UTS Institute for Sustainable Futures

Energy for a Better Life: a sufficient, efficient and 100% renewable model for the Iberian Peninsula

prepared for Greenpeace Spain and Portugal

By The University of Technology Sydney
Institute for Sustainable Futures

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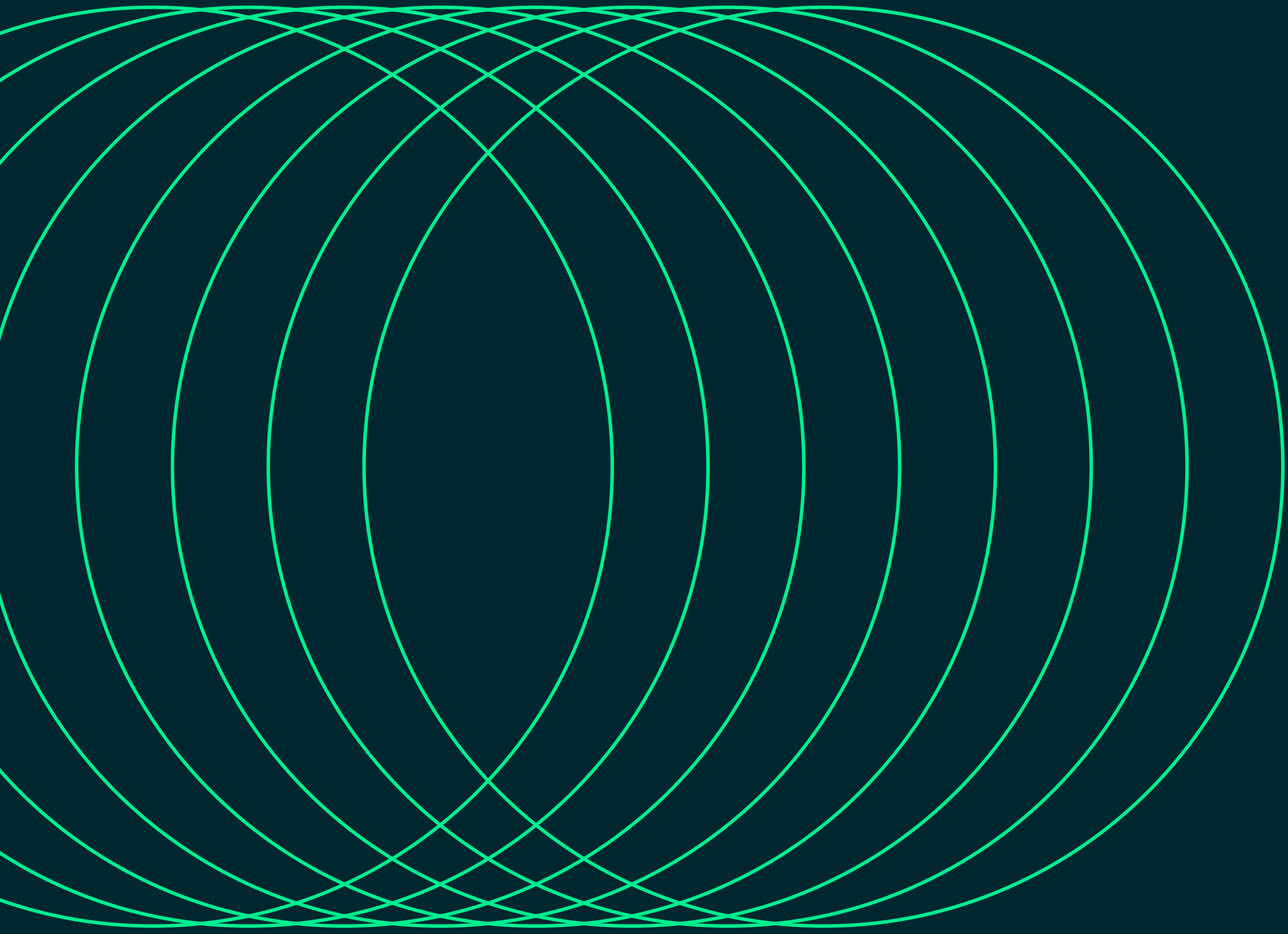

About the authors

The Institute for Sustainable Futures (ISF) was established by the University of Technology Sydney in 1996 to work with industry, government and the community to develop sustainable futures through research and consultancy. Our mission is to create change toward sustainable futures that protect and enhance the environment, human wellbeing and social equity. We seek to adopt an inter-disciplinary approach to our work and engage our partner organisations in a collaborative process that emphasises strategic decision-making.

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All conclusions and any errors that remain are the authors own.

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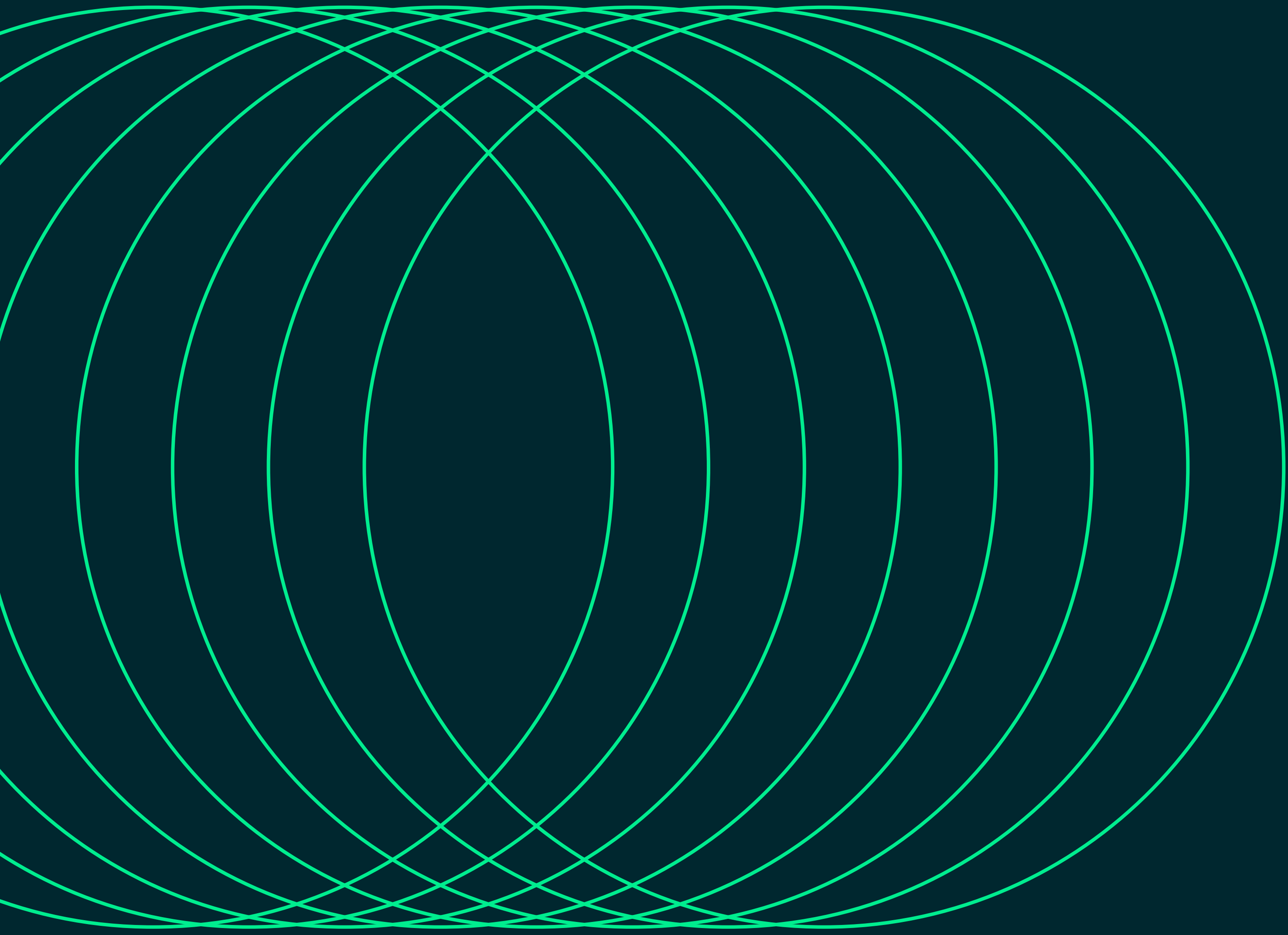
Executive Summary



The energy concept and the associated studies and analyses were conducted during 2025, based on publicly available data and statistics. The research question is answered as follows, based on the present report:

1 To what extent can energy-related emissions can be reduced across the Iberian Peninsula (Spanish mainland, Portugal, the Balearic Islands and Ceuta), with the view to finding a pathway for the Iberian Peninsula to reduce its emissions in a manner aligned with the Paris Agreement?

Achieving the goals of the Paris Climate Agreement (2015) will require the total decarbonisation of the global energy system by 2050, with an emissions peak between 2020 and 2025 and a drastic reduction in non-energy-related greenhouse gases (GHGs), including land-use-related emissions. Based on the Agreement, countries have agreed to regularly report their GHG emissions and submit their 'Nationally Determined Contributions' (NDC), describing their planned measures to reduce GHG emissions. This research analyses rapid decarbonisation of the energy sector for the Iberian Peninsula. Energy demand reduction and the deployment of renewable energy to phase-out fossil-fuel based energy supply across all sectors are key to decarbonising the entire energy system. Furthermore, the absorption of CO_2 by natural sinks neutralises the remaining energy-related CO_2 emissions by 2040.

Energy pathways for Spain and Portugal have been calculated under three different scenarios. The cumulative results for both countries led to pathways for the whole of the Iberian Peninsula:

- The **Business-as-usual** scenario is based on the 2024 National Energy and Climate Plans (NECPs) for Spain and Portugal.
- The **Energia 4.0** scenario assumed a more ambitious carbon-reduction pathway than the NECPs and faster implementation of energy efficiency measures and renewable energy generation.
- The **Energia 4.1** scenario adds a stronger sufficiency component to the 4.0 scenario, to reduce carbon emissions faster and reduce the overall carbon budget for the Iberian Peninsula.

A 'fair allocation' for the carbon budget for the Iberian Peninsula aligns with the Paris Agreement and Greenpeace's principles of climate justice. Greenpeace Spain has been determined to maintain 2.12 $GtCO_2$-e between 2020 and 2050.[1] The same principles were used in this report to calculate a fair allocation carbon budget for Portugal.

Furthermore, the absorption of CO_2 by sinks was calculated using official data from EU national emission accounts. For Spain, an absorption potential of 45.5 $MtCO_2$/yr was calculated, while Portugal's potential was estimated with 1.8 $MtCO_2$/yr. As a result, the allocation of a fair carbon budget is shown in table E1.

E1: Fair allocation carbon budget limits

	Share of the World's Population 2020–2050	Carbon Budget 2020–2050 ($GtCO_2$-e)
Global	100%	400
Spain	0.51%	2.04
Portugal	0.11%	0.45
Total Iberian Peninsula	**0.62%**	**2.49**

By implementing energy efficiency with existing technologies and the phase-out of fossil fuel-based energy supply, the current per capita carbon footprint across the Iberian Peninsula of 4 tCO_2eq can decrease to near zero emissions. The remaining minor emissions of approx. 100kg CO_2 per person originates mainly from non-energy-related industrial processes and synthetic fuel production.

E2: Emissions per capita for the Iberian Peninsula [tCO_2eq/person

Per Capita Emissions tCO_2eq/person	2025	2030	2035	2040	2045	2050
IB-BAU	4.6	3.4	2.4	1.3	0.4	0.2
IB 4.0		2.8	1.7	0.2	0.2	0.2
IB 4.1		2.7	1.4	0.1	0.1	0.1

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[1] Greenpeace Spain, 'Spanish Climate Action: Highest Ambition is Necessary and Possible' (10/06/2024)

2 What level of emissions reductions are technologically possible by 2040 relative to a 'business as usual' case in each of the sectors/industries (listed below), if given the right level of policy support and investment?

While the energy-related CO_2 emissions for the Iberian Peninsula under the BAU scenario decrease by 72% to 65 $MtCO_2$ annually, the Energia 4.0 and 4.1 pathways will decarbonise to 99% by 2040. The remaining 1% of CO_2 emissions originate from the use of synthetic fuels for aviation and shipping as well as industry processes that cannot be electrified with currently available technologies.

Decarbonisation of the power generation and buildings sectors is technically and economically possible if policy support enables investment in clean-energy technologies.

E3: Annual energy-related CO_2 emissions for the Iberian Peninsula under 3 scenarios until 2040

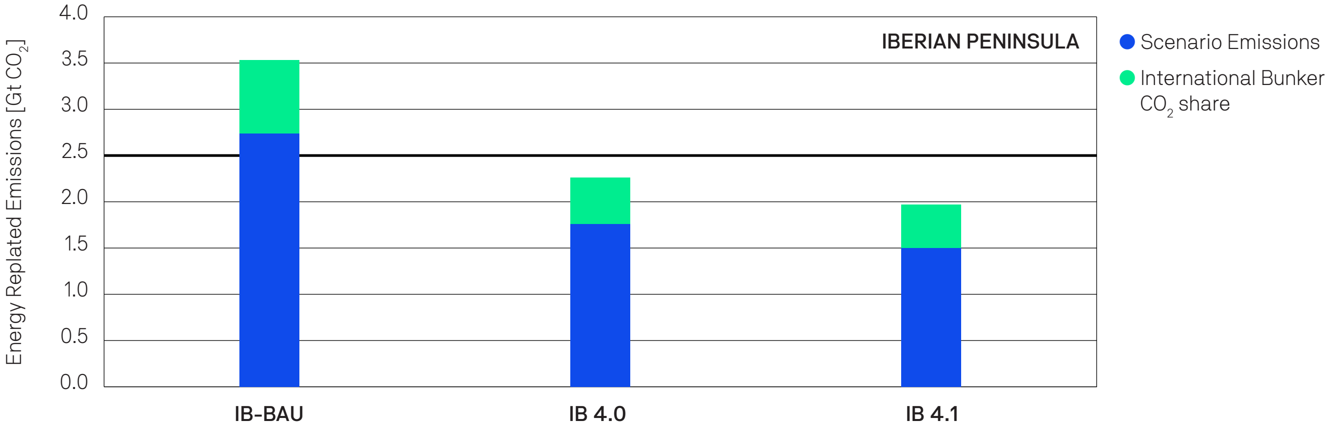
		2020	2025	2040		
	Unit	**Historical**	**Estimation**	**IB BAU**	**IB 4.0**	**IB 4.1**
Industry	[$MtCO_2$/yr]	51	51	13	0	0
Buildings		39	25	4	0	0
Transport		103	141	45	3	3
Power generation		38	35	3	0	0
Total		231	252	65	3	3
Other conversion (part of industry & transport)		8	9	2	0	0
International Travel Share		58	48	15	1	1

Cumulative Carbon Emission 2020 to 2050

The calculated cumulative carbon emissions between 2020 and 2050 range from 3.58 $GtCO_2$ under the BAU scenario to 2.01 $GtCO_2$ under the 4.1 scenario, as shown in the figure below. The IB 4.0 and IB 4.1 scenarios achieve net zero emissions by 2040, while the BAU scenario transitions more slowly to net zero emissions and reaches this by 2050. As discussed above, there will still be emissions between 2045 and 2050, such as those relating to the production of synthetic fuels. These range from 11 $MtCO_2$/a for the BAU scenario to 6 $MtCO_2$/a for the 4.1 scenario. The CO_2 required to produce synthetic fuels is derived from natural sinks in the 4.0 and 4.1 scenarios. The source of CO_2 for these synthetic fuels can be from biomass or from technically captured CO_2. However, the carbon source analysis for synthetic fuels is outside the scope of this research. 50% of the emissions for international transport (aviation, shipping, rail and road) have been added to the national emissions balance for Spain and Portugal. It is assumed that decarbonisation of international travel applies to domestic AND international travel under the IB 4.0 and IB 4.1 scenarios.

By implementing existing energy efficiency technologies across all sectors – from buildings to transport vehicles and all parts of industry – in combination with an ambitious expansion of cost-competitive renewable energies and maximum utilisation of electrification, the Iberian Peninsula can implement a 'fair carbon budget' of under 2 $GtCO_2$ until 2050.

E4: Comparison of carbon budget to total scenario emissions (2020–2050) for the Iberian Peninsula (incl. CO_2 sinks)



3 What technologies/solutions will drive these emissions reductions in each of the sectors/industries listed?

Electrification in conjunction with the continued decarbonisation of the Iberian Peninsula's power sector is vital in all three scenarios. New renewable power generation – predominantly solar photovoltaic systems and onshore wind – will not only replace existing gas power plant capacities and support the phase-out of nuclear energy, they will also have to meet increasing electricity demand as transport, buildings and industry electrify. Sector-coupling in conjunction with modernisation of power system management will enable the electrical power system to join with the transport and heating sectors and create better outcomes such as system flexibility.

Increased electrification requires significantly increased renewable power generation capacities until 2040 and beyond in all scenarios. The capacity for wind (onshore and offshore) will increase from around 36 GW in 2025 to 105 GW under the BAU scenario and to 130 GW under the Energia 4.0 scenario. Solar photovoltaic will need to increase to 184 GW – almost four times the capacity of 2025 – under the Energia 4.0 scenario. The Energia 4.1 scenario requires lower capacities due to further reduced demand; total renewable energy capacities in 2040 would add up to 314 GW – tripling current renewable power generation capacities by 2040.

Heat pumps are key to the decarbonisation of heat supply. Heat pumps can rapidly increase their share of total final energy because they deliver 3.5 times the heat energy relative to their electrical energy input. In addition to this, heat pumps have significant potential to be installed a high rate for the remainder of the decade thanks to maturing of the technology and associated savings in production costs. Furthermore, heat pumps provide good economic outcomes for consumers thanks to their high efficiency, low operating costs and ability to avoid the fuel costs associated with fossil fuel processes for low- and medium-temperature heating needs. For these reasons, the large increase between 2020 and 2030 in heat pumps' share of heat supply is seen as achievable, even in the BAU scenario.

The measures to reduce emissions across **industry** are as diverse as the industry sectors themselves. Technical processes vary significantly across Manufacturing and Construction (steel, aluminium, cement and chemicals). However, electrification of process heat plays a large role in all sectors. Where electrification is not possible, the replacement of fossil fuels with synthetic fuels produced with renewable energy sources is required. A reliable and long-term industry-specific climate and energy policy is mandatory to implement the technologies assumed under all three scenarios.

For the **transport** sector, a combination of sufficiency, efficiency and electrification is required. Sufficiency means lifestyle changes: reduced air travel, increased public transport use, car-sharing or simply the use of a bike or walking to decrease the energy demand for vehicles.

Efficient vehicles, those that are lighter and smaller than current vehicles, can satisfy the remaining transport demand. In combination with sufficiency, technical vehicle efficiency leads to a further significant reduction in transport energy. Electric vehicles play a key role in future transport systems across the Iberian Peninsula.

Across all sectors – buildings, transport, services and industry – electrification is key. Electrification replaces (fossil) fuels with electricity which can be supplied with cost-efficient and carbon-free renewable power generation.

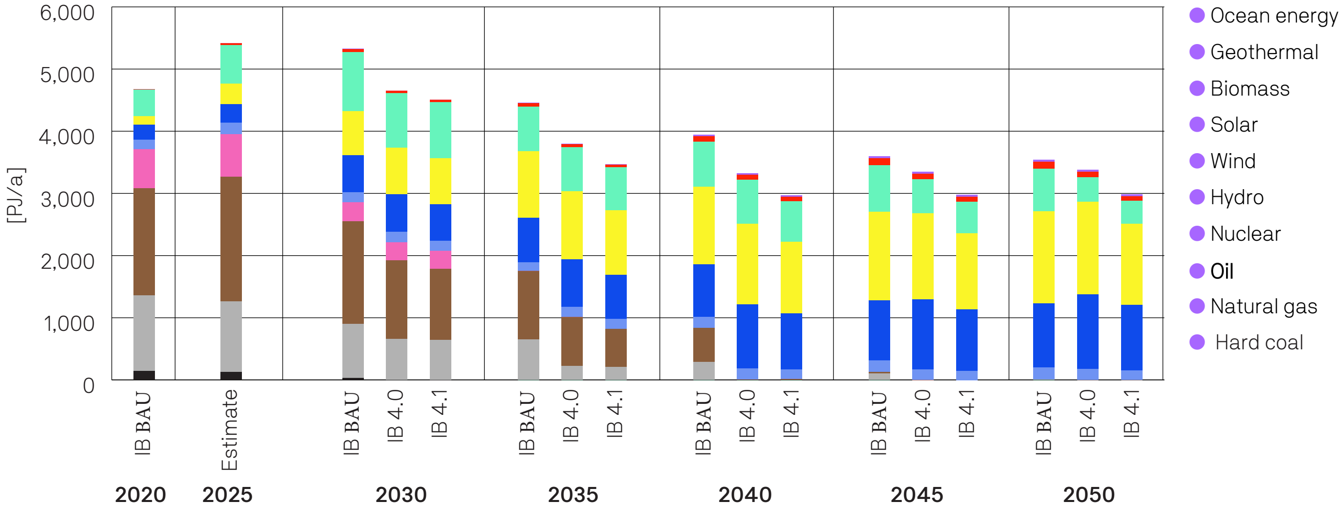
4 What is the overall abatement potential, assumed uptake with a focus on energy supply?

Primary energy is a commonly used metric when discussing fossil fuel demands. It does not account for the conversion efficiency of fuel-to-useful-energy output for example for vehicles with internal combustion engines or fossil fuel power plants. Electrification reduces both conversion losses e.g. in vehicles and losses in power generation when generated with renewable energies such as solar photovoltaic, wind and hydro power. Therefore, the Iberian Peninsula's primary energy demand decreases under all three scenarios due to advanced electrification and high shares of renewable electricity.

Solar photovoltaic and wind power – both from onshore and offshore wind – dominates future supply across all scenarios.

The Energia 4.1 is the most effective scenario regarding the reduction of required energy generation and leads to a reduction of almost 50% by 2040 in comparison to 2025. Under the Energia 4.0 and 4.1 scenarios, all fossil fuels are phased out by 2040 in Spain and Portugal and coal is phased-out by 2030.

E5: Primary energy demand by fuel type for the Iberian Peninsula under each scenario



The BAU scenario for the Iberian Peninsula shows a 7% increase during the first decade (2020–2030). However, it is projected that this trend will reverse and that reductions of 26% will be achieved in the following decade (2030–2040), and 11% per year reduction in the following decade (2040–50).

The Energia 4.0 scenario shows reductions in primary energy demand between 2020 and 2050, achieving a reduction of 5% in the first decade, then a reduction of 29% in the next decade. The Energia 4.1 scenario leads to more substantial decreases in the Iberian Peninsula's primary energy demand: 8% in the first decade, followed by reductions of 36% between 2030 and 2040.

E6: Percent change in primary energy demand between each decade (compared to the same scenario across time periods)

Change in Primary Energy	2020–2030	2030–2040	2020–2040 cumulative change
Iberian Peninsula			
IB BAU	+14%	-26%	-1%
IB 4.0	-5%	-29%	-33%
IB 4.1	-8%	-36%	-41%
Spain			
ES BAU	+6%	-29%	-19%
ES 4.0	-4%	-30%	-34%
ES 4.1	-6%	-37%	-41%
Portugal			
PT BAU	+10%	-9%	0%
PT 4.0	-11%	-19%	-27%
PT 4.1	-16%	-28%	-39%

5 What happens if sufficiency measures to achieve reduced demand across all sectors are introduced along with efficiency, electrification and renewables?

Final energy consumption is the total energy consumed by end users, such as households, industry and agriculture. It is the useful energy that powers, heats or fuels the relevant application, excluding the energy used by the energy sector itself in transformation and delivery. The pattern of energy consumption follows a similar trend to that of primary energy regarding the percentage changes seen in a scenario over time.

The BAU scenario shows a 10% increase per year during the first decade (2020–2030). However, it is projected to shift to a reduction of 21% in the next decade (2030–2040) and a 11% reduction the following decade (2040–2050). The IB 4.0 scenario shows reductions in final energy demand between 2020 and 2050: a reduction of 1% in the first decade and a reduction of 25% in the following decade. The IB 4.1 scenario leads to a more substantial decrease in the Iberian Peninsula's final energy demand: 4% in the first decade, followed by 31% in the following decade.

E7: Change of final energy demand under each scenario for Iberian Peninsula, Spain and Portugal

Change in final energy	2020–2030	2030–2040	2040–2050
Iberian Peninsula			
IB BAU	10%	-21%	-11%
IB 4.0	-1%	-25%	1%
IB 4.1	-4%	-31%	1%
Spain			
ES BAU	6%	-29%	-9%
ES 4.0	-4%	-30%	1%
ES 4.1	-6%	-37%	0%
Portugal			
PT BAU	10%	-9%	-16%
PT 4.0	-11%	-19%	-2%
PT 4.1	-16%	-28%	-2%

The reduction of primary energy associated with crude oils fuels, such as petrol and kerosene, can be seen in the significant reductions achieved in the final energy demand of transport sector by 2040 (less so in the BAU scenario, which retains these fuels until 2050). The reduction in final energy of the transport sector caused by electrification is only enhanced by the shift from private vehicles to public transport and active forms of transport such as walking and cycling in urban areas.

In addition to the growing final energy associated with this energy use, the scenarios also account for population and GDP growth. There are no dramatic shifts in the assumed GDP development under the BAU and Energia 4.0 scenarios for the industry and buildings sectors, while the 4.1 scenario for Spain and Portugal projects a change in socio-economic assumptions alongside the sufficiency measures which lead to reductions in GDP and final energy demand. A breakdown of final energy demand across the sectors are shown in the table below.

E8: Sectoral breakdown of final energy demand under the scenarios

		2020	2025	2030			2040			2050		
Iberian Peninsula		**Historical**	**Estimate**	**IB BAU**	**IB 4.0**	**IB 4.1**	**IB BAU**	**IB 4.0**	**IB 4.1**	**IB BAU**	**IB 4.0**	**IB 4.1**
Transport	[PJ/a]	1,605	1,703	1,735	1,443	1,374	1,040	592	469	644	523	424
Industry	[PJ/a]	903	1,122	1,215	1,192	1,135	1,213	1,149	957	1,318	1,198	957
Other Sectors & Buildings	[PJ/a]	1,246	1,260	1,193	1,109	1,105	1,041	1,066	1,061	974	1,126	1,119
Total	**[PJ/a]**	**3,754**	**4,086**	**4,143**	**3,744**	**3,614**	**3,293**	**2,807**	**2,487**	**2,936**	**2,847**	**2,500**
Spain		**Historical**	**Estimate**	**ES BAU**	**ES 4.0**	**ES 4.1**	**ES BAU**	**ES 4.0**	**ES 4.1**	**ES BAU**	**ES 4.0**	**ES 4.1**
Transport	[PJ/a]	1,357	1,463	1,498	1,261	1,195	875	506	403	573	447	368
Industry	[PJ/a]	732	907	998	964	929	972	930	798	1,052	975	804
Other Sectors & Buildings	[PJ/a]	1,041	1,053	1,010	928	927	871	876	875	807	911	909
Total	**[PJ/a]**	**3,130**	**3,423**	**3,505**	**3,153**	**3,052**	**2,718**	**2,311**	**2,075**	**2,431**	**2,332**	**2,081**
Portugal		**Historical**	**Estimate**	**PT BAU**	**PT 4.0**	**PT 4.1**	**PT BAU**	**PT 4.0**	**PT 4.1**	**PT BAU**	**PT 4.0**	**PT 4.1**
Transport	[PJ/a]	248	240	238	182	179	164	87	67	71	76	55
Industry	[PJ/a]	171	215	218	228	206	241	218	159	267	223	154
Other Sectors & Buildings	[PJ/a]	205	207	183	182	177	170	191	186	167	216	210
Total	**[PJ/a]**	**623**	**663**	**638**	**592**	**562**	**575**	**496**	**412**	**504**	**515**	**419**

The increasing electrification of end uses increases the proportion of final energy demand supplied by electricity. The increasing electricity demand, which goes hand-in-hand with decreased primary and final energy demand, is supplied entirely by renewable energies by 2040.

6

What will be the benefits and challenges posed by each of the roadmaps including the costs, impact on citizens, protection of biodiversity in its deployment, land use/occupation, and use of materials?

Cost benefits

All three scenarios have very low fuel costs for the power sector because generation is based mainly on solar and wind power, which need no fuels. The average annual fuel costs of the Iberian BAU scenario – the sum of Spain and Portugal – will add up to Euro 105 billion between 2020 and 2040 and drop to Euro 87.8 billion between 2020 and 2050. The IB 4.0 scenario has a cost advantage of around Euro 21.9 billion per year (2020–2040) and Euro 15.1 billion per year (2020–2050). The IB 4.1 scenario has even greater cost advantages: Euro 31.9 billion (2020–2040) and Euro 32.9 billion per year (2020–2050).

E9: Iberian Peninsula –Total fuel costs across all sectors between 2020 and 2050 under three different scenarios

IB BAU	Unit	2020–2040	2020–2050	Unit	Annual average 2020–2040	Annual average 2020–2050
Oil	billion Euro	1,709	2,162	[billion Euro/a]	85.5	72.1
Gas	billion Euro	317	379	[billion Euro/a]	15.8	12.6
Coal	billion Euro	4	4	[billion Euro/a]	0.2	0.1
Lignite/Brown coal	billion Euro	0	0	[billion Euro/a]	0.0	0.0
Biomass	billion Euro	69	83	[billion Euro/a]	3.4	2.8
Synthetic Fuels	billion Euro	1	5	[billion Euro/a]	0.1	0.2
Total Fuel Costs	**billion Euro**	**2,100**	**2,633**	**[billion Euro/a]**	**105.0**	**87.8**
IB 4.0	**Unit**	**2020–2040**	**2020–2050**	**Unit**	**Annual average 2020–2040**	**Annual average 2020–2050**
Oil	billion Euro	1,367	1,567	[billion Euro/a]	68.3	52.2
Gas	billion Euro	220	221	[billion Euro/a]	11.0	7.4
Coal	billion Euro	3	3	[billion Euro/a]	0.2	0.1
Lignite/Brown coal	billion Euro	0	0	[billion Euro/a]	0.0	0.0
Biomass	billion Euro	70	81	[billion Euro/a]	3.5	2.7
Synthetic Fuels	billion Euro	2	10	[billion Euro/a]	0.1	0.3
Total Fuel Costs	**billion Euro**	**1,663**	**1,882**	**[billion Euro/a]**	**83.1**	**62.7**
IB 4.1	**Unit**	**2020–2040**	**2020–2050**	**Unit**	**Annual average 2020–2040**	**Annual average 2020–2050**
Oil	billion Euro	1,172	1,341	[billion Euro/a]	58.6	44.7
Gas	billion Euro	216	217	[billion Euro/a]	10.8	7.2
Coal	billion Euro	3	3	[billion Euro/a]	0.2	0.1
Lignite/Brown coal	billion Euro	0	0	[billion Euro/a]	0.0	0.0
Biomass	billion Euro	69	80	[billion Euro/a]	3.5	2.7
Synthetic Fuels	billion Euro	2	6	[billion Euro/a]	0.1	0.2
Total Fuel Costs	**billion Euro**	**1,463**	**1,647**	**[billion Euro/a]**	**73.1**	**54.9**

For Spain, the cumulative costs of investment in new power and heat generation and total fuel costs between 2020 and 2040 are calculated with Euro 2,233 billion Euro or Euro 94 billion annually on average. In comparison, the ES 4.0 scenario decreases cumulative costs for the same time span by Euro 18 billion per year to Euro 76 billion annually on average. The ES 4.1 pathway decreases costs even further to Euro 69 billion per year – a cost advantage compared to the ES 4.0 of Euro 7 billion/year and Euro 25 billion per year of ES BAU.

The results for Portugal are similar with annual savings of Euro 7 billion for the PT 4.0 case and Euro 9 billion annually respectively for the PT 4.1 in comparison to the PT BAU case.

For the whole Iberian Peninsula, the cost advantage for the IB 4.0 pathway adds up to Euro 405 billion between 2020 and 2040 and Euro 669 billion – Euro 32 billion annually – for the IB 4.1.

The fuel cost savings can finance the entire investment in new power generation across the whole Iberian Peninsula.

Reduced material demand

The material demand for energy transition technologies can decrease significantly with recycling measures and further decrease with reduced consumption as projected under the Energia 4.1 scenario. Under both scenarios, between 2024 and 2030, Spain's material demand will reduce 20% for graphite, 50% for copper and up to 80% for the rare earth metals dysprosium and neodymium. Similar values are calculated for Portugal for the 4.0 and 4.1 scenarios as well.

E10: Spain: Material demand under 2 scenarios

Spain **Material Reduction with Recycling**		**Energia 4.0 – with Recycling**				**Energia 4.1 – with Recycling**			
		2030		**2050**		**2030**		**2050**	
		[t/a]	**[%]**	**[t/a]**	**[%]**	**[t/a]**	**[%]**	**[t/a]**	**[%]**
Cobalt	Co	857	46%	2,855	85%	802	46%	2,116	103%
Copper	Cu	40,469	54%	92,869	56%	38,432	55%	73,427	71%
Graphite	Gr	10,510	22%	87,707	54%	9,853	22%	64,951	65%
Dysprosium	Dy	67	79%	79	123%	64	79%	73	171%
Lithium	Li	3,121	43%	11,070	46%	2,887	43%	8,210	56%
Manganese	Mn	11,246	67%	23,243	44%	10,526	67%	17,979	56%
Neodymium	Nd	475	80%	534	472%	461	80%	519	503%
Nickel	Ni	16,607	67%	27,740	43%	15,487	68%	21,357	54%

E11: Portugal: Material demand under 2 scenarios

Portugal **Material Reduction with Recycling**		**Energia 4.0 – with Recycling**				**Energia 4.1 – with Recycling**			
		2030		**2050**		**2030**		**2050**	
		[t/a]	**[%]**	**[t/a]**	**[%]**	**[t/a]**	**[%]**	**[t/a]**	**[%]**
Cobalt	Co	190	41%	691	86%	171	42%	468	103%
Copper	Cu	8,179	49%	20,845	55%	7,384	51%	14,981	68%
Graphite	Gr	2,320	19%	21,414	55%	2,097	20%	14,451	66%
Dysprosium	Dy	13	79%	16	117%	12	79%	14	165%
Lithium	Li	704	40%	2,645	47%	625	41%	1,804	57%
Manganese	Mn	1,855	63%	4,730	40%	1,634	63%	3,254	47%
Neodymium	Nd	92	80%	103	530%	84	80%	95	617%
Nickel	Ni	3,427	64%	6,053	43%	3,046	65%	4,287	52%

There is significant potential to implement material efficiency and reduce mineral demand with the following intervention points.

Five key interventions are required for a green and just energy transition with less minerals:

1. Reduce mineral demand through investment and delivery of shared mobility systems such as improved public transport and smaller, more efficient cars
2. Incentivise battery technology substitution for alternatives requiring less lithium, cobalt or nickel
3. Design for circularity and scale up recycling
4. Prioritise mineral use for essential energy transition needs
5. Protect 'Restricted Areas' from mining development

The analysis shows that reduced consumption leads to reduced energy demand and the demand for minerals.

Reduced land use

The assessment of the solar and wind potential for Spain and Portugal shows that the entire energy demand of the Iberian Peninsula can be met by an order of magnitude, even under strict land-use criteria that excludes high environmental sensitivity areas and agricultural land for food and feed production. The combined Iberian solar, onshore and offshore wind potential under the highest calculated land-use restriction is sufficient to supply more than 12 times the projected electricity demand in 2050. The utilisation of areas on build environment, such as rooftop solar will further reduce the required land use.

The total building footprints in urban areas were calculated to be 2,858 km^2 for the Iberian Peninsula (2,345 km^2 for Spain and 512 km^2 for Portugal). If roof area is assumed to be 100% of the building footprints, the total potential solar photovoltaic capacity would be 71 GW. A more conservative estimation, with assumptions aligned with academic literature relevant to

Europe[2], the total rooftop space would be closer to half of the technical potential giving a value of ~1,429 km^2 of rooftop space in the Iberian Peninsula, with a total potential solar photovoltaic capacity of 36 GW. However, we assumed 100% building footprint utilisation for technical potential in this section.

E12: Rooftop solar potential calculated using building footprint data

	Building Footage (km^2)					Rooftop Solar Potential
Modelling Regions	**Located on Continuous urban fabric**	**Located on Discontinuous urban fabric**	**Located on C&I units and public facilities**	**Located on Road and rail networks and associated land**	**TOTAL Rooftop area (km^2)**	**Solar Potential (MW)**
1. Andalucía	269	132	74	2	476	11,908
2. Aragón	24	28	24	0	76	1,890
3. Asturias, Principado de	9	14	12	0	35	881
4. Cantabria	4	15	5	0	23	586
5. Castilla-La Mancha	100	105	33	0	239	5,969
6. Castilla y León	32	121	36	1	190	4,758
7. Cataluña	99	128	81	1	309	7,719
8. Ceuta	1	1	1	0	2	46
9. Extremadura	77	29	12	0	119	2,969
10. Galicia	22	57	21	0	101	2,514
11. Islas Baleares	19	36	5	0	60	1,493
12. La Rioja	6	6	6	0	18	462
13. Madrid, Comunidad de	41	103	50	2	195	4,875
14. Murcia, Región de	42	23	20	0	85	2,120
15. Navarra, Comunidad Foral de	7	16	12	0	35	874
16. País Vasco	16	17	35	1	69	1,735
17. Valenciana, Comunidad	123	121	68	1	313	7,830
Spain total	**891**	**951**	**493**	**10**	**2,345**	**58,630**
18. Portugal	103	324	84	2	512	12,809
Portugal total	**103**	**324**	**84**	**2**	**512**	**12,809**
Iberian Peninsula TOTAL	**993**	**1,275**	**577**	**12**	**2,858**	**71,439**

Note: Continuous urban fabric (land cover class 1.1.1), Discontinuous urban fabric (landcover class 1.1.2), Industrial or commercial units and public facilities (land cover class 1.2.1) and Road and rail networks and associated land (land cover class 1.2.2) on CORINE Land Cover 2018

Solar potential from greenhouses

Solar potential for greenhouse rooftops is estimated based on the statistics on greenhouse areas. Greenhouse farmland covers an estimated 733 km^2 in Spain[3] and approximately 30 km^2[4] in Portugal. If all greenhouse rooftops were utilised for solar photovoltaic installation, they would create solar potential with around 19,150 MW in Spain and 750 MW in Portugal.

Solar and wind energy can cover the future energy consumption of the Iberian Peninsula more than tenfold, even under strict land-use criteria. The required area for installation can also be significantly reduced by maximising the use of existing roof space on residential and commercial buildings.

