Supporting Information: Towards a New Renewable Power System using Energy Storage: an Economic and Social Analysis

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1 Model formulation

1.1 Mass balances

The general equation for the mass balance of the different processes for a given facility is as follows:

$$\overline{Q}_{jht} = \overline{Q}_{jht-1} + B_{jht} - S_{jht} + \sum_{i} \rho_{ij} P_{iht} + \quad \forall\, j,\, h,\, t \in \overline{T}_h \tag{S1}$$

In this equation, the amount of resource j stored at time t of season h is represented by $\overline{Q}_{rjht}$. B_{rjht} and S_{rjht} denote the amounts of consumed or discharged resource at each location. The amount of reference resource produced or consumed is denoted by P_{riht}. Finally, the parameter ρ_{ij} denotes the conversion factor between resource j and the reference resource of process i.

The production of the reference resource in each process i is limited by the plant capacity:

$$P_{iht} = \eta_{iht} C_i \quad \forall\, i \in \{PV, WT\},\, h,\, t \in \overline{T}_h \tag{S2}$$

$$P_{iht} \leq \eta_{iht} C_i \quad \forall\, i \in I \setminus \{PV, WT\},\, h,\, t \in \overline{T}_h \tag{S3}$$

The plant capacity is denoted by C_i. The parameter η_{ikt} is used to represent the time-varying process capacity, for instance, wind or solar generation, where the capacity is not only a function of the plant size but also of the wind/solar availability. This parameter is calculated using the solar irradiance/ambient (Sánchez and Martín, 2018a; Hlal et al., 2019) temperature or the wind velocity (de la Cruz and Martín, 2016) for each time period and location.

The storage capacity $\overline{C}_j$ is an upper bound for the inventory level in those resources with associated storage.

$$\overline{Q}_{jht} \leq \overline{C}_j \quad \forall\, j \in \hat{S},\, h,\, t \in \overline{T}_h \tag{S4}$$
$$\overline{Q}_{jht} = 0 \quad \forall\, j \notin \hat{S},\, h,\, t \in \overline{T}_h \tag{S5}$$

The set $\hat{S}$ consists of all resources that can be stored (battery power, hydrogen and methane/ammonia in this particular analyzed facilities).

For the specific case of the battery, a minimum level is imposed to avoid problems in the performance and durability of the unit. In this case, a 15% of the capacity is set as minimum level of storage.

$$\overline{Q}_{jht} \geq 0.15\overline{C}_j \quad \forall\, j \in \{\text{Battery}\},\, h,\, t \in \overline{T}_h \tag{S6}$$

There is a maximum value for the capacity ($C_i^{\max}$)for each process involved in the network. The binary variable x_i indicates whether process i is selected in the process network.

$$C_i \leq C_i^{\max} x_i \quad \forall\, i \tag{S7}$$

In this particular case, the process capacities of the battery charge and discharge must be the same (both are determined by the battery specifications):

$$C_{BC} = C_{BD} \tag{S8}$$

Similarly, there is also a maximum value for the storage capacity denoted by $\overline{C}_j^{\max}$. The binary variable $\bar{x}_j$ is equal to 1 if a storage facility for product j is selected.

$$\overline{C}_j \leq \overline{C}_j^{\max} \bar{x}_j \quad \forall\, j \tag{S9}$$

The resource availability is also limited for those resources used as raw materials in the proposed network (indicated by the set $\hat{B}$).

$$B_{jht} \leq B_{jht}^{\max} \quad \forall\, j \in \hat{B},\, h,\, t \in \overline{T}_h \tag{S10}$$
$$B_{jht} = 0 \quad \forall\, j \notin \hat{B},\, h,\, t \in \overline{T}_h \tag{S11}$$

Some resources (includes in the set $\tilde{B}$) could have a maximum annual consumption not to be exceeded. In this particular case, biomass is included in this set with a maximum availability depending of the region.

$$\sum_h \sum_t B_{jht} = \overline{B}_j^{max} \quad \forall\, j \in \tilde{B} \tag{S12}$$

Some resources of the network do not have an associated demand (i.e., they are not in the set $\hat{J}$). Therefore, the outlet flowrate of these species is fixed to 0:

$$S_{jht} = 0 \quad \forall\, j \notin \hat{J},\, h,\, t \in \overline{T}_h \tag{S13}$$

1.2 Mode-based operation

Each of the processes involved can operate in four different operating modes: off, startup, on and shutdown. The binary variable y_{imht} indicates if a process i is operating in a certain mode m. If a process is selected, one of the operating modes must be assigned:

$$\sum_{m \in M_i} y_{imht} = x_i \quad \forall\, i,\, h,\, t \in \overline{T}_h \tag{S14}$$

The set M_i denotes the set of allowed operating modes for process i.

In the particular case of the battery charge and discharge processes, only one of the two could be in on mode at the same time (it is not possible to charge and discharge the battery simultaneously):

$$\sum_{i \in \{BC,BD\}} y_{imht} \leq 1 \quad \forall\, m \in \{ON\},\, h,\, t \in \overline{T}_h \tag{S15}$$

The amount of reference resource consumed or produced by process i, P_{iht}, must be produced or consumed in one of the different operating modes. The variable $\overline{P}_{imht}$ denotes the quantity of reference resource consumed or produced in mode m:

$$P_{iht} = \sum_{m \in M_i} \overline{P}_{imht} \quad \forall\, i,\, h,\, t \in \overline{T}_h \tag{S16}$$

