Supporting Information

Sustainable Energy Transition Considering the Water-Energy Nexus: A Multiobjective Optimization Framework

***Javier Tovar-Facio*[†]*, Lidia S. Guerras*[‡]*, José M. Ponce-Ortega*[†]*, Mariano Martín*[‡*]**

† Department of Chemical Engineering, Universidad Michoacana de San Nicolás de Hidalgo, Francisco J. Múgica S/N, Morelia, Michoacán, 58060, Mexico.

‡ Department of Chemical Engineering, University of Salamanca, Plz. Caídos 1-5, Salamanca, Castilla y León, 37008, Spain.

[*]Corresponding author: Mariano Martín

E-mail: mariano.m3@usal.es

Total number of pages: S1 – S24

Total number of figures: Figure S1 – Figure S6

Total number of tables: Table S1 – Table S8

MATHEMATICAL MODEL

A mixed integer linear programing model is developed to select the optimal mix of renewable technologies that can substitute the electric power production of decommissioned power plants. In this section, the optimization model is presented using energy balances, technical restrictions, and sustainability indicators (water consumption and greenhouse gas emissions).

Sets

First, it is necessary to define the sets used in the model.

EPP: Existing power plants. In other words, the plants already installed that are operating to satisfy the electricity demand. Each element of this set has predefined characteristics like type, location and capacity.

NPP: Available renewable technologies to substitute decommissioned power plants. Each technology has different advantages and disadvantages that play a key role to minimize costs or increase the sustainability of the power system. In this case, it has been considered four potential technologies as replacements: new biomass power plants (NBM), new photovoltaic power plants (NPV), new concentrated solar power plants (NCS) and new wind farms (NEO). However, the approach can be extended to other renewable technologies.

CT: Potential sites to install new power plants. Several potential sites are selected to install one or more power plants. Each site has resources availability or characteristics that do it suitable or not to install a new power plant like biomass availability, wind speed, or solar irradiation.

BP: Biomass producers. Each CT produces a known quantity of biomass every period T; however, biomass can be transported to other CT when suitable.

BRM: Types of biomass as raw material. There are different types of available biomass, and each type has characteristics that affect the design of the new power plant. Moreover, it is possible to have a mix of different biomass types if necessary.

T: Periods of time to discretize the problem.

Energy demand

Energy demand is a parameter (DEM_t) that must be equal to the sum of the energy generated by EPP and NPP. It is important to note that the available capacity of EPP is not enough to satisfy the demand because selected plants will be decommissioned and must be substituted. Certain NPP's must be installed in order to supply the energy demand. Energy from EPP in every period is calculated as a function of the installed capacity of each plant (IC_{epp}) and the time that these plants operate ($wkt_{epp,t}$). On the other hand, energy from NPP in every period is the sum of the energy produced by new renewable power plants and depends on selected capacity, location and technology.

$$DEM_t = \sum_{epp} IC_{epp}\, wkt_{epp,t} + \sum_{npp}\sum_{ct} ef_{npp,ct,t} \qquad \forall t \in T \tag{S1}$$

Energy produced by EPP

The total energy produced from existing power plants is the sum of the energy generated every period by each plant. As mentioned before, energy from individual plants is calculated as a function of the installed capacity (IC_{pp}) and the time that these plants operate ($wkt_{pp,t}$).

$$epef = \sum_{t}\sum_{epp} IC_{epp}\, wkt_{epp,t} \tag{S2}$$

Each power plant works at different capacity levels throughout the year. This is a function of the capacity factor of each technology, so the available working time must be lower than a known value ($DISP_{epp,t}$).

$$wkt_{epp,t} \le DISP_{epp,t} \qquad \forall epp \in EPP, \forall t \in T \tag{S3}$$

Also, the energy generated by an existing power plant cannot be below a fraction of the available capacity (χ_{epp}) in order to avoid a plant shutdown [20], which is represented as follows:

$$wkt_{epp,t} \ge \chi_{epp}\, DISP_{epp,t} \qquad \forall epp \in EPP, \forall t \in T \tag{S4}$$

Energy produced by NPP

The total energy produced by the new renewable power plants is the sum of the energy produced by each technology, in each selected location during each period.

$$npef = \sum_{npp}\sum_{ct}\sum_{t} ef_{npp,ct,t} \tag{S5}$$

The power produced by each technology in a particular location and period can be calculated using the available operating time ($DISP_{npp,ct,t}$), which depends of the capacity factor of each technology, and the used capacity ($uc_{npp,ct,t}$) of each technology in every site to satisfy the demand that varies in each period.

$$ef_{npp,ct,t} = DISP_{npp,ct,t}\, uc_{npp,ct,t} \qquad \forall npp \in NPP, \forall ct \in CT, \forall t \in T \tag{S6}$$

To make sure that new plants are working continuously, a constraint is added to guarantee that at least a fraction, χ_{npp}, of the nominal capacity, $ic_{npp,ct}$, is being produced (minimum operating regime). This restriction is formulated as presented in eq. (7) to avoid bilinear terms.

$$ef_{npp,ct,t} \geq \chi_{npp}\, DISP_{npp,ct,t}\, ic_{npp,ct} \qquad \forall npp \in NPP, \forall ct \in CT, \forall t \in T \tag{S7}$$

The actual minimum operating capacity depends on the technology. The values are taken from the literature for existing and new power plants.[1]

Water consumption

Electric power plants require water to operate, depending on the type of technology[2] and site characteristics like temperature, pressure and humidity[3]. The consumption of water ($epwc_{epp,t}$ and $npwc_{npp,ct,t}$) can be calculated as a function of the energy produced by existing and new power plants as shown in equations (8) and (9), respectively.

$$epwc_{epp,t} = WC_{epp}\, IC_{epp}\, wkt_{epp,t} \qquad \forall epp \in EPP, \forall t \in T \tag{S8}$$

$$npwc_{npp,ct,t} = WC_{npp,ct}\, ef_{npp,ct,t} \qquad \forall npp \in NPP, \forall ct \in CT, \forall t \in T \tag{S9}$$

The total water consumption due to electricity production can be calculated adding the water consumed in each location and period by each technology in both EPP and NPP.

$$twc = \sum_{npp}\sum_{t}\sum_{ct} npwc_{npp,ct,t} + \sum_{epp}\sum_{t} epwc_{epp,t} \tag{S10}$$

