

Supplementary Material

Impacts of Decarbonisation on the Water-Energy-Land (WEL) Nexus: A Case Study of the Spanish Electricity Sector

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Table S1. Acidification impact of the Spanish electricity mix in two scenarios (molc H⁺ equiv)

BAU	2010	2015	2020	2025	2030	2035
BIOMASS (incl CHP)	12.24	12.02	3.08	5.00	10.83	2.09
COAL (incl CHP)	107.73	116.85	70.13	30.63	4.40	4.30
GAS (incl CHP)	96.55	83.30	94.02	102.44	84.08	54.14
OIL (incl CHP)	66.94	48.11	46.98	48.34	58.53	60.06
NUCLEAR	6.52	6.74	6.74	6.74	6.74	6.74
HYDRO	0.51	0.57	0.64	0.64	0.64	0.65
WIND	5.23	6.45	6.03	7.54	10.04	10.04
SOLAR PV	4.59	4.59	4.59	4.59	4.32	13.43
CSP	1.32	1.32	1.32	1.32	5.46	16.96
WAVE	0.00	0.00	0.00	0.00	0.00	0.12
IMPORTS	0.00	0.91	0.00	0.00	1.03	1.03
<i>TOTAL BAU</i>	<i>301.63</i>	<i>280.84</i>	<i>233.52</i>	<i>207.23</i>	<i>186.07</i>	<i>169.56</i>
TARGET2030	2010	2015	2020	2025	2030	2035
BIOMASS (incl CHP)	12.24	5.66	2.13	2.21	2.81	1.47
COAL (incl CHP)	107.73	116.88	39.31	14.21	4.41	3.66
GAS (incl CHP)	96.55	71.35	94.18	97.76	64.91	26.83
OIL (incl CHP)	66.94	47.57	46.76	0.89	28.83	4.47
NUCLEAR	6.52	6.74	5.09	2.93	0.00	0.00
HYDRO	0.51	0.57	0.64	0.64	0.64	0.65
WIND	5.23	6.45	8.01	9.10	10.16	10.16
SOLAR PV	4.59	4.59	4.59	4.59	15.90	19.23
CSP	1.32	1.32	1.32	1.32	1.32	3.47
WAVE	0.00	0.00	0.00	0.00	0.00	0.28
IMPORTS	0.00	3.13	0.00	6.25	8.21	8.23
<i>TOTAL TARGET2030</i>	<i>301.63</i>	<i>264.25</i>	<i>202.03</i>	<i>139.89</i>	<i>137.18</i>	<i>78.45</i>

Table S2. Terrestrial eutrophication impacts of the Spanish electricity mix in two scenarios (molc N equiv)

BAU	2010	2015	2020	2025	2030	2035
BIOMASS (incl CHP)	46.34	46.41	11.90	19.32	41.82	8.08
COAL (incl CHP)	260.61	282.66	169.64	74.08	10.64	10.39
GAS (incl CHP)	155.59	136.18	151.91	164.79	134.69	86.08

OIL (incl CHP)	162.67	116.90	114.16	117.46	142.22	145.94
NUCLEAR	11.71	12.11	12.12	12.12	12.12	12.12

Table S2. *Cont.*

HYDRO	1.68	1.88	2.08	2.09	2.10	2.12
WIND	9.95	12.26	11.48	14.35	19.10	19.10
SOLAR PV	5.77	5.77	5.77	5.77	5.41	18.09
CSP	2.71	2.71	2.71	2.71	11.07	34.24
WAVE	0.00	0.00	0.00	0.00	0.00	0.54
IMPORTS	0.00	1.97	0.00	0.00	2.31	2.31
<i>TOTAL BAU</i>	<i>657.03</i>	<i>618.86</i>	<i>481.76</i>	<i>412.69</i>	<i>381.48</i>	<i>339.01</i>
TARGET2030	2010	2015	2020	2025	2030	2035
BIOMASS (incl CHP)	46.34	20.74	6.80	7.12	9.42	4.69
COAL (incl CHP)	260.61	282.73	95.10	34.37	10.66	8.86
GAS (incl CHP)	155.59	117.35	152.36	157.62	104.90	44.18
OIL (incl CHP)	162.67	115.59	113.63	2.17	70.07	10.87
NUCLEAR	11.71	12.11	9.15	5.26	0.00	0.00
HYDRO	1.68	1.88	2.08	2.09	2.10	2.12
WIND	9.95	12.26	15.24	17.31	19.32	19.32
SOLAR PV	5.77	5.77	5.77	5.77	21.54	26.15
CSP	2.71	2.71	2.71	2.71	2.71	7.32
WAVE	0.00	0.00	0.00	0.00	0.00	1.30
IMPORTS	0.00	6.80	0.00	14.33	18.46	18.50
<i>TOTAL TARGET2030</i>	<i>657.03</i>	<i>577.93</i>	<i>402.84</i>	<i>248.76</i>	<i>259.18</i>	<i>143.31</i>