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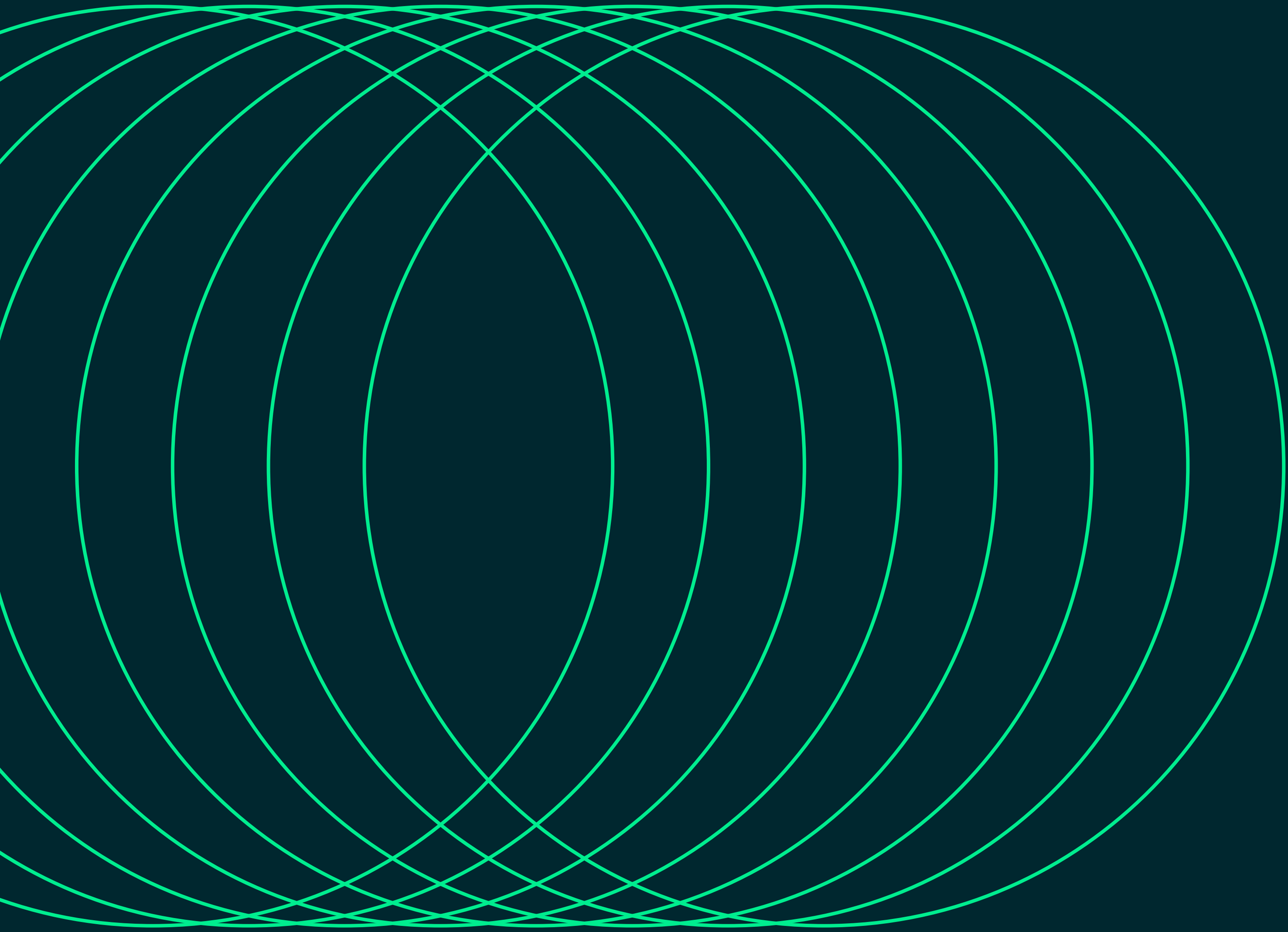
[2] Bódis, K., Kougis, I., Jäger-Waldau, A., Taylor, N., Szabó, S., 2019. A high-resolution geospatial assessment of the rooftop solar photovoltaic potential in the European Union. Renewable and Sustainable Energy Reviews 114, 109309, https://doi-org.ezproxy.lib.uts.edu.au/10.1016/j.rser.2019.109309

[3] Greenhouses farmland in Spain 2022, by crop: https://www.statista.com/statistics/1218871/greenhouse-area-spain-by-crop/?srsltid=AfmBOordlRbTBmkk4zM96ZuGxb5BklS4P_2BYHdt45R_tAwApCE3iURa (24/11/2025)

[4] Ferreira et al (2020). Overview of greenhouse horticulture in Portugal: technology and environment. Conference: VIII Congresso Ibérico de Ciências Hortícolas At: Coimbra, Portugal: https://www.researchgate.net/publication/340351917_Overview_of_greenhouse_horticulture_in_Portugal_technology_and_environment (accessed 27/11/2025)

1

Introduction and Scope of Research



1.1 Context for this research

In 2011 Greenpeace Spain released the Energía 3.0 study which demonstrated that the energy transition to renewables is viable, technically possible and economically profitable, even more if the opportunities of energy efficiency and smart devices and grids, fast response mechanisms, integration and electrification are taken as well as the deployment of intelligence in political, administrative and socioeconomic systems . This report was commissioned as an update of the 3.0 study, reflecting the need to accelerate the decarbonisation of the economy from 2050 to 2040 according with climate justice principles so that the decarbonisation of the Iberian Peninsula is better aligned with the latest climate science. Our report demonstrates that Greenpeace's principles are mandatory if the energy transition of the Iberian Peninsula has a chance to meet the necessary decarbonisation trajectory to be aligned with the Paris Agreement. These principles highlight "that the solution to the climate emergency from an energy point of view lies in the urgent development of an energy system… that prioritises abandoning fossil fuels before 2040… shifting to a 100% renewable, efficient, intelligent, fair energy supply. Something essential to be able to respect planetary limits, achieve climate neutrality in that period and limit the increase in global average temperature to 1.5°C."[5]

As signatories of the Paris Climate Agreement and part of the European Union, both Spain and Portugal submitted National Energy and Climate Plans (NECPs) at the start of the decade for the period of 2021–2030, outlining the transition plan for the defined 10-year period. In addition to this, both Spain and Portugal submitted updated NECPs in 2024 as required by European Member States "to reflect the increased EU 2030 climate and energy ambitions as set by the Fit for 55 legislative package and the RepowerEU plan."[6] Although these updated plans increase the ambition to decarbonise Europe relative to previous commitments made by Member States under EU policies and NDCs under the Paris Agreement[7], there is still a considerable gap between what the science says is necessary to meet the objectives of the Paris Agreement and current policies.

For example, the Climate Action Tracker's assessment of the EU's overall emissions trajectory defines it as insufficient given that "the EU is not fully on track to meet its 2030 target to reduce emissions by at least 55% below 1990 (including LULUCF)."[8] Climate Action Tracker's insufficient assessment was made despite the fact that the EU had a proposed 2040 target of a ~90% reduction relative to 1990s levels (including LULUCF and international credits). This assessment was made prior to the confirmation of the agreement by EU Council, Parliament and Commission to reduce greenhouse gas emissions by 90% of 1990 levels by 2040, involving the purchase of foreign carbon credits to cover 5% of the cuts, which means the EU's own commitment is much lower: 85% at best.[9] The assessment reflects the fact that an ambitious 2040 emissions reduction target is not enough to achieve an emissions trajectory aligned with climate science. The speed at which progress occurs determines how much CO_2 is emitted and how likely the EU will be able to remain under its carbon budget.[10]

The result of this study reflects that it is only with increased ambition – aligned with the Greenpeace objective of "shifting to a 100% renewable, efficient, intelligent, fair energy supply" – that the 'per capita allocation' carbon budget for the Iberian Peninsula can be met in a manner which aligns with the Paris Agreement.

The fair allocation budget was calculated using Greenpeace's principles of climate justice, such that the allocation of the remaining global carbon budget is based on the share of global population.[11] Noting here that the fairness of the carbon budget "only relates to Spain's domestic efforts… in order to fulfil the equity principles of the UN Framework Convention on Climate Change, Spain would have a responsibility to provide substantial financial resources to support emission reductions in Global South countries."[12]

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[5] Greenpeace Spain, Terms of Reference for 'Energy for a Better Life'

[6] EU Commission, National energy and climate plans, <https://commission.europa.eu/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en>, accessed 03/09/2025

[7] For example, the Spanish NECP increased the ambition of the 2030 emission reduction target from 23% to 32% relative to 1990 levels (between 2020-25)

[8] Climate Action Tracker, <https://climateactiontracker.org/countries/eu/>, accessed 03/09/2025

[9] Carbon Market Watch. "Last Chance to Shore Up EU's 2040 Climate Target." Carbon Market Watch, November 20, 2025. https://carbonmarketwatch.org/2025/11/20/last-chance-to-shore-up-eus-2040-climate-target/.

[10] Ibid

[11] Greenpeace Spain, 'Keys to making Spain a world leader in climate action' (10/06/2024)

[12] Ibid

1.1.1 Research questions

The research questions are:

- To what extent can energy-related emissions can be reduced across the Iberian Peninsula (Spanish mainland, Portugal, the Balearic Islands and Ceuta), with the view to finding a pathway for the Iberian Peninsula to reduce its emissions in a manner aligned with the Paris Agreement?
- What level of emissions reductions are technologically possible by 2040 relative to a 'business as usual' case in each of the sectors/industries (listed below), if given the right level of policy support and investment?
- What technologies/solutions will drive these emissions reductions in each of the sectors/industries listed (with as much granularity as possible)?
- What is the overall abatement potential, assumed uptake with a focus on energy supply.
- What happens if sufficiency measures are introduced along with efficiency, electrification and renewables such as meat consumption reduction.
- What will be the benefits and challenges posed by each of the roadmaps including regarding the costs and impact on citizens, the protection of biodiversity in its deployment, the land use/occupation and use of materials?

The sectors/industries included are: aluminium, chemicals, cement, steel, textiles and leather, agriculture and food processing, forestry and wood products, construction and real estate/buildings, power utilities, gas, water utilities, data centres, and transport. The overall goal of this project is to craft a pathway for Spain and Portugal to achieve ambitious emission reductions between the present and 2040, with the objective of the pathways to achieve net zero by 2040.

1.1.2 Geographic Territory

The scope of the Energía 3.0 study was the Spanish mainland, thus the regions modelled in the 3.0 study do not align with the geographic territory analysed in this study. The scope of the geographic territory included in this study is the whole Iberian Peninsula that forms one single energy system, thus including Spain and Portugal and Spanish territories that are connected to the mainland (Balearic Islands and Ceuta), excluding only Spanish or Portuguese territories that are not connected to the mainland, such as the archipelagos of Açores, Madeira, Canary Islands and the city of Melilla (Figure 1).

Figure 1-1: Map of the 18 modelling regions used in this study

Table 1: 18 modelling regions and population

Modelling Regions	Population – Spain 2024[13]; Portugal 2023[14]
1. Andalucía	8,631,862
2. Aragón	1,351,591
3. Principado de Asturias	1,009,599
4. Cantabria	590,851
5. Castilla-La Mancha	2,104,433
6. Castilla y León	2,391,682
7. Cataluña	8,012,231
8. Ceuta	83,179
9. Extremadura	1,054,681
10. Galicia	2,705,833
11. Islas Baleares	1,231,768
12. La Rioja	324,184
13. Comunidad de Madrid	7,009,268
14. Región de Murcia	1,568,492
15. Comunidad Foral de Navarra	678,333
16. País Vasco	2,227,684
17. Comunidad Valenciana	5,319,285
Spain total *	**46,294,956**
18. Portugal **	10,142,079

*Spain total population excludes areas outside of the project scope (i.e. Canarias and Melilla).
**Portugal total population excludes areas outside of the project scope (i.e. Madeira and Açores).

The model inputs used in this report account for the exclusion of the Canary Islands and Melilla from Spain's data, based on current population and GDP statistics. Likewise for Portugal, the exclusion of Madeira and Açores was also accounted for. This was achieved using the following method:

- Reducing population inputs, both historical and future projections, by a scaling factor based on current national statistics[15,16]
- Reducing residential energy demand, both historical and future projections based on national population statistics[11,12]
- Reducing GDP inputs, both historical and future projections, by a scaling factor based on current national statistics[17,18]

As mentioned, the Energía 3.0 study considered only the Spanish mainland. The exact method used by the authors of the 3.0 report to scale national IEA data to the scope of the Spanish mainland was not detailed in the report and thus no alterations to 3.0 data are made when comparing values in Section 1.2.1, as this would have added an additional source of variance to the comparison.

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[13] Spain (2024): Annual population census (Instituto Nacional de Estadistica): https://www.ine.es/dynt3/inebase/index.htm?padre=10607&capsel=11555

[14] Portugal (2023): População residente (N.°) por Local de residencia – 2023 (Instituto Nacional de Estatística): https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_indicadores&indOcorrCod=0007307&contexto=bd&selTab=tab2&xlang=pt#CHG_LANG:en;menu=ine_smenu#

[15] as per reference 9

[16] as per reference 10

[17] Instituto Nacional de Estadística, 'Contabilidad Regional de España – Producto Interior Bruto regional. Serie 2000-2023 ', <https://www.ine.es/dyngs/Prensa/es/CRE2023.htm> (18/12/2024)

[18] Instituto Nacional de Estatística (INE), Produto interno bruto por NUTS III (preços correntes; anual) [Gross Domestic Product by NUTS 3 (current prices; annual)], Excel file, https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=cn_quadros&boui=391542778.

1.2 Energy and Emissions Context of the Iberian Peninsula

The Energía 3.0 study was completed in 2011 and thus 15 years have passed since its release. The Energía 3.0 report demonstrated at the time that the energy transition to renewables, in addition to being necessary and urgent, is viable, technically possible and economically profitable for the whole society, even more if the advantages of the enormous options of energy efficiency and socio-institutional and technological intelligence are seized. The findings of the study marked a milestone at that time and were of enormous importance in demonstrating the falsity of the arguments that were being used (and are still in use) to stop or even prevent the energy transition from happening.

Fifteen years after the launch of the Energía 3.0 report for Spain, despite action to progress the energy transition, it appears clear that it is not happening at the required pace and intensity. It is, therefore, fundamental to check whether it is still possible for Spain and (newly) for Portugal to reach net zero emissions despite financial and planetary limits and the delay in climate action, and to evaluate possible pathways and their implications for emissions, costs, land occupation and use of critical materials.

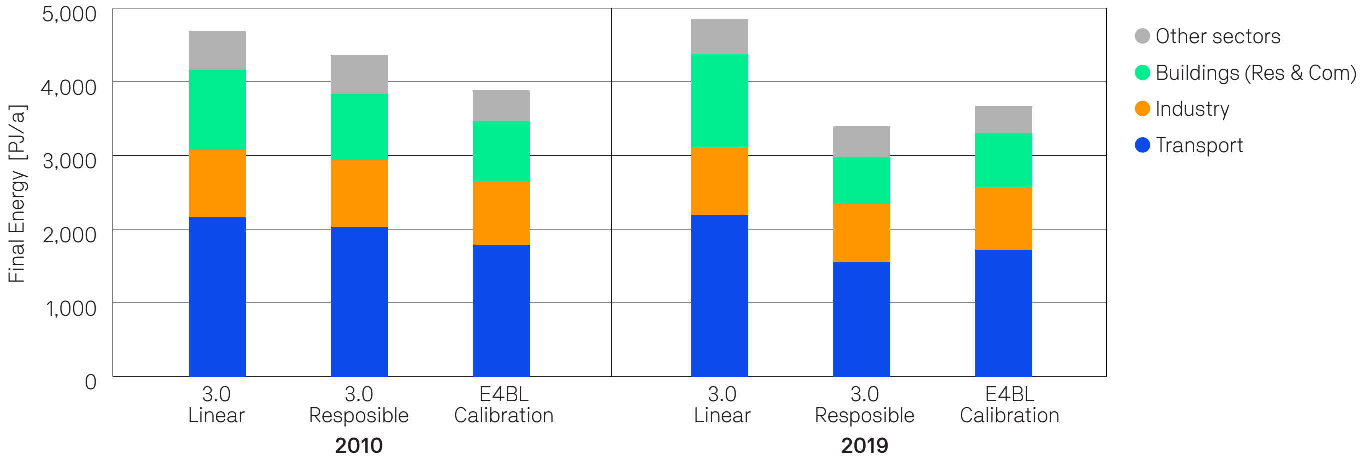
To start, the following sections outline the actual progress made since the publication of the Energía 3.0 report regarding final energy use and total gross emissions. Beyond setting the context, the Energía 3.0 report ensured the calibration of the ‘Energy for a Better Life’ scenarios for Spain (E4BL) was done appropriately. The E4BL scenarios for Spain and Portugal, are the bottom-up pathways explored in this study and form the basis for assessing the potential of the Iberian Peninsula to meet a decarbonisation pathway aligned with a fair-allocation carbon budget.

1.2.1 Contextualising the Spain Scenario relative to the Energía 3.0 study

A comparison is made here between the ‘linear’ and ‘responsible’ transition pathways of the Energía 3.0 study to the historical data calibrated and used in the ‘Energy for a Better Life’ study for Spain, the Balearic Islands and Ceuta (note the difference in scope of the two studies). Figure 1-2 demonstrates both the outcome of the calibration process undertaken and the progress Spain has made in reducing its energy demand relative to the trajectories set out in the Energía 3.0 report. The calibration process is a standard procedure in the development of an energy scenario, ensuring that appropriate historical statistics are used in the development of an energy scenario, as well as the appropriate adjustments for geographic boundaries and accounting for differences such as in the treatment of international travel (in Figure 1-2 the energy demand associated with international travel is combined with domestic energy demand for the purposes of providing a direct comparison).

The authors of this study do not wish to pit data sources against one each other such as the IEA’s national accounts data on the energy consumed in the transport sector against other sources such as Spanish national transport statistics on the usage of roadways and distance travelled by vehicles. This is just to acknowledge that the ‘source of truth’ for this study is IEA data, and that different data sources, assumptions, methodology for accounting for geographic territory, lead to differences in energy values and assumptions. These differences are only enhanced when projections are involved and compared to updated data sources. Figure 2 provides an opportunity to reflect upon the assumptions made in the Energía 3.0 report and the scenario narratives behind them (note: the historical IEA data used in the calibration of the Spanish scenarios remains consistent across all the Spain scenarios).

Figure 1-2: Comparison of Spain's final energy demand across the Energía 3.0 scenarios to data used in the E4BL scenarios for Spain



Regarding the calibration process undertaken, Figure 2 demonstrates that there are differences in the 2010 historical values calculated as the basis for each study in terms of final energy demand (Energía 3.0 scenarios relative to the 'Energy for a Better Life' report scenarios are abbreviated as E4BL in Figure 2. The deviation between the 2010 values stem from a number of factors:

- The Energía 3.0 report used IEA data starting from a base year in 2007, and given that the report was published in 2011, the authors would not yet have had access to the accurate final 2010 published IEA statistics. Thus, the authors would have had to use forecasted/provisional IEA data or estimate the 2010 values based on 2007-2009 trends.
- The Energía 3.0 report also does not explicitly indicate the extent to which modifications to national Population and GDP statistics were undertaken to account for the geographic boundaries of the study, nor the methods for doing so. It is possible that this plays a role in the deviation between the two scenarios. The methods used in this study are discussed in Section 1.1.2 and should be considered if one was to compare results across projections in this study and the Energía 3.0 report (noting that there are already differences with historical data used as the basis of this study).
- The extent to which IEA data is used as the primary source of truth differs from the Energía 3.0 and the methodology used in this study – and is thus likely the largest source of deviation between the studies.[19,20] Example provided below:

The E4BL methodology calculates energy demand using IEA domestic energy statistics and domestic transport statistics from the Energía 3.0 report. This provides an accurate energy intensity value for domestic transport which was then applied to each transport mode in the following fashion (example provided for passenger travel in p-kms, with PT standing for passenger travel and TD standing for transport demand):

$$\textit{calibrated energy intensity}\left[\frac{PJ}{p-km}\right] = TD_{\textit{IEA Domestic}}\left[\frac{PJ}{a}\right] \div PT_{\textit{domestic}}\left[p-km\right]$$

$$TD_{\textit{Total Passenger}}\left[\frac{PJ}{a}\right] = \left(PT_{\textit{Domestic}} + 50\% \times PT_{\textit{international}}\right)\left[p-km\right] \times \textit{energy intensity}\left[\frac{PJ}{p-km}\right]$$

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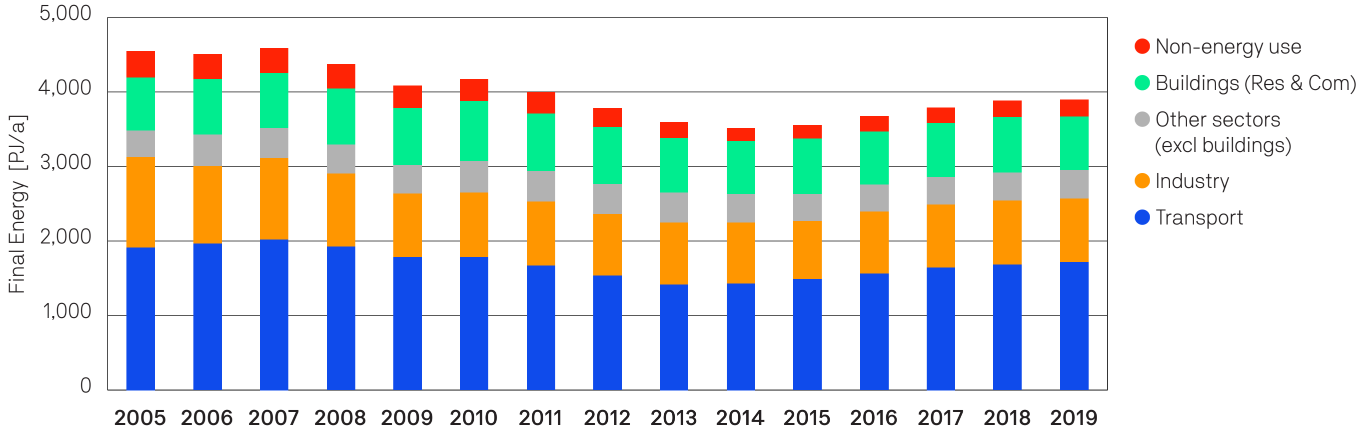
[19] Refer to 'Section 2.1: Databases and model calibration' for a more detailed explanation of the OECM model calibration process.

[20] For example: the 3.0 study utilised other international & national statistics from the Spanish government to calibrate annual transport demand

As can be seen by the 2019 values in Figure 2, the linear scenario expected growth in energy use across the Spanish mainland (with a growth of ~3.5% between 2010 and 2019), predominantly driven by expected growth in the building sector, with transport and industry remaining stable. This growth in energy demand did not eventuate, as can be seen by the calibrated IEA data used in this study. The E4BL calibration data shows more broadly that Spain was able to reduce its energy demand more quickly than anticipated by the linear transition to net zero scenario (net zero by 2050) although slower than the responsible scenario from Energía 3.0. The fact that Spain's trajectory between 2010 and 2019 more closely followed the responsible pathway than the linear transition stem from the fact that the Energía 3.0 report assumed a pronounced increase of energy demand and emissions before 2020, something that did not happen in such a sharp way for a variety of factors such as: climate and energy policies taking effect, related increases in energy efficiency across the economy (household appliances, vehicles, industry), differences in forecasted economic growth, alongside economic pressures caused by the Global Financial Crisis (GFC) and related changes in consumer behaviour which continued after the GFC. Thus, while some of the reductions in energy demand are structural, it is also the case that some of these reductions will not persist to such an extent in a scenario where Spain's GDP will continually grow as opposed to the slow growth and contractions seen between 2008 and 2014.

The context mentioned above – namely that the expected growth of the Energía 3.0 linear scenario did not occur – is reflected in Figure 1-3, which shows the development of Spain's final energy demand between 2005 and 2019 according to the scaled IEA data used in the Spanish scenarios under this study. (Note: the effects of COVID-19 occurred after 2019, so the reductions in energy demand here do not include those associated with the pandemic.)

Figure 1-3: Development of Spain's Final Energy Demand 2005-2019[21]



1.2.2 Progress in the Reduction of Emissions Across the Iberian Peninsula

The focus of this section moves away from historical comparisons of the Energía 3.0 report and the E4BL scenarios, and turns towards the progress the Iberian Peninsula has made as a whole in reducing its emissions, with the data coming from the national accounts of Spain and Portugal.[22] EU policies, such as the 'Fit for 55' package, have their emissions target set relative to a 1990 baseline figure, thus the following figures show data from 1990. Figure 4 provides an overview of the GHG emissions generated by the Iberian Peninsula since 1990, including a breakdown of the emissions from Spain and Portugal. It is clearly shown that Spain accounts for most of the peninsula's emissions, with Spain accounting for a consistent proportion of emissions in each year (~83%). The analysis undertaken also reveals a relationship between energy demand and emissions, as Spain's final energy demand is 5 times greater than Portugal's, and this ratio of 5x also holds for emissions in the same period (2005-2023 for the purposes of energy analysis).

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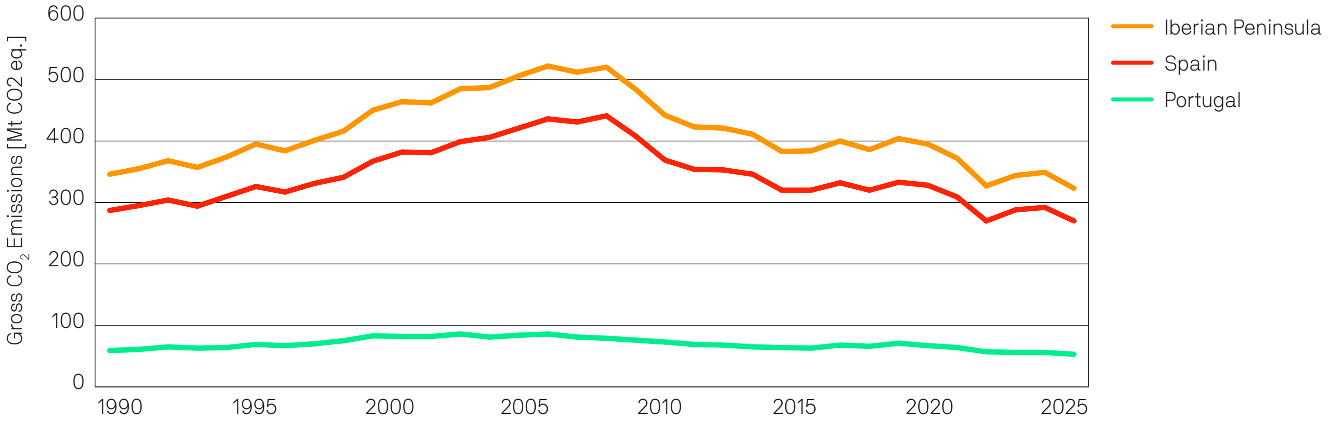
[21] IEA. World Energy Balances . IEA. 2021. <https://www.iea.org/data-and-statistics/data-product/world-energy-balances>

[22] European Environment Agency, EEA greenhouse gases – data viewer, <https://www.eea.europa.eu/en/analysis/maps-and-charts/greenhouse-gases-viewer-data-viewers> (last modified 16/05/2025)

Separate to the inter-regional comparisons, Figure 4 also reveals much of the context of the Iberian Peninsula's emissions. Firstly, from an NECP perspective, Spain and Portugal have emissions reduction targets of 32% and 34% respectively for 2030 (relative to 1990 emission levels).[23,24] These emissions targets are lower than the overall EU target of a 55% reduction, and this relates in part to the fact that between 1991 and 2019, both Spain and Portugal generated an increased amount of annual emissions relative to the 1990 baseline. Although, year-on-year emissions regularly decreased since 2008, they have only recently fallen below 1990 levels with the most recent data for 2023 showing a reduction of 6.5% relative to 1990 levels. Although these reductions are far from the 2030 target of 32-34% reduction in emissions, the gross emissions do not reveal the full context of emissions across the Iberian Peninsula such as the emission intensity of the economy.

Figure 1-4: Historical comparison of Iberian Peninsula, Spain and Portugal's Gross GHG emissions



The data displayed in Figure 1-4 is not sufficient to understand the full context behind the emissions of the Iberian Peninsula. As mentioned above, the Iberian Peninsula has a less rapid 2030 decarbonisation target relative to the EU-wide objective (reductions of 32-34% as opposed to 55%). This is because the updated NECPs consider a range of factors such as historical responsibility and varying national circumstances. The context for the Iberian Peninsula having a less rapid decarbonisation relative to the percentage of the EU-27 levels can be clearly seen in Figure 1-5. Overall Europe was producing many more emissions per person than Spain or Portugal, with the EU-27 having 1.6x the emissions per capita than Spain and 2x the emissions/capita than Portugal (in 1990).

In the above context, the emissions increase in Figure 1-4 can be better understood, the emissions in the Iberian Peninsula didn't only rise at the rate population and GDP grew previously, the Iberian Peninsula (particularly Spain) was growing its economy in the same way much of Europe previously had. Thus, as the Iberian Peninsula sought to improve its economic wellbeing between 1990 and 2008 and improve indicators such as GDP/capita to be aligned with more prosperous EU Member States, it also came close to reaching the emissions/capita of the EU-27.[25]

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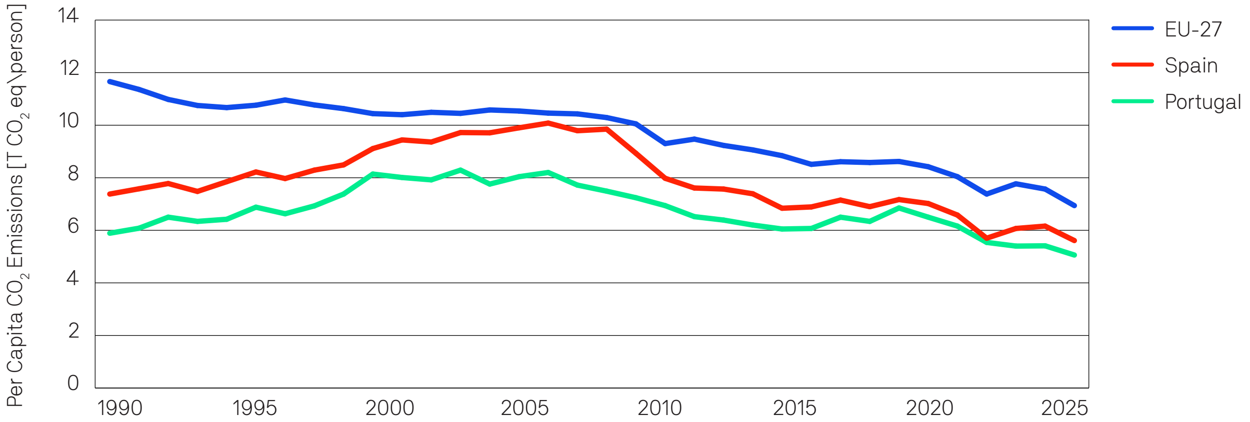
[23] Government of Spain, Ministry for the Ecological Transition and the Demographic Challenge (MITECO), 'Integrated National Energy and Climate Plan – Update for 2023-2030' (September 2024)

[24] Government of Portugal, 'National Energy and Climate Plan 2021-2030 (NECP 2030) – Update/Review' (1/10/2024)

[25] World Bank, GDP per capita (current US$), <https://data.worldbank.org/indicator/NY.GDP.PCAP.CD?locations=ES-PT-EU> (accessed 10/9/25)

Figure 1-5: Historical per capita emissions of: EU-27, Spain and Portugal



Although Figure 1-5 provides a clear picture as to why the EU has set itself a more ambitious 2030 emissions reduction target relative to 1990 than those set out in the Spanish and Portuguese NECPs, it does not directly show data related to economic activity. This is relevant as although emissions-per-capita is an important metric to normalise emissions for the purpose of comparison, it does not reflect the economic output of a region and the number of emissions associated with said output. Figure 1-6 provides insight into the carbon intensity of economic activity in the EU and the Iberian Peninsula, in terms of emissions per unit of GDP (measured in 2010 Euros).[26]

Figure 1-6: Historical carbon intensity of economic activity: EU-27, Spain, Portugal

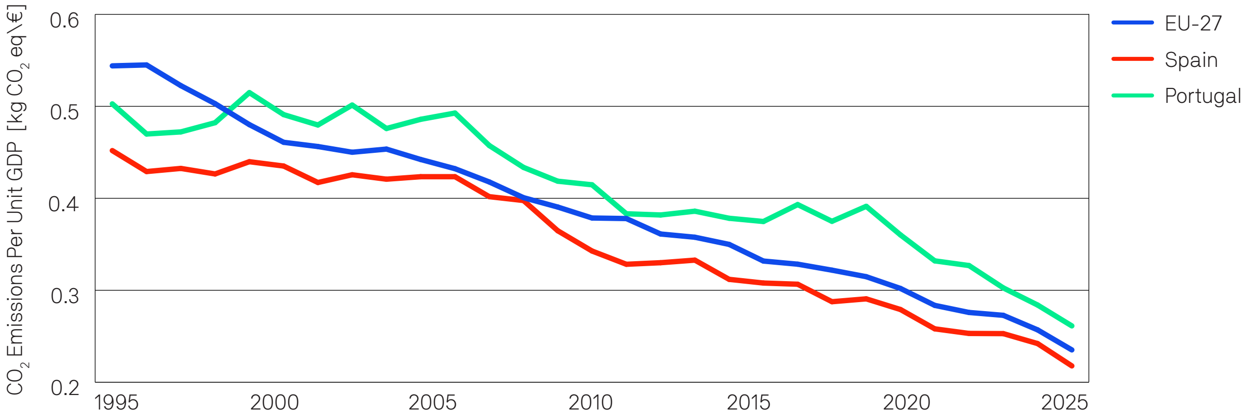


Figure 1-6 has a timeline from 1995 to 2023 due to the availability of historical GDP data. Several interesting trends emerge from this data. Firstly, as in Figure 1-5, the EU-27 data shows a higher emissions intensity in the early 1990s. The ratio between EU-27 and the Iberian Peninsula data differs between the per capita emissions and the per GDP emissions, with the emissions intensity of Europe being closer to the emission intensity of both Spain and Portugal relative to the per capita emission data (particularly Portugal). When comparing the data in the above figures, the emissions per capita values for Portugal are lower than Spain but higher in terms of the emission intensity. It is also of note that, unlike in Figure 1-5, the EU-27 fall below the Portuguese data, demonstrating the progress Europe has made in increasing its GDP while reducing the amount of carbon and energy required to do so.

Perhaps one of the most noteworthy points from Figure 1-6 is the difference between the trends in gross GHG emissions and the emission intensity of the economy in the Iberian Peninsula. Although Spain and Portugal demonstrated a general tendency to generate increasing emissions year-on-year until the end of 2005, and generate emissions higher than the 1990 baseline until 2019, the Iberian Peninsula was able to consistently decrease the emissions intensity of the economy

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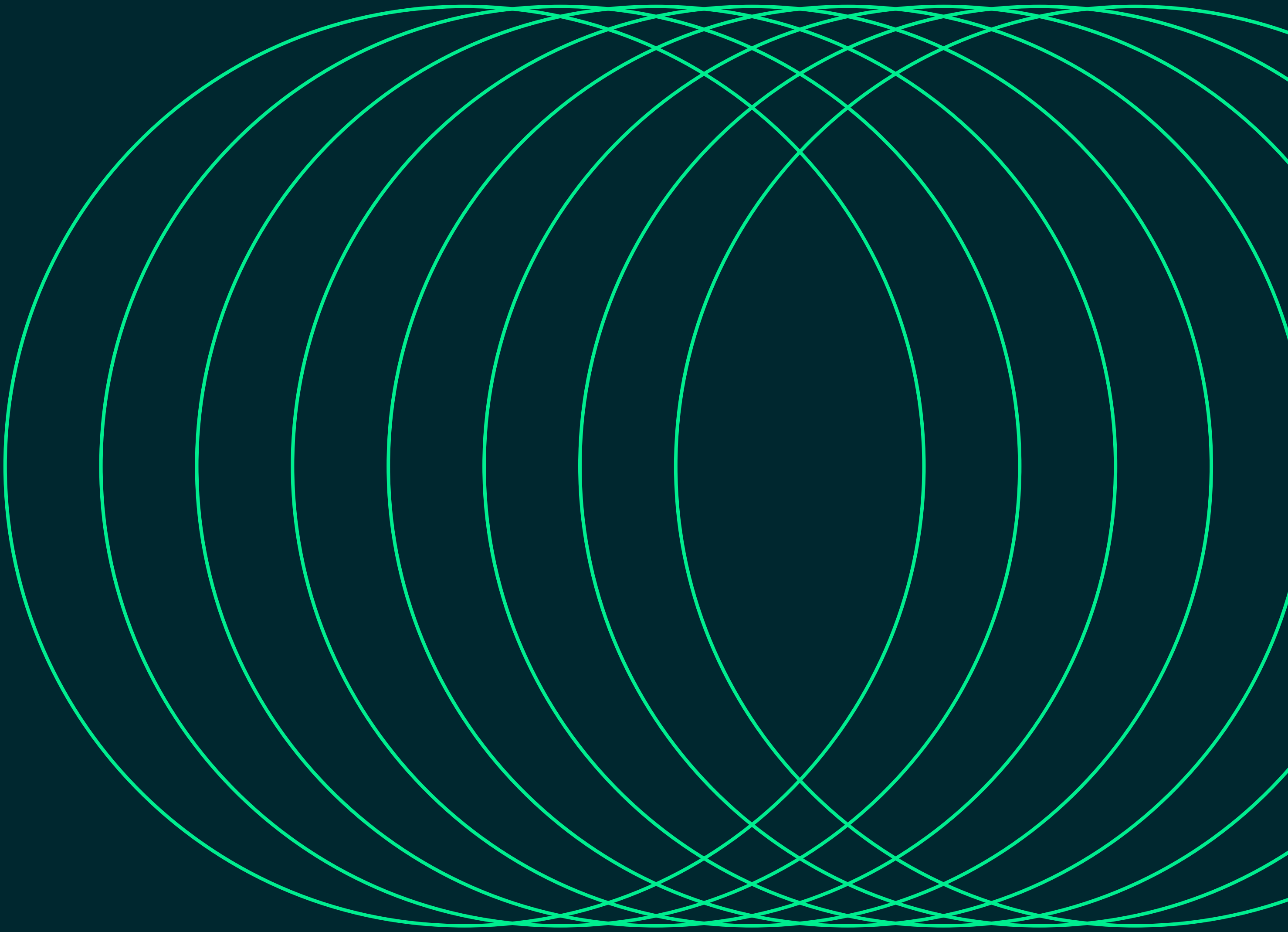
[26] Eurostat, Gross domestic product (GDP) and main components – Chain linked volumes (2010), million euro, <https://ec.europa.eu/eurostat/databrowser/view/nama_10_gdp__custom_17911792/default/table> (Updated 29/08/2025)

during the same periods. Thus, both Spain and Portugal are well positioned to capitalise on the increasing deployment of renewable energy and reductions in the emission intensity of the economy.

2

One Earth Climate Model – Methodology Overview



This work for the Greenpeace Spain is based on the advanced version of the One Earth Climate Model (OECM 2.0). The OECM is an integrated energy assessment model. It was originally developed between 2017 and 2019 as an interdisciplinary research project between the University of Technology Sydney, the German Aerospace Centre (DLR) and the University of Melbourne. The task was to develop a detailed 1.5 °C energy-related greenhouse gas emissions trajectory for 10 world regions. OECM 1.0 was developed based on established DLR and UTS energy models, and consisted of three independent modules:

1. Energy System Model (EM): a mathematical accounting system for the energy sector[27]
2. Transport scenario model TRAEM (TRAnsport Energy Model) with high technical resolution[28]
3. Power system analysis model ([R]E 24/7) which simulates the electricity system on an hourly basis and at geographic resolution to assess the requirements for infrastructure, such as grid connections, between different regions and electricity storage types, depending on the demand profiles and power-generation characteristics of the system.[29]

Based on the OECM, the Institute for Sustainable Futures at the University of Technology Sydney (UTS-ISF), in close co-operation with the UN-convened Net Zero Asset Owners Alliance, updated the OECM 1.0 model. The advanced One Earth Climate Model (OECM 2.0) merges the EM, TRAEM and [R]E 24/7 into one MATLAB-based energy system module. The OECM has now been applied to 19 countries (plus the EU27 region) that form the G20 in 2023, to produce energy scenarios and fair carbon budgets for each country, as well as detailed carbon budgets for key industries in each country.

The Global Industry Classification System (GICS) was used in the OECM 2.0 to enable the design of energy and emissions pathways for clearly defined industry sectors (sectorial pathways). Finding pathways to reduce emissions for industry sectors requires very high technical resolution for the calculation and projection of future energy demands and the supply of electricity, (process) heat, and fuels necessary for each industry. An energy model with high technical resolution must be able to calculate the energy demand based on either the sector-specific gross domestic product (GDP) projections or market forecasts of material flows, such as the demand for steel, aluminium, or cement in tonnes per year. The methodology chapter outlines five fundamental elements of the modelling process (as described below):

(i) databases and model calibration
(ii) sector and sub-sector definitions
(iii) cost calculations
(iv) a demand module, and
(v) a supply module.

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[27] Teske S, Pregger T, Naegler T, Simon S, Pagenkopf J, van den Adel B, et al. Energy scenario results. Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-Energy GHG Pathways for +1.5C and +2C. 2019;:175–401.

[28] Pagenkopf J, van den Adel B, Deniz Ö, Schmid S. Transport transition concepts. Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-Energy GHG Pathways for +15C and +2C. 2019;:131–59.

[29] Teske S. Bridging the Gap between Energy- and Grid Models, Developing an integrated infrastructural planning model for 100% renewable energy systems in order to optimize the interaction of flexible power generation, smart grids and storage technologies, chapter 2,. 2015.

2.1 Databases and Model Calibration

The OECM model uses several databases for the energy statistics, the energy intensities, the technology market shares, and other market or socio-economic parameters. The calculation of the energy balance for the base year is based on the International Energy Agency (IEA) Advanced World Energy Balances[30] and additional sector and national specific databases.

Modifications were applied to the IEA energy statistics in the transport sector to align the OECM methodology with that applied by Greenpeace Spain in their Energía 3.0 report, in which Spain was assigned 50% of international mobility demand in the case of transport between the country of origin and destination. This was undertaken as the IEA data does not capture international transport of passengers or freight between the country of origin and an alternate country of transit. The basis for Greenpeace Spain's decision to use this approach in both the Energía 3.0 and 'Energy for a Better Life study is that the "same criterion has been used to allocate emissions from international flights in the recent regulations that incorporate aviation into the European Emissions Trading System."[31]

The energy statistics for a calculated country and/or region are uploaded via an interface module. The data for each year from 2005 onwards until the last year for which data are available are used to calibrate the model. This process is based on the Energy System Model (EM), which has been developed by the German Aerospace Centre DLR. The market shares are calculated based on the IEA statistics and a technical database for energy intensities for various appliances and applications across all sectors. These data are inputs, and the calibration process is performed with a standardised Excel tool. The calibration method is briefly outlined below using the transport sector as an example. The IEA's Advanced World Energy Balances provides the total final energy demand by transport mode – aviation, shipping, rail, or road – by country, region or globally. However, it provides no further specification of the energy use within each of the transport modes. Therefore, a further division into passenger and freight transport is calculated using percentage shares. These proportions were aligned with the breakdowns utilised in the Energía 3.0 report.[32] To calibrate the model in alignment with the aforementioned choice to capture 50% of international transport demand, the transport demand of the past decades was recalculated using the following method (with the example provided for passenger travel in p-kms, with PT standing for passenger travel and TD standing for transport demand):

$$\textit{calibrated energy intensity}\left[\frac{PJ}{p-km}\right] = TD_{\textit{IEA Domestic}}\left[\frac{PJ}{a}\right] \div PT_{\textit{domestic}}\left[p-km\right]$$

$$TD_{\textit{Total Passenger}}\left[\frac{PJ}{a}\right] = \left(PT_{\textit{Domestic}} + 50\% \times PT_{\textit{international}}\right)\left[p-km\right] \times \textit{energy intensity}\left[\frac{PJ}{p-km}\right]$$

Calibrating the model based on historical data ensures that the basis of the scenario projection for the coming years and decades is correctly mapped and ensures that the changes are calculated most realistically. For the forward projection of the transport demand, the calculation method is reversed: the transport demand for each transport mode is calculated based on the annual change, as a percentage. The calculated total annual passenger kilometres and tonne kilometres are the inputs for the energy demand calculation.

