | 62                          | 784 (9%)                      |
| ST 2030 1.2 Hz/s          | 379 (27 %)                                  | 104                         | 62                          | 1200 (14%)                    |
| ST 2030 1 Hz/s           | 1113 (29 %)                                 | 104                         | 62                          | 1874 (21%)                    |
| DG 2030 No restrictions  | 14 (1%)                                     | 109                         | 62                          | 1495 (17%)                    |
| DG 2030 1.2 Hz/s         | 185 (15%)                                   | 109                         | 62                          | 1699 (19%)                    |
| DG 2030 1 Hz/s            | 850 (26%)                                   | 109                         | 62                          | 2252 (26%)                    |
| ST 2040 No restrictions  | 207 (6%)                                    | 117                         | 65                          | 2543 (29%)                    |
| ST 2040 1.2 Hz/s         | 2151 (60%)                                  | 113                         | 65                          | 4752 (54%)                    |
| ST 2040 1 Hz/s            | 4063 (72%)                                  | 109                         | 65                          | 6238 (71%)                    |
| DG 2040 No restrictions  | 10 (0.4%)                                   | 115                         | 63                          | 3330 (38%)                    |
| DG 2040 1.2 Hz/s         | 599 (25%)                                   | 112                         | 63                          | 3934 (45%)                    |
| DG 2040 1 Hz/s            | 2351 (59%)                                  | 108                         | 63                          | 5513 (63%)                    |
| GCA 2040 No restrictions | 3426 (75%)                                   | 124                         | 68                          | 6972 (80%)                    |
| GCA 2040 1.2 Hz/s        | 4178 (92%)                                   | 121                         | 71                          | 8267 (94%)                    |
| GCA 2040 1 Hz/s          | 6229 (96%)                                   | 119                         | 71                          | 8516 (97%)                    |

The results in the linked paper regarding emissions (~113 kgCO₂/MWh) were calculated by replacing the emission factor of the combined-cycle with the one that allows reaching Paris targets (through a weighted average of the generation and emissions of the other technologies). Regarding LCOE (~134 €/MWh), it was obtained averaging with the LCOE of the other technologies allowing obtain 102 €/MWh for the whole system (weighted average).

Hourly results for each scenario can be found at https://doi.org/10.7910/DVN/R2IVYN
2. Materials and Methods

The historical data were obtained from the Spanish Transmission system operator REE for mainland Spain and the Balearic Islands (the Canary Islands and the Autonomous Cities of Ceuta and Meliilla are not included since they represent isolated grids). REE provides the real, planned and programmed demand, power generation for each technology and international interconnections, and the CO₂ emissions associated with each technology, all with a ten-minute resolution [15]. The historical hourly demand is obtained through an average of the ten-minute values, as well as the historical power output of VRE, hydro and interconnections. The code for the modelling was developed in Visual Basic for Applications (VBA). It is a ruled-based power model based on the merit order stack. After applying technical and inertia constraints considering the methodology described in the accompanying publication, future scenarios’ demand and hourly generation were obtained.

Wind, solar photovoltaic, solar thermal, hydro (Impoundment and diversion hydropower plants) power generation were obtained through projections. International interconnections with France, Spain, Portugal, Andorra and Morocco, and the power with the Balearic Island was also projected. The power outputs of renewable thermal and other renewables (TR), cogeneration and non-renewable waste (CR), nuclear, coal, pumped hydro storage (PHS), and the combined-cycle were modelled considering the flexibility parameters. Hydro, renewable thermal and other renewables (TR) and cogeneration and non-renewable waste (CR) were obtained in a single time series as presented by REE. Projections and modelling were based on the installed capacities provided by the Ten-year Network Development Plan (TYNDP-2018) from ENTSOE [16].

The flexible combined-cycle power output depends on the critical inertia level (CIL) of the system, which in turn rely on the Rate of Change of Frequency (ROCOF) considered. A sensitivity analysis was carried out to determine the ROCOF where there are no curtailment and power grid failures. Finally, CO₂ emissions and the Levelized cost of electricity (LCOE) were obtained with the hourly power generation and literature parameters.

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

Hourly results for the future power system in Spain (2030, 2040) (Original data) (Dataverse).

CRediT Author Statement

K. Guerra: Methodology, Investigation, Formal analysis, Data curation, Software, Writing – original draft; P. Haro: Conceptualization, Methodology, Supervision, Validation, Visualization, Writing – review & editing; R.E. Gutiérrez: Data curation, Visualization, Investigation; A. Gómez-Barea: Writing – review & editing.

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Supplementary Materials

Supplementary material associated with this article can be found in the online version at doi: 10.1016/j.dib.2022.108095.

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