A maximum ($\widetilde{C}_{im}^{\max}$) and minimum ($\widetilde{C}_{im}^{\min}$) value for the amount of reference resource produced or consumed for each mode is introduced:

$$\widetilde{C}_{im}^{\min}\, y_{imht} \leq \overline{P}_{imht} \leq \widetilde{C}_{im}^{\max}\, y_{imht} \quad \forall\, i,\, m \in M_i,\, h,\, t \in \overline{T}_h \tag{S17}$$

The following constraints are related to the transition between operating modes for the same process unit. The maximum rate of change within a mode is limited by an upper bound ($\bar{\Delta}_{im}^{\max}$):

$$\begin{aligned} -\bar{\Delta}_{im}^{\max} - \overline{M}(2 - y_{imht} - y_{imh,t-1}) &\leq \overline{P}_{imht} - \overline{P}_{imh,t-1} \\ &\leq \bar{\Delta}_{im}^{\max} + \overline{M}(2 - y_{imht} - y_{imh,t-1}) \quad \forall\, i,\, m \in M_i,\, h,\, t \in \overline{T}_h \end{aligned} \tag{S18}$$

The binary variable $z_{im'mht}$ is introduced to indicate that process i switches from mode m to mode m' at time t. The possible transitions are defined by the following equation:

$$\begin{aligned} &\sum_{m' \in \overline{TR}_{im}} z_{im'mh,t-1} - \sum_{m' \in \overline{TR}_{im}} z_{imm'h,t-1} = y_{imht} - y_{imh,t-1} \\ &\quad \forall\, i,\, m \in M_i,\, h,\, t \in \overline{T}_h \end{aligned} \tag{S19}$$

where the set TR_i includes all the possible mode-to-mode transitions for the process i, and $\overline{TR}_{im} = \{m' : (m', m) \in TR_i\}$ and $\widehat{TR}_{im} = \{m' : (m, m') \in TR_i\}$.

A process i must remain for a certain minimum number of time periods ($\theta_{imm'}$) in an operating mode m before switching to another mode m':

$$y_{im'ht} \geq \sum_{k=1}^{\theta_{imm'}} z_{imm'h,t-k} \quad \forall\, i,\, (m, m') \in TR_i,\, h,\, t \in \overline{T}_h \tag{S20}$$

Finally, predefined sequences of modes (from mode m to mode m' to mode m'') for a process i can be defined, establishing a fixed stay time for each of the modes involved in the sequence.

$$z_{imm'h,t-\bar{\theta}_{imm'm''}} = z_{im'm''ht} \quad \forall\, i,\, (m, m', m'') \in SQ_i,\, h,\, t \in \overline{T}_h \tag{S21}$$

The set SQ_i denotes the set of predefined sequences for process i and $\bar{\theta}_{imm'm''}$ is the fixed stay time in mode m' in the predefined sequence.

1.3 Continuity constraints

Continuity constraints ensure the feasible transition between seasons. A cyclic schedule is imposed; therefore, the initial mode of a season must be the same as the final one.

$$y_{imh,0} = y_{imh,|\overline{T}_h|} \quad \forall\, i,\, m \in M_i,\, h \tag{S22}$$

$$z_{imm'ht} = z_{imm'h,t+|\overline{T}_h|} \quad \forall\, i,\, (m, m') \in TR_i,\, h,\, -\theta_i^{\max} + 1 \leq t \leq -1 \tag{S23}$$

For the transitions between seasons, the state at the final time of one season and at the initial time of the next season must be the same.

$$y_{imh,|\overline{T}_h|} = y_{im,h+1,0} \quad \forall\, i,\, m \in M_i,\, h \in H \setminus |H| \tag{S24}$$

$$\begin{aligned} &z_{imm'h,t+|\overline{T}_h|} = z_{imm',h+1,t} \\ &\forall\, i,\, (m, m') \in TR_i,\, h \in H \setminus |H|,\, -\theta_i^{\max} + 1 \leq t \leq -1. \end{aligned} \tag{S25}$$

The storage is allowed between seasons. The following equations determine the change in inventory levels from one season to the next.

$$\hat{Q}_{jh} = \overline{Q}_{jh,|\overline{T}_h|} - \overline{Q}_{jh,0} \quad \forall\, j \in \hat{S},\, h \tag{S26}$$

$$\overline{Q}_{jh,0} + n_h\, \hat{Q}_{jh} = \overline{Q}_{j,h+1,0} \quad \forall\, j,\, h \in H \setminus |H| \tag{S27}$$

$$\overline{Q}_{j,|H|,0} + n_{|H|}\, \hat{Q}_{j,|H|} = \overline{Q}_{j,1,0} \quad \forall\, j \tag{S28}$$

1.4 Objective function

The objective of this work is to meet a given power demand $D_{power,h,t}$ using the different proposed technologies (including storage).

$$S_{jht} = D_{jht} \quad \forall\, j \in \hat{J},\, h,\, t \in \overline{T}_h \tag{S29}$$

The goal is to minimize the following objective function:

$$
\begin{aligned}
OC = &\sum_i \sum_{m \in M_i} \sum_h \sum_t J_{imht} + \sum_i \sigma_i \left(\delta_i x_i + \gamma_i C_i\right) + \\
&\sum_{j \in \hat{S}} \left(\alpha_j \bar{x}_j + \beta_j \overline{C}_j\right) + \sum_i \sum_j \sum_h \sum_t \xi_{ij} \rho_{ij} P_{iht} \\
&\sum_h \sum_t \varphi_{CO_2} B_{CO_2,ht}
\end{aligned}
\tag{S30}
$$

which comprises the costs of production and storage.