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30 IEA. World Energy Balances . IEA. 2021. https://www.iea.org/data-and-statistics/data-product/world-energy-balances

31 Greenpeace Spain, 'Energía 3.0 – un sistema energético basado en inteligencia, eficiencia y renovables 100%' (September 2011)

32 Ibid. Teske S, Pregger T, Naegler T, Simon S, Pagenkopf J, van den Adel B, et al. Energy scenario results. Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-Energy GHG Pathways for +1.5C and +2C. 2019; 175–401.

Table 2: Calibration for calculating the transport demand

Calculation Concept	Process	Until 2019	Unit	Comment
Transport demand				
Aviation, shipping, rail and road – Past to Present Annual demand	Data	Database	[PJ/yr]	Data: IEA Advanced World Energy Balances Calibration with Energía 3.0 report data to account for 50% of international transport of passengers and freight.
Passenger share	Input	Literature	[%]	Shares from total energy demand from the Energía 3.0 report
Freight share	Input	Literature	[%]	Shares from total energy demand from the Energía 3.0 report
Average energy intensity – passenger transport	Data	Literature	[MJ/pkm]	Calculated using domestic transport demand statistics from the Energía 3.0 report and IEA domestic energy statistics
Average energy Intensity – freight transport	Data	Literature	[MJ/tkm]	Calculated using domestic transport demand statistics from the Energía 3.0 report and IEA domestic energy statistics
Passenger kilometres	Calculation	= Annual demand/ Energy intensity	[pkm]	Result of above transport calibration process
Tonne kilometres	Calculation		[tkm]	Result of above transport calibration process
Annual growth/decrease – passenger kilometres	Calculation	= Annual demand previous year/ Annual demand calculated year	[%/yr]	Calculated to understand the trend between 2005 and 2020
Annual growth/decrease – tonne kilometres	Calculation		[%/yr]	
Population – indicator of passenger transport development	Data	Database	[million]	Data: UN
GDP per capita – indicator of passenger and freight transport development	Data	Database	[$GDP/ capita]	Data: World Bank
GDP – indicator of freight transport development	Data	Database	[$GDP]	Data: World Bank

Table 3: Methodology of OECM 2.0 – Projection of transport demand based on the changing demand in kilometres

Process	2020-2050	Unit	Comment
Aviation, Navigation, Rail, Road – Projection			
Calculation	= (passenger km previous year) × (increase/decrease in %/yr)	[pkm]	Starting point: base year 2019
Calculation	= (tonne km previous year) × (increase/decrease in %/yr)	[tkm]	Starting point: base year 2019
Input	INPUT in %/yr	[%/yr]	Assumption
Input	INPUT in %/yr	[%/yr]	Assumption
Calculation	INPUT in %/yr	[million]	Assumption based on UN projection
Calculation	= $GDP/population	[$GDP/capita]	
Calculation	INPUT in %/yr	[$GDP]	Assumption based on World Bank projection
Result	Time series 2020-2050: Passenger km per year and region	[pkm/yr]	Input for energy demand calculation
Result	Time series 2020-2050: Freight km per year and region	[tkm/yr]	Input for energy demand calculation

The principles of this calibration methodology using national IEA statistics and projection was used across all sectors.

2.2 Sector Boundaries: Sector and Subsectors

The One Earth Climate Model was developed to calculate energy pathways for geographic regions, as documented by Teske et. al. 2019.[33] The OECM was further developed to meet the requirements of the financial industry and to design energy and emissions pathways for clearly defined industry sectors (sectorial pathways). The finance industry uses different classification systems to describe sub-areas of certain branches of industry. Those scenario sector boundaries are based on the Global Industry Classification Standard (GICS) classification.[34] The GICS is an important system, however the GICS sub-sectors do not match the IEA statistical breakdown of the energy demands of certain industries. Table 4 shows examples of the finance sector calculated with the OECM model, the GICS codes, and the statistical information used. Although the OECM model allows all the GICS code sub-sectors to be calculated, the availability of statistics is the factor limiting the resolution of the sectorial pathways. For example, the statistical data for the textile and leather industry are stored in the IEA database, but the database does not separate the two industries further (see also: '1.5 °C pathways for the Global Industry Classification (GICS) sectors chemicals, aluminium, and steel' [35]).

Table 4: Examples of industry sub-sectors based on the Global Industry Classification Standard (GICS) and the categories of the IEA statistic

Financial Sector	GICS	IEA Statistic Categories	Sector Definition
Transportation	203010 Air Freight & Logistics	World Aviation Bunkers	Fuels delivered to aircraft of all countries that are engaged in international aviation (International aviation bunkers) for the world total aviation bunker demand.
	20301010 Air Freight & Logistics	Domestic Aviation	Aviation fuels to aircraft for domestic aviation – commercial, private, agricultural use.
	203020 Airlines		
	20302010 Airlines		
	203030 Marine	World Marine Bunkers	Fuels delivered to ships of all flags not engaged in international navigation (International marine bunkers) for the whole world marine bunker demand.
	20303010 Marine	Domestic Navigation	Fuels delivered to vessels of all flags not engaged in international navigation.
	203040 Road & Rail	Road	Fuels used in road vehicles and for agricultural and industrial highway use. Excludes military consumption and the motor gasoline used in stationary engines and the diesel oil used in tractors that are not for highway use.
	20304010 Railroads		
	20304020 Trucking	Rail	Rail traffic, including industrial railways, and rail transport laid in public roads as part of urban or suburban transport systems (trams, metros, etc.).
	203050 Transportation Infrastructure	Pipeline Transport	Energy used in the support and operation of pipelines transporting gases, liquids, slurries, and other commodities, including the energy used for pump stations and the maintenance of pipelines.
	20305010 Airport Services		
	20305020 Highways & Rail tracks	Transport equipment (part of Manufacturing)	Manufacture of transportation equipment such as ship building and boat manufacturing, the manufacture of railroad rolling stock and locomotives, air and spacecraft and the manufacture of parts thereof.
	20305030 Marine Ports & Services		
Agriculture	3010 Food & Staples Retailing	**Farming**	Food and tobacco production, excluding the energy demand for agriculture, as defined under the IEA energy statistic 'other sectors'. Additional statistics from industry partners are required because the IEA statistic only provides the accumulated energy demand for agriculture and forestry.
	3020 Food, Beverages, & Tobacco	Food production and supply	

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[33] Teske S, Pregger T, Naegler T, Simon S, Pagenkopf J, van den Adel B, et al. Energy scenario results. Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-Energy GHG Pathways for +1.5C and +2C. 2019; 175–401

[34] Morgan Stanley Capital International (MSCI). website that provides an overview about the Global Industry Classification Standard (GICS). 2021. https://www.msci.com/our-solutions/indexes/gics.

[35] Teske, S., Niklas, S., Talwar, S. et al. 1.5°C pathways for the Global Industry Classification (GICS) sectors chemicals, aluminium, and steel. SN Appl. Sci. 4, 125 (2022). https://doi.org/10.1007/s42452-022-05004-0

Financial Sector	GICS	IEA Statistic Categories	Sector Definition
Forestry	1510 Materials	**Agricultural & Forestry**	Energy demand for all wood and wood products, including pulp and paper and printing. Also includes all energy demands for agricultural services not included in food and tobacco production.
	151050 Paper & Forest Products	Paper & Forest Products	
	15105010 Forest Products		
	15105020 Paper Products		
Chemicals	1510 Materials	**Chemical Industry**	Energy demand for all chemical, petrochemical, glass, and ceramic products.
	151010 Chemicals	Chemical products	
		Petrochemical products	
		Glass & ceramics	
Aluminium	151040 Metals & Mining	**Aluminium**	Energy demand for the production of primary and secondary aluminium, as well as bauxite mining.
	15104010 Aluminium		
Textiles & Leather	2520 Consumer Durables & Apparel	**Textile & Leather Industry**	Energy demand for the textile and leather industry.
	252030 Textiles, Apparel, & Luxury Goods		

2.3 Demand Module

The demand module uses a bottom-up approach to calculate the energy demand for a process (e.g. steel production) or a consumer (e.g. a household) in a region (e.g. a city or country) or transport services over a period. One of the most important elements of this approach is the strict separation of the original need (e.g. to get from home to work), how this need can be satisfied (e.g. with a tram), and the kind of energy required to provide this service (in this case, electricity). This basic logic is the foundation for the energy demand calculation across all sectors: buildings, transport, services, and industry. Furthermore, the energy services required are defined; electricity, heat (broken down into four heat levels: <100 °C, 100–500 °C, 500–1000 °C, > 1000 °C), and fuels for processes that cannot (yet) be electrified. Synthetic fuels, such as hydrogen, are part of both the demand module, because electricity is required to produce it, and the supply module, because it is an energy source for other processes such as manufacturing.

The energy requirements are assigned to specific locations. This modular structure allows regions to be defined and, if necessary, the supply from other areas to be calculated.

The demand and supply modules are independent and can be used individually or sequentially. Within the demand module, energy demands can be calculated as either synthetic load profiles[36], which are then summed to annual energy demands, or only as annual consumption, without hourly resolution. The 24/7 hourly power sector module takes develops an hourly load profile based on the synthetic load profiles and was used in this study for the modelling of the electricity sector, refer to the 'Power Sector Analysis – Methodology' for a detailed explanation of this process.

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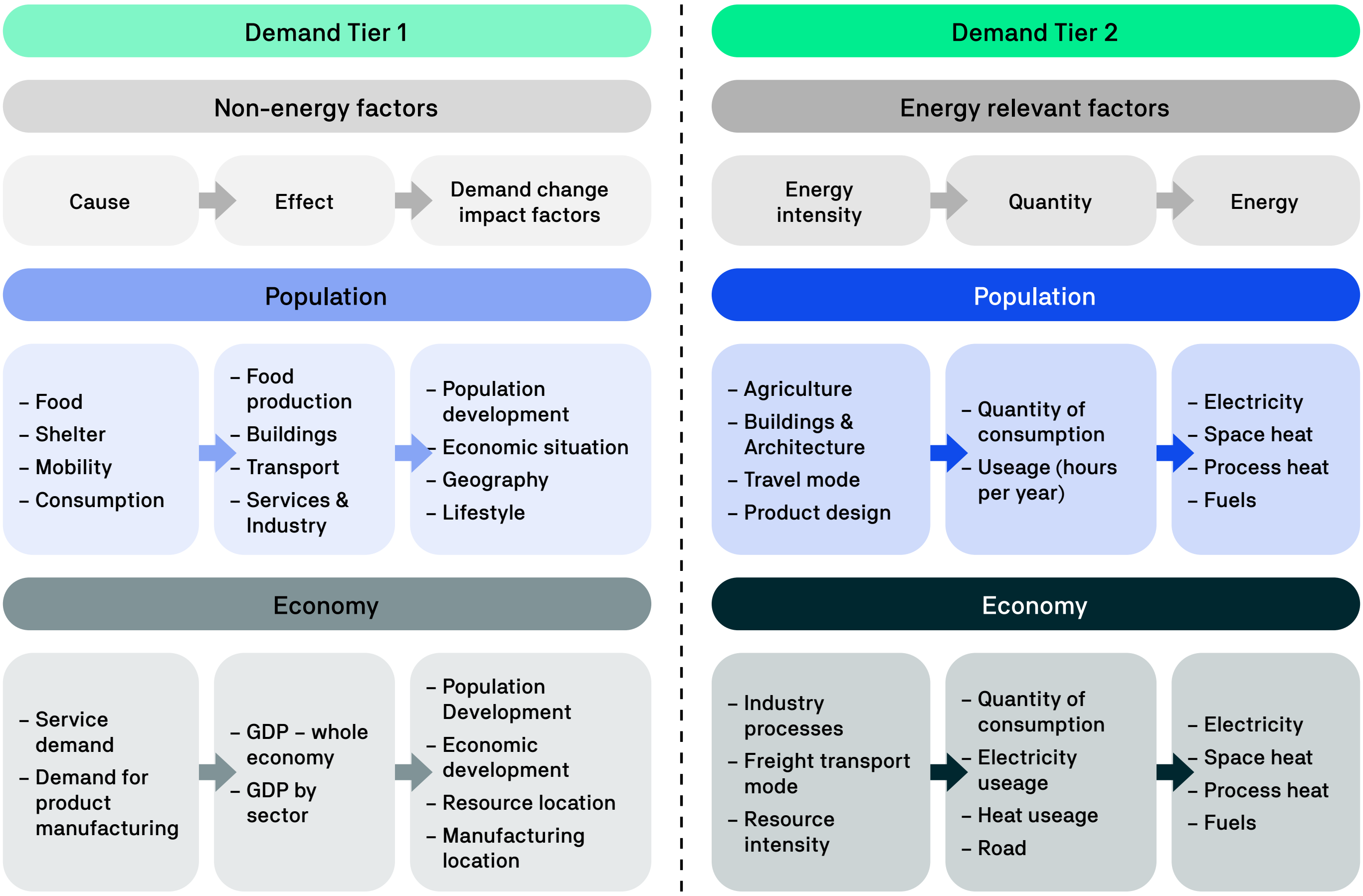
[36] Synthetic load profiles are calculated load profiles based on energy demand assumptions for specific consumer groups usually in hourly resolution over a day, a week or a whole year. Synthetic load profiles are used when measure actual load profiles are not available.

2.3.1 Input parameters

As in basic energy models, the main drivers of the energy demand are the development of the population and economic activity, measured in GDP. Figure 2-1 shows the basic methodology of the OECM demand module. The tier 1 inputs are population and GDP by region and sector. Whereas 'population' defines the number of individual energy services, which determines the energy required per capita, the economic activity (in GDP) defines the number of services and/or products manufactured and sold. The tier 1 demand parameters are determined by the effect that a specific service requires. For the population, the demand parameters are defined by the need for food, shelter (buildings), and mobility and – depending on the economic situation and/or lifestyle of the population – the demand for goods and services.

Figure 2-1: Tier 1 and tier 2 input parameters for the assessment of energy demand



Economic activity (measured in GDP) is a secondary input and is directly and indirectly dependent upon the size of the population. However, a large population does not automatically lead to high economic activity. Both population and projected GDP are inputs from external sources, such as the United Nations or the World Bank. The tier 1 input parameters themselves are strictly non-technical. For instance, the need to produce food can be satisfied without electricity or (fossil) fuels. Food production is a service, which can be provided from the human workforce.

The tier 2 demand parameters are energy-relevant factors. They describe technical applications, their energy intensities, and the extent to which the application is used. For example, if passenger road transport is required, the technical application 'light duty vehicle (LDV)' can be chosen to satisfy the demand. In this example, the energy intensity for an LDV with an internal combustion engine (ICE) is, for example, 1.5 MJ/km. The energy intensity multiplied using the application (vehicle) defines the total energy demand (e.g. if the use is 15,000 km per year, the total energy demand would be 1.5 MJ/km × 15,000 km/yr = 22,500 MJ/yr). The application – in this example, a LDV with ICE – can be replaced with another application, such as an electric vehicle with a reduced energy intensity of 0.5 MJ/km. The transport energy demand decreases, while the transport service (15,000 km) remains stable. In a second step, the actual transport service can be reduced or increased or shifted to another transport mode altogether (such as light rail) by the modeller.

This very basic and simple principle is used for every application in each of the sector categories: Buildings (Residential + commercial), Industry, and Transport. The principle which applies to industry also applies to non-industry typically described as 'other sectors' e.g. agricultural energy demand. Those sectors are broken down into multiple sub-sectors, such as aviation, shipping, rail, and road for transport, and further into applications, such as vehicle types. The modular programming allows the addition of as many subsectors and applications as are required.

2.3.2 Structure of the Demand Module

Each of the three sectors, *Buildings (B*), *Industry (I)* and *Transport (T)*, has standardised sub-structures and applications. The residential sector B (first layer) has a list of household types (second layer) and each household type has a standard set of services (third layer), such as 'lighting', 'cooling', or 'entertainment'. Finally, the applications for each of the services are defined (fourth layer), such as refrigerator or freezer for 'cooling'. The energy intensity of each application can be altered by the modeller to reflect the status quo in a certain region and/or to reflect improvements in energy efficiency. An illustrative example of the residential sector layers is shown in Figure 2-2.

Figure 2-2: Residential sector sub-structures

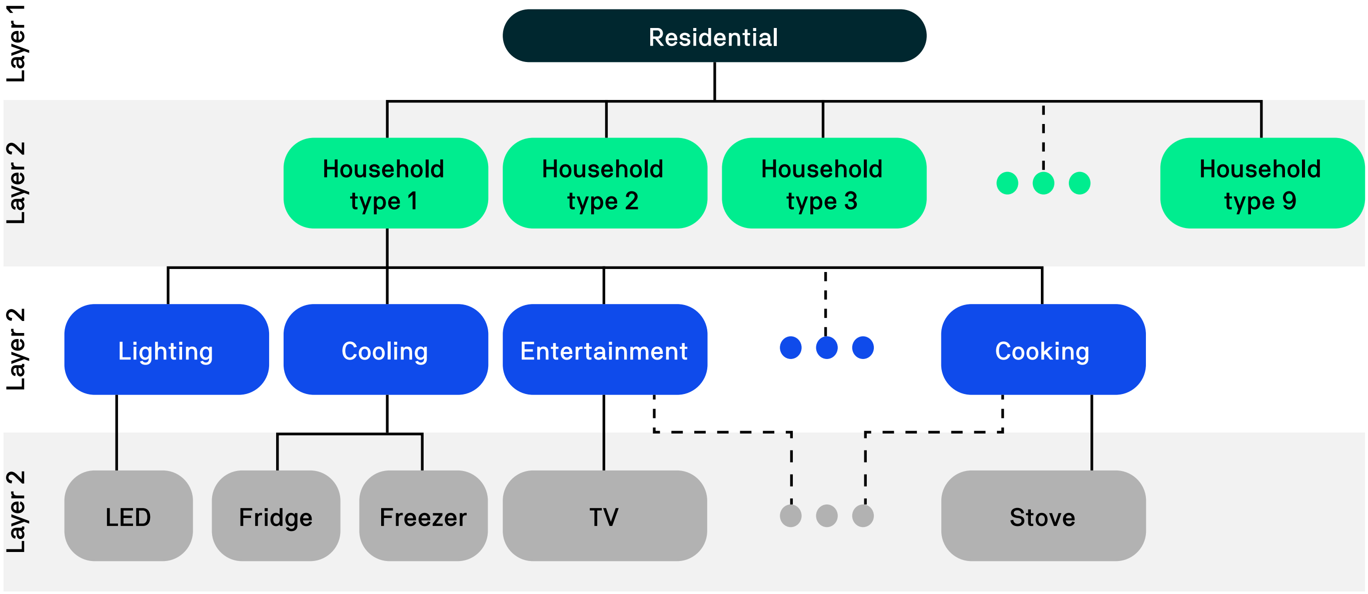


Figure 2-3 shows an example of the model structure of the *Industry* sector. In the second layer, there are different industries – the OECM 2.0 uses the GICS classification system for industry sub-sectors. The quantity of energy for each sub-sector is driven by either GDP or the projected quantity of product, such as the tons of steel produced per year. The market shares of specific manufacturing processes are defined, and each process has a specific energy intensity for electricity, (process) heat, and/or fuels.

Figure 2-3: Calculation of Industry energy demand

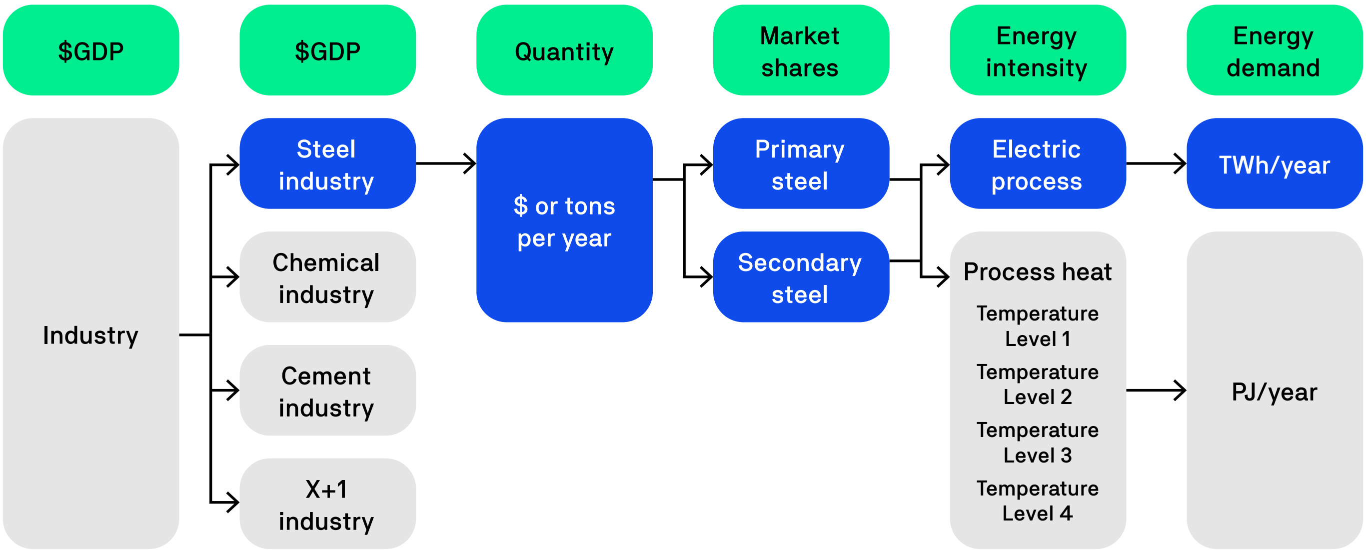
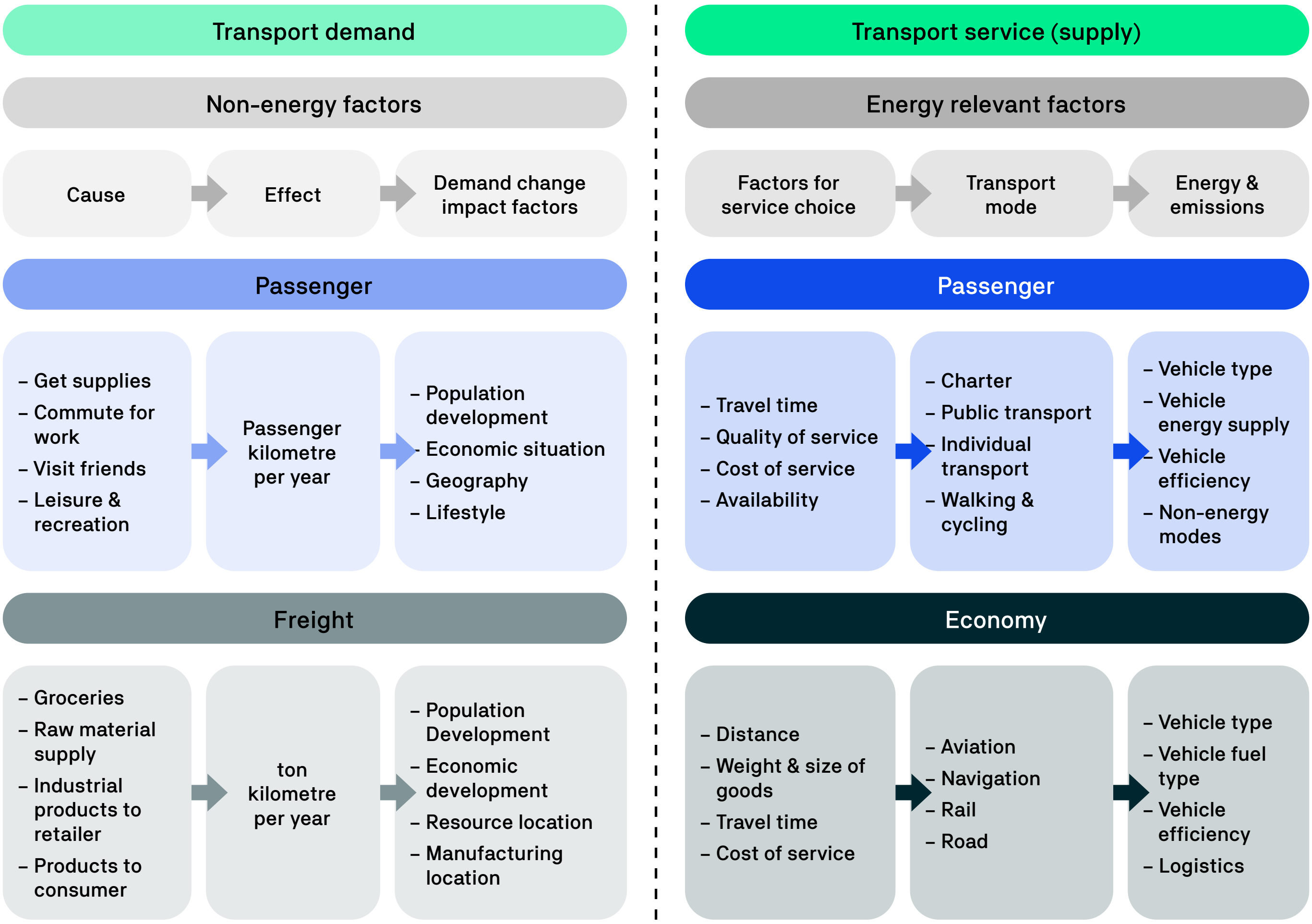


Figure 2-4 shows the structure for the *Transport* sector. Again, the demand is driven by 'non-energy' factors, such as passenger kilometres and freight kilometres, and energy-related factors, such as the transport mode and the energy intensity for the different vehicle options.

Figure 2-4: Calculation of Transport energy demand

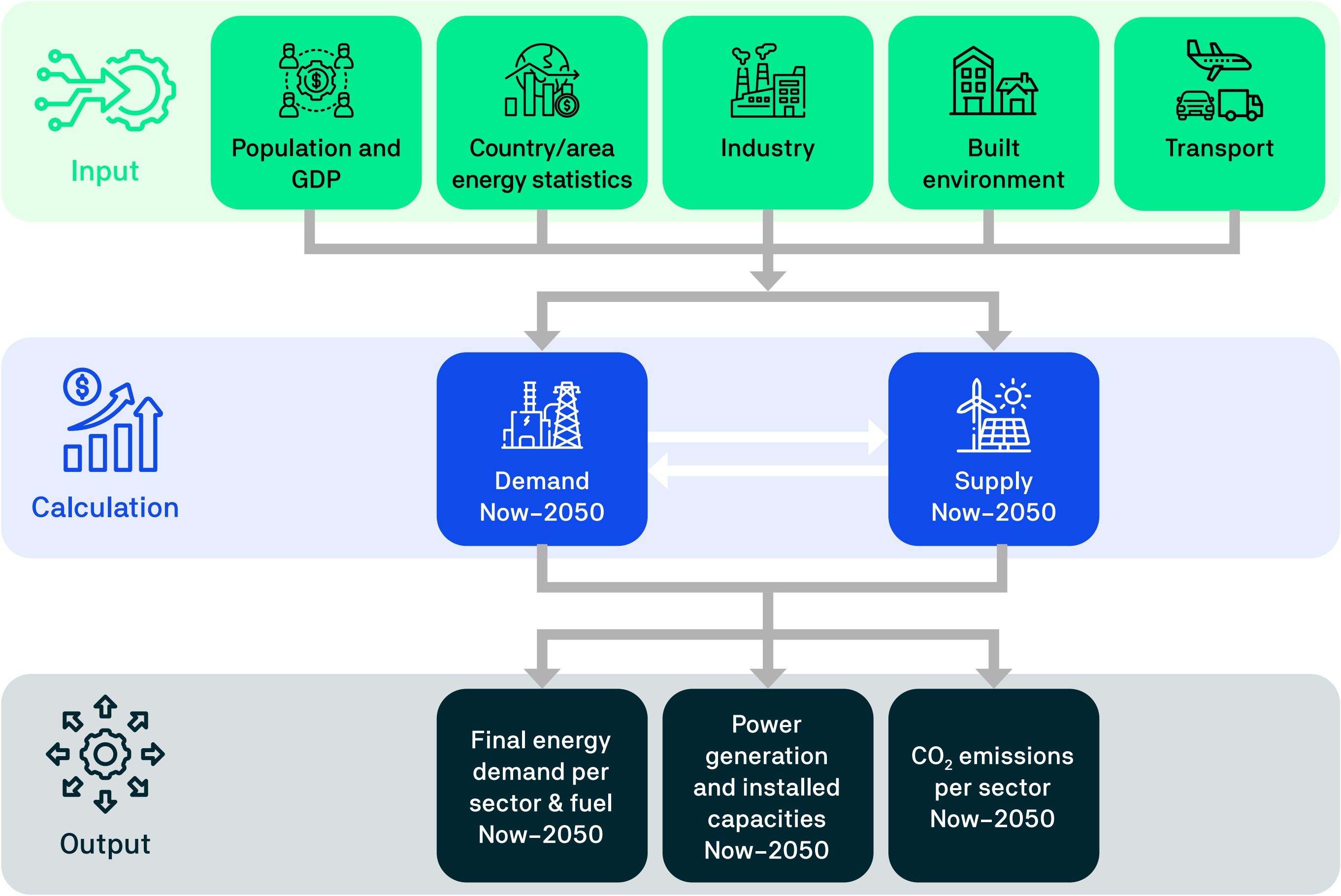


2.4 Power Sector Analysis – Methodology

After the energy demand has been calculated, the annual supply of electricity, heat, and fuels is calculated. The supply does not differentiate between demand sectors. Therefore, the electricity demand for all sectors – Buildings, Industry, and Transport – is aggregated and is provided as a total value (this thus accounts for electricity demand across the entire economy including sectors such as agricultural production). Consequently, no specific electricity-generation mix for the Transport sector, for example, is considered. These annual values are used in conjunction with calibrated proportions of supply technology to provide a breakdown of energy shares across the different supply technologies. After this modelling step is completed in the OECM, an additional power sector analysis step is computed separately in MATLAB using an equilibrium energy balance methodology to assess electricity supply for the Iberian Peninsula given the electricity configuration of the electricity network and interconnections in Spain and Portugal. The MATLAB modelling is undertaken for a given year, so although the OECM model accounts for the entire modelling horizon (until 2050), only a given year is modelled in the power sector methodology.

The energy demand projections and resulting load curve calculations are important factors, especially for power supply concepts with high shares of variable renewable power generation. Calculation of the required dispatch and storage capacities is vital for the security of supply. A detailed bottom-up projection of the future power demand, based on the applications used, demand patterns, and household types, will allow a detailed forecast of the demand. Understanding the infrastructure needs, such as power grids combined with storage facilities, requires an in-depth knowledge of the local loads and generation capacities. However, this model cannot simulate frequencies or ancillary services.

Figure 2-5: Overview – Energy demand and load curve calculation module framework



2.4.1 Meteorological data

Variable power generation technologies are dependent on the local solar radiation and wind regime. Therefore, all the installed capacities in this technology group are connected to regional specific time series. The data were derived from the Renewables.ninja (RE-N DB 2018)[37] database, which allows the hourly power output from wind and solar power plants at specific geographic positions throughout the world to be simulated. Weather data, such as temperature and precipitation for the year 2024 was also available. To utilise climatisation technologies for buildings (air-conditioning, electric heating), the demand curves for households and services were connected to the specific regional temperature time series. The demand for lighting was connected to the solar time series to accommodate the variability in the lighting demand across the year, especially in northern and southern global regions, which have significantly longer daylight periods in summer and very short daylight periods in winter.

For every region included in the model, hourly output traces are utilised for onshore and offshore wind, utility solar, and rooftop solar photovoltaic (photovoltaic). A representative site was selected for each region, with the relevant data collected for variable renewable generation according to generation type (this was necessary given the geographic extent of the study and the level of detail required to simulate a future-generation systems with uncertain spatial distribution). Once the representative sites were chosen, the hourly output values for typical solar arrays and wind farms were selected from the database of Stefan Pfenninger (at ETH Zurich) and Iain Staffell (Renewables.ninja; see above). The model methodology used by the Renewables.ninja database is described by Pfenninger and Staffell (2016a and 2016b)[38], and is based on weather data from global re-analysis models and satellite observations (Rienecker and Suarez 2011[39]; Müller and Pfeifroth, 2015[40]).

Acknowledging that an optimal solar tilt would have slight variation across the Iberian Peninsula, a consistent tilt and azimuth were used in the generation of the solar trace files: tilt of 35° degrees and south facing azimuth angle towards the equator. The onshore wind outputs were calculated at a 110 m hub height to best reflect the scale of wind speed potential out to 2030, 2040 and 2050, and due to the fact the wind speed data for Iberian Peninsula may be somewhat conservative particularly given the fact that projects would be sited to best utilise the local wind resource and would thus have access to better wind resource relative to the representative site for a given comunidad autonoma or location in Portugal. The same principles were applied for offshore wind, where a hub height of 150m was selected to avoid underestimating future wind potential available to taller wind turbines which would likely be utilised in an offshore context. The Vestas V90 2000 was selected in Renewables.ninja to provide a baseline power curve for the development of a trace file from the wind speed data for onshore wind data, while the Vestas V164 7000 was selected to provide a power curve for the development of offshore wind trace files. The base year for all trace files is 2024.

Limitations

The solar and wind resources can differ within one region. Therefore, the potential generation output can vary within a region as well as across the model period (2020–2050). Thus, this model underestimates the diversity of power available in each hour interval. Furthermore, the trace files do not account for local resource optimisation (or the ability of some large-scale solar systems to tilt/track the sun – and thus does not account for this additional generation).

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[37] RE-N DB (2018) Renewables.ninja, online database of hourly time series of solar and wind data for a specific geographic position, data viewed and downloaded between September and October 2022, https://www.renewables.ninja/

[38] Pfenninger, S, Staffell, I. (2016a), Pfenninger, Stefan and Staffell, Iain (2016). Long-term patterns of European photovoltaic output using 30 years of validated hourly reanalysis and satellite data. Energy 114, pp. 1251–1265. doi: 10.1016/j.energy.2016.08.060

Pfenninger, S, Staffell, I. (2016b), Staffell, Iain and Pfenninger, Stefan (2016). Using bias-corrected reanalysis to simulate current and future wind power output. Energy 114, pp. 1224–1239. doi: 10.1016/j.energy.2016.08.068

[39] Rienecker, M, Suarez MJ, (2011) Rienecker MM, Suarez MJ, Gelaro R, Todling R, et al. (2011). MERRA: NASA's modern-era retrospective analysis for research and applications. Journal of Climate, 24(14): 3624–3648. doi: 10.1175/JCLI-D-11-00015.1

[40] Müller, R., Pfeifroth, U (2015), Müller, R., Pfeifroth, U., Träger-Chatterjee, C., Trentmann, J., Cremer, R. (2015). Digging the METEOSAT treasure – 3 decades of solar surface radiation. Remote Sensing 7, 8067–8101. doi: 10.3390/rs70608067

2.4.2 Power Demand Projection and Load Curve Calculation

The OECM power analysis model calculates the development of the future power demand and the resulting possible load curves. The model generates annual load curves with hourly resolution and the resulting annual power demands for four different consumer sectors:

- households
- industry and services
- other sectors including data centres
- transport

The industry and transport sectors utilise a fixed load profile with demand higher during business/daylight hours and returning towards a baseload value outside these hours. These assumptions are in line with general business and industry load profiles, such that there is a high degree of constant demand from heavy industry operation and increased electricity demand in other business sectors. The regional distribution of industry load was proportioned according to regional GDP levels calculated from official GDP/capita statistics.[41] A simple approach was used for the consideration of electrical demand related to the transport sector, such that demand across all transport types are considered in aggregate and load profile shaped using the same logic as industry but proportioned across regions according to population.[42]

A new approach was integrated into the [R]E 24/7 model to accommodate Greenpeace Spain's request to introduce a new demand section into the OECM model: AI & data centres. The demand associated with data centres is described in '5.6 Service Sector'.

It was determined that it would not be appropriate to distribute the electrical load related to data centres according to GDP or population as there is no correlation between these factors. Thus, an alternative approach was used to distribute to the forecasted demand of AI & data centres across the Iberian Peninsula, which was to proportion the load according to land size of each region given that data centres are more likely to be located in larger regions which have the space, infrastructure, and renewable energy potential to accommodate the demand. The same approach is used for electrical demand associated with other sectors & commercial buildings. Thus, the electrical demand of data centres was grouped into the overall category of other sectors & commercial buildings, for the purposes of distribution of demand.[43]

Similarly to transport energy demand (electrical) which is correlated to population, the residential household demand is also distributed according to population.

The household sector load profiles vary based on the following parameters:

- Electrical applications in use across household types.
- Demand pattern of applications across household types (24 h).
- Self-consumption of onside generation from solar photovoltaic changes the load profile.
- Meteorological data:
  - Sunrise and sunset, associated with the use of lighting appliances.
  - Temperature data associated with climatisation requirements.
- Efficiency progress (base year 2018 for 2020 until 2050, in five-year steps):
  - Possibility that the electricity intensity data for each set of appliances will change, e.g. change from compact fluorescent lamp (CFL) light bulbs to light-emitting diodes (LEDs) as the main technology for lighting.

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[41] Instituto Nacional de Estadística, 'Contabilidad Regional de España – Producto Interior Bruto regional. Serie 2000-2023 ', <https://www.ine.es/dyngs/Prensa/es/CRE2023.htm> (18/12/2024)

[42] Instituto Nacional de Estadística, 'Censo anual de población 2021-2024 – Población según comunidad autónoma y provincia y sexo', <https://www.ine.es/jaxiT3/Tabla.htm?t=67988> (accessed 30/06/2025)

[43] Distribution according to land mass was allocated based on the land size values calculated using the [R]E Space methodology – discussed in Chapter 3.

2.4.3 The [R]E 24/7 Dispatch Module

The [R]E 24/7 dispatch module simulates the physical electricity supply with an interchangeable cascade of different power generation technologies. The cascade starts with the calculated load in megawatts for a specific hour. The first-generation technology in the exogenous dispatch order provides all the available generation, and the remaining load is supplied by the second technology until the required load is entirely met. In the case of oversupply, the surplus variable renewable electricity can either be moved to storage, moved to other regions (or countries), or – if neither option is available – curtailed. Non-variable renewable sources will thus be reduced output. In the case of undersupply, electricity will be supplied either from available storage capacities, from neighbouring region, international imports, or from dispatchable power plants. The capacity of the module to accurately simulate interconnections from modelled regions to international countries not included in the selected area (i.e. countries outside Spain and Portugal), was developed for this project in order to better reflect the network of the Iberian Peninsula and increase the accuracy of the model.

The key objective of the modelling is to calculate the load development by region, modifying the residual load (load minus generation), theoretical storage, and interconnection requirements for each region and for the whole survey region, alongside allowable imports and exports to neighbouring countries. The economic battery capacity is a function of the storage and curtailment costs, as well as the availability of dispatch power plants and their costs.

Given that the 24/7 dispatch modelling undertaken in this study was completed for the year 2040 under completely decarbonised energy scenarios, no fossil fuelled power plants or nuclear plants were required to be modelled in the dispatch order. A fixed dispatch order was used in this analysis: variable renewables, distributed storage sources (household batteries and EVs equipped with vehicle-to-grid capacity), interconnection with other interlinked regions within the Iberian Peninsula that allows for exchange of low-cost surplus renewables, utility storage, additional dispatchable renewable generation (such as hydropower or bioenergy generation), and finally interconnection with external countries to the Iberian Peninsula[44]. This dispatch order was chosen to maximise the energy independence of the Iberian Peninsula under the electricity system model, even though this increases curtailment of surplus renewables. As a final step to the dispatch engine, an additional category of demand flexibility was provided for the 24/7 modelling undertaken in this report. The demand response category represents a load which is able to be reduced or turned off when given the appropriate signal by a grid operator or other party (limited by the flexible demand capacity in each region). This is the only form of demand response modelled in the power sector analysis, and thus forms of demand response, such as shifting usage to another period, are not modelled here. Given this limitation, it is appropriate that it is listed last in the dispatch order, as demand reduction would not be actively prioritised ahead of other forms of demand balancing by grid operators (noting that in a two-way market, market price signals could encourage demand reduction by aggregators without the need for brown-outs being imposed on electricity consumers).

Given that the 24/7 dispatch modelling undertaken in this study was completed for the year 2040 under completely decarbonised energy scenarios, no fossil-fuelled power plants or nuclear plants were required to be modelled in the dispatch order. Figure 2-6 provides an overview of the dispatch order used in the 24/7 modelling. The dispatch order used in this analysis was: variable renewables, distributed storage sources (household batteries and EVs equipped with vehicle-to-grid capacity), interconnection with other interlinked regions within the Iberian Peninsula that allow for exchange of low-cost surplus renewables, utility storage, dispatchable generation (such as hydropower or bioenergy generation), interconnection with external countries to the Iberian Peninsula[45], and finally demand flexibility.