Greenhouse gas emissions

All power plants generate greenhouse gas emissions, directly (i.e. burning fuel) or indirectly (i.e. manufacturing), that can be quantified in tons of carbon dioxide equivalent as a function of generated energy using reported values (GHG_{epp} and GHG_{npp})[4]. The greenhouse gas emissions from existing plants ($epghg_{epp,t}$) are a function of the installed capacity times the working time, and emissions from new renewable power plants ($npghg_{npp,ct,t}$) are a function of the energy generated by them ($ef_{npp,ct,t}$).

$$epghg_{epp,t} = GHG_{epp}\ IC_{epp}\ wkt_{epp,t} \qquad \forall epp \in EPP, \forall t \in T \tag{S11}$$

$$npghg_{npp,ct,t} = GHG_{npp}\ ef_{npp,ct,t} \qquad \forall npp \in NPP, \forall ct \in CT, \forall t \in T \tag{S12}$$

Total emissions of electricity production can be calculated with the sum of both terms through equations (S11) and (S12) as follows:

$$tghg = \sum_{t}\sum_{npp}\sum_{ct} npghg_{npp,ct,t} + \sum_{t}\sum_{epp} epghg_{epp,t} + traghg \tag{S13}$$

Renewable power plants

In this model, four technologies are considered to replace the power plants to be decommissioned, such as, biomass power plants, photovoltaic power stations, concentrated solar power tower systems and wind farms, $NPP = \{NBM, NPV, NCS, NEO\}$. However, the model is flexible to consider other technologies such as additional hydro. The objective of the model is to select the best technology, capacity and location considering economic and environmental factors. The capacity, location, and associated costs of the new power plants are defined in the following sections.

Installed capacity

It is possible to install different renewable power technologies in each available site, CT. Each potential location has a predefined minimum ($CMIN^{npp}$) and a maximum ($CMAX^{npp}$) plant capacity that changes for each technology; thus, the selected capacity of each plant ($ic_{npp,ct}$) must be between these known values. The installed capacity is an optimization variable, so the nominal capacity (ic) must be larger than the used capacity (uc) in every period of time as shown in equation (S21), (S27), (S30) and (S34). The new renewable power plants might be installed in the same city simultaneously, but it is not required to install any of them if it is not needed. This is formulated using binary variables (y_{ct}^{npp}) that are equal to one when the plants are installed and zero when they do not exist.

$$y_{ct}^{npp}\, CMIN^{npp} \leq ic_{npp,ct} \qquad \forall npp \in NPP, \forall ct \in CT \tag{S14}$$

$$y_{ct}^{npp}\, CMAX^{npp} \geq ic_{npp,ct} \qquad \forall npp \in NPP, \forall ct \in CT \tag{S15}$$

Capital cost

The capital cost is calculated as a function of the installed capacity using reported constants for each technology (CIC_{npp}) [5]. The values are available in the Supplementary Material of this work. The total capital investment of the project, equation (S17), is the sum of the capital cost of all installed plants calculated with equation (S16).

$$capcost_{npp,ct} = ic_{npp,ct}\, CIC_{npp} \qquad \forall npp \in NPP, \forall ct \in CT \tag{S16}$$

$$tcapcost_{npp} = \sum_{ct} capcost_{npp,ct} \qquad \forall npp \in NPP \tag{S17}$$

Operation and maintenance costs

The operation and maintenance costs ($onmcost_{npp,ct}$) are calculated as a function of the electricity produced by renewable power plants [6], and it is necessary to sum the operation and maintenance costs of every plant ($onmcost_{npp,ct}$) to calculate the total operating and maintenance costs of installed technologies ($tonmcost_{npp}$). These constants can be found in the Supplementary Material of this work.

$$onmcost_{npp,ct} = \sum_{t} ef_{npp,ct,t}\, OM_{npp} \qquad \forall npp \in NPP, \forall ct \in CT \tag{S18}$$

$$tonmcost_{npp} = \sum_{ct} onmcost_{npp,ct} \qquad \forall npp \in NPP \tag{S19}$$

Electricity generation

There are some differences between the way renewable technologies are modelled, one of the most important is the energy source that determines the generation of electricity by power plants.

Biomass

Biomass is burned to produce electricity via a steam turbine. The electricity generated in each period depends on the amount of biomass consumed ($tbmc_{ct,brm,t}$), the biomass energy content (LHV_{brm}) and the plant efficiency (η_{nbm}). However, it is limited by the available working time ($DISP_{nbm,ct,t}$) and plant used capacity ($uc_{nbm,ct,t}$).

$$\eta_{nbm}\sum_{brm}\left(tbmc_{ct,brm,t}\,LHV_{brm}\right)=DISP_{nbm,ct,t}\,uc_{nbm,ct,t}\quad \forall nbm\in NBM,\forall ct\in CT,\forall t\in T \quad \text{(S20)}$$

In order to select the capacity of each biomass plant, the installed capacity ($ic_{nbm,ct}$) must be greater than the used capacity ($uc_{nbm,ct,t}$) in every period of time (t) in order to be able to satisfy the required demand in every period.

$$ic_{nbm,ct}\geq uc_{nbm,ct,t}\qquad \forall nbm\in NBM,\forall ct\in CT,\forall t\in T \qquad \text{(S21)}$$

There is a limited amount of biomass to produce electricity; therefore, the amount of biomass consumed by a plant must be lower or equal than the available amount of biomass, as presented below.

$$\sum_{ct}bmc_{bp,ct,brm,t}\leq AVBM_{bp,brm,t}\qquad \forall bp\in BP,\forall brm\in BRM,\forall t\in T \qquad \text{(S22)}$$

If necessary and feasible, it is possible to transport biomass from different locations to the installed biomass power plants. Biomass transport cost ($tracost$) is calculated as a function of weight of transported biomass using the parameter $UTC_{ct,bp}$ (EUR/ton)[7] in equation (S23). Furthermore, emissions associated with biomass transport ($traghg$) are calculated similarly using the parameter $UTE_{ct,bp}$ (tCO_2/ton)[8] through equation (S24): Both parameters are estimated base on the calculated distance between producers and consumers as shown in the literature [9].

$$tracost=\sum_{brm}\sum_{bp}\sum_{ct}\sum_{t}\left(UTC_{ct,bp}\,bmc_{bp,ct,brm,t}\right) \qquad \text{(S23)}$$

$$traghg=\sum_{brm}\sum_{bp}\sum_{ct}\sum_{t}\left(UTE_{ct,bp}\,bmc_{bp,ct,brm,t}\right) \qquad \text{(S24)}$$