The piece-wise linear approximation used to compute the first term of equation (S30), J_{imht}, is as follows:

$$P_{imht} = \sum_{l \in L_i} \left(\lambda_{imhtl} \left(\hat{P}_{im,l-1} - \hat{P}_{im,l}\right) + \hat{P}_{iml} \omega_{imhtl}\right) \quad \forall\, i,\, m \in M_{ri},\, h,\, t \tag{S31}$$

$$J_{imht} = \sum_{l \in L_i} \left(\lambda_{imhtl} \left(\hat{J}_{im,l-1} - \hat{J}_{im,l}\right) + \hat{J}_{iml} \omega_{imhtl}\right) \quad \forall\, i,\, m \in M_{ri},\, h,\, t \tag{S32}$$

$$\lambda_{imhtl} \le \omega_{imhtl} \quad \forall\, i,\, m \in M_i,\, h,\, t,\, l \in L_i \tag{S33}$$

$$\sum_{l \in L_i} \omega_{iktl} = y_{ikt} \quad \forall\, i,\, m \in M_i,\, h,\, t \tag{S34}$$

2 Modeling Parameters

The values for the parameters in the biomass process changes between the different regions according to the biomass selected following the procedure explained in the manuscript. In this section, the biomass parameters for the province of Almeria are presented as example. The sources from the different data are:

1. **Wind Turbines (WT):** de la Cruz and Martín (2016).
2. **Photovoltaic (PV):** Sánchez and Martín (2018a); Hlal et al. (2019).
3. **Biomass gasifier/gas turbine (BIO)** Sánchez et al. (2019); León and Martín (2016).
4. **Battery charge (BC):** Gonzalez-Castellanos et al. (2020).
5. **Battery discharge (BD)** Gonzalez-Castellanos et al. (2020).
6. **Water electrolysis (EL):** Sánchez and Martín (2018a).
7. **Hydrogen fuel cell (FC):** Kashefi Kaviani et al. (2009); Palys and Daoutidis (2020).
8. **Methane production (CH):** Davis and Martín (2014).
9. **Methane gas turbine (CHGT):** León and Martín (2016).
10. **Air separation (AS):** Sánchez and Martín (2018b).
11. **Ammonia synthesis (NH):** Sánchez and Martín (2018a).
12. **Ammonia based power production (NHGT):** Sánchez et al. (2021).

Parameter $\rho_{i,j}$

Process	Resource	Yield (kW/kW or kg/kW)	Process	Resource	Yield (kW/kW or kg/kW)
PV	Solar	-1	CH	Power	-1
PV	Power	1	CH	H_2	-1.26639437E-01
WT	Wind	-1	CH	CO_2	-6.96619528E-01
WT	Power	1	CH	CH_4	2.40758605E-01
BIO	Power	1	CHGT	Power	1
BIO	Biomass	-1.317336E-04	CHGT	CH_4	-3.0644E-05
BIO	O_2	-1.541830E-05	CHGT	CO_2	8.4271E-05
BC	Power	-1	AS	Power	-1
BC	Battery power	0.97	AS	N_2	9.06520023E-04
BD	Power	1	NH	Power	-1
BD	Battery power	-1.1494	NH	H_2	-7.90036943E-05
EL	Power	-1	NH	N_2	-8.5248111E-04
EL	Water	-4.48263608E-05	NH	NH_3	3.19096482E-04
EL	H_2	5.12612885E-06	NHGT	Power	1
FC	Power	1	NHGT	N_2	8.1258E-04
FC	H_2	-5.5556E-06	NHGT	NH_3	-1.58344E-04

Maximum process capacity C_i^{max}

Process	C_i^{max} (area or kW)	Process	C_i^{max} (area or kW)
PV	5% of total area of the sub-region	FC	100000
WT	5% of total area of the sub-region	CH	14.6
BIO	68050	CHGT	200000
BC	3000	AS	60601
BD	3000	NH	85667
EL	495110.46	NHGT	200000

Maximum storage capacity $\overline{C}_i^{max}$

Resource	$\overline{C}_i^{max}$ (kJ or kg)
Battery	1.08e8
H_2	18000
N_2	650000
CH_4	2e7
NH_3	7e7

Process capital cost δ_i, γ_i

Resource	δ_i (MM$)	γ_i (MM$ / area or MM$/kW)
PV	0.0001	1.60865979e-4
WT	0.0001	4.91e-4
BIO	1.495353e1	2.398390e-3
BC	0	0
BD	0	0
EL	17.72062345	0.00161936
FC	9.4377e-2	1.9593e-3
CH	0.0001	2.327738
CHGT	0.0001	0.882e-3
AS	1.26183952e1	4.568879e-3
NH	1.14249824e1	9.25374128e-3
NHGT	5.2878893e1	0.003882

Storage capital cost α_i, β_i

Resource	α_i (MM$)	β_i (MM$/kJ or MM$/kg)
Battery	0	0.07111
H_2	0.0001	500
N_2	0.0001	12.5
CH_4	0.0001	3.26
NH_3	0.0001	3.1

Piece-wise linear approximation $\hat{P}_{iml}$, $\hat{J}_{iml}$

Resource	(kW)	(MM$/year)	Resource	(kW)	(MM$/year)
PV	0	0	FC	100000	17.5
PV	5.00E+09	0	CH	0	0.25
WT	0	0	CH	3.41	0.44
WT	5.00E+09	0	CH	14.6163	0.66
BIO	0	0.2394925	CHGT	0	0
BIO	69762.321	3.66814385	CHGT	200000	2.6
BC	0	0	AS	0	0
BC	3500	0	AS	60600.98	-10.4334063
BD	0	0	NH	0	0.25
BD	3500	0	NH	5354.18	0.409
EL	0	0	NH	85666.88	0.351
EL	16503.9	-0.17744678	NHGT	0	0
EL	990220.9	-25.3211135	NHGT	600000	-114.0064
FC	0	0			

Storage O&M cost ξ_j

Resource	ξ_j ($/kJ or $/kg)
Battery	83.3333 e-9
H_2	0
N_2	0
CH_4	0.225
NH_3	0

3 Operating Results

The scheduling results for the location of Asturias and Almeria are shown in this section complementing those presented in the manuscript. Therefore, Figure S1 shows the scheduling results for scenario 1 in the province of Almeria, Figure S2 the results for scenario 2 in the region of Asturias, and, finally, Figure S3 the results for scenario 3 in the province of Almeria.