Overall, the dispatch modelling considers the following factors: generation capacity by type, the allocation of capacity according to relevant criteria such as the distribution of generators according to renewable energy potential ,the demand projection and load curve for each region, interconnections with other regions with in the Iberian Peninsula, interconnections with neighbouring countries where they are available, and meteorological data, from which solar and wind power generation are calculated with hourly resolution.

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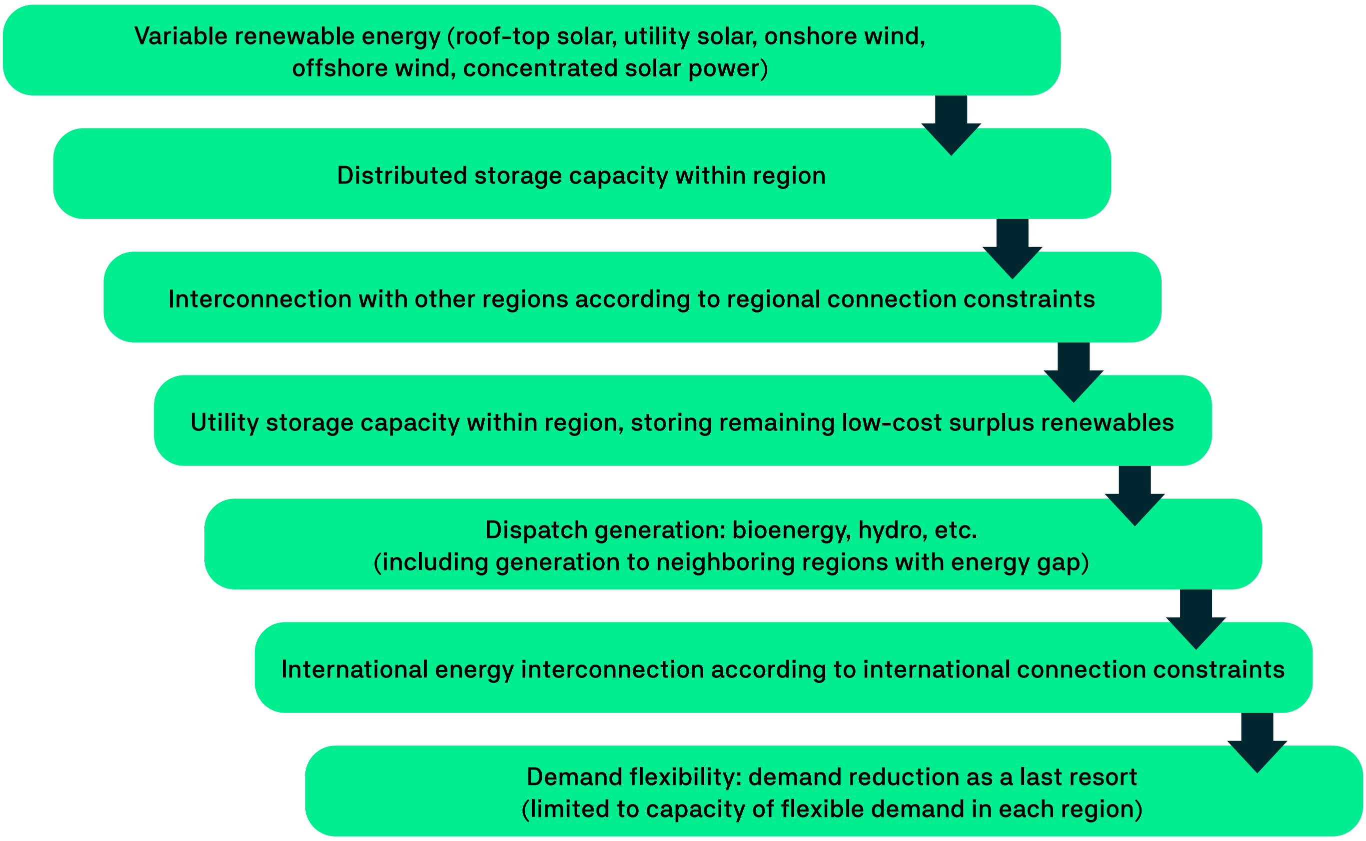
[44] Countries include: France, Andorra, Morocco, and Italy based on the assumption that by 2040 the Apollo-Link project would be available

[45] Countries include: France, Andorra, Morocco, and Italy based on the assumption that by 2040 the Apollo-Link project would be available

Figure 2-6: Methodology dispatch order



The installed capacities are derived from the long-term projections described in Section 5 and the resulting annual generation in megawatt hours is calculated based on meteorological data (in the cases of solar and wind power) or dispatch requirements. It should be noted here that there are some limitations to the modelling undertaken, as well as the dispatch engine of the 24/7 model, these are discussed below. It is noted here that although concentrated solar power (CSP) is placed in the variable renewable category, it does in fact have storage capacity in so far as it is able to self-store excess generation due to its thermal storage capacity (i.e. limited dispatchable capacity). Thus if a CSP has available dispatch in a given interval, but its electrical power is not entirely required in that interval, it's unutilised power can remain as thermal energy which is not called upon (with consideration of the thermal storage limits of the generator). CSP is placed in the variable category as it its underlying source of energy relies upon a variable trace file, and also to ensure its priority dispatch amongst other sources of renewable energy in the 24/7 dispatch engine.

Limitations

The electricity loads are calculated using the assumptions and thus do not reflect the full complexity of electricity demand such as those related to price elasticity of demand by consumers in an electricity market (for example demand management by consumers and aggregators to avoid consuming electricity during periods of high prices). The generation profiles of solar and wind power plants are based on historical meteorological data. Distributed solar power generated on roofs and used directly by the consumer, so-called 'self-consumption', this generation is not necessarily available or seen by grid operators – the granular modelling of self-consumption and available exports at a household or business level was outside of the scope of this modelling exercise. Regarding the dispatch engine, there are limitations of the following nature:

1. Dispatchable power is only called upon to fill supply gaps in the Iberian Peninsula and thus does not get dispatched in cases where there is a supply gap in a neighbouring country (e.g. France).
2. Utility storage only interacts with its nearest neighbouring regions, both regarding storage of surplus generation and dispatch of stored energy (within the boundaries of the Iberian Peninsula).
3. Demand reduction is the only form of demand response modelled in the power sector analysis, thus other forms (such as shifting usage to another period) are not modelled here.

Given the above limitations in the export from the Iberian Peninsula to its neighbours (dispatchable and utility storage), the full levels of export are underestimated relative to the potential of export as we are not replicating the ability of hydropower or utility batteries to export across the border to France (as an example). The export of stored power across international connections could of course occur and would happen under the relevant technical or economic conditions.

However, as this does not occur in the 24/7 dispatch engine, the model does not produce the energy balance which would naturally occur between the Iberian Peninsula and its neighbouring countries, such that imports and exports would be a similar order of magnitude with a similar-sized nation like France. This is explored in more detail in section '7.7 Results – International Energy Exchanges'.

A positive outcome of this limitation of the dispatch engine, is that it maximises energy independence of the Iberian Peninsula, as excess power generated and stored in the Iberian Peninsula is then saved for later consumption (when there is a supply gap within the borders of the peninsula, for example).

2.5 OECM 2.0 output and area of use (including all sectors)

Commodities and/or GDP are the main drivers of the energy demand for industries. The projection of, for example, the global steel demand in tonnes per year over the next decades are discussed with the industry and/or client. The OECM 2.0 can calculate either a single specific sector, or a set of sectors. In the case of this work for Greenpeace Spain, various industry projections are combined to estimate both the total energy supply required and the potential energy-related emissions. Thus, the emissions breakdown of achieving a specific target or budget can be broken down by specific industries. Table 5 provides an overview of the main parameters that can be used to set specific targets for industries.

Energy intensities are both input data for the base year and a Key Performance Indicator (KPI) for future projections. The effect of a targeted reduction in the energy intensity in each year and the resulting energy demand and carbon emissions can be calculated, e.g. for the transport service industry.

All sector demands are supplied by the same energy supply structure in terms of electricity, process heat (for each temperature level), and total final energy. Finally, specific carbon intensities, such as CO_2 per tonne kilometre, CO_2 per tonne of steel or per cubic metre of wastewater treatment, are calculated (and can be used to set industry targets).

Table 5: Example of energy-related key performance indicators (KPIs) for net-zero target setting, calculated with OECM 2.0 for four sectors

Sector	Parameter	Units	Base year 2019	Projection 2025, 2030, 2035, 2040, 2045, 2050
Commodities				
Water Utilities	Water withdrawal	[billion m^3/yr]	Input	Calculated projection with annual growth rates discussed with client
Chemical Industry	Economic development	[$GDP/yr]	Input	
Steel industry	Product-based market projection	[tonnes steel/yr]	Input	
Aviation	Passenger kilometres	[million person km/yr]	Input	
Energy Intensities				
Water Utilities	Waste-water treatment	[kWh/m^3]	Input	Technical target (KPI) Calculated with annual progress ratio based on technical assessment
Chemical Industry	Industry-specific energy intensity	[MJ/$GDP]	Input	
Steel Industry	Energy intensity	[MJ/tonne steel]	Input	
Aviation	Energy intensity per transport service	[MJ/person km]	Input	
Energy Demand				
Water Utilities	Final energy demand	[PJ/yr]	Input	Output – industry-specific scenario(s)
Chemical Industry	Electricity demand	[TWh/yr]	Input	
Steel Industry	Process heat demand by temperature level	[PJ/yr]	Input	
Aviation	Final energy demand	[PJ/yr]	Input	
	Total final energy demand	[PJ/yr]	Input	
Energy Supply				
Water Utilities	Electricity generation by technology	[TWh/yr]	Input	Output – based on developed scenario Supply for all (sub-)sectors.
Chemical Industry	(Process) heat by technology	[PJ/yr]	Input	
Steel Industry	Fuel supply by fuel type	[PJ/yr]	Input	
Aviation	Fuel supply by fuel type	[PJ/yr]		
	Total final energy supply by fuel type	[PJ/yr]	Input	
Energy-related Emissions				
Energy Industry & Utilities	Electricity – specific CO_2 emissions	[gCO_2/kWh]	Calculated	Output – KPI for utilities
	Electricity – total CO_2 emissions	[t CO_2/yr]	Calculated	Output – KPI for utilities
	(Process) heat – specific CO_2 emissions	[gCO_2/kWh]	Calculated	Output – KPI for industry
	Transport service energy	[g CO_2/kilometre]	Calculated	Output – KPI for industry
	(Process) heat – total CO_2 emissions	[t CO_2/yr]	Calculated	Output – KPI for industry
Product specific Emission				
Water Utilities	Emissions intensity	[kg CO_2/m^3]	Calculated	KPI – water utilities
	Total energy-related CO_2 emissions	[t CO_2]	Calculated	KPI – Water utilities
Chemical Industry	Emissions intensity	[kg CO_2/$GDP]	Calculated	KPI – chemical industry
	Total energy-related CO_2 emissions	[tCO_2]	Calculated	KPI – chemical industry
Steel Industry	Emissions intensity	[kg CO_2/t steel]	Calculated	KPI – steel industry
	Total energy-related CO_2 emissions	[t CO_2]	Calculated	KPI – steel industry
Aviation	Emission intensity	[kg CO_2/passenger km]	Calculated	KPI – aviation industry
	Total energy-related CO_2 emissions	[t CO_2]	Calculated	KPI – aviation industry

All input and output OECM data are available as MATLAB-based tables or graphs, or as standard Excel-based reports.

2.6 Model dynamics

A detailed assessment of energy demand based on industry products, such as the amount of steel or aluminium used and/or the economic projections (for example for sub-sectors of the chemical industry), combined with very high technical resolution, allows the development of the electricity and fuel demand to be comprehensively mapped with steadily increasing sector-coupling. A high degree of electrification for heating and transport, to replace fuels, requires an energy scenario to be modelled that includes an electricity system analysis to assess the infrastructure changes required (i.e. the power grid). OECM 2.0 combines an integrated energy assessment tool with a system analysis module. Net-zero pledges for specific industries lead to more-detailed energy scenarios for specific industry sectors. The steel industry, for example, favours hydrogen-based steel production, which will have a significant impact on the hydrogen demand and the electricity needed to produce it. OECM 2.0 takes this development into account and allows the modeller to change from yearly to hourly resolution when developing load curves for industries and/or the entire power system, when simulating an electricity supply with high shares of variable renewable power plants. Another example in which a long-term scenario analysis must be combined with a system analysis occurs in the chemical industry. The switch to electrical process heat will not only significantly increase the power requirement, but also the power load. The decision to use electric or hydrogen-based process heat requires the analysis of the regional infrastructure to allow the development of a cost-effective solution.

OECM 2.0 is modular and currently includes 20 different industry sectors and subsectors. Its expansion to more sectors and sub-sectors is possible without great effort, which increases the accuracy of the analysis of electricity and fuel requirements. This interaction between a technology change in one sector (e.g. to move to electric process heat) and the technical and cost implications for other sectors (e.g. power utilities and grid operators) is a central component of the model dynamics.

2.7 Methodologies for identifying and reporting Scope 1, 2, and 3 emissions

Analysing and reporting Green House Gas (GHG) emissions is important, and the focus is no longer on direct energy-related CO_2 emissions but includes other GHGs emitted by industries. These increasingly include the indirect emissions that occur in supply chains[46]. The Greenhouse Gas Protocol, a global corporate GHG accounting and reporting standard[47], distinguishes between three 'scopes':

- **Scope 1** – emissions are direct emissions from owned or controlled sources.
- **Scope 2** – emissions are indirect emissions from the generation of purchased energy.
- **Scope 3** – emissions are all the indirect emissions (not included in *Scope 2*) that occur in the value chain of the reporting company, including both upstream and downstream emissions.

The United States Environmental Protection Agency (US EPA) defines Scope 3 emissions as 'the result of activities from assets not owned or controlled by the reporting organisation, but that the organisation indirectly impacts in its value chain. They include upstream and downstream of the organisation's activities.'[48] According to the US EPA, Scope 3 emissions include all sources of emissions not within an organisation's Scope 1 and 2 boundaries, and the Scope 3 emissions of one organisation are the Scope 1 and 2 emissions of another organisation. Scope 3 emissions, also referred to as 'value chain emissions' or indirect emissions, often represent most of an organisation's total GHG emissions.

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[46] Hertwich EG, Wood R. The growing importance of scope 3 greenhouse gas emissions from industry. Environmental Research Letters. 2018;13:104013.

[47] WRI & WBCSD. Greenhouse Gas Protocol. WRI & WBCSD. https://ghgprotocol.org/.

[48] EPA. Scope 3 Inventory Guidance

Whereas the methodologies of Scope 1 and Scope 2 are undisputed, the method of calculating Scope 3 emissions is an area of ongoing discussion and development.[49,50,51] The main issues discussed are data availability, reporting challenges, and the risk of double counting. MSCI, for example, avoids double counting by using a 'de-duplication multiplier of approximately 0.205'.[52] This implies that the allocation of emissions based on actual data is not possible. Accounting methodologies for Scope 3 emissions have been developed for entity-level accounting and reporting.[53]

Ducoulombier (2021)[54] found that the reporting of Scope 3 emissions ('indirect emissions') is incomplete and that reporting standards to support the comparison of companies are missing. Schulman et al. (2021)[55] found that over 80% of emissions in the food industry are Scope 3 emissions, and that the data reported by the Customer Data Platform (CDP), a global data service for investors, companies, cities, states and regions, are incomplete and inconsistent throughout.

In 2009, Huang et al. suggested that 'Protocol organisations should actively make more specific Scope 3 guidelines available for their constituents by developing sector-specific categorisations for as many sectors as they feasibly can and create broader industry-specific protocols for others'. Therefore, the accounting methodology for Scope 3 emissions requires significant improvement and has been under discussion for more than a decade. The OECM model focuses on the development of 1.5°C net-zero pathways for industry sectors classified under the Global Industry Classification Standard (GICS) for countries or regions or at the global level. Emissions methodologies for entity-level Scope 3 require bottom-up entity-level data to arrive at exact figures. Thus, data availability and accounting systems for whole industry sectors on a regional or global level present significant challenges. Therefore, the Scope 3 calculation methodology had to be simplified for country-, regional-, and global-level calculations and to avoid double counting. In the Greenhouse Gas Protocol, Scope 3 emissions are categorised into 15 categories, shown in Table 6.

Table 6: Upstream and downstream Scope 3 emissions categories

Upstream			**Downstream**		
Greenhouse Gas Protocol Scope 3		OECM 2.0 – emissions included in the following sectors	Greenhouse Gas Protocol Scope 3		OECM 2.0 – emissions included in the following sectors
U1	Business travel	Part of the respective transport mode (aviation, road, rail, etc.)	D1	Use of solid products	All sector uses of solid products are included
U2	Purchased goods and services	All sector-specific goods and services are included	D2	Downstream transportation and distribution	Sector-specific transportation and distribution and end-of-life treatment are included. This includes the actual use of the product, e.g., emissions when driving a manufactured car.
U3	Waste generated in operations	All waste generated in sector-specific operations are included	D3	End-of-life treatment of solid products	
U4	Fuel- and energy-related activities	All sector fuel- and energy-related activities are included	D4	Investments	Not included
U5	Employee commuting	Part of the respective transport mode (aviation, road, rail, etc.)	D5	Downstream leased assets	Not included
U6	Upstream transportation and distribution	Part of the respective transport mode (aviation, road, rail, etc.)	D6	Processing of solid products	All sector processing of solid products is included
U7	Capital goods	Not included	D7	Franchises	Not included
U8	Upstream-leased assets	Not included			

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[49] Baker B. Scope 3 Carbon Emissions: Seeing the Full Picture – . MSCI. 2020

[50] Lombard Odier. Debunking 7 misconceptions on scope 3 emissions. Lombard Odier. 2021.

[51] Liebreich M. Climate and Finance – Lessons from a Time Machine | BloombergNEF. BloombergNEF. 2021. https://about.bnef.com/blog/liebreich-climate-and-finance-lessons-from-a-time-machine/.

[52] MSCI. Global Industry Classification Standard (GICS®) Methodology Guiding Principles and Methodology for GICS. 2020

[53] WRI & WBCSD. Technical Guidance for Calculating Scope 3 Emissions, Supplement to the Corporate Value Chain (Scope 3) Accounting & Reporting Standard. 2013.

[54] Ducoulombier F. Understanding the Importance of Scope 3 Emissions and the Implications of Data Limitations. The Journal of Impact and ESG Investing. 2021;1:63–71.

[55] Schulman DJ, Bateman AH, Greene S. Supply chains (Scope 3) toward sustainable food systems: An analysis of food & beverage processing corporate greenhouse gas emissions disclosure. Cleaner Production Letters. 2021; 1:100002.

To include all the upstream and downstream categories shown in Table 6. for an entire industry sector is not possible because firstly, complete data are not available – for example, how many kilometres employees for the agricultural or forestry sector commute – and secondly, it is impossible to avoid double-counting – for example, when calculating Scope 3 for the car industry. Table 6 identifies how the 15 categories are handled in the proposed OECM 2.0 methodology.

The OECM methodology is based on the 'Technical Guidance for Calculating Scope 3 Emissions' of the World Resource Institute[56], but is simplified to reflect the higher level of industry- and country-specific pathways. The OECM defines the three emissions scopes as follows:

- **Scope 1** – All direct emissions from the activities of an organisation or under their control, including fuel combustion on site (such as gas boilers), fleet vehicles, and air-conditioning leaks.
  - *Limitations of the OECM Scope 1 analysis:* Only economic activities covered under the sector-specific GICS classification for the sector are included. All energy demands reported by the IEA 'Advanced World Energy Balances' for the specific sector are included.
- **Scope 2** – Indirect emissions from electricity purchased and used by the organisation. Emissions are created during the production of energy and are eventually used by the organisation.
  - *Limitations of the OECM Scope 2 analysis:* Due to poor data availability, the calculation of emissions focuses on the electricity demand and 'own consumption'.
- **Scope 3** – GHG emissions caused by the analysed industry that are limited to sector-specific activities and/or products classified in GICS.
  - *Limitations of the OECM Scope 3 analysis:* Only sector-specific emissions are included. Travelling, commuting, and all other transport-related emissions are reported under 'Transport'. The lease of buildings is reported under 'Buildings'. All other financial activities, such as 'Capital goods', are excluded because no data are available for the GICS industry sectors and would lead to double-counting. The OECM is limited to energy-related carbon dioxide (CO_2) and energy-related methane (CH_4) emissions. All non-energy related GHG gases are calculated outside the OECM model by Meinshausen et. al. 2019.[57]

The main difference from the World Resources Institute (WRI) concept is that the interactions between industries and/or other services are kept separate. The OECM reports only emissions directly related to the economic activities classified by GICS. Furthermore, the industries are broken down into three categories: Primary Class, Secondary Class, and End-use Activity Class.

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[56] WRI & WBCSD (2013) Technical guidance for calculating scope 3 emissions, supplement to the corporate value chain (Scope 3) accounting & reporting standard. https://ghgprotocol.org/sites/default/files/standards/Scope3_Calculation_Guidance_0.pdf

[57] Meinshausen M, Dooley K. Mitigation Scenarios for Non-energy GHG. In: Teske S, editor. Achieving the Paris Climate Agreement Goals Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5°C and +2°C. Springer Open; 2019

Table 7: Schematic representation of OECM Scopes 1, 2, and 3 according to GICS classes to avoid double counting

	Primary Class					Secondary Class				End-use Activity Class			
		Scope 1	Scope 2	Scope 3			Scope 1	Scope 2	Scope 3		Scope 1	Scope 2	Scope 3
CO_2	**GICS 10 Energy**				CO_2	**GICS 55 Utilities**				**All other Industries & Services**			
CH_2, AFOLU					CH_2 AFOLU								
CH_4					CH_4								
N_2O					N_2O								
					CFCs								
Total GHG		**Sum of Scopes 1, 2, & 3 equals total emissions**			**Total GHG**		**Sum of Scopes 1, 2, & 3 equals total emissions**				**Sum of Scopes 1, 2, & 3 equals total emissions**		

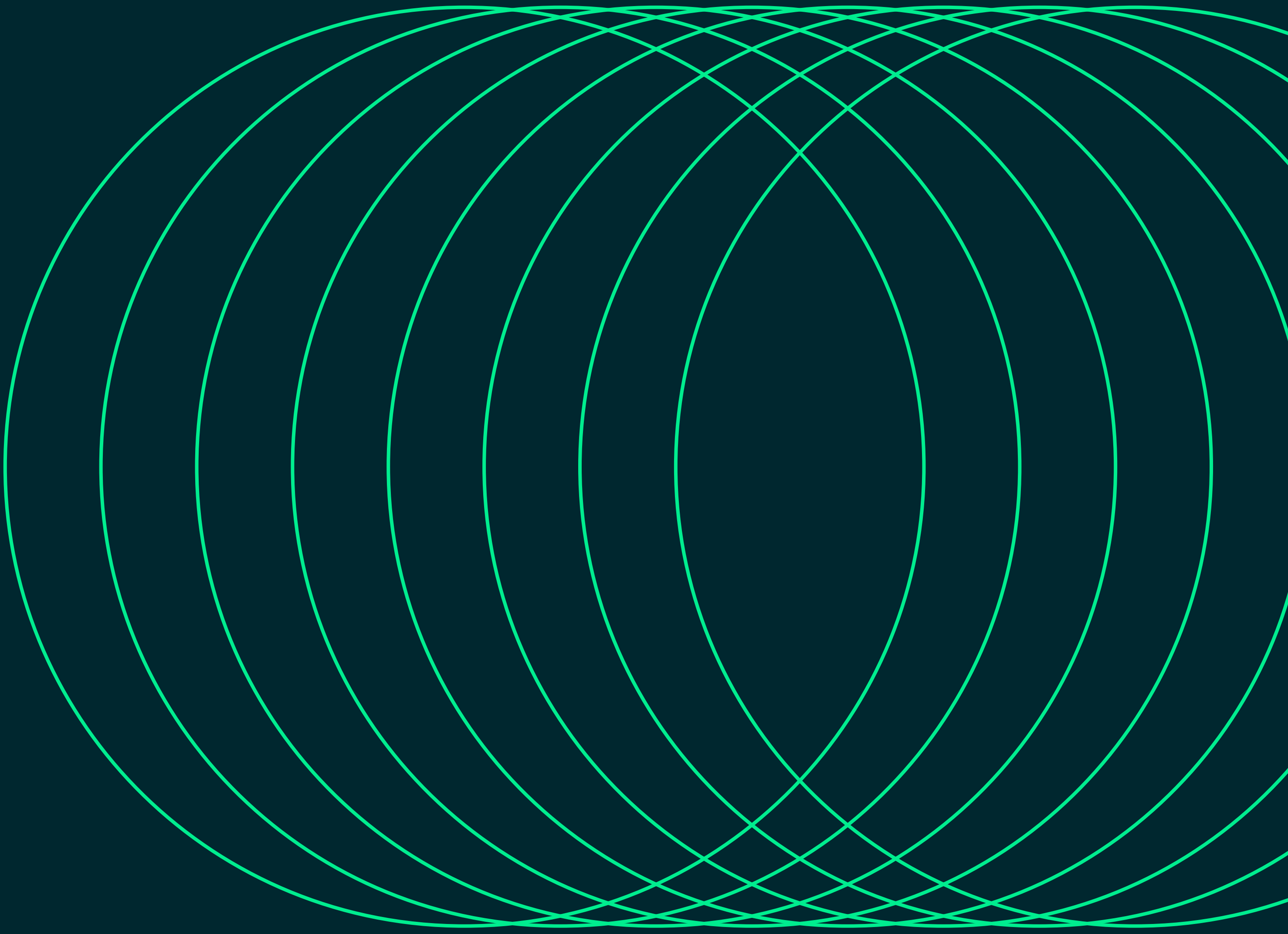
Table 7 shows a schematic representation of the OECM *Scope 1*, *2*, and *3* calculation method according to GICS class, used to avoid double counting. The sum of *Scopes 1*, *2*, and *3* for each of the three categories is equal to the actual emissions. Example: Total annual global energy-related CO_2 emissions are 35 Gt each year.

- The sum of *Scope 1, 2,* and *3* for the primary class (primary energy industry) is 35 Gt CO_2.
- The sum of *Scope 1, 2,* and *3* for the secondary class (secondary energy industry/utilities) is 35 Gt CO_2.
- The sum of *Scope 1, 2,* and *3* for end use activities (all end use sectors) is 35 Gt CO_2.

Double-counting can be avoided by defining a primary class for the primary energy industry, a secondary class for the supply utilities, and an end use class for all the economic activities that use the energy from the primary- and secondary-class companies. Furthermore, the separation of all emissions by defined industry categories – such as GICS – streamlines the accounting and reporting systems. The volume of data required is reduced and reporting is considerably simplified under the OECM methodology. Achieving the global target of 1.5 °C and global net-zero emissions by 2050 under the Paris Agreement for a specific industry sector, requires all its business activities with other sectors to also commit to a 1.5 °C – net-zero emissions targets. For this research, net-zero emissions for the Iberian Peninsula are aimed for 2040.

3

Scenario Narratives



3.1 Scenario Narratives

Scenario studies cannot predict the future, but they can describe what is needed for a successful pathway in terms of technology implementation and investments. Scenarios also help us to explore the possible effects of transition processes, such as supply costs and emissions. The energy demand and supply scenarios in this study are based on information about current energy structures and today's knowledge of energy resources and the costs involved in deploying them.

However, to develop a long-term energy scenario for the Iberian Peninsula requires a shared vision to shape the ambitions and assumptions in the development of the net-zero pathway. This section provides an overview of the narratives which explain the primary technology solutions and high-level sectoral pathways by which the Iberian Peninsula can achieve the transformation of our energy, transport and industrial systems presented in the modelling.

Our report demonstrates that the principles of Greenpeace, are completely necessary if the energy transition of the Iberian Peninsula has a chance to meet a decarbonisation trajectory aligned with the Pairs Agreement. These principles highlight "that the solution to the climate emergency from an energy point of view lies in the urgent development of an energy system… that prioritises abandoning fossil fuels before 2040… shifting to a 100% renewable, efficient, intelligent, fair energy supply. Something essential to be able to respect planetary limits, achieve climate neutrality in that period and limit the increase in global average temperature to 1.5°C."[58] This section provides an overview of the assumed future developments for energy demand and supply to achieve the overall goal to decarbonise the Iberian Peninsula.

3.2 The Scenario Definitions

In this analysis, three different scenarios have been calculated, which are explained in the following sections.

3.2.1 The 'Business as Usual' Continuity Scenario (BAU)

The brief for the 'Business as Usual' scenario was to model the Iberian Peninsula with continuity in respect to its current trajectory i.e. one that remains within the framework of current policies based on the most recent available data. To this effect, the modelling of the BAU scenario was based on the 2024 NECPs for both Spain[59] and Portugal.[60]

Thus, the BAU scenario captures the current trajectory of the Spain and Portugal, with their aims of increasing their ambition in line with EU legislation alongside the potential to expand on the current progress within the current policy framework. Refer to section '1.2.2 Progress in the Reduction of Emissions Across the Iberian Peninsula' for an analysis of how the Iberian Peninsula has demonstrated a consistent reduction in the emission intensity of the economy over the past decades, despite overall growth in the economy and gross GHG emissions. Thus, both Spain and Portugal are well positioned to capitalise on the increasing deployment of renewable energy and reductions in the emission intensity of the economy.

According to the NECPs, both Spain and Portugal have a target of 55% emissions reductions ***relative to 2005 levels*** by 2030. This target equates to a reduction level of 32% and 34% relative to 1990 emission levels, for Spain and Portugal respectively. As per the above discussion on the existing trajectory and the current pace of the peninsula's energy transition, the BAU scenario was allowed to over achieve emissions reduction set out in the NECP by a small margin As an indicator of the ambition of the BAU scenarios the 2030 carbon emissions reductions are stated: Portugal achieves a 42% reduction relative to their 1990 emissions (beating the updated NECP), likewise Spain's decarbonisation trajectory also exceeds the emissions reductions outlined in the revised NECP and achieves a reduction of 43% relative to 1990 emission levels.

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[58] Greenpeace Spain, Terms of Reference for 'Energy for a Better Life'

[59] Government of Spain, Ministry for the Ecological Transition and the Demographic Challenge (MITECO), 'Integrated National Energy and Climate Plan – Update for 2023-2030' (September 2024)

[60] Government of Portugal, 'National Energy and Climate Plan 2021-2030 (NECP 2030) – Update/Review' (1/10/2024)

3.2.2 The Energía 4.0 Scenario (E4.0)

The brief for the Energía 4.0 scenario was to take the same principles applied in Greenpeace Spain's 2011 Energía 3.0[61] report for the Spanish mainland and update the approach by accelerating the decarbonisation of the economy from 2050 to 2040 according with climate justice principles so that the decarbonisation of the Iberian Peninsula is better aligned with the latest climate science.

More explicitly, the principles stated that this scenario should use 'efficient, intelligent, 100% renewable energy system, with high citizen participation. Including the same criteria from the 3.0 scenario i.e. cover all energy services demanded by society, with maximum energy efficiency, minimum energy demand, and exclusive use of renewable energy sources that are obtained within the same territorial area'[62] (allowing for exports and imports when of technical benefit or necessity).

The Energía 4.0 scenario follows the same base model of the BAU scenario (e.g. population and GDP growth), however, an ambitious decarbonisation pathway is applied. With the pathway beating the targets of the updated NECP 2030 documents and the proposed EU target of a 90% reduction of emissions relative to 1990 (by 2040).

The Energía 4.0 scenario for Spain achieves a 50% reduction by 2030 and a 97% reduction by 2040, while Portugal achieves a 64% reduction by 2030 and a 96% reduction by 2040 (all values relative to 1990). The E 4.0 scenario demonstrates that with the increased ambition – that the fair allocation carbon budget for the Iberian Peninsula can be met in a manner which aligns with the Paris Agreement.

In addition to meeting these emissions reductions, the Energía 4.0 scenario demonstrates a pathway to achieving effective net-zero emissions by 2040 is technically possible for the Iberian Peninsula, without changes to the base assumptions (population and GDP growth), maintaining the phase-out of nuclear power, and avoiding the use of carbon capture and storage, or other emerging or unproven technologies. This was achieved with the following alterations:

- Accelerated implementation of solar photovoltaic, onshore, and offshore wind installation by 2040.
- Accelerated phase-out of oil and gas for residential and industrial process heating.
- Accelerated phase-out of ICE vehicles towards EVs, in addition to:
- Transition towards public transport as well as increase of active transport modes (such as walking and cycling in urban areas), to reduce passenger transport especially vehicles with internal combustion engines (ICE).

3.2.3 The Energía 4.1 Sufficiency Scenario (E4.1)

The brief for the Energía 4.1 scenario was to extend on the efficiency measures applied in Greenpeace Spain's 2011 Energía 3.0 scenario and incorporate sufficiency measures, such that Iberian Peninsula can achieve its carbon budget calculated based on a fair allocation of the remaining 1.5°C global carbon budget.[63]

More explicitly, the principles stated that this scenario should incorporate Greenpeace Spain's interpretation of sufficiency which would can co-exist with good living (*buena vida*) in the context of the climate crisis. In practice, this means the authors of this report were to consider "a series of activities or infrastructures that are totally or partially renounced", which are considered to be "harmful for the environment and for people or overflows" due to the fact that they do not "guarantee a decent quality of life for the entire population" or because they can be considered as unnecessary in relation to their associated energy demand or emissions where appropriate alternatives exist or reductions can be made without direct impact to quality of life for the overall population of the Iberian Peninsula.

The sufficiency measures used in this study have a quantifiable impact on final energy demand alongside the installed generation capacity required to meet the demand, particularly from the point of view of 2050. However, as the power sector and broader economy of the Iberian Peninsula is already assumed to be decarbonised by 2040 under the E 4.0 scenario, the CO_2 emissions reductions possible under the E 4.1 are limited relative to the already ambitious E4.0 scenario.[64]

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[61] Dr García-Casalsunder et al., under contract and in collaboration with Greenpeace Spain, 'Energía 3.0 – un sistema energetico basado en inteligencia, eficiencia y renovables 100%' (September 2011)

[62] Greenpeace Spain, Terms of Reference for 'Energy for a Better Life'

[63] Greenpeace Spain, 'Keys to making Spain a world leader in climate action' (10/06/2024)

[64] The demand reductions which take place between 2030–2040 have a slight impact on emissions, and the demand reductions after 2040 make a negligible impact due to the 2040 net-zero emission target already being met

3.3 Primary Energy – Oil, Gas and Coal

Decarbonisation requires a complete phase-out of all fossil fuels associated with energy use from the Iberian Peninsula. As the Iberian Peninsula uses a negligible amount of lignite (brown coal), the phase-out applies to three main categories of fossil fuels: fuels derived from crude oil, natural gas, and hard coal (black coal). The fuels currently in use are phased out according to their carbon intensity and depending on the fastest possible introduction of alternative technologies – with the phase-out rate dependent upon the scenario.

The phase-out of fossil fuels across scenarios is shown in Figure 3-1, with five-year increments used to illustrate the gradual changes that occur in the BAU scenario. Fuels derived from crude oil are primarily associated with the transport sector. Their phase-out requires a technology change towards electric vehicles in tandem with a major shift towards other transport modes such as rail, public transport, and active transport like walking and cycling. The carbon intensity of gas is lower than hard coal – although methane emissions during extraction and transportation can nullify this advantage.

Given the context of continuing decarbonisation of the energy supply across the Iberian Peninsula alongside substantial interest in the rollout of renewables in the electricity network (by governments in the NECP, and by industry), hard coal is rapidly phased out from the electricity system by 2030 in the IB 4.0 and IB 4.1 scenarios. The BAU scenario follows the trend of hard coal decarbonisation, but only achieves this milestone by 2035.

Unlike hard coal, natural gas has a variety of uses across sectors in the Iberian Peninsula (heating in industry and other sectors, CHP generation industry and power, and in power generation). Given the use cases of gas and the current availability of technological alternatives that could be implemented at scale, the decarbonisation of gas has a 'longer tail' for both power and heating, while still achieving significant reductions: 46% by 2030 and 82% by 2035 under the IB 4.0 and IB 4.1 scenarios.

The step-change in reductions between 2030 and 2035, is achieved thanks to the near complete phase-out of gas from the power sector, which takes place in this period. This phase-out rate is not achievable in the heating sector, thus it is only achieved by the 2040 net-zero target date. The oil phase-out is primarily achieved through electric mobility and the shift to active and public transport alongside electrification of space and process heating.

Fossil fuels for energy use are phased out by 2040 under the IB 4.0 and IB 4.1 scenarios and remaining minor oil demand is for non-energy use such as feedstock for the chemical industry.

Figure 3-1: Iberian Peninsula – phase-out of fossils for domestic energy supply over time under three different scenarios

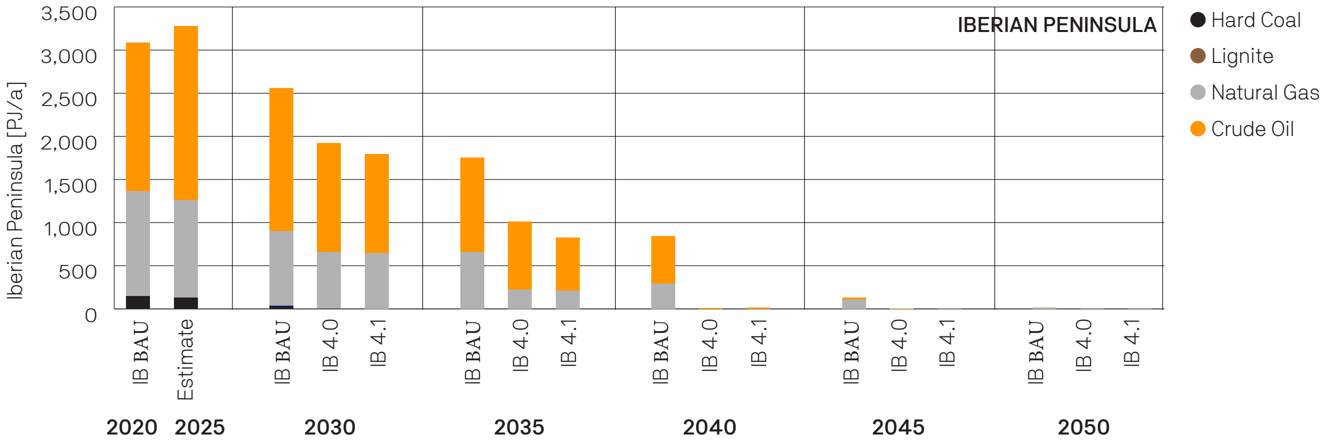
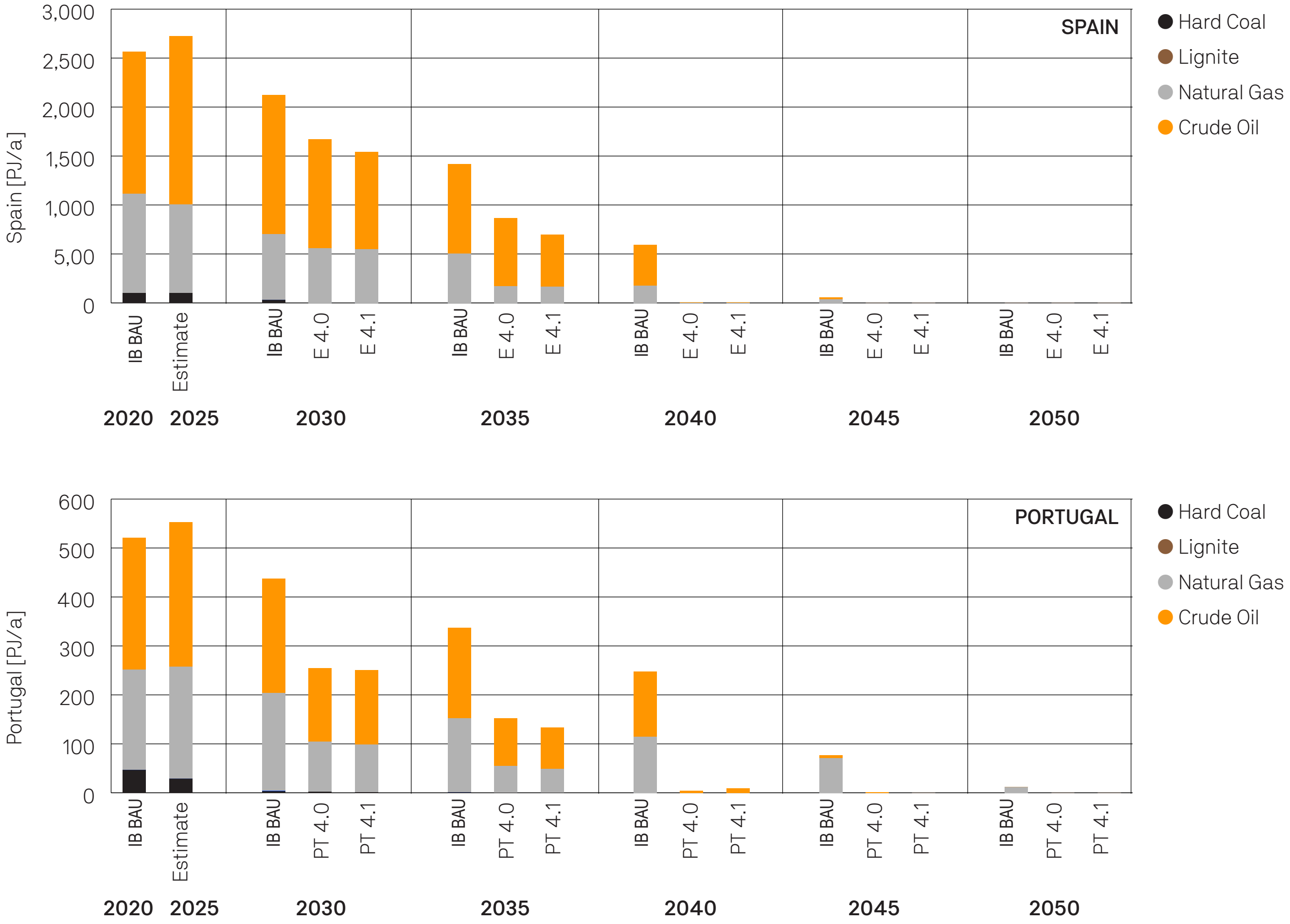


Figure 3-2: Spain (top) and Portugal (bottom) – phase-out of fossils for domestic energy supply over time under three different scenarios



3.4 Power Utilities

The cornerstone of energy-related CO_2 emissions reduction is the decarbonisation of the electricity sector. This can be achieved via a rapid phase-out of coal power generation, alongside a slower – yet ambitious – phase-out of gas power. This is only possible with an accelerated increase in the deployment of onshore wind and solar photovoltaic (both utility scale and smaller scale distributed systems).