Thus, the biomass consumed by a new power plant, installed in the site CT, is the sum of biomass sent from all biomass producers BP.

$$tbmc_{ct,brm,t}=\sum_{bp}\left(bmc_{bp,ct,brm,t}\right)\qquad \forall ct\in CT,\forall brm\in BRM,\forall t\in T \qquad \text{(S25)}$$

Photovoltaic power plants

The energy produced by each installed photovoltaic panel ($ef_{npv,ct,t}$) depends on the used area ($ua_{npv,t}$), solar resource ($DSI_{ct,t}$), and technology efficiency (η_{npv}); thereupon, every location has a particular solar resource that makes some places more suitable than others.

$$ef_{npv,ct,t} = \eta_{npv}\, DSI_{ct,t}\, ua_{npv,ct,t} \qquad \forall npv \in NPV, \forall ct \in CT, \forall t \in T \qquad \text{(S26)}$$

It is important to note that this technology cannot work 24 hours a day. To account for This, the model considers day periods and night periods so that $ef_{npv,ct,t}$ will be zero during night periods. Consequently, this technology cannot contribute to satisfy nightly demand for electricity.

To select a capacity, the installed capacity must be greater than the used capacity in every period. This is correlated with the area, and the final required area must be greater than the used area to satisfy energy demand in each period.

$$ic_{npv,ct} \geq uc_{npv,ct,t} \qquad \forall npv \in NPV, \forall ct \in CT, \forall t \in T \qquad \text{(S27)}$$

$$ia_{npv,ct} \geq ua_{npv,ct,t} \qquad \forall npv \in NPV, \forall ct \in CT, \forall t \in T \qquad \text{(S28)}$$

Concentrated solar power

In this case, a large area of sunlight is concentrated onto a located point to heat a transfer fluid that produces steam to generate electricity. The amount of energy produced ($ef_{ncs,ct,t}$) depends on the area of heliostats used ($ua_{ncs,t}$), direct solar irradiance ($DSI_{ct,t}$), and the process efficiency (η_{ncs}). As mentioned in the previous section, each location has different solar resources, and the sites with the best solar resources require less area to produce certain amount of energy than those with poor solar resources.

$$ef_{ncs,ct,t} = \eta_{ncs}\, DSI_{ct,t}\, ua_{ncs,ct,t} \qquad \forall ncs \in NCS, \forall ct \in CT, \forall t \in T \qquad \text{(S29)}$$

Unlike photovoltaic panels, this technology can be coupled with thermal energy storage technologies to increase the capacity factor of the plants, so it is established that CSP is able to work during day and night periods.

In the same way as for solar panels, the installed capacity and effective area of the concentrated solar system must be greater than the capacity and area used in every period.

$$ic_{ncs,ct} \geq uc_{ncs,ct,t} \qquad \forall ncs \in NCS, \forall ct \in CT, \forall t \in T \tag{S30}$$

$$ia_{ncs,ct} \geq ua_{ncs,ct,t} \qquad \forall ncs \in NCS, \forall ct \in CT, \forall t \in T \tag{S31}$$

As presented in equations (S26) and (S29), the capacity of solar technologies is highly dependent of the area used; nevertheless, the area that can be used in each site is limited. The model includes a restriction where the sum of the area utilized by solar technologies in the selected locations must be lower or equal to the available area.

$$ia_{npv,ct} + ia_{ncs,ct} \leq AD_{ct} \qquad \forall ct \in CT \tag{S32}$$

Wind farms

Electricity generated by wind farms ($ef_{neo,ct,t}$) depends of wind power density of a location ($WPD_{ct,t}$), turbines efficiency (η_{neo}), swept area of turbine blades (SA), and number of turbines used ($ut_{ct,t}$).

$$uc_{neo,ct,t} = \eta_{neo} WPD_{ct,t} \left(ut_{ct,t} SA \right) \qquad \forall neo \in NEO, \forall ct \in CT, \forall t \in T \tag{S33}$$

The capacity installed and the area (in this case the area refers to the area of circle created by the blades) must be larger than the capacity and area used in every period.

$$ic_{neo,ct} \geq uc_{neo,ct,t} \qquad \forall neo \in NEO, \forall ct \in CT, \forall t \in T \tag{S34}$$

$$ia_{neo,ct} \geq ua_{neo,ct,t} \qquad \forall neo \in NEO, \forall ct \in CT, \forall t \in T \tag{S35}$$

Total annual cost

One of the objectives in energy transition is to minimize the cost related to new renewable technologies. Therefore, total annual cost is calculated taking into account the annualized capital cost of the renewable power plants installed, the operation and maintenance costs of NPP and EPP, and the biomass transport cost.

$$tcost = \sum_{npp} CRF_{npp}\, tcapcost_{npp} + \sum_{npp} tonmcost_{npp} + \sum_{epp} tonmcost_{epp} + tracost \tag{S36}$$

Multi-objective optimization approach

A sustainable system requires to go beyond economic objective functions, and mathematical optimization models are a powerful tool in decision making when it seeks to satisfy more than one objective. In the mathematical model, we have different objectives to minimize simultaneously, such as, total annual cost, water consumption, and greenhouse gas emissions. In order to minimize all the objectives, we use a normalized multiobjective function as follows:

$$\min \ mof = \varphi_{tcost} + \varphi_{twc} + \varphi_{tghg} \tag{S37}$$

The single objective functions are normalized using utopian and Nadir solutions, as follows:

$$\varphi_{tcost} = \frac{tcost - \Phi_{\mathrm{c}}^{\min}}{\Phi_{\mathrm{c}}^{\max} - \Phi_{\mathrm{c}}^{\min}} \tag{S38}$$

$$\varphi_{twc} = \frac{twc - \Phi_{\mathrm{w}}^{\min}}{\Phi_{\mathrm{w}}^{\max} - \Phi_{\mathrm{w}}^{\min}} \tag{S39}$$

$$\varphi_{tghg} = \frac{tghg - \Phi_{\mathrm{g}}^{\min}}{\Phi_{\mathrm{g}}^{\max} - \Phi_{\mathrm{g}}^{\min}} \tag{S40}$$

NOMENCLATURE

In this paper we have stablished that lowercase symbols are optimization variables, and uppercase symbols are known parameters.