The process capacity results for all the studied regions have been included in Table S1 for scenario 1. Table S2 includes the capacities for scenario 2, in which biomass is introduced. Finally, Table S3 presents the process capacities for scenario 3.

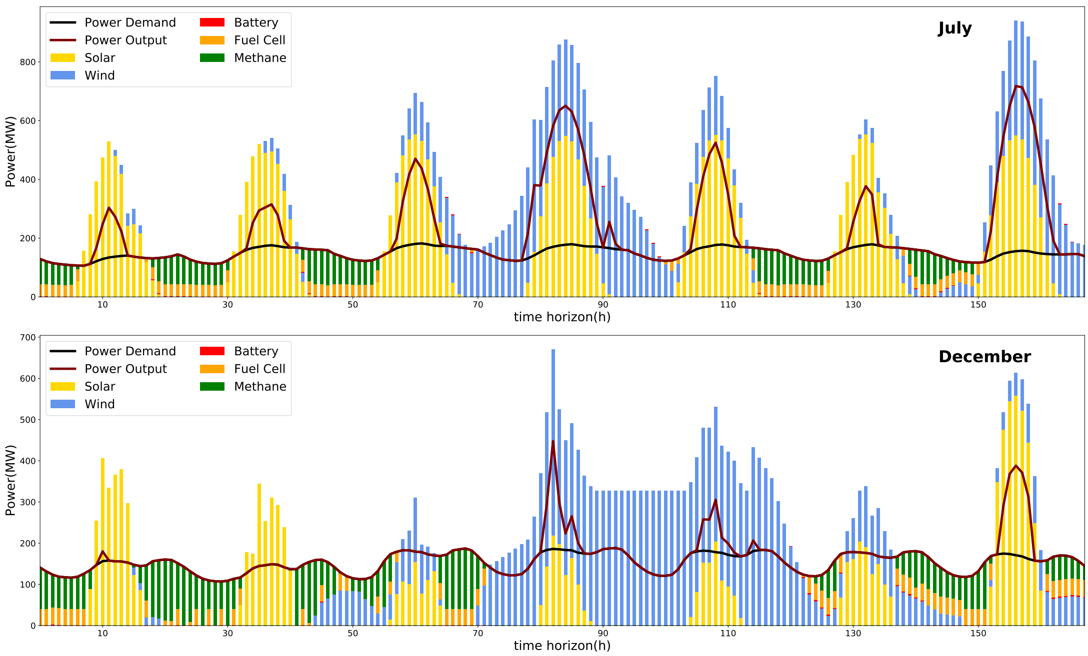

Figure S1: Scheduling results for the Scenario 1 in Almeria

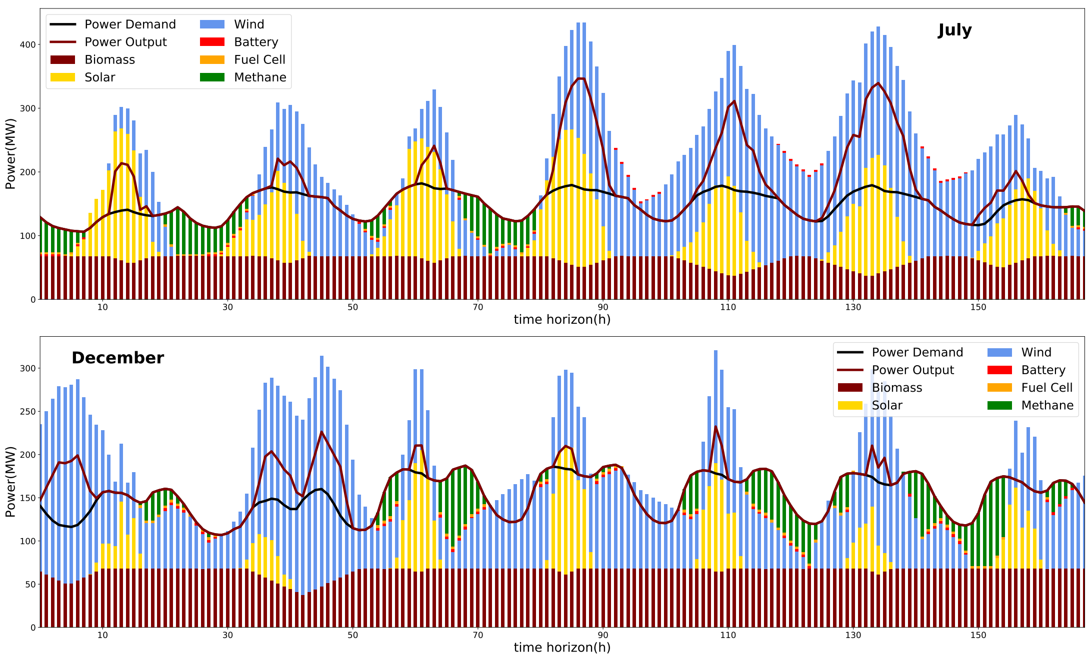

Figure S2: Scheduling results for the Scenario 2 in Asturias

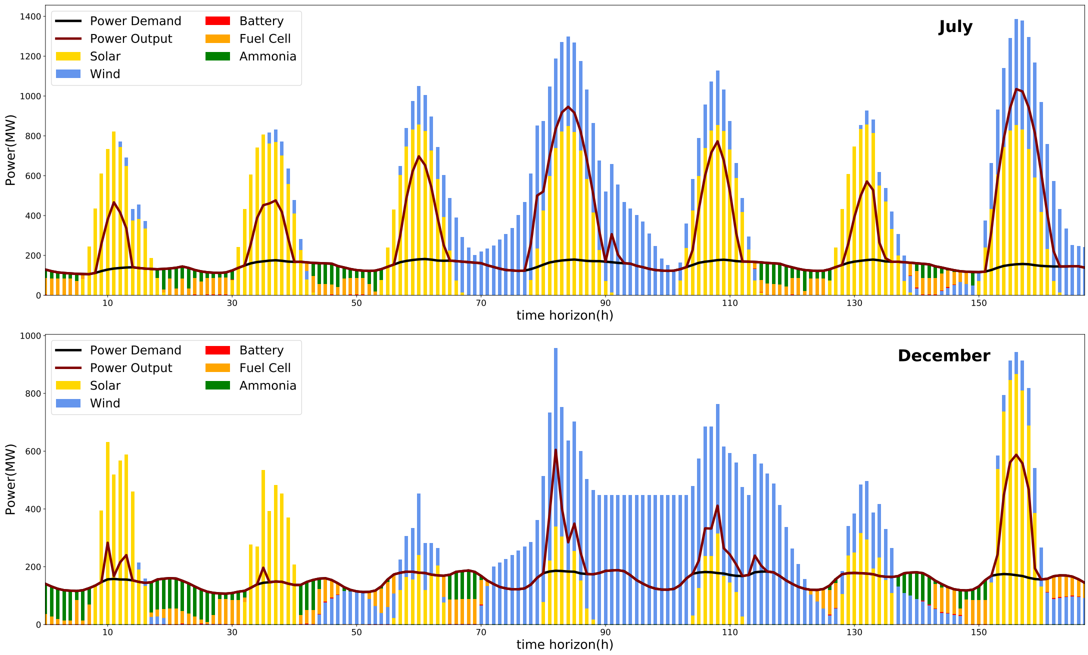

Figure S3: Scheduling results for the Scenario 3 in Almeria

Table S1: Process capacities for the scenario 1

	Asturias	Almeria	Badajoz	Teruel	Leon	Coruña	Cordoba	Ciudad Real	Sevilla	Zaragoza	Burgos	Navarra	Soria	Salamanca
Solar (ha)	193.18	282.87	525.90	281.30	378.33	188.53	667.06	508.22	333.82	232.04	298.11	216.15	288.94	392.37
Wind (ha)	107.55	98.22	134.35	96.88	115.08	101.89	165.09	134.66	117.36	102.55	101.04	106.59	102.70	117.46
Battery (MW)	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Electrolysis (MW)	173.76	223.08	223.08	221.34	223.08	150.56	223.08	223.08	223.08	201.03	221.88	183.41	223.08	223.08
Fuel Cell (MW)	14.16	40.65	56.32	43.25	49.94	11.79	65.62	56.83	49.03	27.84	43.47	18.39	45.71	49.91
CH_4 production (kW)	6.64	7.90	8.67	7.89	8.45	5.71	8.75	8.81	8.34	7.48	8.04	6.82	8.14	8.68
CH_4 Turbine (MW)	174.55	148.06	144.17	146.43	139.74	177.00	134.87	140.44	140.50	159.50	146.21	170.31	143.97	147.36