Other renewables, such as offshore wind, play an important role in diversifying the supply mix from the perspective of having sufficient variable renewable generation, as do other technologies that can be considered more dispatchable such as solar thermal (limited dispatchability associated with thermal storage). Alongside these variables and limited dispatchable renewables, are other traditional dispatchable generation sources such as hydropower, which has been a staple of power generation across the Iberian Peninsula in previous decades. In addition to the above pumped hydro energy storage (PHES), stationary battery storage, EVs enabled with 'vehicle-to-grid (V2G)', biopower, and demand flexibility all play roles in ensuring the generation mix across the Iberian Peninsula is sufficient to meet demand.

It is relevant to mention here that Spain currently has nuclear power generation in the supply mix, and this has been the case since the early 1970s. There are currently seven operating reactors in Spain which are all more than 40 years old –the same age as two earlier Spanish reactors that were shut down in 2006 and 2012[65] and the age at which the cost of maintenance and repair starts mounting. Further, an agreement between the plants' operating companies and the Spanish Government states that four reactors are scheduled to be phased out by 2030 and the remaining three by 2035.[66]The agreement was made to provide policy certainty to companies operating in the power sector and promote an orderly transition towards renewables, while maintaining grid stability and ensuring sufficient supply while additional renewable capacity and storage is built. The modelling undertaken in this study aligns with these legislated policy measures.

During this project, the Iberian Peninsula experienced a system black event (blackout) across the entirety of the electricity network. The following textbox summarises what occurred and notes that renewable energy was not the cause of the blackout.[67,68]

Blackout event

On the 28th of April 2025, the Iberian Peninsula experienced a blackout. More specifically, "at 12:33:30 there was a zero voltage in the Iberian Peninsula with a corresponding disconnection of the Spanish and Portuguese electricity system from the European interconnected system".[102] In accordance with regulations, the Spanish Government formed the Committee for the Analysis of Circumstances that Concurred in the Electricity Crisis to investigate the causes behind the blackout.

In the days following the blackout event, a high volume of media attention was given to what occurred, with varying degrees of fact-based reporting and speculation. It was known in the aftermath of the blackout that there were several preceding phases of the grid collapse thanks to publicly available data and information provided by Red Eléctrica de España:

1. Initial gird disturbance event: 12:00:00–12:30:00pm,
2. Second event: ~1.5 seconds later,
3. Cascade failure impacting interconnection with France: ~3.5 seconds later,
4. Massive loss of power: around 15 GW of generation vanished within ~5 seconds (60% of Spain's demand).

Despite this information, the cause of the grid disturbances was unknown at the time.[103] Those sceptical of renewables and the extent they can power the grid implicated Spain's high proportion of renewables in the blackout – without having sufficient grounds to do so. It is a common talking point amongst those who are anti-renewables, that baseload power is required to have a stable electrical system. Those who are more technical may instead refer to the fact that variable renewables do not provide traditional system inertia. In either case, the report 'of the circumstances surrounding the electricity crisis' found that the sceptics were mistaken – **renewable energy was not the cause of the blackout, it was voltage regulation issues**.

In summary the report found:

- The blackout was not caused by a lack of inertia or an over-reliance on renewables.
- The system showed insufficient dynamic voltage control capabilities to maintain stable voltage.
- Thermal plants, which were supposed to stabilise the grid, underperformed.
- Grid management issues and failures in voltage regulation were the root cause, not the integration of renewables.

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[65] World Nuclear Association, Nuclear Power In Spain, <https://world-nuclear.org/information-library/country-profiles/countries-o-s/spain>, (last updated 12/01/2024)

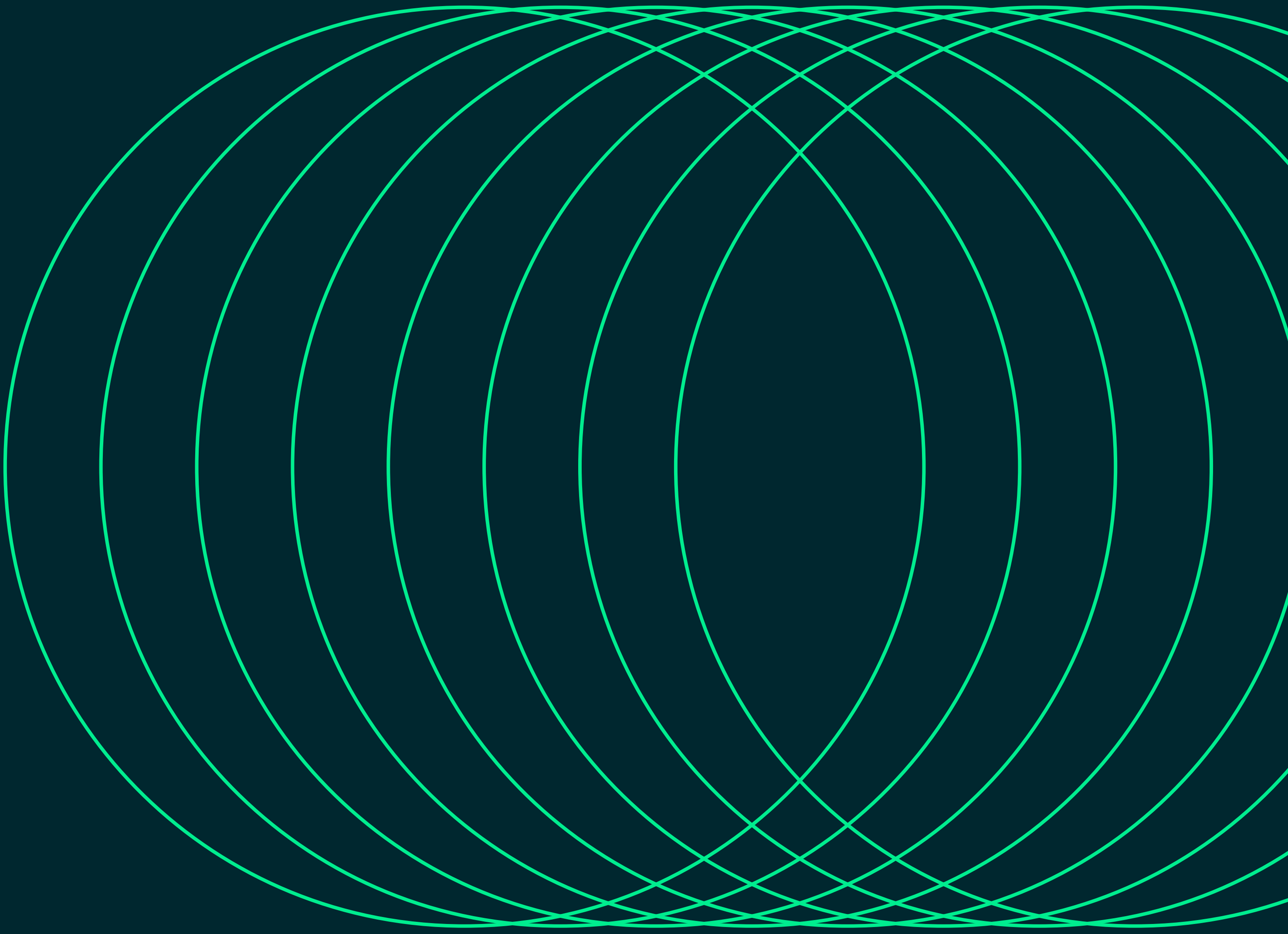
[66] Government of Spain, Ministry for the Ecological Transition and the Demographic Challenge (MITECO), 'Integrated National Energy and Climate Plan – Update for 2023-2030' (September 2024)

[67] Spanish Government – Committee for the Analysis of Circumstances that Concurred in the Electricity Crisis, 'Non-confidential version of the report of the committee for the analysis of the circumstances surrounding the electricity crisis of the April 28, 2025', 17th June 2025

[68] Carbon Brief, 'Q&A: What we do – and do not – know about the blackout in Spain and Portugal', <https://www.carbonbrief.org/qa-what-we-do-and-do-not-know-about-the-blackout-in-spain-and-portugal/> , (30th April 2025, accessed 23rd June 2025)

4

Iberian Peninsula: Renewable Energy Potential



The solar and wind potential of the Iberian Peninsula was assessed as an input for energy scenario development. In this section, the technical potential of renewable energy has been assessed under space-constrained conditions.

In this chapter, potentials for solar energy, onshore wind energy and offshore wind energy for the Iberian Peninsula were conducted using geospatial analysis.

4.1 Mapping Methodology for solar and onshore wind potential – [R]E Space

A spatial analysis was conducted to assess the Iberian Peninsula's solar and wind energy resources for different scenarios using the software ESRI ArcGIS Pro 3.4.0, which allows spatial analysis and maps the results. It was used to allocate solar and onshore wind resources for the 18 modelling regions.

The [R]E Space methodology is part of the One Earth Climate Model (OECM) methodology to map solar energy potential and onshore energy potential. Open-source data and maps from various sources were collated and processed to visualise the countries and more in detail Spanish regions. The main data sources and assumptions made for this mapping are summarised in Table 8.

Table 8: Iberian Peninsula – [R]E 24/7 – Spatial analysis & mapping – data sources

Data	Assumptions	Source
Land use	Only land classes suitable for solar or onshore wind were considered for renewable energy projects (see 'Appendix 9.2' for more detailed information). The selection of land classes differs between areas for solar energy and onshore wind energy, and between scenarios. For example, agricultural land use classes are not considered in Scenario 3 (See the next page for details of the three scenarios used in the spatial analysis).	CORINE Land Cover 2018, Europe[69]
Digital Elevation Model (DEM)	For both solar and onshore wind analyses, any land with a slope of >30% was excluded from all scenarios.	SRTM 90m DEM[70]
Protected Areas	All protected areas designated national parks, wildlife reserves, conservation areas, and buffer zones were excluded from all scenarios.	World Database on Protected Areas[71]
Solar Irradiance (direct normal irradiation: DNI)	Areas with annual average direct normal insolation/irradiation (DNI) values ≥1,000 kWh/m^2/year were considered for solar projects	Global Solar Atlas[72]
Wind Speeds	Areas with wind speeds ≥5 m/s were considered at a height of 100m were considered for onshore wind projects.	Global Wind Atlas[73]
Environmental Sensitivity Index (ISA) map for Spain (Scenario 2 only)	Among five sensitivity levels, areas allocated only with 'low (4)' or 'moderate (3)' sensitivity was considered for renewable energy projects. As the equivalent spatial data was not available for Portugal, we applied the same ratio calculated from this data to Portugal.	Gallego-Castillo & Victoria[74] The Spanish Government (the Ministry for Ecological Transition and Demographic Challenge)[75]

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[69] CORINE Land Cover 2018: https://land.copernicus.eu/en/products/corine-land-cover/clc2018

[70] SRTM 90m DEM: https://srtm.csi.cgiar.org/

[71] World Database on Protected Areas: https://www.protectedplanet.net/en/thematic-areas/wdpa?tab=WDPA

[72] Global Solar Atlas: https://globalsolaratlas.info/map

[73] Global Wind Atlas: https://globalwindatlas.info/en

[74] Gallego-Castillo & Victoria, The Spanish Environmental Sensitivity Index (ISA): https://pypsa-spain.readthedocs.io/en/latest/ISA_index.html

[75] The Spanish Government: https://www.miteco.gob.es/en/calidad-y-evaluacion-ambiental/temas/evaluacion-ambiental/zonificacion_ambiental_energias_renovables.html

Data	Assumptions	Source
Individual building footage in Spain and in Portugal	Assumed rooftop areas based on the building footage located the 'continuous urban fabric (code 1.1.1)', the 'discontinuous urban fabric' land cover class (code 1.1.2), the Industrial or commercial units and public facilities (code 1.2.1), and the 'road and rail networks and associated land (code 1.2.2) in the CORINE Land Cover map.	European Commission's Joint Research Centre[76]

4.1.1 Scenario developments for spatial analysis

For this spatial analysis and mapping, the following three scenarios were generated and assessed using the mapping procedure in Figure 4-1. The scenario narratives were selected and generated carefully to address ongoing concerns in Spain and Portugal related to renewable energy deployments, including competition for land between energy projects and biodiversity conservation (Scenario 2), and agriculture and food production (Scenario 3). Scenario 1 was calculated to assess the potential in non-protected and technically suitable areas to deploy solar and onshore wind. Scenario 2 was calculated to capture ecosystems potentially sensitive to the deployment of land-based solar and onshore wind energy outside officially protected areas, and to explore the impact on the transition of limiting land-based renewables projects in sensitive areas. Although the improved independent environmental sensitivity map is available for Spain from SEO/BirdLife's 'Renovables Responsables' initiative, the Spanish Government's maps is used in this project because at the time this study was prepared, the Renovables Responsables sensitivity map did not yet provide clear guidance on which areas would be suitable or unsuitable for renewables deployment. Scenario 3 was evaluated only for solar energy to assess the potential overlapping of energy and food sovereignty land use in Spain and Portugal.

Based on these narratives, the following land resource constraints were incorporated into the geospatial processing for each scenario:

- **Scenario 1:** Available land – excluding protected areas (PA), extreme topography (slope >30% [mountainous areas, S30], and certain land-cover classes, including high density built-up areas, forests and natural areas (e.g. marshes, beaches, heathland), permanent water bodies (LU) ('Appendix 9.2' provides detailed information on LU).
- **Scenario 2:**
  - Spain: available land – excluding PA, S30, LU, and areas assigned under 'Maximum', 'Very high' or 'High' on the Environmental Sensitivity Index (ISA) map of the Spanish Ministry for Ecological Transition and Demographic Challenge.
  - Portugal: calculated by applying Spanish area ratios from Scenario 2 to Portugal's national land area.
- **Scenario 3 (solar potential only):** Available land – excluding PA, S30, LU, ISA, and areas under agricultural land classes (AgriLU) on the CORINE Land Cover map.

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[76] Martinez, Ana; Goch, Katarzyna; Florio, Pietro; Cristiano Giovando (2023): DBSM R2023 – Individual building footprints for EU27 from the hierarchical conflation of OSM, Microsoft Buildings and ESM R2020. European Commission, Joint Research Centre (JRC) [Dataset] PID: http://data.europa.eu/89h/60c6b14d-3dda-4034-b461-390dc8ed8665

The following table includes information on areas included and excluded from the criteria (Table 9):

Table 9: Areas included and excluded on each criterion

Criteria	Spain	Portugal
Protected areas (PA)	**Applied to all scenarios (solar + onshore wind):** Included (outside of PAs): 360,398 km² (72.3%) Excluded (PAs): 138,102 km² (27.7%)	**Applied to all scenarios (solar + onshore wind):** Included (outside of PAs): 68,834 km² (77.6%) Excluded (PAs): 19,819 km² (22.4%)
Slope (S30)	**Applied to all scenarios (solar + onshore wind):** Included (slope ≤ 30%): 434,613 km² (87.2%) Excluded (slope > 30%): 63,887 km² (12.8%)	**Applied to all scenarios (solar + onshore wind):** Included (slope ≤ 30%): 82,323 km² (92.9%) Excluded (slope > 30%): 6,330 km² (7.1%)
Environmental Sensitivity Index (ISA) map	**Applied to scenario 2 &3:** **Constraints for solar:** Included ('Low' or 'Medium'): 195,122 km² (39.2%) Excluded ('Maximum', 'Very high' or 'High'): 302,962 km² (60.8%) **Constraints for onshore wind:** Included ('Low' or 'Medium'): 176,105 km² (35.4%) Excluded ('Maximum', 'Very high' or 'High'): 321,938 km² (64.6%)	N/A
Land use classes for solar	**Applied to scenarios 1&2 (LU)** Included: 363,612 km² (73.0%) Excluded: 134,736 km² (27.0%) **Applied to scenario 3 (LU + AgriLU)** Suitable: 122,428 km² (24.6%) Not suitable: 376,072 km² (75.4%)	**Applied to scenarios 1&2 (LU)** Included: 65,068 km² (73.4%) Excluded: 23,548 km² (26.6%) **Applied to scenario 3 (LU + AgriLU)** Included: 22,416 km² (25.3%) Excluded: 66,237 km² (74.7%)
Land use classes for onshore wind	**Applied to scenarios 1&2 (LU)** Included: 306,386 km² (61.5%) Excluded: 191,962 km² (38.5%)	**Applied to scenarios 1&2 (LU)** Included: 55,649 km² (62.8%) Excluded: 32,967 km² (37.2%)

Note: This table shows land area (km²) and percentages of included and excluded areas per criterion (Table 8). Values are calculated independently for each criterion without considering interactions. For data processing methods, see Figure 15.

The land areas available for potential solar and onshore wind power generation were calculated and visualised at the national and provincial levels using GIS. The land-cover map, elevation (digital elevation model: DEM), solar irradiation (direct normal irradiation: DNI) and wind speed data were obtained from open-source datasets above as raster data. They were all converted into binary maps (0 = area not suitable as a potential area, 1 = area suitable as a potential area) against all the assumptions in Table 8. The World Database on Protected Areas dataset was also converted from polygon to raster data (TIFF), assigning value 0 to all protected areas. And then all the raster data in TIFF were combined into one binary map by overlaying to generate **Scenario 1** maps for solar and onshore wind potentials, respectively. The raster maps include a value of 1 (land included in the potential area) or a value of 0 (land not included in the potential area).

In this project, **Scenario 2** maps were also generated by overlaying the Spanish government's Environmental Sensitivity Index (ISA) dataset (the Spanish Ministry for Ecological Transition and Demographic Challenge) to map areas with multiple levels of environmental constraints (Table 10). The layer was derived from multi-criteria evaluation techniques using GIS and a comprehensive analysis of legislation and policies from EU and national levels. ISA is represented using levels (from 'Maximum' to 'Low') for both solar photovoltaic and wind turbine developments. The Scenario 2 maps only considered areas assigned as 'Low' or 'Moderate' sensitivity levels as suitable for renewable energy developments. Therefore, the original values were reclassified into value of 1 for 'Low' or 'Moderate' areas or value of 0 for the rest of areas with higher environmental sensitivity, and then overlayed with Scenario 1 maps to obtain Scenario 2 maps.

Table 10: Environmental indicators considered to generate the Spanish government's Environmental Sensitivity Index (ISA)

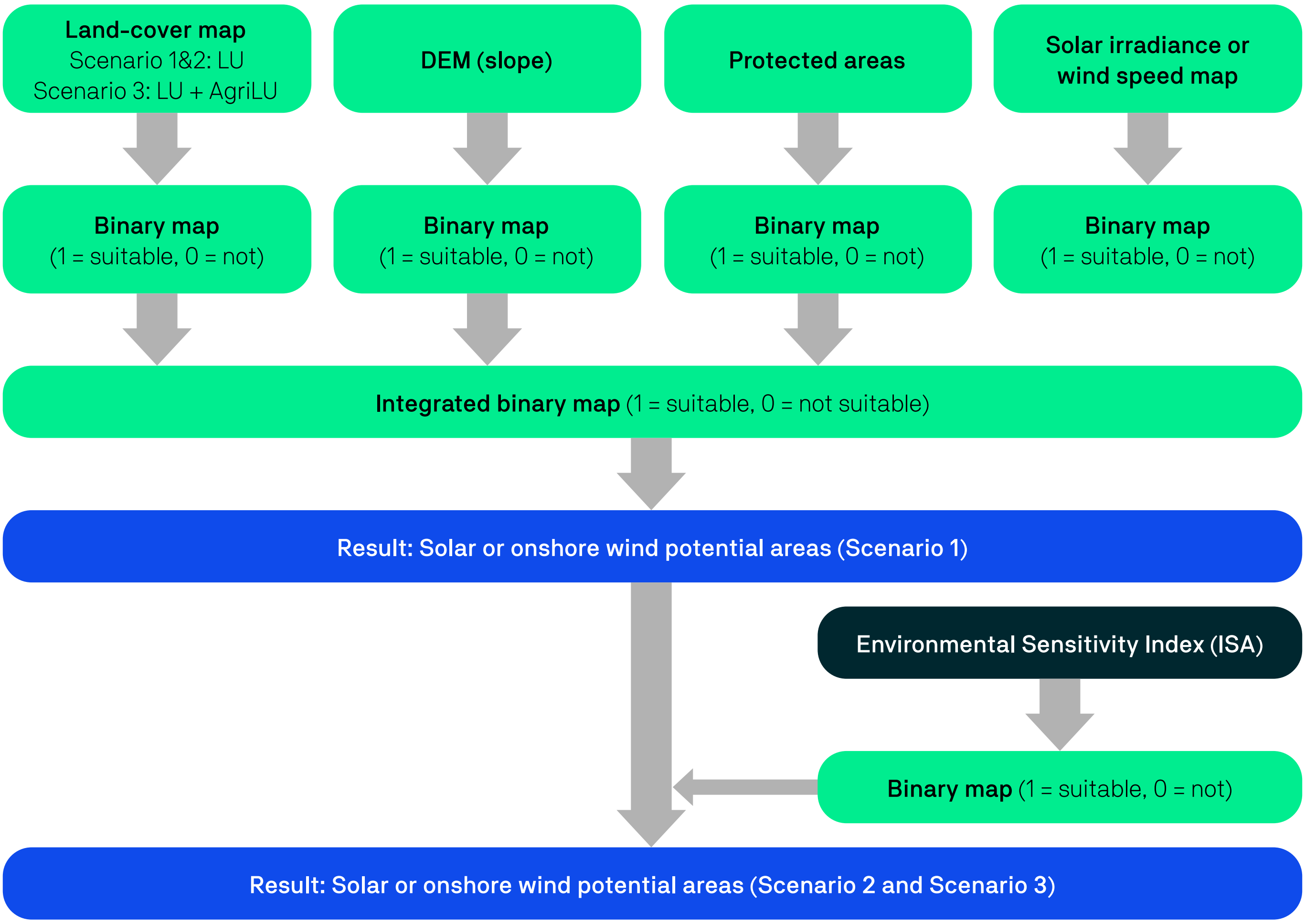
Environmental considerations integrated into the Spanish Environmental Sensitivity Index (ISA)
– Urban areas
– Water bodies and flood zone
– Plans for threaded species
– Protection areas for birds against collision and electrocution on high voltage power lines
– Ecological connectivity and wild highways
– Important Bird and Biodiversity Conservation Areas in Spain
– Habitats of Community interest
– Natura 2000 sites (ZEPA, LIC and ZEC)
– Protected Natural Areas
– RAMSAR wetlands
– Specially Protected Areas of Mediterranean Importance
– Biosphere Reserves
– Sites of Geological Interest
– Visibility
– The Camino de Santiago
– Traditional livestock routes
– Public Utility Forests
– UNESCO World Heritage sites

An equivalent ISA dataset was not available for Portugal. Therefore, the solar and onshore wind potential areas for Scenario 2 in Portugal were calculated by applying the area ratios derived from Scenario 2 results for Spain to Portugal's national land area.

In addition to PA, S30, and LU, **Scenario 3** map for solar potential excluded areas assigned under land use classes for agricultural production on the CORINE Land Cover 2018 to avoid the competition for land with food and feed production. The scenario also considered the impacts on biodiversity and wildlife by excluding areas assigned under 'Maximum', 'Very high' or 'High' on the Environmental Sensitivity Index (ISA) map like Scenario 2.

Scenario 3 was only applied to solar since the spacing for wind turbines more readily allows the design and development of wind turbines to occur in a manner which does not directly interfere with possible agricultural production of a variety of crops. It is recognised by the authors that solar also has the potential to be developed in a manner which allows solar plants to co-exist with agricultural production e.g. agrivoltaics and solar panels integrated into greenhouse production

Figure 4-1: [R]E Space methodology – solar potential analysis and onshore wind potential analysis



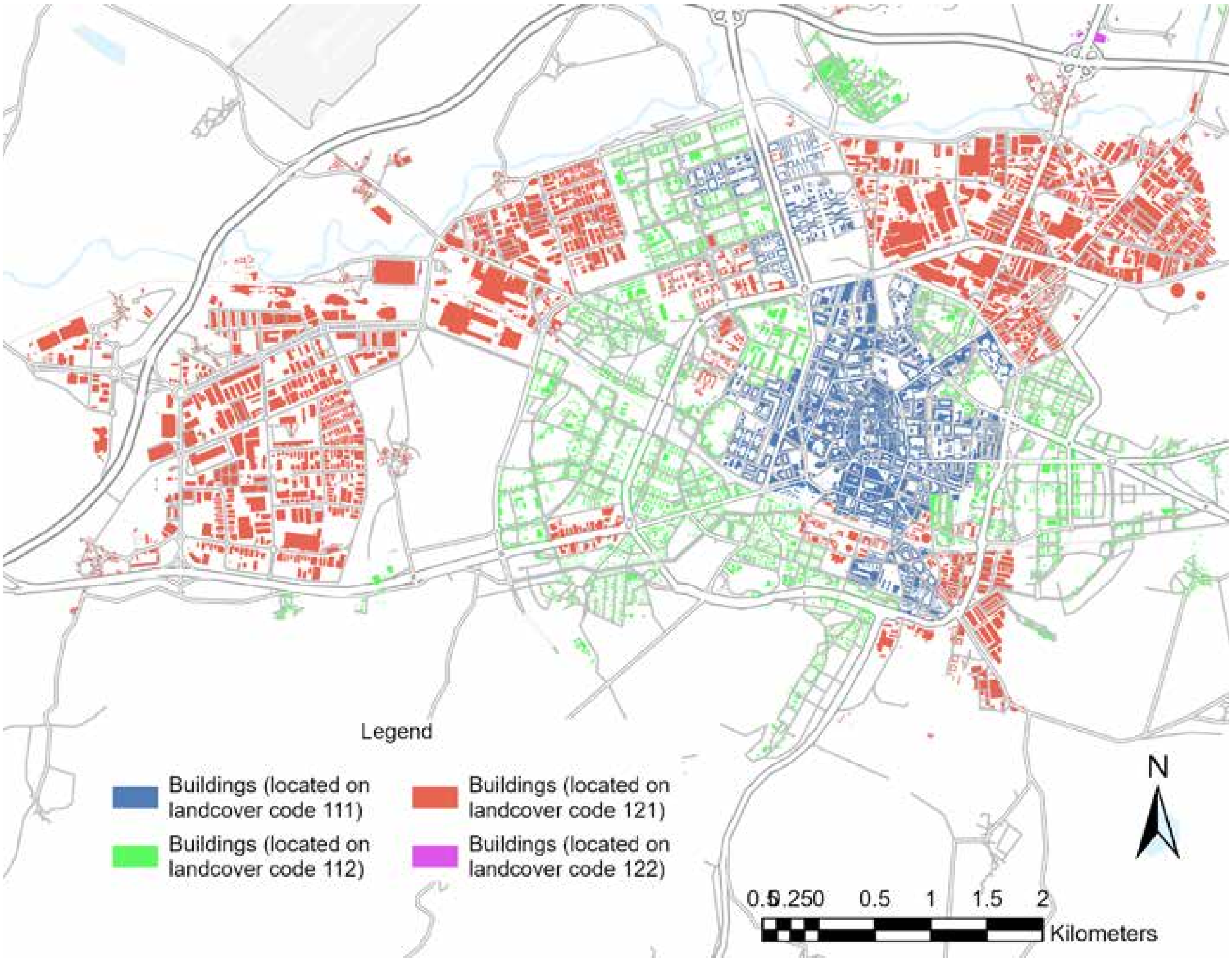
4.1.2 Rooftop solar potential assessments

In addition to Scenario 1 to 3, analysis to estimate the rooftop solar potential in included in this study. This responds to increasing demand for rooftop solar in the urban areas in these countries, where solar resources are also abundant. In Spain and Portugal, installation of solar panels is incentivised through various schemes from the national and regional governments, yet uptake of installation has been low relative to the potential across the Iberian Peninsula.

The rooftop solar potential was calculated using a building footprint dataset generated by the European Commission Joint Research Centre (JRC) for European countries. The rooftop areas were estimated from building footprints located in the 'continuous urban fabric (code 1.1.1)', the 'discontinuous urban fabric' land cover class (code 1.1.2), the Industrial or Commercial units (C&I units) and public facilities (code 1.2.1), and the 'road and rail networks and associated land (code 1.2.2) (Figure 4-2), and the solar potential was then calculated from the rooftop areas. Code 1.1.1 cover class usually includes higher density urban areas, consisting of mid- to high-rise buildings. Code 1.1.2 cover class usually refers to urban structures associated with vegetated areas, which consist of single dwellings, blocks of low-rise apartments, streets, parks, small agricultural parcels, and other vegetated areas.

This study assumed that the estimated building footprint is representative of available rooftop area for solar panel installation as a theoretical maximum potential, and does not account for the reduced rooftop space for solar photovoltaic installation due to a range of constraining factors related to the buildings and locations, such as orientation, structural obstructions, shading effects, building codes and safety requirements, and roof condition and age. There are also factors, such as photovoltaic design considerations, and household economic decisions regarding purchasing a system that matches their load profile. The estimation of available area for solar photovoltaic installation could vary by locations or assumptions significantly, for example, Bódis (2019) indicated that approximately half (49–64%) of roofs appeared to be suitable for photovoltaic in Europe [77] , while the US study reported that only 26% of the total rooftop area which was assumed from building footage on dwellings was suitable for photovoltaic deployment[78].

Figure 4-2: Example of building footprint data urban landcover class on the CORINE Land Cover 2018



Note: Continuous urban fabric (land cover code 1.1.1); discontinuous urban fabric (land cover class 1.1.2); industrial or commercial units and public facilities (land cover class 1.2.1), and road and rail networks and associated land (land cover class 1.2.2).

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77 Bódis, K., Kougis, I., Jäger-Waldau, A., Taylor, N., Szabó, S., 2019. A high-resolution geospatial assessment of the rooftop solar photovoltaic potential in the European Union. Renewable and Sustainable Energy Reviews 114, 109309, https://doi-org.ezproxy.lib.uts.edu.au/10.1016/j.rser.2019.109309

78 Gagnon, P., Margolis, R., Melius, J., Phillips, C., and Elmore, R.2016. Rooftop Solar Photovoltaic Technical Potential in the United States: A Detailed Assessment. National Renewable Energy Laboratory (NREL), https://docs.nrel.gov/docs/fy16osti/65298.pdf

4.2 Mapping Methodology for Offshore Wind

The Spanish and Portuguese governments have already declared future regions of the Iberian Peninsula coastline as areas suitable for future offshore wind development zones based on a range of technical, economic, and political considerations. There are biodiversity sensitivity areas within the Spanish and Portuguese Exclusive Economic Zones (EEZs). The EU Biodiversity Strategy 2030 aims to legally protect at least 30% of the EU's land and sea areas[79]. The current marine Natura 2000 area covers only 21% of Spain's marine area and 27% of Portugal's marine area while aiming to get the protection of 30% of marine areas by 2030. However, there are concerns that offshore wind projects could be developed in areas with high biodiversity.

In this project, the offshore wind potential was assessed using the geographic dataset of 'High potential areas for offshore wind energy development' (*Zonas de alto potencial para el desarrollo de la energía eólica marina: ZAPER*) under the Spanish government's Maritime Spatial Planning Plans (POEM), which was drawn up in accordance with Royal Decree 363/2017. ZAPER cover 4,948km^2 in total.

To address the issue that the proposed ZAPER overlaps with parts of the proposed areas for adaption of the marine Natura 2000 network, prepared by WWF Spain in 2021[80], this analysis intersected two spatial datasets – (1) ZAPER and (2) the proposed Natura 2000 network – to identify the overlapping areas; and then calculated the offshore wind potential within the ZAPER including and excluding these overlapping areas (Table 11).

Due to the geographical scope and availability of data, this project only considered the proposed areas in the Atlantic Marine Region (MATLpLIC) and the Mediterranean Marine Region (MMEDpLIC) within the Spanish EEZ. Portugal has its own 'Offshore Renewable Energy Allocation Plan' (*Plano de Afetação para as Energias Renováveis Offshore*) equivalent to Spanish government's ZAPER. However, the equivalent data for Portugal was not available for download for this spatial analysis.

Table 11: Spain – Offshore wind – GIS-mapping – data sources

Data	Source
Marine Spatial Planning (Ordenación del Espacio Marítimo) High potential areas for offshore wind energy development (Zonas de alto potencial para el desarrollo de la energía eólica marina: ZAPER)	Spanish government[81]
List of proposals for adaptation and improvement of knowledge of the Natura 2000 Network (Listado de propuestas de adecuación y de mejora de conocimiento de la Red Natura 2000) (Note: Atlantic Marine Region (MATLpLIC) and Mediterranean Marine Region (MMEDpLIC) only)	WWF Spain 2021[82]

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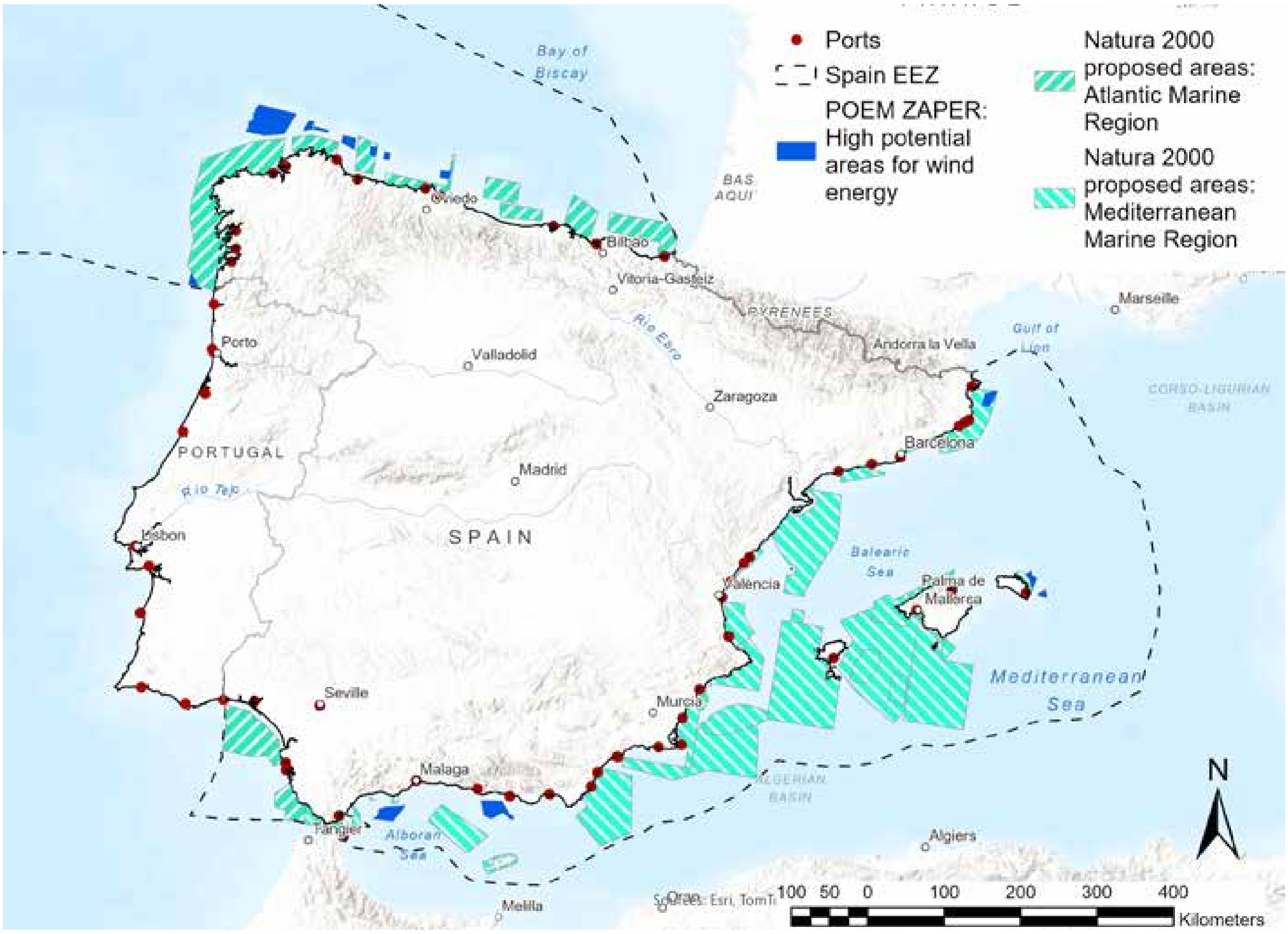
[79] European Commission, Biodiversity Strategy for 2030: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52020DC0380

[80] Aranda, Fuertes, García del Moral & Ayala (2021) Propuesta de adecuación de la Red Natura 2000 marina: https://intemares.es/sites/default/files/propuesta_adecuacion_rn2000.pdf

[81] Ordenación del Espacio Marítimo: https://www.miteco.gob.es/es/cartografia-y-sig/ide/descargas/costas-medio-marino/poem.html;

[82] Ibid.

Figure 4-3: Spanish government's High potential areas for offshore wind energy development' (ZAPER) and proposed areas for adaption of the marine Natura 2000 network, prepared by WWF Spain



4.3 Mapping the Iberian Peninsula

The modelled areas of the Iberian Peninsula have a power sector that is fuelled by a variety of sources. For example, in 2020 electricity generation across the peninsula predominantly came from the four energy technologies: wind, nuclear, gas and hydro. The calibrated OECM model (based on IEA statistics) uses the relative contribution of each technology, as shown in the table below (with the IEA statistics aligning with national statistics such as this from Red Electrica[83]):

Table 12: Spain and Portugal generation sources as a percentage of total generation in 2020

Generation Technology	Spain	Portugal
Wind	25%	28%
Nuclear	25%	0%
Gas	19%	28%
Hydro	13%	27%
Sum of Four Main Generation Sources	**82%**	**83%**

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[83] Red Electrica, Generación total, <https://www.sistemaelectrico-ree.es/es/informe-del-sistema-electrico/generacion/generacion-de-energia-electrica/generacion-total-de-energia-electrica> , (Accessed 8/9/25)

The breakdown of energy generation across the peninsula has not remained static in the last few years, as can be seen by the national statistics of Spain. While wind, nuclear and hydropower have remained fairly consistent (regarding percentage of total generation, solar photovoltaic has gone from 6.2% of generation in 2020 to 17% in 2024.[84] In the same period, non-renewable generation decreased from 55.5% to 43.2%.[85] Given the importance of solar and wind to the Iberian Peninsula – both now and into the future – mapping of the solar and wind potential was undertaken for the modelled areas. Mapping the solar and wind resources of the Iberian Peninsula aims to quantify the short- and long-term potentials and to quantify the impacts of accounting for additional restrictions on access to areas that are sensitive for biodiversity as well as for agricultural needs.

4.3.1 Solar Potential

The yearly total solar irradiation (DNI) levels in the Iberian Peninsula range from 349.2–3,039.3 kWh/m^2, with Spain showing 349.2–3,039.3 kWh/m^2 and Portugal showing 503.3–2,163.7 kWh/m^2 (Global Solar Atlas). The Iberian Peninsula's solar potential has been mapped under three different scenarios.

Table 13 shows the results of the solar potential areas under Scenario 1 (LU + PA + S30) (Figure 4-4), Scenario 2 (LU + PA + S30 + ISA) (Figure 4-5) and Scenario 3 (LU +PA+S30+ISA+AgriLU) (Figure 4-6). Scenarios 1 and 2 indicate extremely high solar energy potential across the Iberian Peninsula, and Scenario 3 still presents potential far greater than capacity required under the scenarios by 2040 to fully decarbonise (this remains the same under 2050 under all scenarios independent of the growth in population, GDP, and energy demand).