Definitions

CA set of existing carbon power stations

CC set of existing combined cycle

CG set of existing cogeneration power plants

CS set of existing concentrated solar power

EO set of existing onshore wind power plants

HY set of existing hydroelectric power station

PV set of existing photovoltaic power plants

NU set of existing nuclear power plants

NBM set of new potential biomass power plants

NCS set of new potential concentrated solar power

NEO set of new potential onshore wind power stations

NPV set of new potential photovoltaic power stations

Sets

bp	Biomass producers, BP= {47 provinces of Spain}
brm	Varieties of biomass available, BRM= {forest, straw, miscanthus}
ct	Available sites to install a new renewable plant, CT= {47 provinces of Spain}
epp	Existing power plants, EPP= {CC, CA, HI, NU, EO, PV, CS, CG, NPV, NCS, NEO, BM}
npp	New renewable power plants, NPP= {NPV, NCS, NEO, NBM}
t	Number of periods to discretize a year, T= {24 periods, months day/night}

Binary variables

y_{ct}^{npp}	Existence of a new renewable power plant

Continuous variables

$bmc_{bp,ct,brm,t}$	Biomass from production sites and consumed in installation sites, ton/period
$capcost_{npp,ct}$	Capital investment cost of new plants, €
$ef_{npp,ct,t}$	Individual energy flow produced by each technology, MWh/period
epef	Energy produced by the existing power plant, MWh/month
$epghg_{epp,t}$	CO_2 equivalent in existing power plants, ton/period
$epwc_{epp,t}$	Water consumption of existing power plants, m^3/MWh/period
$ia_{npp,ct}$	Total required area in function of installed capacity, km^2
$ic_{npp,ct}$	Required capacity for the new renewable power plants, MW
mof	objective function
npef	Energy produced by the new renewable power plant, MWh/month

$npwc_{npp,ct,t}$	Water consumption of new renewable power plants, m^3/MWh/period
$npghg_{npp,ct,t}$	CO_2 equivalent in new renewable power plants, ton/period
$onmcost_{npp,ct}$	Operation and maintenance cost of new plants, €/y
taa	Total affected area by renewable electricity production, km^2
$tbmc_{ct,brm,t}$	Total consumed biomass in each site in each period, ton/period
$tcapcost_{npp}$	Total capital investment cost of each renewable power plant, €
$tcost$	Total annualized cost that includes capital investment costs, operation and maintenance cost, and transport cost, €/y
$tghg$	Total CO_2 equivalent, ton/year
$tonmcost_{npp}$	Total operation and maintenance cost of each renewable power plant, €/y
$tracost$	Total transport cost of biomass, €/y
$traghg$	Total transport cost of biomass, €/y
twc	Total water consumption by electricity production, m^3/MWh/year
$ua_{npp,ct}$	Used area in each period, km^2
$uc_{npp,ct,t}$	Used capacity in each period, MW
$wkt_{epp,t}$	Time that existing power plants work, h/y
φ_{twc}	Scalarized value of total water consumption
φ_{ghg}	Scalarized value of total CO_2 equivalent
φ_{tcost}	Scalarized value of total annualized cost

Parameters

AD_{ct}	Available area in each potential installation site, km^2
$AVBM_{bp,brm,t}$	Available biomass in each production site, ton/period
CIC_{npp}	Specific investment cost, €/MW
$CMIN^{npp}$	Minimum required capacity for the installation of a new plant, MW
$CMAX^{npp}$	Maximum allowed capacity for a new plant, MW
DEM_t	Energy demand in each period, MWh/period

$DISP_{epp,t}$	Time that the existing power plants can work in function of their capacity factor, h/y
$DISP_{npp,ct,t}$	Time that the new power plants can work in function of their capacity factor, h/y
$DSI_{ct,t}$	Solar resource
GHG_{epp}	CO_2 equivalent generation coefficient for existing power plants, tCO_2eq/MWh
$GHG_{npp,ct}$	CO_2 equivalent generation coefficient for existing power plants, tCO_2eq/MWh
IC_{epp}	Installed capacity of existing power plants, MW
LHV_{brm}	Low heating value, MWh/ton
OM_{npp}	Fixed fraction of the capital investment costs over the entire lifetime of the technology to calculate O&M.
SA	Swept area of turbine blades, km^2
$UTC_{ct,bp}$	Transport cost from production sites to consume places, €/km/ton
$UTE_{ct,bp}$	Transport emissions from production sites to consume places, tCO_2/km/ton
$WPD_{ct,t}$	Wind power density
WC_{epp}	Water consumption coefficient for existing technologies, m^3/MWh
$WC_{npp,ct}$	Water consumption coefficient for new technologies, m^3/MWh
η_{npp}	Efficiency of new power plants
$\Phi_c^{\min}$	Total water consumption in utopia point, €/y
$\Phi_g^{\min}$	Total CO_2 equivalent in utopia point, tCO_2eq/y
$\Phi_w^{\min}$	Total annualized cost in utopia point, m^3/y
$\Phi_c^{\max}$	Total water consumption in Nadir point, €/y
$\Phi_g^{\max}$	Total CO_2 equivalent in Nadir point, tCO_2eq/y
$\Phi_w^{\max}$	Total annualized cost in Nadir point, m^3/y

GEOGRAPHIC INFORMATION

Figure S1 presents a map with the 47 provinces of Spain used in the case study.