Biomass (MW)	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ASU (MW)	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NH_3 (MW)	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NH_3 power production (MW)	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table S2: Process capacities for the scenario 2

	Asturias	Almeria	Badajoz	Teruel	Leon	Coruña	Cordoba	Ciudad Real	Sevilla	Zaragoza	Burgos	Navarra	Soria	Salamanca
Solar (ha)	103.59	158.03	254.72	155.79	240.79	104.68	259.25	277.53	188.44	129.70	195.67	126.04	187.44	285.63
Wind (ha)	59.09	48.17	37.71	47.45	57.05	56.32	28.62	46.94	40.38	54.83	58.90	61.78	57.73	58.36
Battery (MW)	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Electrolysis (MW)	85.16	118.81	160.46	112.57	149.89	74.97	162.42	179.59	129.01	102.96	132.41	98.62	137.87	150.05
Fuel Cell (MW)	3.14	18.81	43.44	22.91	38.35	0.00	44.36	45.40	34.64	8.30	32.53	9.34	33.50	37.91
CH_4 production (kW)	3.10	3.69	3.57	3.62	4.54	2.64	3.04	4.25	3.24	3.57	4.46	3.40	4.42	4.00
CH_4 Turbine (MW)	117.52	101.85	95.43	98.72	98.44	120.75	88.08	98.98	86.84	111.00	104.26	118.06	103.30	106.48
Biomass (MW)	68.05	68.05	61.63	68.05	52.88	68.05	68.05	52.88	68.05	68.05	52.88	61.30	52.88	52.88
ASU (MW)	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NH_3 (MW)	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NH_3 power production (MW)	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table S3: Process capacities for the scenario 3