Table 13: Iberian Peninsula's potential for utility-scale solar photovoltaic

Scenario 1 (LU + PA + S30)					
Modelling Regions	**Total Land Area (km^2)**	**Solar Potential Area (km^2)**	**Solar Potential Area (%)**	**Solar Potential (GW)**	**Electricity generation (GWh/a)**
1. Andalucía	87,529	52,490	60.0	1,312.3	1,771,546
2. Aragón	47,714	25,977	54.45	649.4	876,720
3. Asturias, Principado de	10,607	2,113	19.9	52.8	71,305
4. Cantabria	5,279	1,516	28.7	37.9	51,159
5. Castilla-La Mancha	79,444	50,651	63.8	1,266.3	1,709,471
6. Castilla y León	94,251	53,581	56.8	1,339.5	1,808,342
7. Cataluña	32,104	12,861	40.1	321.5	434,057
8. Ceuta	20	9	42.2	0.2	291
9. Extremadura	41,659	26,165	62.8	654.1	883,060
10. Galicia	29,583	10,483	35.4	262.1	353,808
11. Islas Baleares	5,022	2,843	56.6	71.1	95,953
12. La Rioja	5,031	2,599	51.7	65.0	87,704
13. Madrid, Comunidad de	8,030	4,020	50.1	100.5	135,675
14. Murcia, Región de	11,312	7,459	65.9	186.5	251,743
15. Navarra, Comunidad Foral de	10,367	4,598	44.3	114.9	155,172
16. País Vasco	7,261	2,267	31.2	56.7	76,505
17. Valenciana, Comunidad	23,285	11,286	48.5	282.2	380,907
Spain total	**498,498**	**270,916**	**54.3**	**6,773**	**9,143,417**
18. Portugal	88,651	48,906	55.2	1,223	1,650,569
Portugal total	**88,651**	**48,906**	**55.2**	**1,223**	**1,650,569**
Iberian Peninsula TOTAL	**587,150**	**319,822**	**54.5**	**7,996**	**10,793,986**

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[84] Ibid.

[85] Ibid.

Scenario 2 (LU + PA + S30 + ISA)					
Modelling Regions	**Total Land Area (km^2)**	**Solar Potential Area (km^2)**	**Solar Potential Area (%)**	**Solar Potential (GW)**	**Electricity generation (GWh/a)**
1. Andalucía	87,529	39,040	44.6	976.0	1,317,585
2. Aragón	47,714	15,595	32.7	389.9	526,333
3. Asturias, Principado de	10,607	1,574	14.8	39.4	53,127
4. Cantabria	5,279	1,204	22.8	30.1	40,618
5. Castilla-La Mancha	79,444	36,911	46.5	922.8	1,245,755
6. Castilla y León	94,251	45,367	48.1	1134.2	1,531,126
7. Cataluña	32,104	10,448	32.5	261.2	352,628
8. Ceuta	20	6	27.5	0.1	190
9. Extremadura	41,659	9,249	22.2	231.2	312,147
10. Galicia	29,583	7,193	24.3	179.8	242,749
11. Islas Baleares	5,022	2,310	46.0	57.8	77,963
12. La Rioja	5,031	2,156	42.8	53.9	72,752
13. Madrid, Comunidad de	8,030	3,213	40.0	80.3	108,441
14. Murcia, Región de	11,312	6,372	56.3	159.3	215,047
15. Navarra, Comunidad Foral de	10,367	3,727	35.9	93.2	125,776
16. País Vasco	7,261	1,976	27.2	49.4	66,677
17. Valenciana, Comunidad	23,285	8,784	37.7	219.6	296,445
Spain total	**498,498**	**195,122**	**39.1**	**4,878**	**6,585,359**
18. Portugal	88,651	*34,696	39.1	*867	1,171,001
Portugal total	**88,651**	***34,696**	**39.1**	***867**	**1,171,001**
Iberian Peninsula TOTAL	**587,150**	**229,818**	**39.1**	**5,746**	**7,756,360**

Note: Portugal's solar potential areas (km^2) and solar potential (GW) for Scenarios 2 were estimated by applying the same ratio of solar potential area (km^2) to national land area (km^2) as in Spain (39.1%).

Scenario 3 (LU +PA+S30+ISA+AgriLU)					
Modelling Regions	**Total Land Area (km²)**	**Solar Potential Area (km²)**	**Solar Potential Area (%)**	**Solar Potential (GW)**	**Electricity generation (GWh/a)**
1. Andalucía	87,529	7,935	9.1	198.4	267,810
2. Aragón	47,714	4,094	8.6	102.3	138,158
3. Asturias, Principado de	10,607	192	1.8	4.8	6,495
4. Cantabria	5,279	257	4.9	6.4	8,674
5. Castilla-La Mancha	79,444	7,673	9.7	191.8	258,957
6. Castilla y León	94,251	10,142	10.8	253.6	342,303
7. Cataluña	32,104	2,106	6.6	52.7	71,078
8. Ceuta	20	5	24.8	0.1	171
9. Extremadura	41,659	1,901	4.6	47.5	64,167
10. Galicia	29,583	1,628	5.5	40.7	54,945
11. Islas Baleares	5,022	309	6.2	7.7	10,431
12. La Rioja	5,031	576	11.5	14.4	19,446
13. Madrid, Comunidad de	8,030	1,386	17.3	34.7	46,786
14. Murcia, Región de	11,312	1,415	12.5	35.4	47,750
15. Navarra, Comunidad Foral de	10,367	657	6.3	16.4	22,182
16. País Vasco	7,261	416	5.7	10.4	14,032
17. Valenciana, Comunidad	23,285	2,786	12.0	69.7	94,032
Spain total	**498,498**	**43,479**	**8.7**	**1,087**	**1,467,408**
18. Portugal	88,651	*7,734	8.7	*193	261,019
Portugal total	**88,651**	***7,734**	**8.7**	***193**	**261,019**
Iberian Peninsula TOTAL	**587,150**	**51,213**	**8.7**	**1,280**	**1,728,427**

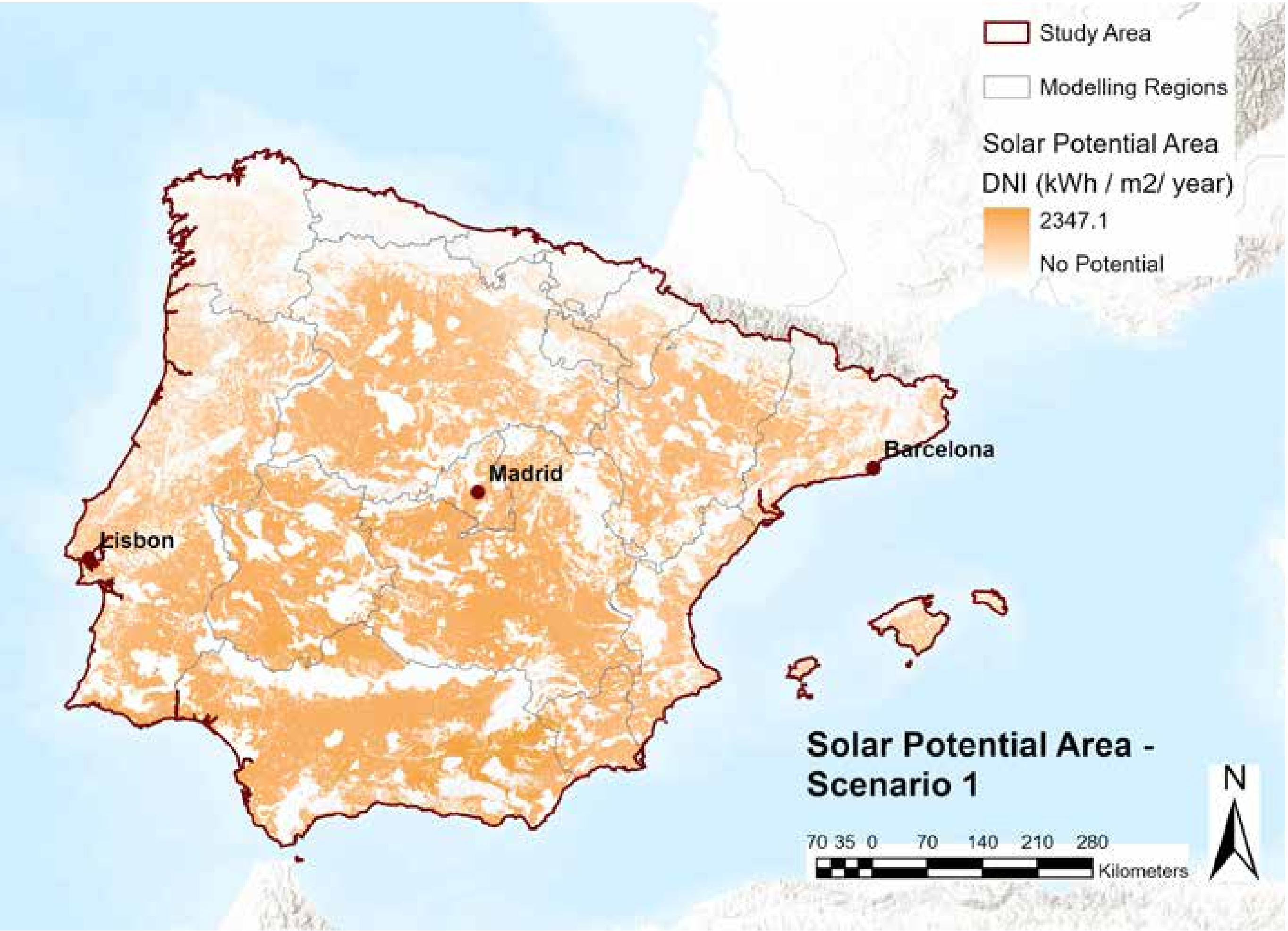
Note: Portugal's solar potential areas (km²) and solar potential (GW) for Scenarios 3 were estimated by applying the same ratio of solar potential area (km²) to national land area (km²) as in Spain (8.7%).

Scenario 1 provides **319,822 km²** (270,916km² for Spain and 48,906km² for Portugal) of areas with solar potential and a total potential for solar photovoltaic capacity of **7,996 GW** (6,773GW for Spain and 1,223GW from Portugal). The installed capacity within Solar Potential Area is expected to generate **10,793,986 GWh/a** (9,143,417 GWh/a for Spain and 1,650,569 GWh/a). Scenario 1 excludes all protected areas (accounting for 26.9% of the Iberian Peninsula's total land areas) and areas with slopes >30%, (accounting for 12.0%) because installing and maintaining solar panels in steep areas is unrealistic and undesirable for the risk of heavy runoff. Most agricultural and rural land use classes, and some urban land-use classes (i.e. discontinuous urban fabric) in CORINE Land Cover 2018 dataset are included in this scenario. However, certain land use classes (e.g. all forest land use classes, continuous urban fabric, road and rail networks and associated land, and water bodies) are excluded in the scenarios selected for the consideration of solar energy potential. The detailed land cover class table indicating which classes were considered suitable for renewable energy potential maps is provided in Appendix 7.3. Results from a separate rooftop solar potential analysis using building footprints from all urban land classes are provided later in this section.

Figure 4-5 shows the solar potential areas for **Scenario 2.** The scenario excluded areas deemed high to maximum in the Environmental Sensitivity Index (ISA) (48% of the total land unsuitable for solar energy),thus the solar potential areas decrease to **229,818 km²** (195,122km² for Spain and 34,696km² for Portugal). However, solar energy in the Iberian Peninsula can still harvest **5,746 GW** (4,878GW for Spain, 867.4GW from Portugal) of solar photovoltaic under this scenario. The installed capacity within Solar Potential Area is expected to generate **7,756,360 GWh/a** (6,585,359 GWh/a for Spain and 1,171,001 GWh/a for Portugal).

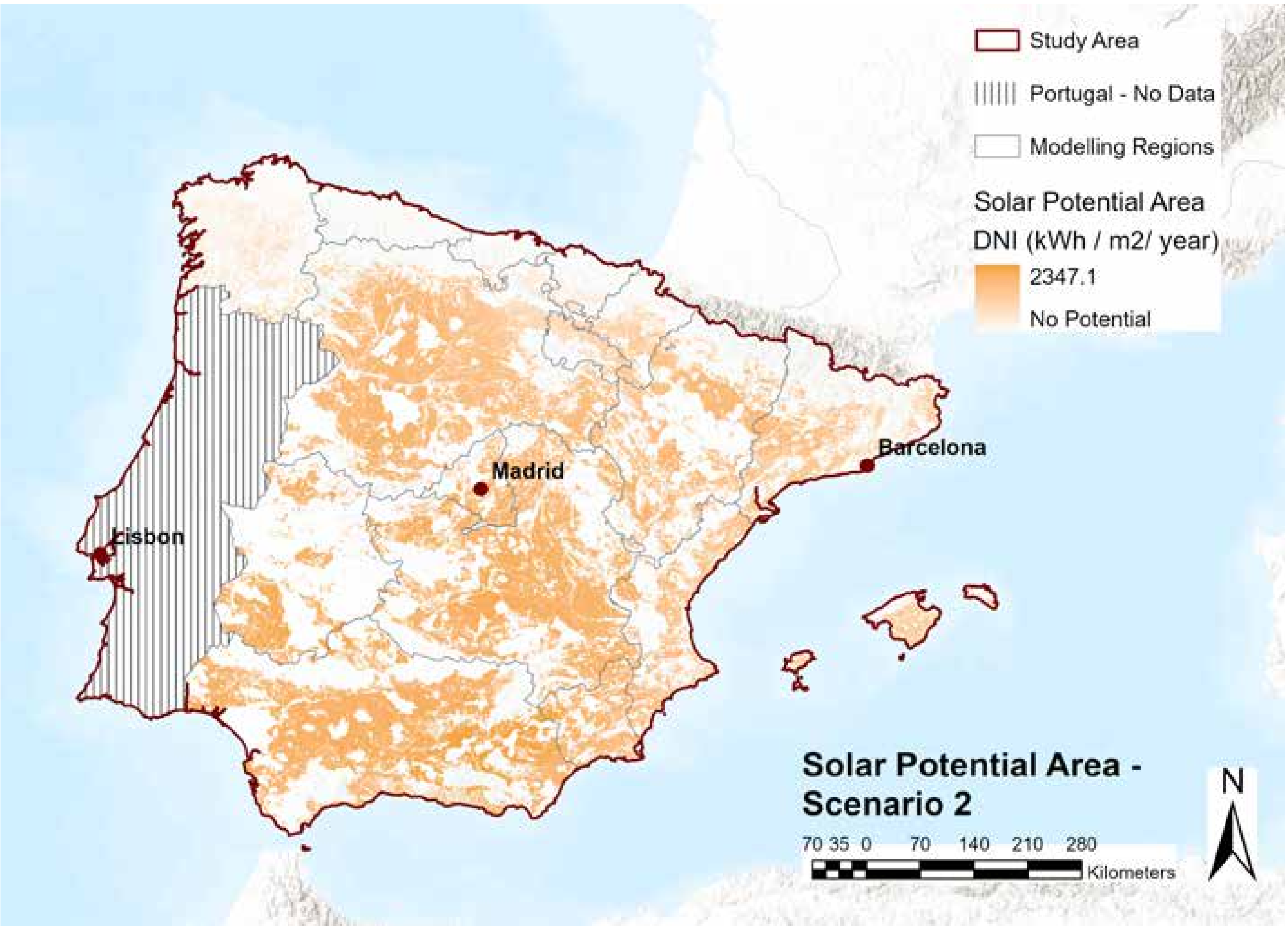
Scenario 3 excluded all crop production land classes from the land cover map for solar energy deployment, reducing solar potential area to only 8.7% of the total area of the Iberian Peninsula (Figure 4-6). This scenario presents solar potential areas of **51,213 km²** (43,479km² for Spain, 7,734km² for Portugal) with a total potential solar photovoltaic capacity of **1,280 GW** (1,087 GW for Spain, 193.4GW for Portugal). The installed capacity within Solar Potential Area is expected to generate **1,728,427 GWh/a** (1,467,408 GWh/a for Spain and 261,019 GWh/a for Portugal). Although this potential is significantly reduced from the solar potentials identified in Scenario 1 or Scenario 2 the potential capacity of this scenario is still far more than that required by the E4BL scenarios. The potential under each mapping scenario was divided by the solar generation for 2050 in each of the E4BL scenarios, to provide a ratio of how many times larger the potential is, this is shown after the map figures in Table 14.

Figure 4-4: Iberian Peninsula – Solar Potential Areas (Scenario 1: LU + PA + S30)



Note: While Spain has the ISA environmental sensitivity map, no equivalent dataset was available for Portugal for this spatial analysis. Portugal's solar potential areas (km²) and solar potential (GW) for Scenarios 2 were estimated by applying the same ratio of solar potential area (km²) to national land area (km²) as in Spain (39.1%).

Figure 4-5: Iberian Peninsula – Solar Potential Areas (Scenario 2: LU + PA + S30 + PT10+ISA)



Note: While Spain has the ISA environmental sensitivity map, no equivalent dataset was available for Portugal for this spatial analysis. Portugal's solar potential areas (km²) and solar potential (GW) for Scenarios 3 were estimated by applying the same ratio of solar potential area (km²) to national land area (km²) as in Spain (8.7%).

Figure 4-6: Iberian Peninsula – Solar Potential Areas (Scenario 3: LU + PA + S30 + PT10+ISA+AgriLU)

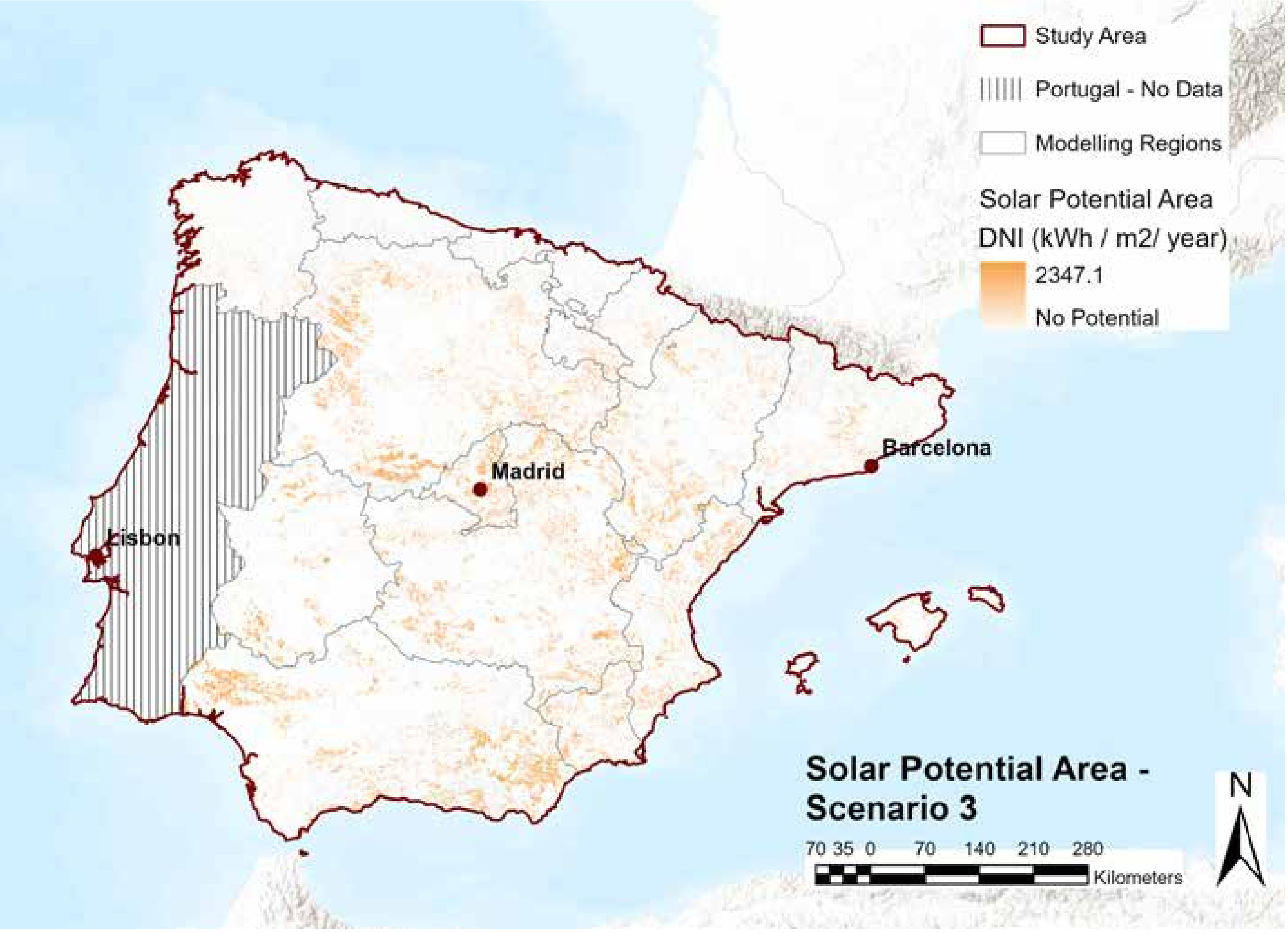


Table 14: Ratio of solar potential to required solar generation in 2050 for each E4BL scenario

Mapping Scenario	BAU	4.0	4.1
Scenario 1	37	40	46
Scenario 2	26	29	33
Scenario 3	5.9	6.5	7.4

Rooftop solar photovoltaic is important because it does not require additional land space. Beyond the three scenarios above, solar potential from urban rooftops and from greenhouses are calculated separately, using building footprint data and greenhouse area data, respectively.

Solar potential of rooftops

In this project, solar potential from rooftops of buildings located in urban fabric areas was also calculated separately (Table 15). The total building footprints in urban areas were calculated to be **2,858 km^2** for the Iberian Peninsula (2,345 km^2 for Spain and 512km^2 for Portugal). If roof area is assumed to be 100% of the building footprints, the total potential solar photovoltaic capacity would be **71 GW**. As described in the mapping methodology section, this estimate does not include adjustments for reduced usable rooftop space. If a more realistic estimation of practical rooftop potential was to be made in line with assumptions aligned with academic of literature relevant to Europe[86], the total rooftop space would be closer to half of the technical potential giving a value of ~**1,429 km^2** of rooftop space in the Iberian Peninsula, with a total potential solar photovoltaic capacity of **36 GW**. However, we assumed 100% building footprint utilisation for technical potential in this section.

Table 15: Rooftop Solar potential calculated using building footprint data

	Building Footage (km^2)					Rooftop Solar Potential
Modelling Regions	**Located on Continuous urban fabric**	**Located on Discontinuous urban fabric**	**Located on C&I units and public facilities**	**Located on Road and rail networks and associated land**	**TOTAL Rooftop area (km^2)**	**Solar Potential (MW)**
1. Andalucía	269	132	74	2	476	11,908
2. Aragón	24	28	24	0	76	1,890
3. Asturias, Principado de	9	14	12	0	35	881
4. Cantabria	4	15	5	0	23	586
5. Castilla-La Mancha	100	105	33	0	239	5,969
6. Castilla y León	32	121	36	1	190	4,758
7. Cataluña	99	128	81	1	309	7,719
8. Ceuta	1	1	1	0	2	46
9. Extremadura	77	29	12	0	119	2,969
10. Galicia	22	57	21	0	101	2,514
11. Islas Baleares	19	36	5	0	60	1,493
12. La Rioja	6	6	6	0	18	462
13. Madrid, Comunidad de	41	103	50	2	195	4,875
14. Murcia, Región de	42	23	20	0	85	2,120
15. Navarra, Comunidad Foral de	7	16	12	0	35	874
16. País Vasco	16	17	35	1	69	1,735
17. Valenciana, Comunidad	123	121	68	1	313	7,830
Spain total	**891**	**951**	**493**	**10**	**2,345**	**58,630**
18. Portugal	103	324	84	2	512	12,809
Portugal total	**103**	**324**	**84**	**2**	**512**	**12,809**
Iberian Peninsula TOTAL	**993**	**1,275**	**577**	**12**	**2,858**	**71,439**

Note: Continuous urban fabric (land cover class 1.1.1), Discontinuous urban fabric (landcover class 1.1.2), Industrial or commercial units and public facilities (land cover class 1.2.1) and Road and rail networks and associated land (land cover class 1.2.2) on CORINE Land Cover 2018.

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[86] Bódis, K., Kougis, I., Jäger-Waldau, A., Taylor, N., Szabó, S., 2019. A high-resolution geospatial assessment of the rooftop solar photovoltaic potential in the European Union. Renewable and Sustainable Energy Reviews 114, 109309, https://doi-org.ezproxy.lib.uts.edu.au/10.1016/j.rser.2019.109309

The potential under both the ‘full rooftop utilisation’ and the ‘half rooftop utilisation’ assumptions for rooftop potential mapping scenario was divided by the rooftop solar generation for 2050 in each of the E4BL scenarios, to provide a ratio of how many times larger the potential is, this is shown in the table below:

Table 16: Ratio of rooftop solar potential to required solar generation in 2050 for each E4BL scenario*

Mapping Scenario	BAU	4.0	4.1
Full Rooftop Utilisation	1.8	2.0	2.3
Half Rooftop Utilisation	0.9	1.0	1.1

*Note: a value <1 indicates insufficient potential relative to the generation expected under a scenario in 2050. This occurs only when reducing the total rooftop potential by half, and this does not inherently represent a flaw in the scenario as the E4BL scenarios are not forecasts, but possible futures.

Solar Potential of greenhouses

Solar potential for greenhouse rooftops is estimated based on the statistics on greenhouse areas. Greenhouse farmland covers an estimated 733km^2 in Spain[87] and approximately 30km^2[88] in Portugal. If all greenhouse rooftops were utilised for solar photovoltaic installation, they would create solar potential with around 19,150 MW in Spain and 750 MW in Portugal.

4.3.2 Onshore Wind Potential

The overall onshore wind resources are not as high in the Iberian Peninsula compared to the solar potential. The wind speeds in the Iberian Peninsula range from **0.78 to 17.3 m/s** at 100 m height (Global Wind Atlas). In this analysis, we included only areas with an average annual wind speed of ≥ 5 m/s for onshore projects. The Iberian Peninsula’s wind potential has been mapped under two different scenarios. The summary of the two scenarios is described in Section 3.1.

Table 17 shows that the overall total onshore wind potential area under all restrictions is **199,152 km^2** (165,142km^2 for Spain and 34,010km^2 for Portugal), which indicates a capacity of **995.8 GW** (825.7 GW for Spain and 170 GW for Portugal) for **Scenario 1**. The installed capacity within the onshore wind area is expected to generate **2,340,035 GWh/a** (1,940,422 GWh/a for Spain and 399,613 GWh/a for Portugal). While there is a significant amount of potential across the Iberian Peninsula, the potential is more limited under **Scenario 2** to avoid the high environmental sensitive areas which accounts for 64.7% of the study area (Table 17). The total onshore wind potential area for Scenario 2 is **99,448km^2** (84,434 km^2 for Spain and 15,014 km^2 for Portugal), which indicates a capacity of **497.2 GW** (422.2 GW for Spain and 75.1 GW for Portugal) and potential electricity generation of **1,168,520 GWh/a** (992,105 GWh/a for Spain and 176,415 GWh/a for Portugal).

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[87] Greenhouses farmland in Spain 2022, by crop: https://www.statista.com/statistics/1218871/greenhouse-area-spain-by-crop/?srsltid=AfmBOordlRbTBmkk4zM96ZuGxb5BklS4P_2BYHdt45R_tAwApCE3iURa (24/11/2025)

[88] Ferreira et al (2020). Overview of greenhouse horticulture in Portugal: technology and environment. Conference: VIII Congresso Ibérico de Ciências HortícolasAt: Coimbra, Portugal: https://www.researchgate.net/publication/340351917_Overview_of_greenhouse_horticulture_in_Portugal_technology_and_environment (accessed 27/11/2025)

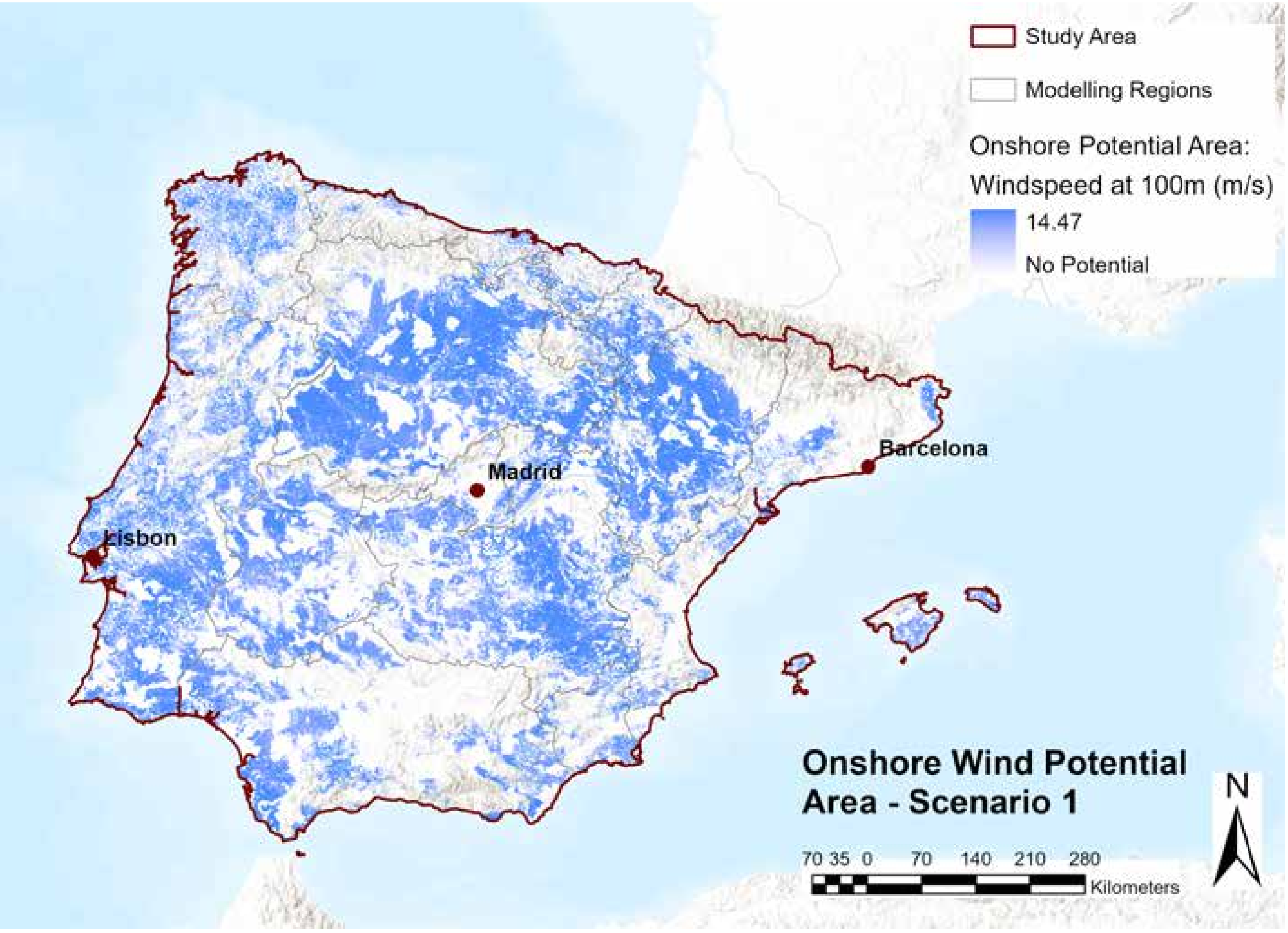
Table 17: Iberian Peninsula potential for utility-scale onshore wind power

Scenario 1 (LU + PA + S30)					
Modelling Regions	**Total Land Area (km^2)**	**Onshore wind Potential Area (km^2)**	**Onshore wind Potential Area (%)**	**Onshore wind Potential (GW)**	**Electricity generation (GWh/a)**
1. Andalucía	87,529	19,518	22.3	97.6	229,339
2. Aragón	47,714	20,977	44.0	104.9	246,478
3. Asturias, Principado de	10,607	1,104	10.4	5.5	12,972
4. Cantabria	5,279	966	18.3	4.8	11,345
5. Castilla-La Mancha	79,444	33,148	41.7	165.7	389,490
6. Castilla y León	94,251	45,518	48.3	227.6	534,832
7. Cataluña	32,104	3,439	10.7	17.2	40,405
8. Ceuta	20	3	16.2	0.0	39
9. Extremadura	41,659	15,722	37.7	78.6	184,731
10. Galicia	29,583	8,560	28.9	42.8	100,584
11. Islas Baleares	5,022	1,710	34.1	8.6	20,094
12. La Rioja	5,031	1,394	27.7	7.0	16,382
13. Madrid, Comunidad de	8,030	1,300	16.2	6.5	15,275
14. Murcia, Región de	11,312	2,838	25.1	14.2	33,342
15. Navarra, Comunidad Foral de	10,367	3,917	37.8	19.6	46,023
16. País Vasco	7,261	1,408	19.4	7.0	16,548
17. Valenciana, Comunidad	23,285	3,621	15.5	18.1	42,542
Spain total	**498,498**	**165,142**	**33.1**	**825.7**	**1,940,422**
18. Portugal	88,651	34,010	38.4	170.0	399,613
Portugal total	**88,651**	**34,010**	**38.4**	**170.0**	**399,613**
Iberian Peninsula TOTAL	**587,150**	**199,152**	**33.9**	**995.8**	**2,340,035**

Scenario 2 (LU + PA + S30 + ISA)					
Modelling Regions	**Total Land Area (km^2)**	**Onshore wind Potential Area (km^2)**	**Onshore wind Potential Area (%)**	**Onshore wind Potential (GW)**	**Electricity generation (GWh/a)**
1. Andalucía	87,529	9,612	11.0	48.1	112,939
2. Aragón	47,714	9,661	20.2	48.3	113,521
3. Asturias, Principado de	10,607	276	2.6	1.4	3,237
4. Cantabria	5,279	250	4.7	1.3	2,938
5. Castilla-La Mancha	79,444	18,251	23.0	91.3	214,443
6. Castilla y León	94,251	27,989	29.7	139.9	328,865
7. Cataluña	32,104	1,660	5.2	8.3	19,500
8. Ceuta	20	1	4.3	0.0	10
9. Extremadura	41,659	4,771	11.5	23.9	56,063
10. Galicia	29,583	2,338	7.9	11.7	27,466
11. Islas Baleares	5,022	1,024	20.4	5.1	12,028
12. La Rioja	5,031	849	16.9	4.2	9,977
13. Madrid, Comunidad de	8,030	783	9.8	3.9	9,202
14. Murcia, Región de	11,312	1,949	17.2	9.7	22,905
15. Navarra, Comunidad Foral de	10,367	2,232	21.5	11.2	26,229
16. País Vasco	7,261	493	6.8	2.5	5,793
17. Valenciana, Comunidad	23,285	2,297	9.9	11.5	26,988
Spain total	**498,498**	**84,434**	**16.9**	**422.2**	**992,105**
18. Portugal	88,651	15,014	16.9	75.1	176,415
Portugal total	**88,651**	**15,014**	**16.9**	**75.1**	**176,415**
Iberian Peninsula TOTAL	**587,150**	**99,448**	**16.9**	**497.2**	**1,168,520**

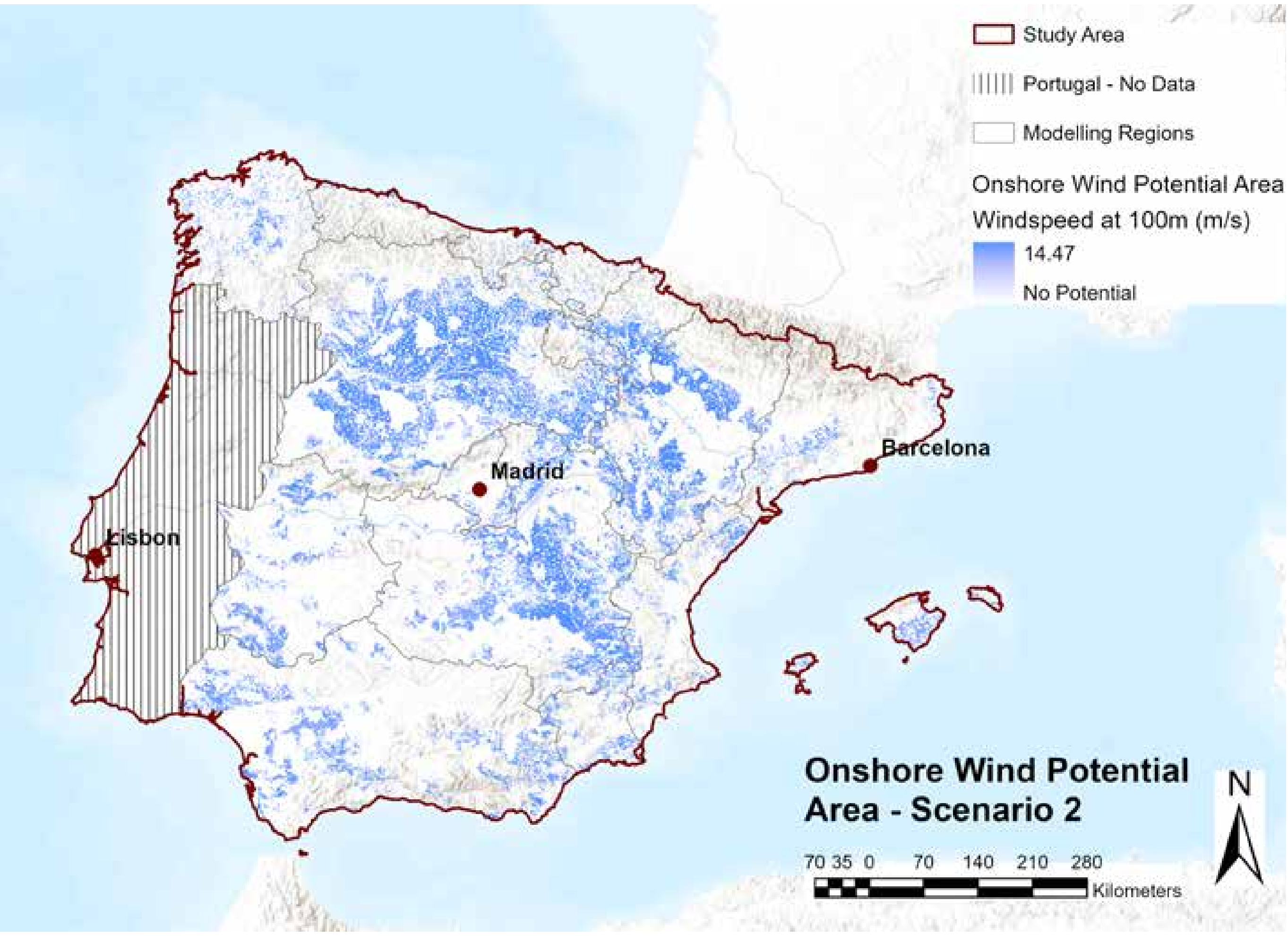
Note: Portugal's onshore wind potential areas (km^2) and onshore wind potential (GW) for Scenarios 2 was estimated by applying the same ratio of onshore wind potential area (km^2) to national land area (km^2) as in Spain (16.9%).

Figure 4-7: Iberian Peninsula – Onshore Wind Potential Areas (Scenario 1: LU + PA + S30)



Note: While Spain has the ISA environmental sensitivity map, no equivalent dataset was available for Portugal for this spatial analysis. Portugal's onshore wind potential areas (km²) and onshore wind potential (GW) for Scenarios 2 was estimated by applying the same ratio of onshore wind potential area (km²) to national land area (km²) as in Spain (16.9%).

Figure 4-8: Iberian Peninsula – Onshore Wind Potential Areas (Scenario 2: LU + PA + S30 + PT10)



While the onshore wind potential is of a lower magnitude than the solar potential mapped in the section above, the overall results show that both countries have large wind energy potential, with the potential being many times greater than what is required under the E4BL scenarios. The potential under each mapping scenario was divided by the onshore wind generation for 2050 in each of the E4BL scenarios and is shown in the table below:

Table 18: Ratio of onshore wind potential to required onshore wind generation in 2050 for each E4BL scenario

Mapping Scenario	BAU	4.0	4.1
Scenario 1	10	7.2	8.1
Scenario 2	4.8	3.6	4.0

4.3.3 Assessment of Government Offshore Wind Zones (the Spanish EEZ only)

This section provides results of a spatial analysis to examine overlaps between the Spanish government's 'High Potential Areas for Offshore Wind Energy Development' (ZAPER) and the proposed Natura 2000 network areas. Portugal has a comparable 'Offshore Renewable Energy Allocation Plan' (*Plano de Afetação para as Energias Renováveis Offshore*); however, comparable data were not available for this analysis.

The area designated as ZAPER covers 4,948 km² in total, which has 24.7 GW (24,741 MW) of offshore wind potential if offshore wind developments occur in all these areas. However, our analysis identified that approximately 132.5km² of the ZAPER in the Atlantic Marine Region and approximately 250km² of the ZAPER in the Mediterranean Marine Region were found within the proposed areas for adoption into the Natura 2000 network (Table 19, and Figure 4-10). Notably, the entire NOR-6 area lies within the proposed Natura 2000 network in the Atlantic Marine Region, and the entire LEBA-1 area is located within the Mediterranean Marine Region.