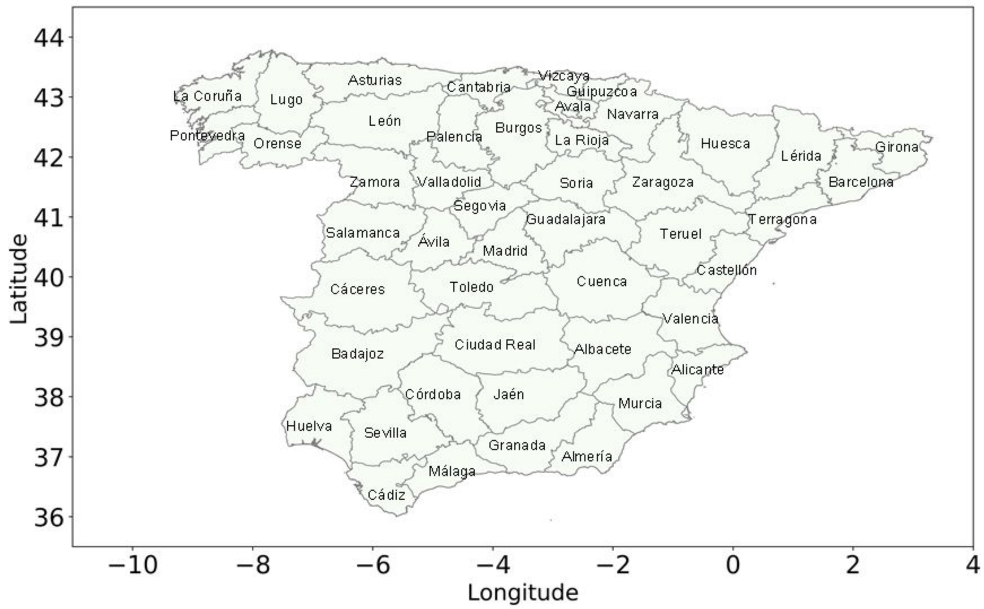

Figure S1. Provinces in the Spanish Peninsula.

GENERATION STRUCTURE OF THE CURRENT POWER SYSTEM

Tables S1 and S2 present the percentage share of the technologies that are consider in the current system.

Table S1. Percentage share of each technology in electricity supply using a multiobjective optimization function.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
CA	4.5	1.6	1.8	1.8	1.8	1.7	3.9	1.7	2.7	1.8	4.4	2.2
NU	21.8	23.8	26.1	26.5	26.2	25.1	22.8	24.2	24.6	25.8	23.0	24.3
CC	26.8	18.1	13.5	14.1	16.7	25.4	30.6	31.3	32.8	30.5	28.6	27.9
CG	11.8	12.8	14.0	14.3	14.1	13.5	12.3	13.0	13.2	13.9	12.4	13.1
EO	23.8	27.1	28.0	22.9	20.8	15.7	14.5	15.0	14.0	17.7	22.1	21.1
PV	1.9	2.6	3.6	4.0	4.5	4.6	4.3	4.2	3.8	3.2	2.2	2.1
HI	8.8	13.0	10.5	13.5	11.6	9.3	6.9	6.0	5.7	5.2	6.5	8.6
CS	0.6	1.0	2.5	2.9	4.2	4.7	4.7	4.5	3.1	1.9	0.8	0.7

Table S2. Percentage share of each technology in electricity supply (elaborated with information from REE[10]).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
CA	13.5	11.9	4.3	4.0	1.8	2.2	3.0	1.7	2.3	3.5	2.6	1.8
NU	22.2	25.3	27.7	25.5	21.0	24.3	23.6	24.7	25.6	23.6	16.4	21.3
CC	14.1	13.0	11.2	15.0	20.6	26.7	32.0	34.3	27.8	29.2	18.5	13.5
CG	11.7	12.7	13.6	13.7	13.5	12.7	11.3	11.5	12.1	13.0	11.8	11.5
EO	26.3	19.3	25.3	25.4	24.2	16.8	15.1	13.3	19.4	19.3	35.1	26.5
PV	2.1	3.2	4.1	3.7	4.7	4.7	4.4	4.7	4.2	4.0	2.4	2.4
HI	9.4	13.2	11.2	10.6	10.2	8.5	7.3	6.1	6.3	5.8	12.8	22.7
CS	0.7	1.4	2.5	2.1	3.9	4.1	3.3	3.6	2.3	1.6	0.3	0.3

PARAMETERS USED IN THE CASE STUDY

In this section additional parameters that were used to solve the mathematical model are presented, such as, water consumption, capital cost factor, operation and maintenance cost factor, and used demand.

Table S3. Water consumption of electricity supply technologies.

Technology	L/kWh	Source
Combined cycle	Calculated using equation 42S	Calculated[3]
Coal	Calculated using equation 41S	Calculated[3]
Cogeneration	Calculated using equation 42S	Calculated[3]
Nuclear	Calculated using equation 41S	Calculated[3]
Hydro	4.961	Reported[2]
Wind power	0.043	Reported[2]
Photovoltaic	0.33	Reported[2]
Concentrated solar power	Calculated using equation 41S	Calculated[3]
Biomass	Calculated using equation 41S	Calculated[3]

Rankine Cycle

$$WC(L/kWh) = -2.297\times10^{-4}\left(T^2\right) + 0.798\left(H^2\right) + 7.090\left(p^2\right) + 2.2\times10^{-2}\left(T\right)\left(H\right)$$
$$+2.993\times10^{-2}\left(T\right)\left(p\right) - 0.515\left(H\right)\left(p\right) - 1.533\times10^{-2}\left(T\right) - 1.417\left(H\right)$$
$$-12.574\left(p\right) + 7.6256$$

(41S), taken from Reference [3]

Combined cycle

$$WC\left(L/kWh\right) = -4.75\times10^{-4}\left(T^2\right) + 1.255\left(H^2\right) + 8.083\left(p^2\right) + 3.453\times10^{3}\left(T\right)\left(H\right)$$
$$+5.833\times10^{-2}\left(T\right)\left(p\right) + 1.292\left(H\right)\left(p\right) - 3.447\times10^{-2}\left(T\right) - 3.255\left(H\right)$$
$$-16.555\left(p\right) + 9.690$$

(42S), taken from Reference [3]

Where:

WC: Water Consumption, L/kWh

T: Temperature, °C

H: Humidity

p: Pressure, atm

Table S4. Operation and maintenance cost different power technologies.

Technology	EUR/MWh	Source
Combined cycle	86.3	Reported [6]
Coal	55.6	Reported [6]
Cogeneration	86.3	Reported [6]
Nuclear	21.6	Reported [6]
Hydro	≈ 0	Reported [6]
Wind power	25.6	Reported [6]
Photovoltaic	41.9	Reported [6]
Concentrated solar power	81.3	Reported [6]
Biomass	86.3	Reported [6]

Table S5. Capital investment cost of renewable energy technologies.

Technology	EUR/kW	Source
Wind power	1290	Reported [5]
Photovoltaic	860	Reported [5]
Concentrated solar power	4070	Reported [5]
Biomass	3330	Reported [5]

Table S6. Electricity demand used in the case study.