	Asturias	Almeria	Badajoz	Teruel	Leon	Coruña	Cordoba	Ciudad Real	Sevilla	Zaragoza	Burgos	Navarra	Soria	Salamanca
Solar (ha)	317.52	438.76	702.26	454.45	520.08	320.60	817.36	659.43	442.59	414.62	511.56	338.84	395.48	684.40
Eolica (ha)	127.51	134.02	202.79	132.19	162.66	121.03	270.22	202.63	162.77	133.00	131.85	127.32	154.92	157.87
Bateria (MW)	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Electrolisis (MW)	195.07	321.43	440.39	319.87	354.76	167.41	446.17	430.76	332.89	246.86	310.74	196.57	304.09	373.14
Fuel Cell (MW)	78.29	85.17	95.09	79.02	81.42	84.64	95.98	90.19	81.35	76.52	78.90	91.99	84.13	84.78
CH4 (kW)	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CH4GT (MW)	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Biomass (MW)	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ASU (MW)	9.18	13.18	23.11	14.96	17.39	7.43	29.36	23.38	13.20	11.54	14.86	8.59	14.75	19.92
NH3 (MW)	10.94	17.13	27.82	17.54	21.13	9.14	30.02	27.12	17.98	14.12	17.22	10.65	17.61	22.27
NH3GT (MW)	111.27	104.39	106.26	111.52	109.12	106.07	105.37	107.93	109.03	111.68	111.64	97.58	108.16	113.35

4 Social Index

First, in Table S4, all required data to calculate the social index are presented. The data for this particular case study have been obtained from these sources:

1. **Lost installed capacity:** Wikipedia contributors (2021).
2. **Loss of jobs:** Ministerio para la Transicion Ecologica y el Reto Demografico (2021), El Comercio (2017), La Voz de Asturias (2018), Diario de Pontevedra (2019), Diario de Burgos (2017).
3. **GDP:** Instituto Nacional de Estadistica (2020)
4. **Active population:** Instituto Nacional de Estadistica (2021c)
5. **Unemployment rate:** Instituto Nacional de Estadistica (2021d)
6. **Population decline:** Instituto Nacional de Estadistica (2021f)
7. **Aging index:** Instituto Nacional de Estadistica (2021a)
8. **Total population:** Instituto Nacional de Estadistica (2021e)
9. **Area:** Ministerio para la Transicion Ecologica y el Reto Demografico (2005)
10. **Youth migration:** Instituto Nacional de Estadistica (2021b)

With this data, the index is calculation following the instructions explained in the manuscript. The first three items, related to the energy transition, are collected in Table S5. The last items of the index are included in Table S6.

In the manuscript, the Figure with the trade off between economic and social issues is presented for scenario 1. In this supplementary information, the figures for scenario 2 (Figure S4) and scenario 3 (Figure S5) are included.

Table S4: Data for the social index calculation

	Lost installed capacity (MW)	Loss of jobs	GDP (million €)	Active population	Unemployment rate (%)	Population decline (20 years) (%)	Aging index	Total population	Area(km2)	Youth migration (10 years)
Asturias	2162.7	2390	23258.67	447.4	14.09	-5.37	224.57	1018784	10604	-6.194
Teruel	1101	504	3367.24	61.6	10.6	-1.68	175.91	134176	14797	-1896
Leon	2025	960	10006.59	193.7	14.12	-9.10	241.01	456439	15570	-5850
Coruña	2895	436	26682.18	507.8	12.7	1.21	193.56	1121815	7950	-756
Almeria	1159	269	13979.83	358.8	17.14	40.47	84.56	727945	8775	-2835
Cordoba	324	129	14534.33	371.6	20.07	1.59	124.93	781451	13771	-10573
Badajoz	0	0	12423.26	308.9	21.47	1.55	129.37	672137	21766	-8080
Ciudad Real	0	0	10689.03	228	19.99	3.86	134.42	495045	19813	-9299
Sevilla	0	0	39535.35	922.4	23.81	12.41	95.38	1950219	14036	-7452
Zaragoza	0	0	27348.81	475.6	12.97	14.68	139.41	972528	17274	49
Burgos	466	440	10505.02	171.4	9.88	3.00	175.56	357650	14022	-3707
Navarra	0	0	20047.45	313.6	11.45	21.60	121.58	661197	9801	2525
Soria	0	0	2380.73	42.1	9.73	-2.23	194.89	88884	10303	-1056
Salamanca	0	0	7048.64	148.2	16.24	-5.86	215.81	329245	12349	-6097

Table S5: First items of the social index related to the energy transition

	Loss of installed capacity in the region vs. total capacity lost			Loss of jobs related to energy transition vs. total employment in the region				Loss of installed capacity vs. total GDP of the region			
	Lost installed capacity (MW)	MW (%)	Index Contribution	Loss of jobs	Active Population	% lost	Index Contribution	Lost installed capacity (MW)	GDP (millions €)	MW/M€	Index Contribution
Asturias	2162.70	19.48	7.47	2390	447400	0.534	6.53	2162.7	23258.67	0.0930	2.84
Teruel	1101.00	9.92	3.80	504	61600	0.818	10.00	1101	3367.24	0.3270	10.00
Leon	2025.00	18.24	6.99	960	193700	0.496	6.06	2025	10006.59	0.2024	6.19
Coruña	2895.00	26.08	10.00	436	507800	0.086	1.05	2895	26682.18	0.1085	3.32
Almeria	1159.00	10.44	4.00	269	358800	0.075	0.92	1159	13979.83	0.0829	2.54
Cordoba	324.00	2.92	1.12	129	371600	0.035	0.42	324	14534.33	0.0223	0.68
Badajoz	0.00	0.00	0.00	0	308900	0.000	0.00	0	12423.26	0.0000	0.00
Ciudad Real	0.00	0.00	0.00	0	228000	0.000	0.00	0	10689.03	0.0000	0.00
Sevilla	0.00	0.00	0.00	0	922400	0.000	0.00	0	39535.35	0.0000	0.00
Zaragoza	0.00	0.00	0.00	0	475600	0.000	0.00	0	27348.81	0.0000	0.00
Burgos	466.00	4.20	1.61	440	171400	0.257	3.14	466	10505.02	0.0444	1.36
Navarra	0.00	0.00	0.00	0	313600	0.000	0.00	0	20047.45	0.0000	0.00
Soria	0.00	0.00	0.00	0	42100	0.000	0.00	0	2380.73	0.0000	0.00
Salamanca	0.00	0.00	0.00	0	148200	0.000	0.00	0	7048.64	0.0000	0.00