Figure 4-9: High potential areas for offshore wind energy development (ZAPER) overlaying the proposed Natura 2000 network areas by WWF Spain (2021): Atlantic Marine Region

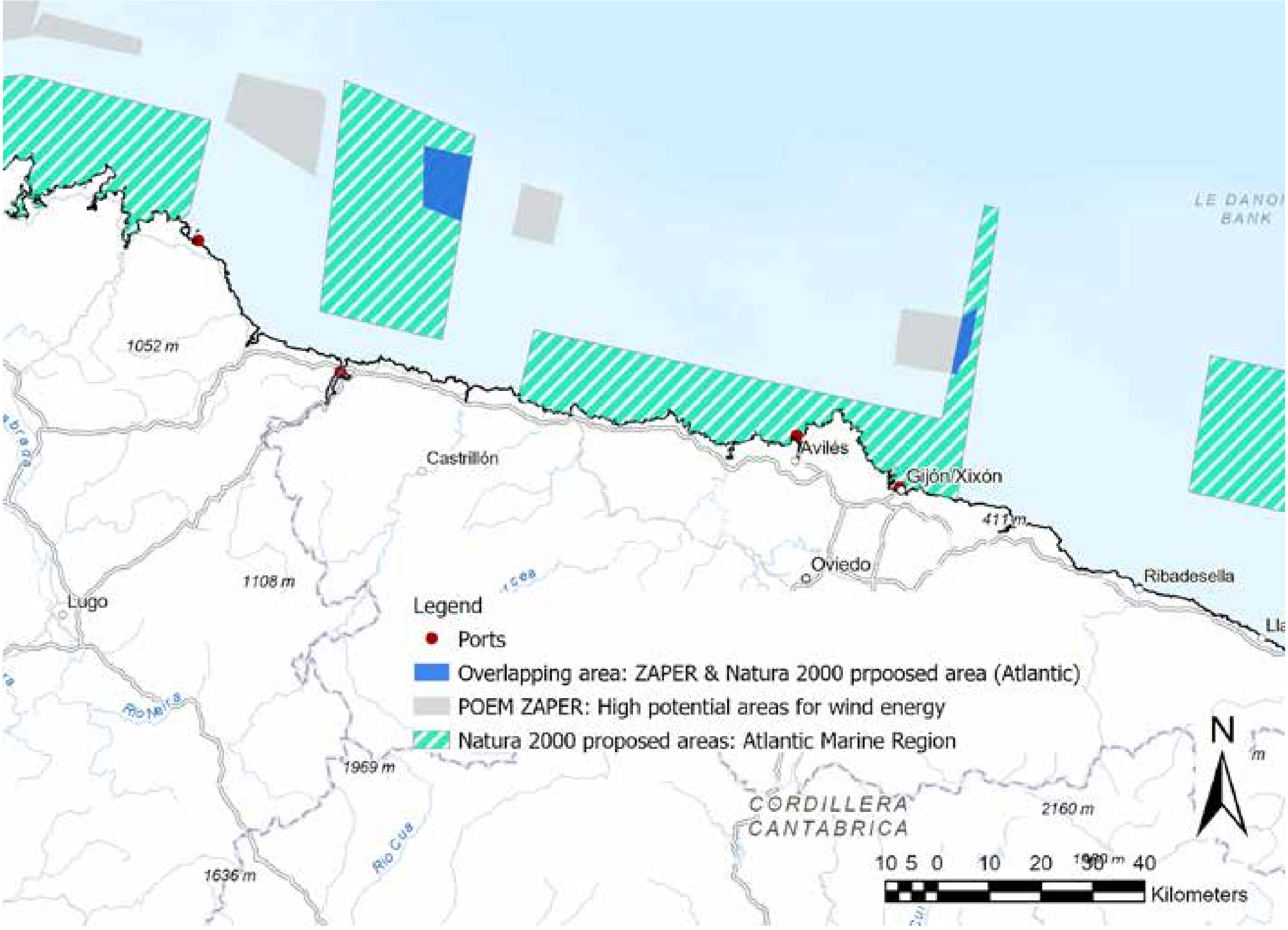


Figure 4-10: High potential areas for offshore wind energy development (ZAPER) overlaying the proposed Natura 2000 network areas by WWF Spain (2021): Mediterranean Marine Region

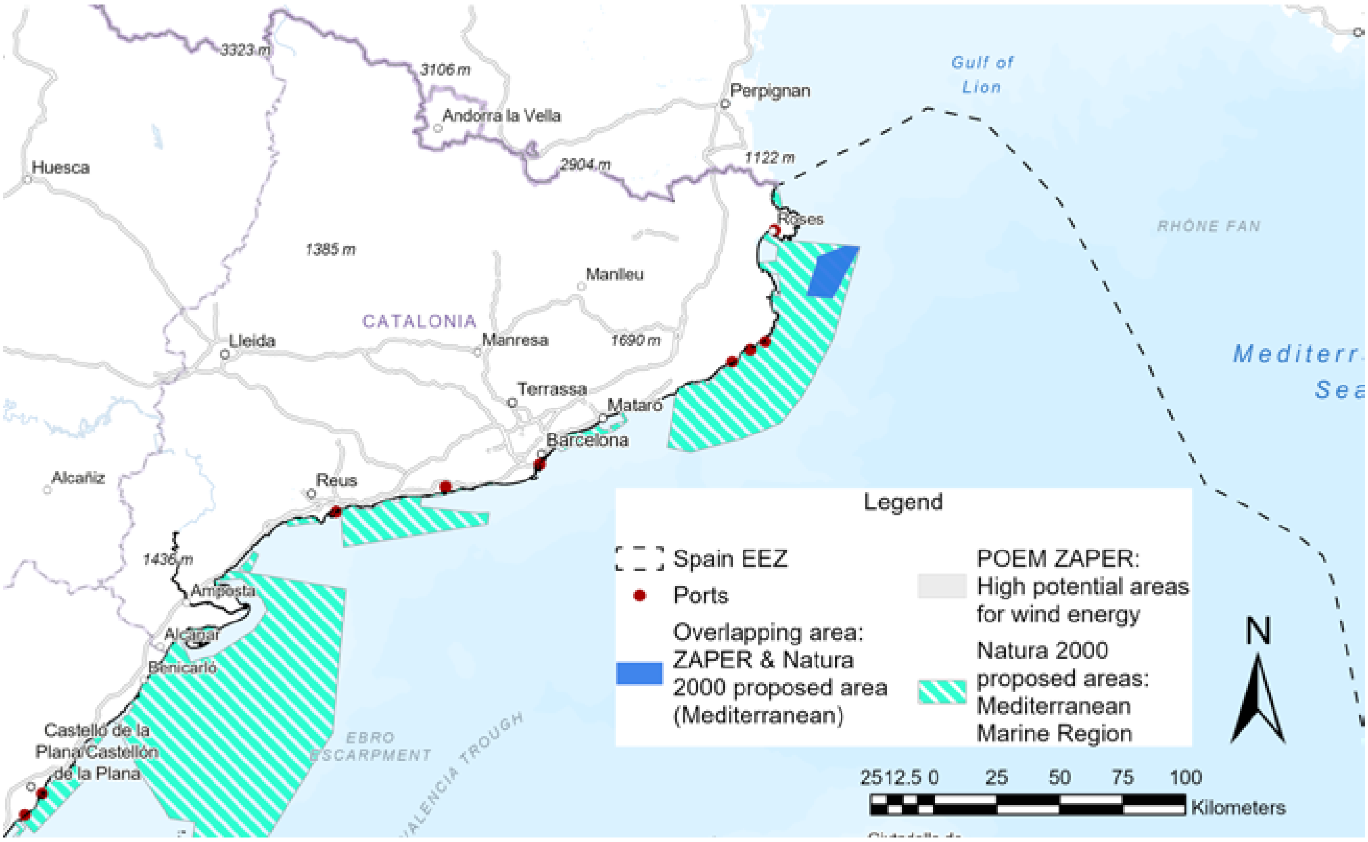


Table 19: Overlapping areas between ZAPER and the proposed expansion of the Natura 2000 network area

Name of proposed Natura 2000 network	Name of areas under ZAPER	Area (km²)
Atlantic Marine Region		
Frente marino de Ribadeo (adaption proposal)	NOR-6	103.9
ESZZ12003 Sistema de canones submarinos de Aviles (adaption proposal)	NOR-8	28.6
TOTAL (Atlantic Marine Region)		**132.5**
Mediterranean Marine Region		
Girona (Adaptation proposal)	LEBA-1	250.2
TOTAL (Mediterranean Marine Region)		**250.2**
TOTAL overlapping areas		**382.7**

Excluding these ZAPER areas currently located within the proposed Natura 2000 network areas, the total offshore wind potential of the ZAPER was identified as 22.8 GW. The expected electricity generation would be 98,966 GWh/a from all current ZAPER areas, while it would be 91,313 GWh/a excluding the current overlapping areas with proposed Natura 2000 areas (Table 20).

Table 20: Offshore wind potential from 'High potential areas for offshore wind energy development' (ZAPER)

Polygon codes	Offshore wind Potential Area (km^2)*	Offshore wind Potential (MW)**	Electricity generation (GWh/a)
CAN-FV1	192.2	961	3,844
CAN-FV2	16.3	81.5	326
CAN-GC1	163.9	819.5	3,278
CAN-LANZ1	97.4	487	1,948
CAN-TEN1	21.3	106.5	426
CAN-TEN2	70.8	354	1,416
ESAL-1	534.2	2,671	10,684
ESAL-2	688.4	3,442	13,768
LEBA-1 (overlapping with the proposed Natura 2000 network in the Mediterranean Marine Region)	250.0	1,250	5,000
LEBA-2	147.4	737	2,948
LEBA-3	77.7	389	1,554
NOR-1	117.6	588	2,352
NOR-2	1,806.4	9,032	36,128
NOR-3	113.0	565	2,260
NOR-4	77.7	389	1,554
NOR-5	236.3	1,182	4,726
NOR-6 (overlapping with the proposed Natura 2000 network in the Atlantic Marine Region)	105.0	525	2,100
NOR-7	80.2	401	1,604
NOR-8 (overlapping with the proposed Natura 2000 network in the Atlantic Marine Region)	152.5	763	3,050
TOTAL All ZAPER	4,948	24,742	98,966
TOTAL ZAPER outside the proposed areas for adaptation of the Natura 2000 network (TOTAL – overlapping area in Table 19)	4,566	22,828	91,313

Note: * Asociación Empresarial Eólica (AEE)[89] **Installed capacity (MW) was calculated using 5MW/km^2.

As discussed above the offshore wind mapping exercise does not seek to calculate technical potential for the whole of the Iberian Peninsula like was done solar and onshore wind generation. Instead, the mapping utilises existing geospatial data layers for areas designated for the possible development for offshore wind turbines, alongside nature exclusion zones, to provide an assessment of how much offshore wind generation could occur in these zones. The results for Spain show that there is still a large generation capacity achievable in this area, with the potential being greater than what is required under the E4BL scenarios for Spain. The possible generation in the ZAPER areas was divided by the offshore wind generation for 2050 in each of the E4BL Spain scenarios to show the ratio between the two:

Table 21: Ratio of offshore wind potential to required offshore wind generation in 2050 for each E4BL scenario

Mapping Scenario	BAU	4.0	4.1
All ZAPER	1.2	1.5	1.6
ZAPER excl. Natura 2000	1.1	1.3	1.5

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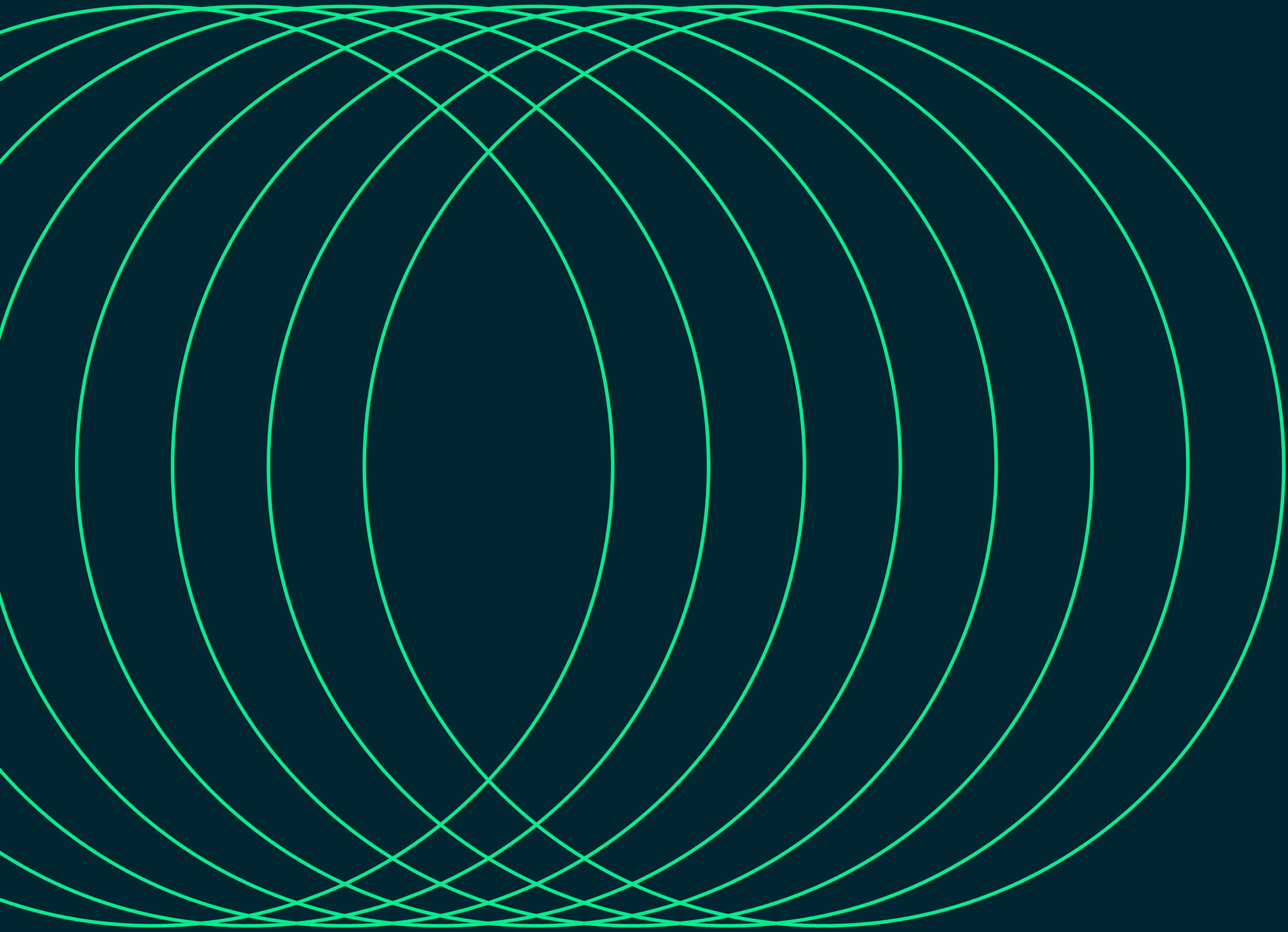
[89] Asociación Empresarial Eólica (AEE): GT Eólica Marina (10 March 2023) https://aeeolica.org/wp-content/uploads/2023/08/230228-GT-Eolica-Marina-Analisis-POEM-Final-Resumen.pdf

5

Technical and Economic Assumptions for Demand Sectors



Modelling the energy system involves a variety of methodological requirements, which pose specific challenges when addressed on the national level: the quantitative projection of developments in (future) technologies and potential markets; a consistent database of renewable energy potentials and their temporal and spatial distributions; reliable data on the current situations in all regions; an assessment of energy flows and emissions across all energy subsectors, such as industry, transport, residential, etc.; and a comprehensive assessment of all CO_2 emissions, in order to assess the impact of the energy system on climate change. Finally, analysing and assessing the energy transition requires a long-term perspective on future developments.

Changes to energy markets need long-term decisions to be made because infrastructure changes are potentially required and are therefore independent of short-term market developments. The energy market cannot function optimally without long-term infrastructure planning. Grid modifications and the roll-out of smart metering infrastructure, for example, require several years to implement. These technologies form the basis of the energy market and allow energy trading. Therefore, the time required for infrastructure planning and other substantial transformation processes must be considered in the scenario-building approach.

5.1 Socio-Economic Assumptions

Spain's population growth until 2050 is based on the Instituto Nacional de Estadística (INE) 2022–2072 long-term population forecast and accounts for the necessary reductions of the Canary Islands and Melilla (based on current INE statistics).[90] Portugal's population projection was based on Eurostat long-term projections.[91] This equates to small-scale growth in Spain's population. For Portugal, this equates to small-scale reduction in overall population (0.37%/year for Spain, -0.34% for Portugal).

The long-term GDP development growth rate is based on OECD long-term projections with the BAU and E4.0 scenarios using OECD's baseline projection for GDP, and the E4.1 scenario using their 'energy transition' scenario projections.[92] This decision was made to reflect that, under the sufficiency scenario, there may be economic effects of a rapid energy transition that includes behavioural change across portions of society and changes to current economic activities. The OECD notes that, "incorporating the impact of the energy transition on long-run potential output trajectories should, in principle, account for two main impact channels. The first is the direct impact of decarbonising an economy's energy sources, which, as pointed out by Pisani-Ferry is akin to a negative supply shock. The second is the positive impact of avoiding environmental damages on the economy."[93] However, the OECD only considers the first channel with its current methodology, which is to say that OECD methodology treats long-term decarbonisation as equivalent to the pricing of a negative externality (such as tax on emissions or considering the social cost of carbon).

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[90] Instituto Nacional de Estadística, Table 36643 'Population residing in Spain on January 1, by sex, age and year', <https://www.ine.es/jaxiT3/Tabla.htm?t=36643&L=1>

[91] Eurostat, 'Population on 1st January by age, sex and type of projection', https://ec.europa.eu/eurostat/databrowser/view/proj_23np/default/table?lang=en&category=proj.proj_23n (Last Updated 28/08/2023)

[92] OECD Data Explorer, Economic Outlook No 114 – December 2023 – Long-term baseline projections', variable: (GDphotovoltaicD) Gross domestic product, volume, USD at 2015 Purchasing Power Parities, https://data-explorer.oecd.org/vis?lc=en&df[ds]=DisseminateArchiveDMZ&df[id]=DF_EO114_LTB&df[ag]=OECD&df[vs]=&av=true&dq=.GDphotovoltaicD..A&to[TIME_PERIOD]=false&vw=tb&lb=bt&pg=0&pd=2020%2C2050

[93] OECD (Guillemette & Château), 'Long-term scenarios: incorporating the energy transition', Economic Policy Paper No. 33 (December 2023)

Table 22: The Iberian Peninsula – Population and economic development 2019 to 2050

Socio-Economic Assumptions		2019	2020	2025	2030	2035	2040	2045	2050
Population	[million]	55.2	55.5	56.5	58.0	58.9	59.3	59.6	59.7
GDP – Baseline	[billion – 2015 USD]	1,497	1,340	1,912	2,048	2,197	2,347	2,497	2,672
GDP – Energy Transition	[billion – 2015 USD]	1,497	1,340	1,912	2,043	2,185	2,326	2,462	2,616
GDP – 4.1 incl. sufficiency94	[billion – 2015 USD]	1,497	1,340	1,912	2,037	2,171	2,303	2,436	2,586
GDP growth rate– Baseline	[%/a – for given year]	2.1%	-10.8%	2.0%	1.4%	1.4%	1.3%	1.3%	1.4%
GDP growth rate – Energy Transition	[%/a – for given year]	2.1%	-10.8%	2.0%	1.2%	1.3%	1.1%	1.1%	1.2%

In addition to the ‘energy transition’ GDP forecast being utilised for the E 4.1 scenario, reductions on the output of certain industrial sectors were undertaken (whether in terms of material or economic output – depending on the sector calculation methodology).[95] Thus, additional reductions to GDP were implicitly undertaken in the E 4.1 scenario. It is noted here that, although the OECD’s ‘energy transition’ scenarios equate to slower long-term GDP growth over the modelling horizon and additional efficiency measures also have underlying GDP impacts, this slower growth does not equate to substantial emissions savings. The fact that emission reductions are not caused by GDP reductions relates to the fact that the OECD forecasts that it will take time for the market to recalibrate to the effective cost of emitting carbon, and thus the power sector and economy more broadly is largely decarbonised by the time the deviation in GDP growth occurs.[96]

5.2 Sectorial assumptions and Technical Parameters

To make scenarios comparable with each other, the technical assumptions need to be transparent and documented. This section provides an overview about the assumed development of consumption, production, and energy intensity. All technical assumptions are based on best available technologies regarding high energy conversion efficiencies.

- **Market development** – current and assumed development of the demand by sector, such as cement produced, passenger kilometres travelled or assumed market volume in Euros gross domestic product ($GDP).
- **Energy intensity** – activity-based: energy use per unit of service and/or product; for example, in megajoules (MJ) per passenger kilometres travelled (MJ/pkm), MJ per ton of steel (MJ/ton steel), aluminium, or cement.
- **Energy intensity** – finance-based: energy use per unit of investment in MJ per $ GDP (MJ/$GDP) contributed by, for example, the forestry or agricultural sector.

The following sections provides an overview to all input-assumptions for the demand development.

Furthermore, scenario assumption includes sector-specific narratives for future changes. In the following section, we provide the assumptions for the main four demand sectors:

1. Transport.
2. Buildings.
3. Service sector.
4. Industry.

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[94] Includes estimation of direct and indirect GDP reductions which occur due to reductions in industry activities referenced in footnote 91.

[95] Industry sectors effected by sufficiency demand reductions: Steel, Cement, Paper & Wood, Chemical (alongside transport).

[96] The GDP reductions which take place between 2030 and 2040 have a slight impact on emissions, and the demand reductions after 2040 make a negligible impact due to the 2040 net-zero emission target already being met.

5.3 Transport

To develop a future transport scenario, the technical parameters of all vehicular options are required to project the energy demands. The following section provides an overview of the vehicular energy intensities for passenger and freight transport. Based on these, the actual utilisation of vehicles – in terms of annual kilometres per vehicle – was estimated to calculate the energy demand over time until 2050. The energy intensities for the different vehicle types and each available drivetrain play an important role in the calibration of transport modes and projections. Each transport mode has different vehicular options. Each of the vehicles has different drivetrain and efficiency options. The technical variety of passenger vehicles, for example, is extremely large. The engine sizes for five-seater cars range from around 20 kW to >200 kW. Furthermore, drivetrains can use a range of fuels, from gasoline, diesel, and biodiesel to hydrogen and electricity. Each vehicle has a different energy intensity in megajoules per passenger-kilometre (MJ/pkm). Therefore, the energy intensities provided in the following tables are average values.

5.3.1 Individual Transport

Passenger transport by road is the most common and most important form of travel (TUMI 2021).[97] There are numerous technical options to ‘move people with vehicles’: bicycles, motorcycles, tricycles, city cars, and four-wheel-drive SUVs. Each vehicle has a very different energy intensity per kilometre. Although this research aims for high technological resolution, simplifications are required. Table 23 shows the energy intensities for the main vehicle types (electric and those with ICEs) and forms the basis for the energy scenario calculations.

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[97] TUMI (2021), Teske, S., Niklas, S., Langdon, R., (2021), TUMI Transport Outlook 1.5 °C – A global scenario to decarbonise transport; Report prepared by the University of Technology Sydney for the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH; published by TUMI Management, Deutsche Gesellschaft für International Zusammenarbeit (GIZ) GmbH, Friedrich-Ebert-Allee 36 + 40, 53113 Bonn, Germany; https://www.transformative-mobility.org/assets/publications/TUMI-Transport-Outlook.pdf

Table 23: Energy intensities of individual transport – road transport

Individual Transport			Passengers		Vehicle Demand	Consumption per Passenger	Energy Demand
			Average Passengers per Vehicle	Assumed Occupation Rate	Average	Average	Assumption for Scenario Calculation
		Fuel			**litre/100 km**	**litre/100 pkm**	**[MJ/pkm]**
Scooters & motorbikes	2-wheeler	Gasoline	1	1	3.0	3.0	1.21
		Electricity			**kWhel/100 km**	**kWhel/100 pkm**	**[MJ/pkm]**
E-bikes	2-wheeler	Battery	1	1	1.0	1.0	0.04
Scooters	2-wheeler	Battery	1	1	1.8	1.9	0.06
Motorbikes	2-wheeler	Battery	1	1	4.8	4.8	0.17
Rickshaw	3-wheels	Battery	3	2	8.0	4.0	0.14
		Fuels	**0**	**0**	**litre/100 km**	**litre/100 pkm**	**[MJ/pkm]**
Cars	small	ICE-oil	2	1.8	5.0	2.8	1.12
	medium	ICE-oil	4	2	7.5	3.8	1.51
	large	ICE-oil	5	2	10.5	5.3	2.11
	small	ICE-gas	2	1.8	4.5	2.5	0.63
	medium	ICE-gas	4	2	7.0	3.5	1.41
	large	ICE-gas	5	2	10.0	5.0	1.25
	small	ICE-bio	2	1.8	5.0	2.8	0.91
	medium	ICE-bio	4	2	7.5	3.8	1.51
	large	ICE-bio	5	2	10.5	5.3	1.72
	small	Hybrid-oil	2	1.8	4.0	2.2	0.89
	medium	Hybrid-oil	4	2.5	6.0	2.4	0.96
	large	Hybrid-oil	5	2.5	8.5	3.4	1.37
		Electricity			**kWhel/100 km**	**kWhel/100 pkm**	**[MJ/pkm]**
	small	Battery	2	1.8	16.0	8.9	0.32
	medium	Battery	4	2	25.0	12.5	0.45
	large	Battery	5	2	32.5	16.3	0.59
	large	Fuel Cell	4	2	37.5	18.8	1.36

5.3.2 Public Transport

There is a huge variety of public transport vehicles – from rickshaws to taxis and from mini-buses to long-distance trains. The occupation rates for these vehicles are key factors in calculating the energy intensity per passenger per kilometre. For example, a diesel-powered city bus transporting 75 passengers uses, on average, about 27.5 litres per 100 kilometres. If the bus operates at full capacity during peak hour, the energy demand per passenger is as low as 400 ml per 100 kilometres, lower than almost all fossil-fuel-based road transport vehicles. However, if the occupancy drops to 10% – e.g. for a night bus – the energy intensity increases to 3.7 litres per 100 km, equal to that of a small energy-efficient car. Occupation rates vary significantly and depend on the time of day, day of the week and season.

There are also significant regional differences, even within a province. Again, the parameters shown in Table 24 are simplified averages and are further condensed for the scenario calculations. Although high technical resolution is possible for the scenario model, it would convey an accuracy that does not exist because the statistical data required for this resolution are not available at the regional level.

Table 24: Energy intensities for public transport – road and rail transport

			Passengers		Vehicle Demand	Consumption per Passenger	Energy Demand
Public Transport			**Average Passengers per Vehicle**	**Assumed Occupation Rate**	**Average**	**Average**	**Assumption for Scenario Calculation**
Buses		**Fuels**			**litre/100 km**	**litre/100 pkm**	**[MJ/pkm]**
	small	Diesel	12	40%	8.8	1.8	0.73
	small	Bio	12	40%	8.8	1.8	0.60
	12 m	Diesel	75	40%	27.5	0.9	0.37
	12 m	Bio	75	40%	27.5	0.9	0.30
	large	Diesel	135	40%	57.5	1.1	0.43
		Electricity	**0**	**0**	**kWhel/100 km**	**kWhel/100 pkm**	**[MJ/pkm]**
	small	Battery	12	40%	31	6.4	0.23
	small	Fuel Cell	12	40%	77	15.9	0.57
	12 m	Battery	75	40%	143	4.8	0.17
	12 m	Fuel Cell	75	40%	358	11.9	0.43
	large	Overhead Lines	135	40%	263	4.9	0.18
Trains		**Fuels**	**0**	**0**	**litre/100 km**	**litre/100 pkm**	**[MJ/pkm]**
	Metros	Diesel	400	40%	150	0.9	0.38
	Metros	Bio	400	40%	150	0.9	0.31
	Commuter Trains	Diesel	600	40%	300	1.3	0.50
	Commuter Trains	Bio	600	40%	300	1.3	0.41
		Electricity	**0**	**0**	**kWhel/100 km**	**kWhel/100 pkm**	**[MJ/pkm]**
	Trams	Electric	300	40%	495	4.1	0.14
	Metros	Electric	300	40%	1,200	10.0	0.14
	Commuter Trains	Electric	600	40%	1,950	8.1	0.17

5.3.3 Freight Transport

The energy intensity data for freight transport are not as diverse as those for passenger transport because the transport vehicle types are standard and the fuel demands are well known. However, the utilisation rates of the load capacities vary significantly, and consistent data are not available for the calculated regional and global levels. Therefore, the assumed utilisation rate greatly influences the calculated energy intensity per tonne-km (tkm). The average energy intensities per tkm used in the scenarios are shown in Table 25 and are largely consistent with those from other sources in the scientific literature (EEA 2021).[98] The assumed energy intensities for electric and fuel cell/hydrogen freight vehicles are only estimates because these technologies are still in the demonstration phase. Therefore, none of the scenarios factor in large shares of electric freight transport vehicles before 2035.

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[98] European Environment Agency, https://www.eea.europa.eu/publications/ENVISSUENo12/page027.html

Table 25: Energy intensities for freight transport – road and rail transport

Freight Transport			Maximum Load Capacity (tonnes)	Assumed utilisation Rate	Vehicle Demand	Consumption per Tonne	Energy Demand
					Average	Average	Assumption for Scenario Calculation
Trucks		Fuels			litre/100 km	litre/tkm	[MJ/tkm]
	3.5 t	Diesel	3.5	40%	11	7.9	3.16
	3.5 t	Bio	3.5	40%	11	7.9	2.57
	7.5 t	Diesel	7.5	40%	20	6.5	2.61
	7.5 t	Bio	7.5	40%	20	6.5	2.13
	12.5 t	Diesel	12.5	40%	25	5.0	2.01
	12.5 t	Bio	12.5	40%	25	5.0	1.64
		Electricity			**kWhel/100 km**	**kWhel/ton-km**	**[MJ/tkm]**
	3.5 t	Battery	3.5	40%	19	13.6	1.34
	3.5 t	Fuel Cell	3.5	40%	46	33.2	1.33
	7.5 t	Battery	7.5	40%	41	13.6	0.49
	7.5 t	Fuel Cell	7.5	40%	100	33.2	1.19
	12.5 t	Battery	12.5	40%	68	13.6	0.49
	12.5 t	Fuel Cell	12.5	40%	166	33.2	1.19
Trains		Fuels			litre/100 km	litre/tkm	[MJ/tkm]
	Freight–740 m	Diesel	1,000	40%	300	0.8	0.30
	Freight–740 m	Bio	1,000	40%	300	0.8	0.25
		Electricity			**kWhel/100 km**	**kWhel/tkm**	**[MJ/tkm]**
	Freight–740 m	Electric	1,000	40%	5,840	14.6	0.53

5.3.4 Assumptions – Transport

The standard OECM modelling procedure does not account for international travel within the boundaries of a given country due to the nature of the IEA statistics. As discussed in sections '1.2.1 Progress in the Reduction of Final Energy Across Spain' and '2.1 Databases and Model Calibration', the calibration of transport demand utilises both IEA data alongside data from the Energía 3.0 report (freight vs passenger transport breakdown, breakdown of domestic and international travel). In this process, 50% of the travel and energy demand associated with international travel was accounted for, which aligns with the methodology used in the Energía 3.0.[99]

Section 'Primary Energy – Oil, Gas and Coal' under the 'Scenario Narratives' chapter provided an overview of the principles behind the decarbonisation of the transport sector, with electric vehicles playing an important role in road transport alongside mode shift towards other transport modes such as rail, public transport, and active transport like walking and cycling. These principles are applied differently amongst the three scenarios. For example, the BAU & E 4.0 scenarios differ in the pace and extent to which these changes take place as can be seen in Figure 3-1: petrol and kerosene still play a predominant role in the BAU transport sector by 2040, while in the E 4.0 scenario a more ambitious decarbonisation pathway is followed achieving the net-zero by this time. As 2040 is the year by which the net-zero target is imposed, it is thus accompanied by a complete phase-out of ICE vehicles across both freight and passenger transport segments.

In addition to the principles applying differently to the BAU and E 4.0 scenarios, there are also the sufficiency measures which were applied to the E 4.1 scenario, which go beyond the technology and mode shifts applied in the E 4.0 scenario and look to demand-reduction measures such as those outlined in the list below. The sufficiency-reduction measures were aligned with the ambitious measures outlined in the reports 'A radical transformation of mobility in Europe' and 'Transforma el Transporte' (applying measures which were relevant and achievable in the context of the Iberian Peninsula).[100,101]

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[99] Greenpeace Spain, 'Energía 3.0 – un sistema energetico basado en inteligencia, eficiencia y renovables 100%' (September 2011)

[100] Climact & New Climate Institute, B. Martin & J. Emmrich et. al., 'A radical transformation of mobility in Europe: Exploring the decarbonisation of the transport sector by 2040', (September 2020)

[101] Greenpeace Spain, 'Transforma el Transporte: Una guía para descarbonizar la movilidad en 2040', (September 2020)

The measures included:

- 10% reduction in freight transport by 2040, with this reduction slightly relaxing until 2050 to allow for population and GDP growth in an economy which has already decarbonised (in tonne.km, relative to 2019).[102]
- >35% reduction of aviation passenger transport by 2040, and >55% by 2050 (in passenger.km, relative to 2019).[103]
- >15% reduction of passenger transport (excluding aviation) across 2040-2050 (in passenger.km, relative to 2019).[104]

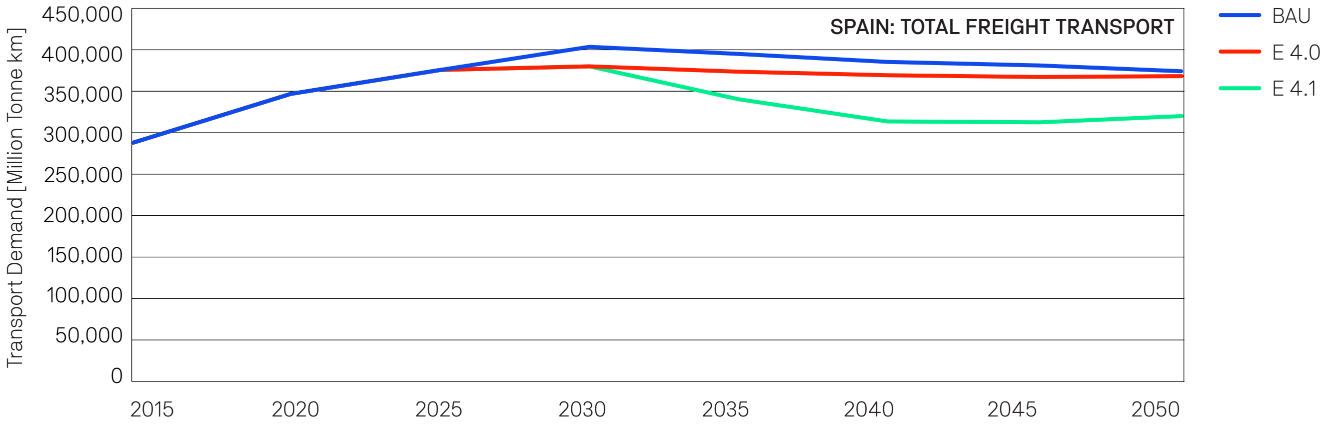
The freight and passenger transport demand for Spain are shown in the chapter below to illustrate the aggregate impact of the sufficiency measures and provide a comparison of the transport assumptions across the three scenarios. Noting that under both the E 4.0 and E 4.1 scenarios, that reductions which occur between 2030 and 2040 are the most impactful in terms of lowering emissions, as both these scenarios are set to achieve net-zero emissions from 2040 onwards. Further details behind the transport modelling are also provided in Section 4.5.3.

5.3.5 Transport demand projections

The aggregate impacts of the sufficiency measures are illustrated for Spain (Figure 5-1 and Figure 5-2) and Portugal (Figure 27 and Figure 28). The historical data shows 2019 as the 2020 data is not representative due to the effects of COVID-19. The sufficiency measures for Portugal follows the same reductions relative to the E4.0 scenario. It should be noted that the data displayed in these figures are derived from scaled domestic transport statistics, using the scaling factor discussed in the methodology sections, and thus the data reflects the increase caused by the inclusion of 50% of international cross-border travel.

While these figures illustrate the overall impact of the sufficiency measures on aggregate transport demand, they do not reflect the mode shift behind the aggregate values. For this reason, the breakdown across transport categories is provided for both freight and passenger transport for Spain (Table 26, Table 27) and Portugal (Table 28, Table 29).

Figure 5-1: Spain – total freight transport demand under the BAU, ES 4.0 and ES 4.1 scenarios



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[102] Note: this reduction was undertaken despite an increase of +15% freight transport 2020-2050 being accounted for in the report titled 'A radical transformation of mobility in Europe' (refer to footnote 95 for reference)

[103] Reductions of 36% and 56% respectively

[104] Reduction of 16% by 2040 and increasing slightly to 17% by 2050

Figure 5-2: Spain – total passenger transport demand under the BAU, ES 4.0 and ES 4.1 scenario

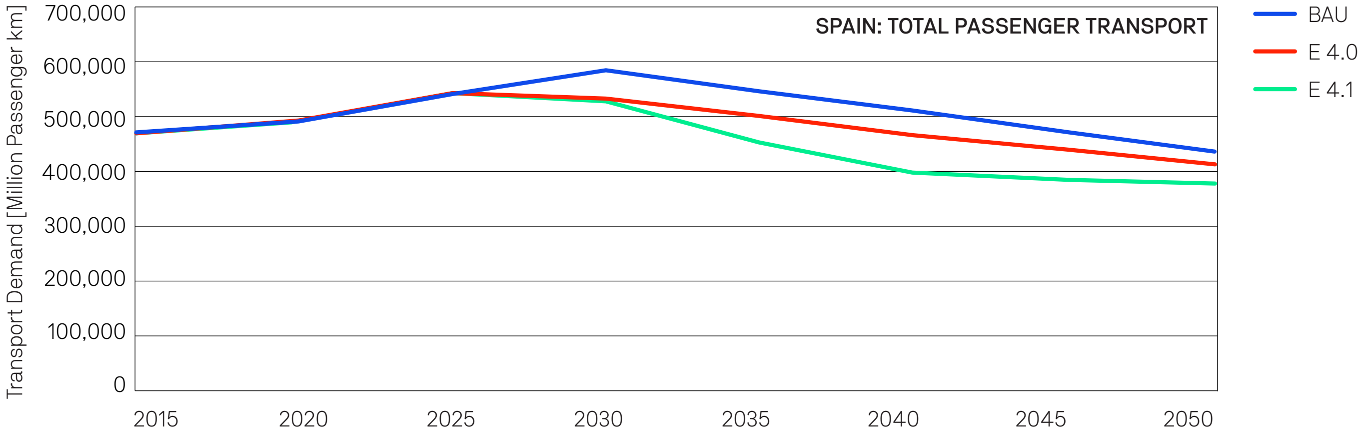

Table 26: Spain: Transport Sector – assumed development of freight km

Spain – Freight	2019	2030			2040			2050		
[million T-km/a]	Historical	BAU	ES 4.0	ES 4.1	BAU	ES 4.0	ES 4.1	BAU	ES 4.0	ES 4.1
Aviation	7,871	8,548	8,464	8,043	8,335	7,655	5,075	7,538	6,254	3,463
Navigation	103,188	118,166	118,345	118,052	124,209	133,998	130,403	129,913	151,722	147,652
Rail	11,415	13,576	14,613	14,969	17,379	18,706	24,383	22,246	23,945	39,718
Road	224,504	260,514	238,163	236,358	235,605	210,012	153,896	213,077	185,189	128,989
Total	**346,979**	**400,805**	**379,584**	**377,423**	**385,527**	**370,371**	**313,757**	**372,773**	**367,110**	**319,821**

Table 27: Spain – Transport sector – assumed development of passenger kilometres

Spain – Passenger	2019	2030			2040			2050		
[million p-km/a]	Historical	BAU	ES 4.0	ES 4.1	BAU	ES 4.0	ES 4.1	BAU	ES 4.0	ES 4.1
Aviation	77,433	85,957	83,437	79,701	94,950	75,459	50,292	85,871	61,656	34,317
Navigation	1,888	2,053	1,963	1,958	2,090	2,136	2,085	2,144	2,352	2,295
Rail	16,800	21,690	21,690	22,219	27,764	27,764	36,192	35,541	35,541	58,952
Road	396,071	468,781	426,471	422,184	387,938	366,650	311,329	316,974	315,220	281,560
Total	**492,191**	**578,480**	**533,560**	**526,063**	**512,743**	**472,010**	**399,898**	**440,530**	**414,769**	**377,125**

Figure 5-3: Portugal – total freight transport demand under the BAU, PT 4.0 and PT 4.1 scenarios

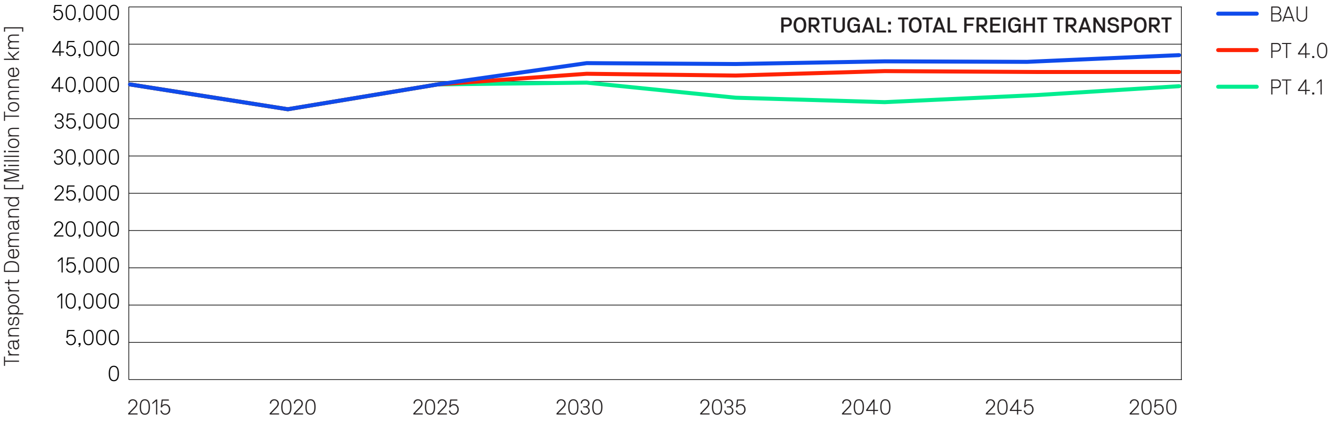

Figure 5-4: Portugal – total passenger transport demand under BAU the PT 4.0 and PT 4.1 scenarios

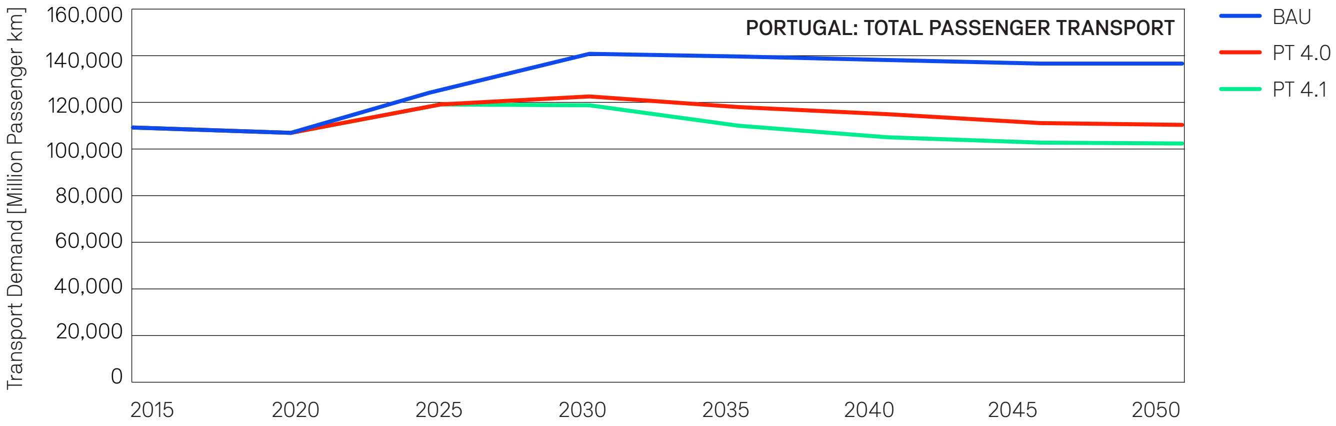

Table 28: Portugal: Transport Sector – assumed development of freight km

Portugal – Freight	2019	2030			2040			2050		
[million T-km/a]	Historical	BAU	PT4.0	PT4.1	BAU	PT4.0	E4.1	BAU	PT4.0	PT4.1
Aviation	281	307	287	283	305	273	179	287	223	122
Navigation	19,940	22,835	23,411	22,869	24,003	24,003	23,445	25,105	25,105	24,034
Rail	2,302	2,738	3,098	2,805	3,505	3,505	4,568	3,965	4,486	7,441
Road	13,929	16,163	13,876	14,015	14,618	13,030	9,125	13,901	11,490	7,649
Total	**36,453**	**42,043**	**40,651**	**39,972**	**42,430**	**40,810**	**37,317**	**43,098**	**41,304**	**39,246**

Table 29: Portugal: Transport sector – assumed development of passenger kilometres

Portugal Passenger	2019	2030			2040			2050		
[million p-km/a]	Historical	BAU	PT4.0	PT4.1	BAU	PT4.0	PT4.1	BAU	PT4.0	PT4.1
Aviation	2,802	2,494	3,004	2,291	2,275	2,717	1,820	2,053	2,220	1,242
Navigation	161	146	178	158	148	226	168	152	292	185
Rail	15,897	39,251	20,349	20,845	41,640	26,049	33,955	43,750	33,344	44,906
Road	88,985	107,357	99,727	94,851	103,369	85,738	69,946	99,276	73,712	56,656
Total	**107,844**	**149,249**	**123,258**	**118,739**	**147,434**	**114,730**	**105,889**	**145,230**	**109,568**	**102,988**

5.4 Buildings

The energy demand is calculated with the national building stock in m^2 multiplied by energy intensity for heating and cooling plus current electricity demand for both the residential and commercial building sector, with projections for stock and energy intensity based on updated CRREM data (Carbon Risk Real Estate Monitor).[105] It is assumed that heating and cooling will move predominantly to electricity – mainly heat pumps. Some role has also been assumed for solar thermal collectors for water and space heating for residential houses, but not apartments. The cornerstone for the buildings sector in all scenarios is significantly improved energy efficiency through the mandatory requirement of insulation and double glazing.