Period	Demand (MWh)
JAN-D	12157902
JAN-N	10356731.3
FEB-D	11112831
FEB-N	9466485.67
MAR-D	11460555
MAR-N	9762695
APR-D	10430325
APR-N	8885091.67
MAY-D	10725264
MAY-N	9136336
JUN-D	10989117
JUN-N	9361099.67
JUL-D	12059730
JUL-N	10273103.3
AUG-D	11461932
AUG-N	9763868
SEP-D	10926477
SEP-N	9307739.67
OCT-D	10780497
OCT-N	9183386.33
NOV-D	11053521
NOV-N	9415962.33
DEC-D	11485584
DEC-N	9784016

ENERGY TRANSITION: TRADE-OFF ANALYSIS

The presented multiobjective formulation enables to perform trade-off analysis between the objectives. For example, we can explore the behavior of the system when we assign different levels of priority to each objective. In this case the multiobjective function of the model is multiplied by weight factor that prioritize certain objective (water consumption, total annual cost and/or greenhouse gas emissions) as follows:

$$\min \ mof = w_1\left(\varphi_{twc}\right) + w_2\left(\varphi_{tcost}\right) + w_3\left(\varphi_{tghg}\right) \qquad \text{(S43)}$$

Table S7 presents examples of different weight factors that can be consider for each objective. Mentioned weight factors were used to solve the mathematical model, and the results of all the scenario presented by Table S7 are presented in Figure S2.

Table S7. Levels of priority assigned to each objective.

Scenario	Weight factors		
	w_1	w_2	w_3
Min GHG	0	0	1
Min TAC	0	1	0
Min Water	1	0	0
Min MO	0.333	0.333	0.333
A	0	0.5	0.5
B	0.5	0	0.5
C	0.5	0.5	0
D	0	0.66	0.33
E	0.66	0	0.3
F	0.66	0.33	0
G	0	0.33	0.66
H	0.33	0	0.66
I	0.33	0.66	0

Scenarios named as Min GHG, Min TAC and Min Water consider only one objective. The Scenarios A to I examine the effect of considering 2 objectives using different weights.

Moreover, the scenario Min MO considers the three objectives at the same time with the same level of priority. The effect of the weights in the objective function can be observed in Figure S2. Each point presented in the figure is a different solution, and it represents a combination of renewable energy plants and a generation structure like the one presented in Figure S3 and Figure S4, respectively.

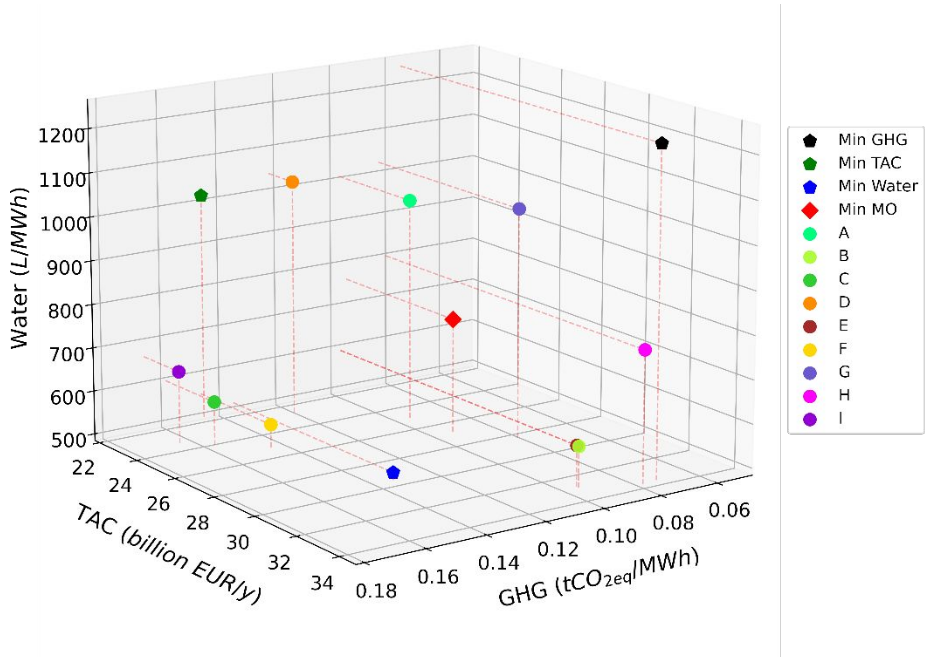

Figure S2. Trade-off between the objectives considered.

On the other hand, it is possible to investigate intermediate solutions as presented below. As it can be observed in the paper, to reduce freshwater use and greenhouse gas emissions, the multi-objective solution requires an investment 23.46% larger that the case where TAC is minimized. In the following section two intermediate TAC solutions (Trade-off of cost S1 and S2) were calculated between the minimum TAC solution (22,133.31 MEUR/y) and the solution of the TAC of multi-objective solution (27,325.67 MEUR/y). The selected values are 25,594.88 MEUR/y and 23,864.10 MEUR/y because they are equidistant from the selected limits. The results of both cases are presented in Table S8, and the optimal technologies and locations and the generation structure are presented below.

Table S8. Summary of environmental and economic results.

Variable (units)	Base Case	Transition Min TAC	Transition Min MO	TAC trade-off Min MO-S1	TAC trade-off Min -S2
GHG ($MtCO_2eq/y$)	47.647	36.838	23.975	26.702	32.392
Water (hm^3/y)	303.766	253.09	189.856	199.347	195.974
tCO_2eq/MWh	0.19	0.15	0.10	0.11	0.13
L/MWh	1,218	1,015	761	799	786
TAC (MEUR/y)	12,360.01	22,133.31	27,325.67	25,594.88	23,864.1
Capital cost (MEUR)	-	71,716.56	136,052.5	114,603.6	95,455.0
epef (TWh/y)	249.3	154.2	117.3	118.5	131.1
npef (TWh/y)	-	95.2	132.1	130.9	118.2
Renewable (TWh/y)	141.2	175.0	199.7	198.2	187.5
Nonrenewable (TWh/y)	108.1	74.3	49.7	51.2	61.8

Trade-off of cost Min MO-S1

In this scenario, the total annual cost has an upper bound of 25,594.88 MEUR/y; therefore, biomass technology becomes attractive because it is not necessary to oversize the installed capacity since the capacity factor of this technology does not depend of variant condition like solar and wind resources. However, greenhouse gas emissions and water consumption increase 10.21% and 4.76%, respectively, with respect to the MO solution, with a restriction of reducing TAC by 6.33%. If we compare the selected energy mix suggested by this scenario with the original MO problem, the main difference is the preference of biomass over wind and concentrated solar power. An installed capacity of 2,815 MW of NBM power technology reduces the installed capacity of NPV, NCS and NEO by 2.09%, 21.58% and 35%29%, respectively, as shown in Figure S3. Figure S4 shows that the energy mix corresponding to the existing technology remains the same while biomass partially substitutes wind and CSP. This solution seems to be less sustainable than the multi-objective solution, but biomass technology gives more flexibility to the electric system than wind and solar technologies, which availability of energy resource is uncertain.