Table S6: Last items of the social index related to the general social environment

	GDP of the region vs. total GDP of the country			Unemployment rate		Population decline over the last 20 years		Aging Index		Population density		Youth migration				GDP per capita	
	GDP (millions €)	% GDP	Index Contribution	Unempl. rate	Index Contribution	Ppopulation decline (%)	Index Contribution	Aging index	Index Contribution	Pop. density (/km^2)	Index Contribution	Youth migration	Total population	Ratio	Index Contribution	GDP per capita (€/person)	Index Contributor
Asturias	23258673	10.49	4.38	14.09	3.10	-5.37	9.25	224.57	8.95	96.08	3.40	-6194	1018784	-0.61	4.38	22829.84	8.95
Teruel	3367236	1.52	9.73	10.60	0.62	-1.68	8.50	175.91	5.84	9.07	9.97	-1896	134176	-1.41	7.94	25095.67	5.84
Leon	10006588	4.51	7.95	14.12	3.12	-9.10	10.00	241.01	10.00	29.32	8.44	-5850	456439	-1.28	7.36	21923.17	10.00
Coruña	26682181	12.03	3.46	12.70	2.11	1.21	7.92	193.56	6.97	141.11	0.00	-756	1121815	-0.07	1.99	23784.83	6.97
Almeria	13979829	6.30	6.88	17.14	5.26	40.47	0.00	84.56	0.00	82.96	4.39	-2835	727945	-0.39	3.41	19204.51	0.00
Cordoba	14534325	6.55	6.73	20.07	7.34	1.59	7.84	124.93	2.58	56.75	6.37	-10573	781451	-1.35	7.68	18599.15	2.58
Badajoz	12423261	5.60	7.30	21.47	8.34	1.55	7.85	129.37	2.86	30.88	8.32	-8080	672137	-1.20	7.01	18483.23	2.86
Ciudad Real	10689033	4.82	7.76	19.99	7.29	3.86	7.38	134.42	3.19	24.99	8.77	-9299	495045	-1.88	10.00	21592.04	3.19
Sevilla	39535345	17.82	0.00	23.81	10.00	12.41	5.66	95.38	0.69	138.94	0.16	-7452	1950219	-0.38	3.38	20272.26	0.69
Zaragoza	27348811	12.33	3.28	12.97	2.30	14.68	5.20	139.41	3.51	56.30	6.40	49	972528	0.01	1.67	28121.36	3.51
Burgos	10505020	4.74	7.81	9.88	0.11	3.00	7.56	175.56	5.82	25.51	8.73	-3707	357650	-1.04	6.28	29372.35	5.82
Navarra	20047454	9.04	5.25	11.45	1.22	21.60	3.81	121.58	2.37	67.46	5.56	2525	661197	0.38	0.00	30319.94	2.37
Soria	2380731	1.07	10.00	9.73	0.00	-2.23	8.61	194.89	7.05	8.63	10.00	-1056	88884	-1.19	6.95	26784.70	7.05
Salamanca	7048640	3.18	8.74	16.24	4.62	-5.86	9.35	215.81	8.39	26.66	8.64	-6097	329245	-1.85	9.88	21408.50	8.39