Table S3. Fresh water eutrophication impacts of the Spanish electricity mix in two scenarios (kg P equiv)

BAU	2010	2015	2020	2025	2030	2035
BIOMASS (incl CHP)	0.54	0.53	0.14	0.22	0.48	0.09
COAL (incl CHP)	17.81	19.32	11.60	5.06	0.73	0.71
GAS (incl CHP)	1.94	1.69	1.90	2.06	1.69	1.09
OIL (incl CHP)	0.12	0.09	0.09	0.09	0.11	0.11
NUCLEAR	0.35	0.36	0.36	0.36	0.36	0.36
HYDRO	0.03	0.03	0.04	0.04	0.04	0.04
WIND	0.44	0.54	0.51	0.63	0.84	0.84
SOLAR PV	0.44	0.44	0.44	0.44	0.42	1.11
CSP	0.05	0.05	0.05	0.05	0.21	0.65
WAVE	0.00	0.00	0.00	0.00	0.00	0.00
IMPORTS	0.00	0.04	0.00	0.00	0.06	0.06
<i>TOTAL BAU</i>	<i>21.73</i>	<i>23.10</i>	<i>15.11</i>	<i>8.96</i>	<i>4.94</i>	<i>5.06</i>
TARGET2030	2010	2015	2020	2025	2030	2035
BIOMASS (incl CHP)	0.54	0.25	0.09	0.09	0.12	0.06
COAL (incl CHP)	17.81	19.33	6.50	2.35	0.73	0.61
GAS (incl CHP)	1.94	1.45	1.90	1.97	1.31	0.54
OIL (incl CHP)	0.12	0.09	0.08	0.00	0.05	0.01
NUCLEAR	0.35	0.36	0.28	0.16	0.00	0.00
HYDRO	0.03	0.03	0.04	0.04	0.04	0.04
WIND	0.44	0.54	0.67	0.76	0.85	0.85
SOLAR PV	0.44	0.44	0.44	0.44	1.30	1.55
CSP	0.05	0.05	0.05	0.05	0.05	0.15

Table S3. Cont.

WAVE	0.00	0.00	0.00	0.00	0.00	0.00
IMPORTS	0.00	0.15	0.00	0.35	0.48	0.48
<i>TOTAL TARGET2030</i>	<i>21.73</i>	<i>22.69</i>	<i>10.05</i>	<i>6.22</i>	<i>4.92</i>	<i>4.30</i>

Table S4. Marine eutrophication impacts of the Spanish electricity mix in two scenarios (kg N equiv)

BAU	2010	2015	2020	2025	2030	2035
BIOMASS (incl CHP)	2.51	2.52	0.65	1.05	2.27	0.44
COAL (incl CHP)	26.44	28.68	17.21	7.52	1.08	1.05
GAS (incl CHP)	14.55	12.73	14.20	15.41	12.60	8.05
OIL (incl CHP)	14.86	10.68	10.43	10.73	12.99	13.33
NUCLEAR	1.25	1.29	1.29	1.29	1.29	1.29
HYDRO	0.15	0.17	0.19	0.19	0.19	0.19
WIND	0.99	1.22	1.14	1.42	1.89	1.89
SOLAR PV	0.62	0.62	0.62	0.62	0.59	1.88
CSP	0.23	0.23	0.23	0.23	0.94	2.92
WAVE	0.00	0.00	0.00	0.00	0.00	0.04
IMPORTS	0.00	0.18	0.00	0.00	0.18	0.18
<i>TOTAL BAU</i>	<i>61.60</i>	<i>58.32</i>	<i>45.97</i>	<i>38.47</i>	<i>34.03</i>	<i>31.28</i>
TARGET2030	2010	2015	2020	2025	2030	2035
BIOMASS (incl CHP)	2.51	1.12	0.36	0.38	0.50	0.25
COAL (incl CHP)	26.44	28.69	9.65	3.49	1.08	0.90
GAS (incl CHP)	14.55	10.97	14.25	14.74	9.81	4.13
OIL (incl CHP)	14.86	10.56	10.38	0.20	6.40	0.99
NUCLEAR	1.25	1.29	0.97	0.56	0.00	0.00
HYDRO	0.15	0.17	0.19	0.19	0.19	0.19
WIND	0.99	1.22	1.51	1.72	1.92	1.92
SOLAR PV	0.62	0.62	0.62	0.62	2.23	2.70
CSP	0.23	0.23	0.23	0.23	0.23	0.58
WAVE	0.00	0.00	0.00	0.00	0.00	0.10
IMPORTS	0.00	0.62	0.00	1.12	1.44	1.44
<i>TOTAL TARGET2030</i>	<i>61.60</i>	<i>55.49</i>	<i>38.16</i>	<i>23.25</i>	<i>23.80</i>	<i>13.21</i>