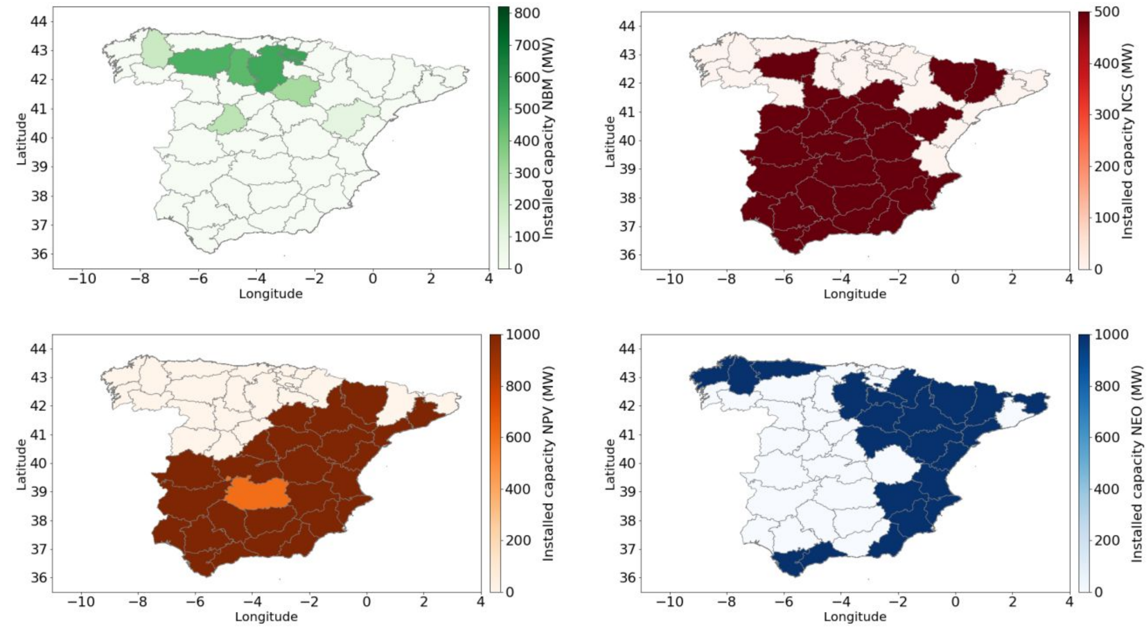

Figure S3. Required capacity and location of renewable energies. Trade-off of cost Min MO-S1.

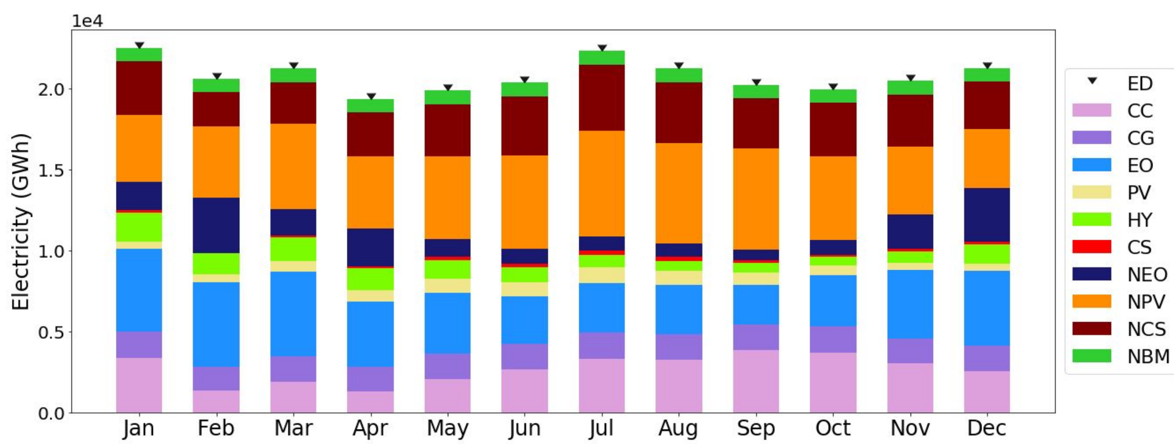

Figure S4. Structure generation of PES. Trade-off of cost Min MO-S1.

Trade-off of cost Min MO-S2

In this case, the upper bound for the TAC is set to 23,864.10 MEUR/y, the results in Figure S5 and Figure S6 show that a cost reduction (12.67%) results in the need to increase the biomass installed capacity while the installed capacity of wind and CSP falls. An installed capacity of 8,180 MW of biomass power technology reduces the installed capacity of NCS and NEO by 68.05% and 49.22%, respectively. Consequently, greenhouse gas emissions and water consumption increase 21.31% and 3.22%, respectively. Biomass technology increases the greenhouse gas emissions but requires less installed capacity due to its higher capacity factor and gives more flexibility to the electric system than wind and solar technologies.