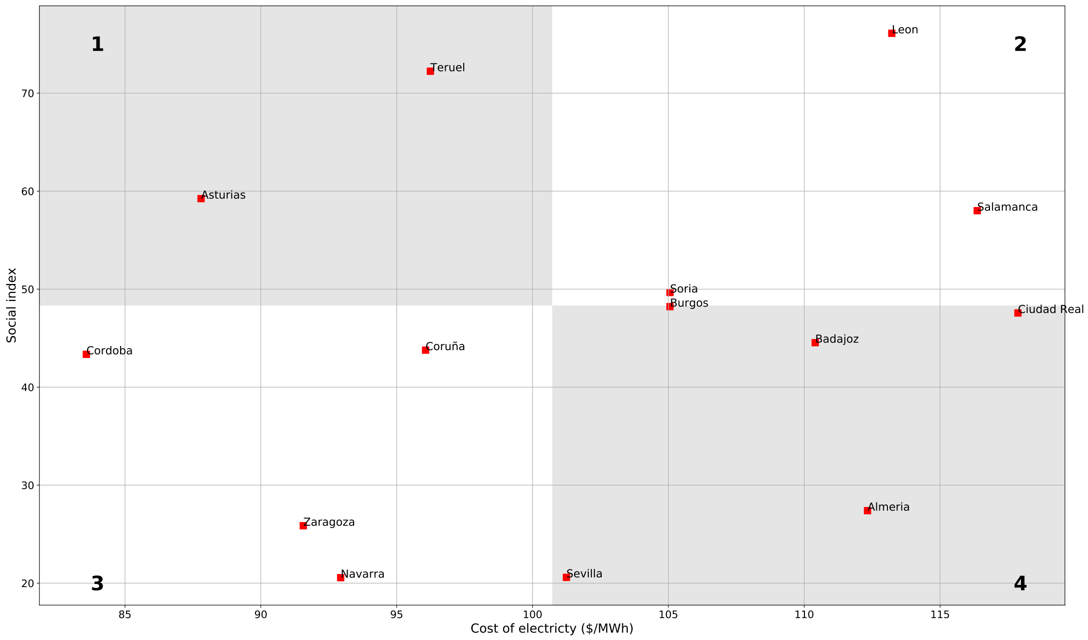

Figure S4: Social and economic results for scenario 2

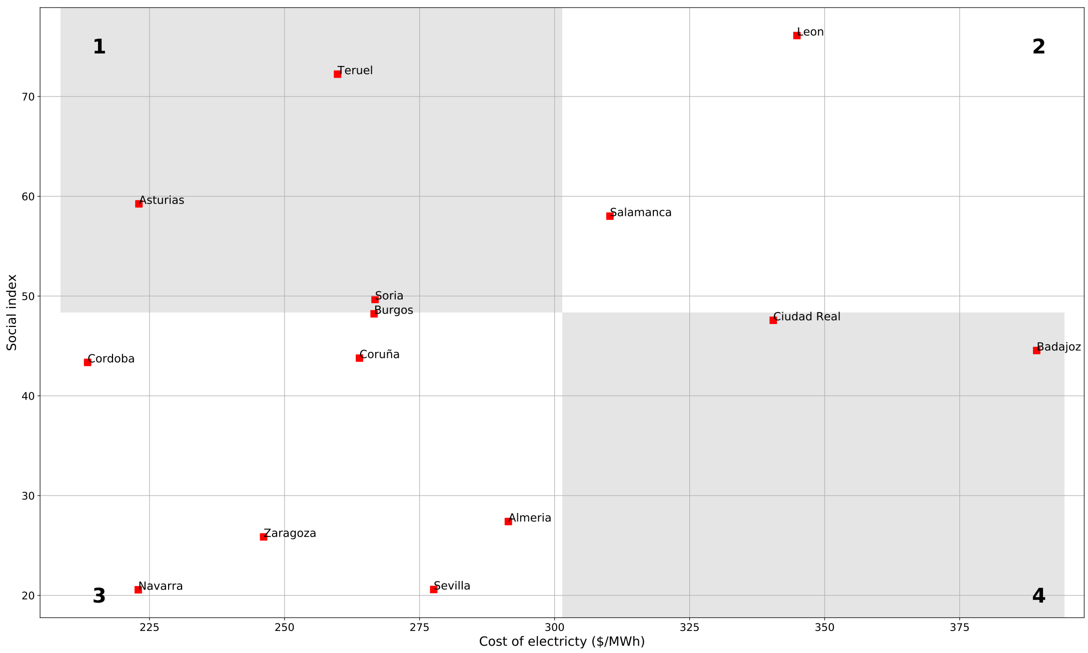

Figure S5: Social and economic results for scenario 3

Nomenclature

Indices / sets/ subsets

$\hat{B}$	resources use as raw material of the network
$\tilde{B}$	resources with a maximum annual availability
$h \in H$	seasons in the multiscale time representation
$i \in I$	processes evaluated in the power to fuel network
$j \in J$	resources involved in the network
$\hat{J}$	product with associated demand
$l \in L$	segments in operating cost piecewise-linear approximations
L_i	segments in piecewise-linear approximation
$m \in M$	operating modes for each of the process
M_i	operating modes for a process
$\hat{S}$	resources that could be stored
$t \in T$	time periods in the multiscale time representation
$\overline{T}_h$	time periods in season h
$\overline{TR}_{im}$	mode transitions to reach mode m
$\widehat{TR}_{im}$	mode transtions to progress from mode m
TR_i	predefined sequences of mode transitions

Parameters

$B_{jht}^{\max}$	maximum resource that can be consumed
$\overline{B}_j^{max}$	maximum annual resource than can be consumed
$C_i^{\max}$	maximum production capacity
$\overline{C}_i^{\max}$	maximum storage capacity
$\widetilde{C}_{im}^{\max}$	maximum production in a given mode
$\widetilde{C}_{im}^{\min}$	minimum production in a given mode
$D_{power,h,t}$	power demand
$\hat{J}_{iml}$	operating cost for piecewise-linear approximation
$\overline{M}$	big-M parameter
n_h	number of repetition of the horizon scheduling for a season
$\hat{P}_{iml}$	production level for piecewise-linear approximation
ρ_{ij}	conversion factor of the different products with respect to the reference resource
η_{iht}	availability of production capacity for wind/solar
$\bar{\Delta}_{im}^{\max}$	maximum rate of change
$\theta_{imm'}$	minimum stay time in a certain mode
$\bar{\theta}_{imm'm''}$	fixed stay time for a predefined sequence
$\theta^{\max}$	stay time in a mode
σ_i	conversion factor between capital and operating cost for a process
δ_i	fixed capital cost coefficient
γ_i	unit capital cost coefficient
α_j	annualized fixed capital cost for storing
β_j	annualized unit capital cost for storing
Δt	length of one time period

λ_{imhtl}	coefficient for piecewise-linear approximation
ξ_j	O&M cost for storing
φ_{CO_2}	Cost of captured carbon dioxide

Variables

B_{jht}	amount of resource consumed
C_i	production capacity for different processes
$\overline{C}_j$	storage capacity for different resources
J_{imht}	process operating cost not related to capital cost
OC	Operating cost
P_{iht}	amount of reference resource produced
$\overline{P}_{imht}$	reference resource produced in certain mode
$\overline{Q}_{jht}$	inventory level
$\hat{Q}_{jh}$	net inventory in a season
S_{jht}	amount of resource release
x_i	binary variable to select process units
$\overline{x}_i$	binary variable to select storage units
y_{imht}	binary variable to select a mode for a specific process
$z_{imm'ht}$	binary variable for mode transitions
w_{rimhtl}	binary variable for piecewise-linear aproximation

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