Table S5. Fresh water ecotoxicity impacts of the Spanish electricity mix in two scenarios (CTU equiv.)

BAU	2010	2015	2020	2025	2030	2035
BIOMASS (incl CHP)	7882.69	6614.88	1695.88	2753.12	5959.69	1152.02
COAL (incl CHP)	143299.18	155424.42	93279.54	40735.85	5852.79	5715.74
GAS (incl CHP)	32872.93	28932.79	32126.94	34792.08	28389.65	18089.61
OIL (incl CHP)	6042.97	4342.61	4240.77	4363.61	5283.41	5421.52
NUCLEAR	25327.49	26184.74	26199.06	26199.06	26199.06	26199.06
HYDRO	736.61	821.26	906.87	912.29	917.70	923.11
WIND	161837.52	199534.57	186717.52	233422.82	310713.56	310713.56
SOLAR PV	58228.38	58228.38	58228.38	58228.38	55925.52	113807.73
CSP	942.98	942.98	942.98	942.98	3831.75	11829.41
WAVE	0.00	0.00	0.00	0.00	0.00	11.35
IMPORTS	0.00	3770.56	0.00	0.00	8260.02	8339.56
<i>TOTAL BAU</i>	<i>437170.75</i>	<i>484797.19</i>	<i>404337.94</i>	<i>402350.19</i>	<i>451333.15</i>	<i>502202.67</i>

Table S5. *Cont.*

TARGET2030	2010	2015	2020	2025	2030	2035
BIOMASS (incl CHP)	7882.69	4472.50	2894.29	2939.85	3267.30	1994.59
COAL (incl CHP)	143299.18	155465.18	52292.07	18899.84	5863.91	4874.32
GAS (incl CHP)	32872.93	24990.49	32238.44	33308.98	22186.90	9413.32
OIL (incl CHP)	6042.97	4293.86	4221.32	80.45	2602.84	403.87
NUCLEAR	25327.49	26184.74	19789.60	11381.56	0.00	0.00
HYDRO	736.61	821.26	906.87	912.29	917.70	923.11
WIND	161837.52	199534.57	247892.93	281683.14	314424.36	314424.36
SOLAR PV	58228.38	58228.38	58228.38	58228.38	128213.76	150278.17
CSP	942.98	942.98	942.98	942.98	942.98	4230.62
WAVE	0.00	0.00	0.00	0.00	0.00	27.53
IMPORTS	0.00	13004.99	0.00	46181.55	66046.52	66682.47
<i>TOTAL TARGET2030</i>	<i>437170.75</i>	<i>487938.95</i>	<i>419406.89</i>	<i>454559.01</i>	<i>544466.26</i>	<i>553252.36</i>

Table S6. Water consumption impacts of the Spanish electricity mix in two scenarios (m3 equiv)