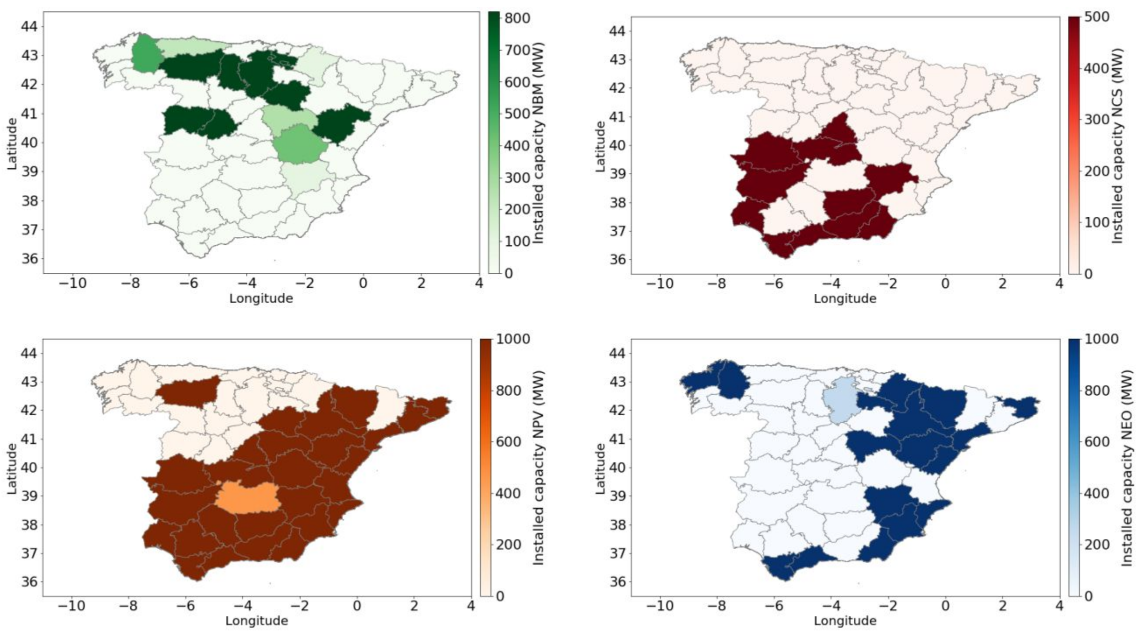

Figure S5. Required capacity and location of renewable energies. Trade-off of cost Min MO-S2.

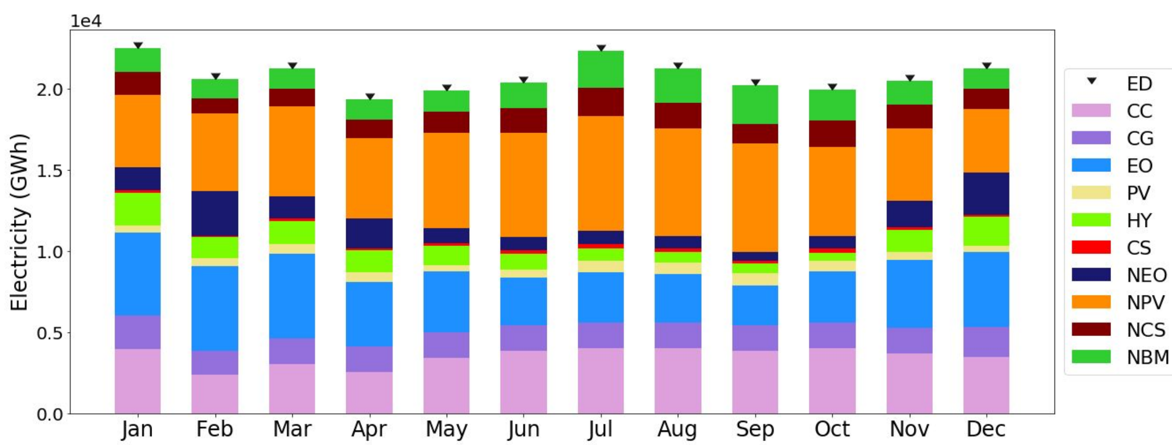

Figure S6. Structure generation of PES. Trade-off of cost Min MO-S2.

As shown above, the mathematical model proposed gives helpful information to decisionmakers towards guiding the energy transition. For example, this type of analysis can be useful when a country needs to meet an emissions reduction target like those raised in the Paris agreement. However, in future work we will consider additional information about power plant flexibility in the model, i.e. start-up time, start-up cost, part-load efficiency, and ramp rate, in order to include the maximization of flexibility in the optimization objective.

REFERENCES

(1) Gonzalez-Salazar, M. A.; Kirsten, T.; Prchlik, L. Review of the Operational Flexibility and Emissions of Gas- and Coal-Fired Power Plants in a Future with Growing Renewables. *Renew. Sustain. Energy Rev.* **2018**, *82*, 1497–1513. https://doi.org/10.1016/j.rser.2017.05.278.

(2) Jin, Y.; Behrens, P.; Tukker, A.; Scherer, L. Water Use of Electricity Technologies: A Global Meta-Analysis. *Renew. Sustain. Energy Rev.* **2019**, *115*, 109391. https://doi.org/10.1016/j.rser.2019.109391.

(3) Guerras, L. S.; Martín, M. On the Water Footprint in Power Production: Sustainable Design of Wet Cooling Towers. *Appl. Energy* **2020**, *263*, 114620. https://doi.org/10.1016/j.apenergy.2020.114620.

(4) IPCC. AR5 Climate Change 2014: Mitigation of Climate Change — IPCC https://www.ipcc.ch/report/ar5/wg3/ (accessed Apr 14, 2020).

(5) Tsiropoulos, I.; Tarvydas, D.; Zucker, A. Cost Development of Low Carbon Energy Technologies - Scenario-Based Cost Trajectories to 2050, 2017 Edition. *JRC Sci. Policy Reports* **2018**. https://doi.org/10.2760/490059.

(6) NEA; IEA; OECD. *Projected Costs of Generating Electricity 2015*; OECD Publishing: Paris, 2015. https://doi.org/10.1787/cost_electricity-2015-en.

(7) Rogers, J. G.; Brammer, J. G. Analysis of Transport Costs for Energy Crops for Use in Biomass Pyrolysis Plant Networks. *Biomass and Bioenergy* **2009**, *33* (10), 1367–1375. https://doi.org/10.1016/j.biombioe.2009.05.018.

(8) European Environment Agency. Specific CO2 emissions per tonne-km and per mode of transport in Europe — European Environment Agency https://www.eea.europa.eu/data-and-maps/daviz/specific-co2-emissions-per-tonne-2#tab-chart_2 (accessed Apr 15, 2020).

(9) Ng, R. T. L.; Maravelias, C. T. Design of Cellulosic Ethanol Supply Chains with Regional Depots. *Ind. Eng. Chem. Res.* **2016**, *55* (12), 3420–3432. https://doi.org/10.1021/acs.iecr.5b03677.

(10) REE. Demanda de energía eléctrica en tiempo real, estructura de generación y emisiones de CO2 https://demanda.ree.es/visiona/peninsula/demanda/total (accessed Jan 29, 2020).