BAU	2010	2015	2020	2025	2030	2035
BIOMASS (incl CHP)	37.97	41.66	10.68	17.34	37.53	7.25
COAL (incl CHP)	159.07	172.53	109.16	45.22	6.50	6.34
GAS (incl CHP)	190.30	171.59	185.85	196.78	153.96	92.86
OIL (incl CHP)	31.51	22.64	22.11	22.75	27.55	28.27
NUCLEAR	289.16	298.95	299.11	299.11	299.11	299.11
HYDRO	0.37	0.42	0.47	0.47	0.48	0.48
WIND	6.85	8.45	7.90	9.88	13.15	13.15
SOLAR PV	24.41	24.41	24.41	24.41	22.92	73.48
CSP	18.04	18.04	18.04	18.04	41.37	101.75
WAVE	0.00	0.00	0.00	0.00	0.00	0.00
IMPORTS	0.00	26.75	0.00	0.00	21.48	21.48
<i>TOTAL BAU</i>	<i>757.68</i>	<i>785.43</i>	<i>677.73</i>	<i>634.00</i>	<i>624.05</i>	<i>644.18</i>
TARGET2030	2010	2015	2020	2025	2030	2035
BIOMASS (incl CHP)	37.97	14.32	0.66	0.95	3.01	0.46
COAL (incl CHP)	159.07	172.57	58.05	20.98	6.51	5.41
GAS (incl CHP)	190.30	152.23	187.18	191.42	127.41	55.94
OIL (incl CHP)	31.51	22.39	22.01	0.42	13.57	2.11
NUCLEAR	289.16	298.95	225.93	129.94	0.00	0.00
HYDRO	0.37	0.42	0.47	0.47	0.48	0.48
WIND	6.85	8.45	10.49	11.92	13.31	13.31
SOLAR PV	24.41	24.41	24.41	24.41	87.41	105.72
CSP	18.04	18.04	18.04	18.04	18.04	197.90
WAVE	0.00	0.00	0.00	0.00	0.00	0.00
IMPORTS	0.00	92.28	0.00	139.44	171.74	171.77
<i>TOTAL TARGET2030</i>	<i>757.68</i>	<i>804.05</i>	<i>547.24</i>	<i>538.00</i>	<i>441.48</i>	<i>553.09</i>

Table S7. Land use impacts of the Spanish electricity mix in two scenarios (kg C deficit)

BAU	2010	2015	2020	2025	2030	2035
BIOMASS (incl CHP)	7749.92	8065.77	2067.85	3356.98	7266.87	1404.70
COAL (incl CHP)	13887.52	15062.61	9039.98	3947.83	567.21	553.93

GAS (incl CHP)	32604.96	28293.42	31783.94	34570.62	28327.08	18186.85
OIL (incl CHP)	4886.35	3511.44	3429.09	3528.41	4272.16	4383.84
NUCLEAR	844.75	873.35	873.82	873.82	873.82	873.82
HYDRO	511.82	585.67	665.44	670.48	675.52	680.56
WIND	6476.42	7984.98	7472.07	9341.13	12434.15	12434.15
SOLAR PV	1006.35	1006.35	1006.35	1006.35	825.32	9079.04
CSP	471.62	471.62	471.62	471.62	1929.19	5966.20
WAVE	0.00	0.00	0.00	0.00	0.00	0.00
IMPORTS	0.00	263.77	0.00	0.00	548.93	552.11
<i>TOTAL BAU</i>	<i>68439.72</i>	<i>66118.96</i>	<i>56810.14</i>	<i>57767.24</i>	<i>57720.26</i>	<i>54115.21</i>
TARGET2030	2010	2015	2020	2025	2030	2035
BIOMASS (incl CHP)	7749.92	3244.88	727.03	782.58	1181.86	501.03
COAL (incl CHP)	13887.52	15066.56	5067.77	1831.64	568.29	472.38
GAS (incl CHP)	32604.96	24292.70	31853.94	33020.10	21944.94	9139.61
OIL (incl CHP)	4886.35	3472.01	3413.36	65.05	2104.66	326.57
NUCLEAR	844.75	873.35	660.05	379.61	0.00	0.00
HYDRO	511.82	585.67	665.44	670.48	675.52	680.56
WIND	6476.42	7984.98	9920.19	11272.41	12582.65	12582.65
SOLAR PV	1006.35	1006.35	1006.35	1006.35	11415.76	14342.05
CSP	471.62	471.62	471.62	471.62	471.62	2847.17
WAVE	0.00	0.00	0.00	0.00	0.00	0.00
IMPORTS	0.00	909.75	0.00	3107.03	4389.22	4414.67
<i>TOTAL TARGET2030</i>	<i>68439.72</i>	<i>57907.87</i>	<i>53785.74</i>	<i>52606.87</i>	<i>55334.51</i>	<i>45306.69</i>

Table S8. Resource use impacts of the Spanish electricity mix in two scenarios (kg Sb equiv)

BAU	2010	2015	2020	2025	2030	2035
BIOMASS (incl CHP)	2.25× 10 ⁻²	2.03× 10 ⁻²	5.20× 10 ⁻³	8.44× 10 ⁻³	1.83× 10 ⁻²	3.53× 10 ⁻³
COAL (incl CHP)	6.22× 10 ⁻²	6.74× 10 ⁻²	4.05× 10 ⁻²	1.77× 10 ⁻²	2.54× 10 ⁻³	2.48× 10 ⁻³
GAS (incl CHP)	6.08× 10 ⁻²	5.30× 10 ⁻²	5.93× 10 ⁻²	6.44× 10 ⁻²	5.27× 10 ⁻²	3.37× 10 ⁻²
OIL (incl CHP)	1.46× 10 ⁻²	1.05× 10 ⁻²	1.02× 10 ⁻²	1.05× 10 ⁻²	1.28× 10 ⁻²	1.31× 10 ⁻²
NUCLEAR	3.00× 10 ⁻¹	3.10× 10 ⁻¹	3.10× 10 ⁻¹	3.10× 10 ⁻¹	3.10× 10 ⁻¹	3.10× 10 ⁻¹
HYDRO	5.99× 10 ⁻³	6.73× 10 ⁻³	7.50× 10 ⁻³	7.55× 10 ⁻³	7.60× 10 ⁻³	7.65× 10 ⁻³
WIND	3.15× 10 ⁻¹	3.89× 10 ^{-1d}	3.64× 10 ⁻¹	4.55× 10 ⁻¹	6.05× 10 ⁻¹	6.05× 10 ⁻¹
SOLAR PV	5.73× 10 ⁻¹	5.73× 10 ⁻¹	5.73× 10 ⁻¹	5.73× 10 ⁻¹	5.37× 10 ⁻¹	1.77
CSP	2.64× 10 ⁻³	2.64× 10 ⁻³	2.64× 10 ⁻³	2.64× 10 ⁻³	1.06× 10 ⁻²	3.28× 10 ⁻²
WAVE	0	0	0	0	0	0
IMPORTS	0	3.48× 10 ⁻²	0	0	4.98× 10 ⁻²	5.00× 10 ⁻²
<i>TOTAL BAU</i>	<i>1.36</i>	<i>1.47</i>	<i>1.37</i>	<i>1.45</i>	<i>1.61</i>	<i>2.83</i>
TARGET2030	2010	2015	2020	2025	2030	2035
BIOMASS (incl CHP)	2.25× 10 ⁻²	1.18× 10 ⁻²	6.42× 10 ⁻³	6.56× 10 ⁻³	7.56× 10 ⁻³	4.42× 10 ⁻³
COAL (incl CHP)	6.22× 10 ⁻²	6.74× 10 ⁻²	2.27× 10 ⁻²	8.20× 10 ⁻³	2.54× 10 ⁻³	2.11× 10 ⁻³
GAS (incl CHP)	6.08× 10 ⁻²	4.56× 10 ⁻²	5.94× 10 ⁻²	6.15× 10 ⁻²	4.09× 10 ⁻²	1.72× 10 ⁻²

Table S8. *Cont.*

OIL (incl CHP)	1.46×10^{-2}	1.04×10^{-2}	1.02×10^{-2}	1.94×10^{-4}	6.29×10^{-3}	9.75×10^{-4}
NUCLEAR	3.00×10^{-1}	3.10×10^{-1}	2.34×10^{-1}	1.35×10^{-1}	0	0
HYDRO	5.99×10^{-3}	6.73×10^{-3}	7.50×10^{-3}	7.55×10^{-3}	7.60E-03	7.65×10^{-3}
WIND	3.15×10^{-1}	3.89×10^{-1}	4.83×10^{-1}	5.49×10^{-1}	6.13E-01	6.13×10^{-1}
SOLAR PV	5.73×10^{-1}	5.73×10^{-1}	5.73×10^{-1}	5.73×10^{-1}	2.10E+00	2.55
CSP	2.64×10^{-3}	2.64×10^{-3}	2.64×10^{-3}	2.64×10^{-3}	2.64E-03	1.34×10^{-2}
WAVE	0	0	0	0	0	0
IMPORTS	0	1.20×10^{-1}	0	2.75×10^{-1}	3.98×10^{-1}	3.99×10^{-1}
<i>TOTAL TARGET2030</i>	<i>1.36</i>	<i>1.54</i>	<i>1.40</i>	<i>1.62</i>	<i>3.18</i>	<i>3.61</i>