5.4.1 Assumptions – Building sector

It is assumed that heating and cooling will move predominantly to electricity – mainly heat pumps – with the overall heating supply aligned with the principles utilised in the 'Net Zero' heat supply scenario endorsed by Greenpeace Spain in the 'Hoja De Ruta De La Calefacción Renovable' report published by the group of organisations in 'La Plataforma por la Descarbonización de la Calefacción y el Agua Caliente'.[106] It is noted here that although this study assumes a coefficient of performance (COP) for heat pumps of 3.9, we have taken a more conservative value of 3.5 to account for cool weather conditions and the variability of COPs across the country due to temperature, size and system quality. These assumptions are aligned with key criteria set out by Greenpeace based on the outcomes of the CLEVER scenario (A Collaborative Lower Energy Visions for the European Region).[107] Throughout the modelling period, the value for residential space per person remains below the CLEVER limit of 40m^2/person, with the Iberian Peninsula having 38m^2/person in 2040, with this decreasing after 2040 as building stock grows slower than population growth. Key statistics for the building sector are shown below.

5.4.2 Technical Parameters – Buildings

The residential sector is expected to only grow by 0.1–0.3% per year in relation to the total building stock in billion m^2, with the growth trajectory starting at 0.3% in 2025 and decreasing to 0.1% by 2040 (with the growth trajectory remaining consistent across the Iberian Peninsula). The commercial building sector is assumed to increase at a higher rate as the building stock is an order of magnitude smaller than residential floor space (thus a 0.1–0.3% growth would lead to negligible growth in stock). Table 30 and Table 31 show the key parameters for the residential and commercial buildings for Spain and Portugal (noting that energy intensity here accounts for both heat and electrical energy).

As a result of the very low building stock growth over the analysed time horizon, energy efficiency improvements are almost entirely a direct result of refurbishment of existing buildings.

Table 30: Spain – Building stock: Development and energy intensities for Spain under the E 4.0 and 4.1 scenarios

Buildings Spain		**2019**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Building Stock: Residential	[billion m^2]	1.75	1.75	1.76	1.78	1.80	1.81	1.82	1.82
Building Stock: Commercial	[billion m^2]	0.35	0.35	0.36	0.39	0.43	0.46	0.51	0.55
Spain: BAU									
Residential Buildings: Energy Intensity	[kWh/m^2]	90	91	87	83	77	71	64	58
Commercial Buildings: Energy Intensity	[kWh/m^2]	120	102	99	87	73	57	43	31
Spain: Scenario E.4.0 and E 4.1									
Residential Buildings: Energy Intensity[108]	[kWh/m^2]	90	91	87	82	75	67	59	52
Commercial Buildings: Energy Intensity[109]	[kWh/m^2]	120	102	99	86	70	53	37	23

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[105] Carbon Risk Real Estate Monitor (CRREM), <https://crrem.org/> & data obtained via communication with Prof Bienert

[106] La Plataforma por la Descarbonización de la Calefacción y el Agua Caliente (Rivas et al.), Hoja De Ruta De La Calefacción Renovable',

[107] CLEVER, <https://clever-energy-scenario.eu/>

[108] Calculated on basis of total heat and electricity demand (final energy)

[109] Ibid.

Table 31: Portugal – Building stock: Development and energy intensities for Spain under the E 4.0 and 4.1 scenarios

Buildings Portugal		**2019**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Building Stock: Residential	[billion m^2]	0.44	0.44	0.44	0.44	0.48	0.52	0.52	0.52
Building Stock: Commercial	[billion m^2]	0.11	0.11	0.11`	0.12	0.13	0.14	0.15	0.16
Portugal: BAU									
Residential Buildings: Energy Intensity	[kWh/m^2]	70	73	67	56	47	42	38	36
Commercial Buildings: Energy Intensity	[kWh/m^2]	79	64	60	44	32	25	20	18
Portugal: Scenario E.4.0 and E 4.1									
Residential Buildings: Energy Intensity[110]	[kWh/m^2]	70	73	67	55	46	40	35	32
Commercial Buildings: Energy Intensity[111]	[kWh/m^2]	79	64	60	43	31	23	17	13

5.5 Services and Industries

The following sector summaries provide a high-level outline of the expected pathways and primary technology solutions for each of the subsectors included in the model. The expected production pathways for all service and industry sectors are the same across scenarios, except for the aluminium industry and the iron and steel industry. The variations in assumptions for these industries for the different scenarios are explained in the relevant sections below.

The key points common to all subsectors can be summarised as:

1. **Energy efficiencies** are prioritised, to be achieved mainly via technology improvements and switching to more efficient processes.
2. **Electrification** is undertaken whenever possible as the primary way of delivering energy services.
3. **Renewable energy** is accelerated for the purposes of both power and heat supply.
4. **Hydrogen and Synthetic fuels are used for industrial processes** – electrification is preferred to hydrogen and/or synthetic fuels due to higher efficiencies; these fuels are prioritised for feedstock and high temperature heating for industrial processes where electrification is not suitable.
5. **Industry Specific Energy Intensities** – Energy intensities are assumed to decrease per $ GDP or per service unit (e.g. passenger km) or product (e.g. MJ per ton of steel) to align with the best achievable levels over time – whether that be aligned with data from the IEA or with best practices from the EU.[112]

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[110] Calculated on basis of total heat and electricity demand (final energy)

[111] Ibid.

[112] IEA Energy Efficiency 2022, https://www.iea.org/reports/energy-efficiency-2022

5.6 Service Sector

The service sector is sub-divided into three subsectors: Water utilities, agriculture and food processing and forestry and wood products.

5.6.1 Water Utilities

Energy demand is calculated via water withdrawal in billion m^3. Energy intensity – in this case only electricity intensity – is based on Melbourne water utility publications. It is assumed that the biomass content of the sewage water will be used to generate electricity for self-consumption, which is quite common in the international context. Improvements in efficiency will be achieved with more efficient pumps and processes. Demand development is based on population growth projections.

5.6.2 Agriculture and Food Processing

Energy demand is calculated via $/GDP and energy intensities. Product- and country-specific energy intensities for the different food products (based on MJ/tons) were outside the scope of the research. Average energy intensities calculated with energy demand and market volumes are projected into the future under the assumption of energy efficiency progress of 1% per year through better machinery. Farming machinery – including vehicles – is assumed to electrify over time. Food processing machines replace thermal heat generation with electrical heat. Market development is based on population and GDP growth.

5.6.3 Forestry and Wood Products

Energy demand is calculated via $/GDP and energy intensities. Average energy intensities calculated with energy demand and market volumes are projected into the future under the assumption of energy efficiency progress of 1% per year through improvement of technical equipment. Forestry machinery – including vehicles – are assumed to electrify over time. Wood product machines replace thermal process heat demand with electrical heat. Market development is based on average national GDP growth.

As discussed in earlier chapters, sufficiency measures were applied to the 'wood and paper' industry such that reductions in output aligned with the trajectory of the CLEVER scenario. For this sector, this meant a reduction of output by 10% relative to 2015 levels by 2050.[113]

5.6.4 Data Centres and AI

A new methodology was developed and implemented in this report to model and analyse the possible impact of data centres and AI on the electrical demand of the Iberian Peninsula. The literature reviewed in the development of this methodology was a report commissioned by Greenpeace Germany: 'Environmental Impacts of Artificial Intelligence', and publicly available data from Independent Commodity Intelligence Services (ICIS) from their work on 'Forecasting European power demand from data centres to 2035'.[114,115]

Historic values of data centre demand are estimated to be ~3 TWh (10 PJ) in the period 2020-25 for Spain and Portugal. As can be seen below in Table 32 and Table 33, this is forecasted to grow significantly in the coming years, with values for data centre demand across the Iberian Peninsula reaching values of 34 TWh by 2040 and 59 TWh by 2050 (125 PJ and 212 PJ, respectively). The forecasts used in this table were used across all E4BL scenarios.

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[113] CLEVER, <https://clever-energy-scenario.eu/>

[114] Öko-Institut, 'Environmental Impacts of Artificial Intelligence', (Published 14/05/2025)

[115] ICIS, 'Data centres: Hungry for power – Forecasting European power demand from data centres to 2035', <https://www.icis.com/explore/resources/data-centres-hungry-for-power/>

Table 32: Spain: Assumed development of electricity demand for offices and data centres (excl. climatisation)

Commercial and public services: Electricity Demand Calculation		2020	2025	2030	2035	2040	2045	2050
Total Electricity Consumption Offices and Data Centres	[TWh/a]	67	74	81	91	109	125	135
Assumed annual growth rate	[%/a]	-9.9%*	1.0%	1.2%	1.0%	0.9%	0.9%	0.9%
Electricity Demand	[TWh/a]	65	72	76	80	84	88	92
	[PJ/a]	234	259	272	288	302	316	331
Assumed annual growth rate	[%/a]	0.0%	1.6%	17%	17%	21.0%	6.0%	1.0%
Electricity Demand	[TWh/a]	2.3	2.4	5.3	12	25	37	43
	[PJ/a]	8.3	8.6	19	42	91	133	155

Table 33: Portugal: Assumed development of electricity demand for offices and data centres (excl. climatisation)

Commercial and public services: Electricity Demand Calculation		2020	2025	2030	2035	2040	2045	2050
Total Electricity Consumption Offices and Data Centres	[TWh/a]	15	20	23	27	33	39	42
Assumed annual growth rate	[%/a]	-8.5%*	3.1%	1.2%	1.0%	0.9%	0.9%	1.0%
Electricity Demand	[TWh/a]	15	20	22	23	24	25	26
	[PJ/a]	52	70	78	83	86	92	94
Assumed annual growth rate	[%/a]	0.0%	1.6%	21.0%	21.0%	21.0%	6.0%	1.0%
Electricity Demand	[TWh/a]	0.5	0.5	1.4	3.6	9.4	14	16
	[PJ/a]	1.8	1.9	5.0	13.0	34	50	57

*Note: negative growth rate in 2020 due to COVID-19.

5.6.5 Technical Parameters – Service Sector

Table 34 and Table 35 show technical and economic assumptions for energy demand projection of the service sector for Spain and Portugal. The energy intensities are based on average industry standards and an analysis by UTS-ISF (Teske et. al. 2022)[116].

Table 34: Spain –Service sector – market development and energy intensities for Spain under the ES 4.0

Services		2020	2025	2030	2035	2040	2045	2050
Water Utilities								
Water withdrawal – total	[billion m^3]	31	31	31	30	30	30	30
- of which is Saltwater	[billion m^3]	0.4	0	0	0	1	1	1
Saltwater share (of total water withdrawal)	[%]	1%	1%	2%	2%	2%	2%	2%
Agricultural water	[billion m^3]	20	20	20	20	20	19	19
Municipal water	[billion m^3]	5	5	5	5	5	5	5
Industrial water	[billion m^3]	6	6	6	6	6	6	6
Water Utilities Energy Intensities								
Water pumping & Distribution	[kWh/m^3]	0.18	0.18	0.18	0.18	0.18	0.17	0.17
Desalination	[kWh/m^3]	4.50	4.44	4.39	4.33	4.28	4.23	4.17
Wastewater Treatment	[kWh/m^3]	0.06	0.06	0.06	0.05	0.05	0.05	0.05
Average Electricity Intensity (across all processes)	[kWh/m^3]	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Average Heat Intensity (across all processes)	[MJ/m^3]	31.22	31.04	30.73	30.42	30.12	29.82	29.52

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[116] Teske et. al. 2022, Teske, S., Nagrath, K., Niklas, S. (2022). Decarbonisation Pathways for Services. In: Teske, S. (eds) Achieving the Paris Climate Agreement Goals . Springer, Cham. https://doi.org/10.1007/978-3-030-99177-7_6

Services		2020	2025	2030	2035	2040	2045	2050
Agriculture								
Agriculture – Economic Value	[bn $]	26	33	35	38	40	43	46
Food & Processing Industry	[bn $]	30	31	32	35	37	39	42
Tobacco Industry – Economic Value	[bn $]	16	23	24	26	27	29	31
Average Energy Intensity Agriculture & Food Processing	[MJ/$GDP]	3.49	3.44	3.40	3.36	3.31	3.27	3.23
Tobacco Products Industries	[MJ/$GDP]	0.40	0.40	0.39	0.39	0.38	0.38	0.37
Forestry & Wood								
Forestry Industry – Economic Value	[bn $]	8.5	10.9	11.7	12.5	13.3	14.1	15.1
Wood – Industry – Economic Value	[bn $]	10.6	15.1	16.1	17.2	18.3	19.5	20.8
Pulp & Paper Industry	[bn $]	8.7	12.3	13.1	14.1	15.0	15.9	17
Forestry – total	[MJ/$GDP]	3.38	3.34	3.30	3.25	3.21	3.17	3.13
Wood Products Industries	[MJ/$GDP]	16.5	16.3	16.1	15.9	15.7	15.5	15.3
Pulp Mills	[MJ/$GDP]	269	266	262	259	256	253	249
Paperboard Mills	[MJ/$GDP]	67	66	65	64	64	63	62

Table 35: Portugal –Service sector – market development and energy intensities for Spain under the PT 4.0

Services		2020	2025	2030	2035	2040	2045	2050
Water Utilities								
Water withdrawal – total	[billion m³]	9.1	9.1	9.0	8.9	8.8	8.7	8.6
– of which is Saltwater	[billion m³]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Saltwater share (of total water withdrawal)	[%]	1%	1%	1%	1%	1%	1%	1%
Agricultural water	[billion m³]	7.2	7.2	7.1	7.0	6.9	6.9	6.8
Municipal water	[billion m³]	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Industrial water	[billion m³]	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Water Utilities Energy Intensities								
Water pumping & Distribution	[kWh/m³]	0.18	0.18	0.18	0.18	0.18	0.17	0.17
Desalination	[kWh/m³]	4.50	4.44	4.39	4.33	4.28	4.23	4.17
Wastewater Treatment	[kWh/m³]	0.06	0.06	0.06	0.05	0.05	0.05	0.05
Average Electricity Intensity (across all processes)	[kWh/m³]	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Average Heat Intensity (across all processes)	[MJ/m³]	9.15	9.09	9.00	8.91	8.82	8.73	8.65
Agriculture								
Agriculture – Economic Value	[bn $]	3.0	4.5	4.9	5.4	5.8	6.2	6.7
Food & Processing Industry	[bn $]	2.6	3.8	4.2	4.5	4.9	5.2	5.6
Tobacco Industry – Economic Value	[bn $]	2.1	3.1	3.4	3.7	4.0	4.3	4.6
Average Energy Intensity Agriculture & Food Processing	[MJ/$GDP]	3.49	3.44	3.40	3.36	3.31	3.27	3.23
Tobacco Products Industries	[MJ/$GDP]	0.40	0.40	0.39	0.39	0.38	0.38	0.37
Forestry & Wood								
Forestry Industry – Economic Value	[bn $]	0.4	0.4	0.6	0.6	0.7	0.7	0.8
Wood Industry – Economic Value	[bn $]	1.8	2.2	2.7	2.1	1.7	1.7	1.7
Pulp & Paper Industry	[bn $]	1.5	1.8	2.2	1.7	1.4	1.4	1.4
Forestry – total	[MJ/$GDP]	3.38	3.34	3.30	3.25	3.21	3.17	3.13
Wood Products Industries	[MJ/$GDP]	16.5	16.3	16.1	15.9	15.7	15.5	15.3
Pulp Mills	[MJ/$GDP]	269	266	262	259	256	253	249
Paperboard Mills	[MJ/$GDP]	67	66	65	64	64	63	62

5.7 Industry Sector

The industry sector is sub-divided in five subsectors: chemical, cement, steel, aluminium and textile and leather.

5.7.1 Chemical Industry

The chemical industry energy demand has been calculated with average energy intensities and production volumes of the main chemical product sectors: pharmaceuticals, agricultural, inorganic and consumer products, fibre and rubber and petrochemicals. Energy intensities are average values based on International Energy Agency data. Behind these sectors lie six prominent chemical production processes, which account for most of the energy consumption and emissions. They are: ethylene production by steam cracking, ammonia production by Haber-Bosch, aromatics extraction, methanol production, butylene production, and chloro-alkali production. Thus, all E4BL scenarios developed using the OECM methodology are underpinned by a detailed bottom-up approach of modelling the chemical sector, such that main product sectors are aligned with both IEA reginal data and data relating to the six production processes.

The chemical industry is assumed to see high uptake of electrification, coupled with the use of hydrogen and synthetic fuels (including ammonia) replacing gas as a feedstock. In the E.4.1 scenario, it is assumed that the production volume for ammonia (used for fertiliser) decreases by 1% per year from 2025 to 2050.

As discussed in earlier chapters, sufficiency measures were applied to the chemical industry, such that reductions in output aligned with the trajectory of the CLEVER scenario. Given the bottom-up production approach, which has been calibrated to Spain and Portugal's industrial output as well as IEA data, the chemical sector across the Iberian Peninsula largely remained within production limits for the sector – particularly relating to final energy consumption. This is thanks to several factors such as electrification of processes and the pathways for the underlying production of base chemicals developed under the E 4.0 pathway. Under the E 4.1 pathway, the reduction in final energy is aligned with the CLEVER scenario, such that an overall reduction of ~22% occurs by 2050 relative to 2015 levels. [117]

5.7.2 Textile and Leather

The textiles and leather sector is not a large consumer of energy in Spain or Portugal and has a minor influence on the energy scenario results, but it is included due to the OECM model structure. Market development is based on average national GDP growth.

5.7.3 Cement Industry

Cement production is assumed to grow moderately (in line with GDP growth) until 2050. Energy intensities are reduced significantly by 2% on average. Clinker replacement substances such as gypsum, ground limestone, and industrial by-products such as fly ash are increasingly used.

As discussed in earlier chapters, sufficiency measures were applied to the cement industry, such that reductions in output aligned with the trajectory of the CLEVER scenario. The cement sector across the Iberian Peninsula under the E 4.0 already remained significantly lower than cement production limits outlined by the CLEVER scenario, thus the sufficiency reduction to this sector were not explicitly required to meet what was determined to be sustainable and sufficient levels under the analysis taken for the European region.[118] The E 4.1 scenario included a modest reduction in the output of the cement industry of 3% relative to the E 4.0 scenario, with this reduction occurring by 2040 so that the reduction in output would play a minor role in helping to accelerate the success of achieving the 2040 Net-Zero target.

5.7.4 Aluminium Industry

For the aluminium industry, it is assumed that the production of alumina and aluminium remains on current levels and that there no global structural changes in the current supply chain of the industry. Furthermore, it is assumed that the aluminium industry will increase efficiency significantly.

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[117] CLEVER, <https://clever-energy-scenario.eu/>

[118] CLEVER, <https://clever-energy-scenario.eu/>

5.7.5 Iron and Steel Industry

The iron and steel industry includes iron ore mining. It is assumed that the ratio between domestic iron ore mining and steel production remains at current levels. The basic oxygen furnace (BOF) process currently used for domestic steel manufacturing is phased out and replaced by hydrogen-based steel production entirely. While the Spanish steel industry ranks 17th globally regarding crude steel production, Portugal's steel industry is very small. It is assumed that the global structure of the steel industry – regarding market shares and production location – will remain unchanged over the entire scenario period (2050).

As discussed in earlier chapters, sufficiency measures were applied to the steel industry, such that reductions in output aligned with the trajectory of the CLEVER scenario. For this sector, this meant a reduction of output by 15% relative to 2015 levels by 2050, with a reduction of 10% being achieved by 2040. [119]

5.7.6 Assumptions – Industry Sector

As discussed in section '5.1 Socio Economic Assumptions', the E 4.1 scenario applies sufficiency measures to the steel, cement, paper and wood, and chemical sectors. The remaining service sectors maintain a consistent development pathway across the E 4.0 and 4.1 scenarios.

Further details of the technical assumptions across service and industry sectors are provided below in sections '5.6 Service Sector' and '5.7 Industry Sector', with the table illustrating the technical assumptions for the ES 4.0 Spain scenario. This was chosen as the Spanish economy is the main driver of energy and emissions, and that the ES 4.0 scenario demonstrates the main pathway to achieve net-zero emissions in a manner aligned with the Paris Agreement.

5.7.7 Technical Parameters – Industry Sector

Table 36 and Table 37 shows the technical and economic assumptions for the energy demand projection of the service sector for Spain and Portugal. The energy intensities are based on average industry standards and an analysis by UTS/ISF (Teske et. al. 2022).[120]

Table 36: Spain – Industry sector – market development and energy intensities for Spain under the ES 4.0

Industry Sector		2025	2030	2035	2040	2045	2050
Chemical Industry							
Market Chemical Industry	[bn $ GDP]	150.9	152.7	154.3	155.8	157.2	158.7
Steel Industry							
Annual production volume – iron & steel industry	[Mt/a]	14.6	15.5	16.5	17.6	18.9	20.4
Primary steel production – share on total production	[%]	50%	45%	40%	37%	35%	35%
Secondary/scrap steel – share on total production	[%]	50%	55%	60%	63%	65%	65%
Average Energy Intensity in steel production	[GJ/ton]	9.8	9.5	11.0	10.3	10.6	10.6
Energy Intensity – PRIMARY steel (FINAL ENERGY)	[GJ/ton]	13.6	13.6	12.7	11.2	10.7	10.3
Energy Intensity – SECONDARY steel (FINAL ENERGY)	[GJ/ton]	6.1	6.1	9.8	9.7	10.5	10.7
Aluminium Industry							
Annual production volume – aluminium industry	[Mt/a]	0.4	0.4	0.4	0.4	0.4	0.4
Primary aluminium production – share of total production	[%]	65%	47%	29%	29%	29%	29%
Secondary/scrap aluminium – share of total production	[%]	35%	53%	71%	71%	71%	71%
Primary Aluminium – Energy intensity – Electricity (Anode, Electrolysis + Ingot)	[PJ/Mt]	54.4	53.1	51.7	50.5	49.2	48.0
Secondary Aluminium – Energy intensity – Electricity (Anode, Electrolysis + Ingot)	[PJ/Mt]	2.7	2.7	2.6	2.5	2.5	2.4

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[119] CLEVER, <https://clever-energy-scenario.eu/>

[120] Teske et. al. 2022 Teske, S., Niklas, S., Talwar, S. (2022). Decarbonisation Pathways for Industries. In: Teske, S. (eds) Achieving the Paris Climate Agreement Goals . Springer, Cham. https://doi.org/10.1007/978-3-030-99177-7_5

Industry Sector		2025	2030	2035	2040	2045	2050
Cement Industry							
Cement – production volume	[Mt/a]	12	13	14	15	16	18
Clinker – production volume (based on clinker to cement ratio)	[Mt/a]	7.7	8.4	8.8	9.0	9.2	9.5
Thermal energy intensity – per ton of Clinker	[GJ/ton]	3.4	3.3	3.3	3.2	3.2	3.1
Cement production – electricity intensity	[kWh/t]	103	87	85	83	81	79
Thermal energy intensity – per ton of Cement (final energy)	[GJ/ton]	8.8	8.2	7.8	7.4	7.1	6.7
Product Energy Intensity (thermal + electricity)	[GJ/ton cement]	9.2	8.6	8.1	7.8	7.4	7.0
Textile & Leather Industries							
Textile Industries – Economic value	[bn $ GDP]	8.8	9.3	10.0	10.7	11.2	12.1
Leather Industry – Economic value	[bn $ GDP]	2.9	3.1	3.3	3.6	3.8	4.0
Total Textile & Leather	[bn $ GDP]	11.7	12.5	13.3	14.2	15.1	16.1
Textile Mills – Energy Intensities	[MJ/$GDP]	4.42	4.29	4.07	3.87	3.68	3.49
Textile Products Mills – Energy Intensities	[MJ/$GDP]	4.47	4.33	4.12	3.91	3.72	3.53
Clothing Industries – Energy Intensities	[MJ/$GDP]	0.84	0.81	0.77	0.73	0.7	0.66
Textile Industry – average energy intensity	[MJ/$GDP]	2.64	2.70	2.57	2.44	2.38	2.26
Leather and Allied Products Industries – Energy Intensity	[MJ/$GDP]	1.45	1.41	1.34	1.27	1.21	1.15

Table 37: Portugal – Industry sector – market development and energy intensities for Spain under the PT 4.0

Industry Sector		2025	2030	2035	2040	2045	2050
Chemical Industry							
Market Chemical Industry	[bn $ GDP]	11.8	15.6	16.9	18.2	19.4	20.7
Steel Industry							
Annual production volume – Iron & Steel Industry	[Mt/a]	0.0	0.0	0.0	0.0	0.0	0.0
Primary steel production – share on total production	[%]	60%	45%	40%	37%	35%	35%
Secondary/scrap steel – share on total production	[%]	40%	55%	60%	63%	65%	65%
Average Energy Intensity in steel production	[GJ/ton]	1.4	9.5	11.0	10.3	10.6	10.6
Energy Intensity – PRIMARY steel (FINAL ENERGY)	[GJ/ton]	13.5	13.6	12.7	11.2	10.7	10.3
Energy Intensity – SECONDARY steel (FINAL ENERGY)	[GJ/ton]	4.3	6.1	9.8	9.7	10.5	10.7
Aluminium Industry							
Annual production volume – aluminium Industry	[Mt/a]	0.0	0.0	0.0	0.0	0.0	0.0
Primary aluminium production – share of total production	[%]	68%	55%	29%	29%	29%	29%
Secondary/scrap aluminium – share of total production	[%]	32%	45%	71%	71%	71%	71%
Primary Aluminium – Energy intensity – Electricity (Anode, Electrolysis + Ingot)	[PJ/Mt]	55.8	53.1	51.7	50.5	49.2	48.0
Secondary Aluminium – Energy intensity – Electricity (Anode, Electrolysis + Ingot)	[PJ/Mt]	2.8	2.7	2.6	2.5	2.5	2.4
Cement Industry							
Cement – production volume	[Mt/a]	4.5	5.0	5.5	5.9	6.4	6.8
Clinker – production volume (based on clinker-to-cement ratio)	[Mt/a]	3.2	3.3	3.4	3.5	3.6	3.7
Thermal energy intensity – per ton of Clinker	[GJ/ton]	6.2	2.2	2.1	2.1	2.0	2.0
Cement production – electricity intensity	[kWh/t]	116	95	93	91	86	79
Thermal energy intensity – per ton of Cement (final energy)	[GJ/ton]	6.2	2.2	2.1	2.1	2.0	2.0
Product Energy Intensity (thermal + electricity)	[GJ/ton cement]	6.7	2.5	2.5	2.4	2.4	2.3

Industry Sector		2025	2030	2035	2040	2045	2050
Textile & Leather Industries							
Textile Industries – Economic value	[bn $ GDP]	5.9	8.4	9.1	9.8	10.4	11.1
Leather Industry – Economic value	[bn $ GDP]	2.0	2.8	3.0	3.3	3.5	3.7
Total Textile & Leather	[bn $ GDP]	7.8	11.2	12.1	13.0	13.9	14.8
Textile Mills – Energy Intensities	[MJ/$GDP]	4.5	4.3	3.2	2.4	1.8	1.4
Textile Products Mills – Energy Intensities	[MJ/$GDP]	4.6	4.4	3.3	2.5	1.8	1.4
Clothing Industries – Energy Intensities	[MJ/$GDP]	0.9	0.8	0.6	0.5	0.3	0.3
Textile Industry – average energy intensity	[MJ/$GDP]	1.8	1.7	1.3	1.0	0.7	0.5
Leather and Allied Products Industries – Energy Intensity	[MJ/$GDP]	1.5	1.4	1.4	1.3	1.3	1.3

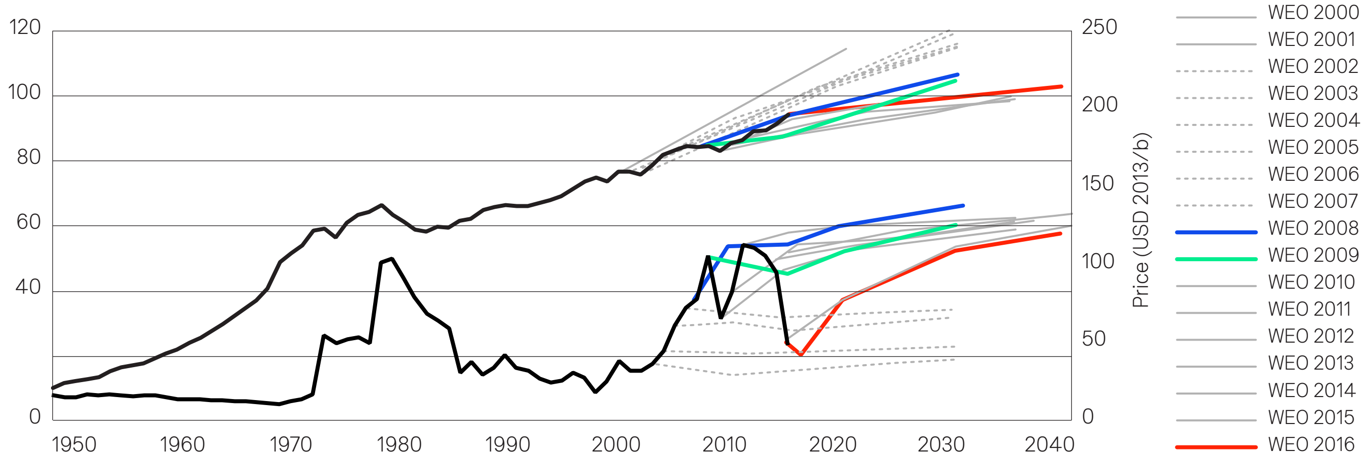
5.8 Technology and fuel cost projections

The speed of an energy system transition also depends on overcoming economic barriers. These largely involve the relationships between the cost of renewable technologies and of their fossil and nuclear counterparts. The projection of these costs is vital for our scenarios, to ensure a valid comparison of energy systems. However, there have been significant limitations to these projections in the past in terms of investment and fuel costs.

Moreover, efficiency measures generate costs that are usually difficult to determine, which depend on technical, structural, and economic boundary conditions. Therefore, in the context of this study, we have assumed uniform average costs of 3 cents per kWh of avoided electricity consumption in our cost accounting.

During the last decade, fossil fuel prices have seen huge fluctuations. Figure 5-5 shows the oil prices since 1997. After extremely high oil prices in 2012, we are currently in a low-price phase. Gas prices saw similar fluctuations (IEA 2017).[121] Therefore, fossil fuel price projections have also seen considerable variations (IEA 2017;[121] IEA 2013[122]) and this has influenced the scenario results.

Figure 5-5: Historical development and projections of oil prices (bottom lines) and historical world oil production and projections (top lines) by the World Energy Outlook (WEO) published by the International Energy Agency (IEA), according to Wachtmeister et al. (2018)



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[121] IEA (2017): IEA (2017) World Energy Outlook 2017. International Energy Agency, Organization for Economic Co-operation and Development, Paris.

[122] IEA 2013: IEA (2013) World Energy Outlook 2013. International Energy Agency, Organization for Economic Co-operation and Development, Paris.

Although oil-exporting countries have provided the best oil price projections in the past, institutional price projections have become increasingly accurate, with the IEA leading the way in 2018 (Roland Berger 2018).[123] An evaluation of the oil price projections of the IEA since 2000 by Wachtmeister et al. (2018)[124] showed that price projections have varied significantly over time. Whereas the IEA's oil production projections seem comparatively accurate, oil price projections showed errors of 40%–60%, even when made only 10 years ahead. Between 2007 and 2017, the IEA price projections for 2030 varied from US$70 to US$140 per barrel, providing significant uncertainty regarding future costs in the scenarios. Despite this limitation, the IEA provides a comprehensive set of price projections. Therefore, we based our scenario assumptions on these projections, as described below.

However, because most renewable energy technologies provide energy without fuel costs, the projections of investment costs become more important than fuel cost projections, and this limits the impact of errors in the fuel price projections. It is only for biomass that the cost of feedstock remains a crucial economic factor for renewables. These costs range from negative costs for waste wood (based on credit for the waste disposal costs avoided), through inexpensive residual materials, to comparatively expensive energy crops. Because bioenergy has significant market shares in all sectors in many regions, a detailed assessment of future price projections is provided below.

All cost projections in this analysis are based on a publication by Teske et al. (2019).[125] and base year updated in 2025 with cost projections of the International Energy Agency – World Energy Outlook 2025, Stated Policy Scenario (STEP) (IEA WEO 2025)[126]. The parameterisation of the models requires many assumptions about the development of the characteristic technologies, such as specific investments and fuel costs. Therefore, because long-term projections are highly uncertain, we must define plausible and transparent assumptions based on background information and up-to-date statistical and technical information.

Investment cost projections also pose challenges for scenario development. Available short-term projections of investment costs depend largely on the data available for existing and planned projects. Learning curves are most used to assess the future development of investment costs as a function of their future installations and markets (McDonald and Schrattenholzer 2001[127]; Rubin et al. 2015[128]). Therefore, the reliability of cost projections largely depends upon the uncertainty of future markets and the availability of historical data.

Fossil fuel technologies provide a large cost data set featuring well-established markets and large annual installations. They are also mature technologies, so many cost-reduction potentials have already been exploited.

For conventional renewable technologies, the picture is more mixed. For example, like fossil fuels, hydropower is well established and provides reliable data on investment costs. Other technologies, such as solar photovoltaic and wind, are experiencing tremendous installation and cost-reduction developments. However, solar photovoltaic and wind are the focus of cost monitoring, and big data are already available on existing projects. Their future markets are not readily predictable, as seen in the evolution of IEA market projections over recent years in the World Energy Outlook series (compare, for example, IEA WEO 2007, IEA WEO 2014, IEA WEO 2017 and IEA WEO 2025). Small differences in cost assumptions for photovoltaic and wind lead to large deviations in the overall costs, so cost assumptions must be made with particular care.

Furthermore, many technologies have only relatively small markets, such as geothermal, modern bioenergy applications, and concentrated solar power plants (CSP), for which costs are still high and future markets are insecure. The cost-reduction potential is correspondingly high for these technologies. This is also true for technologies that might become important in a transformed energy system but are not yet widely available. Hydrogen production, ocean power, and synthetic fuels might deliver important technology options in the long term after 2040, but their cost-reduction potential cannot be assessed with any certainty today.

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[123] Roland Berger (2018) 2018 oil price forecast: who predicts best? Roland Berger study of oil price forecasts. Report is no longer available online.

[124] Wachtmeister H, Henke P, Höök M (2018) Oil projections in retrospect: Revisions, accuracy and current uncertainty. Applied Energy 220:138–153. doi: https://doi.org/10.1016/j.apenergy.2018.03.013

[125] Teske S (2019), Achieving the Paris Climate Agreement Goals – Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5 °C and +2.0 °C, ISBN 978-3-030-05842-5, Springer, Switzerland 2019; Chapter 5, written by Dr Thomas Pregger, Dr Sonja Simon, and Dr Tobias Naegler of the German Aerospace Center/DLR

[126] IEA (2025), World Energy Outlook 2025, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2025, Licence: CC BY 4.0 (report); CC BY NC SA 4.0 (Annex A)

[127] McDonald A, Schrattenholzer L (2001) Learning rates for energy technologies. Energy Policy 29 (4):255–261. doi: https://doi.org/10.1016/S0301-4215(00)00122-1

[128] Rubin ES, Azevedo IML, Jaramillo P, Yeh S (2015) A review of learning rates for electricity supply technologies. Energy Policy 86:198–218. doi: https://doi.org/10.1016/j.enpol.2015.06.011

Therefore, cost assumptions are a crucial factor in evaluating scenarios. Because costs are an external input into the model and are not calculated internally, we assume the same progressive cost developments for all scenarios. In the next sections, we present a detailed overview of our assumptions for power and renewable heat technologies, including the investment, fuel costs, and potential CO_2 costs in the scenarios.

5.8.1 Power technologies

The focus of cost calculations in our scenario modelling is the power sector. We compared the specific investment costs estimated in previous studies (Teske et al. 2015 and Teske et al. 2019), which were based on a variety of studies, including the European-Commission-funded New Energy Externalities Development for Sustainability (NEEDS) project (NEEDS 2009), projections of the European Renewable Energy Council (Zervos et al. 2010), investment cost projections by the IEA (IEA 2014), and current cost assumptions by IRENA and IEA (IEA 2016c). We found that investment costs generally converged, except for photovoltaic. Therefore, for consistency, the investments in the power sector and its operation and maintenance costs are based primarily on the investment costs within WEO 2016 (IEA 2016c) up to 2040, including their regional disaggregation. We extended the projections until 2050 based on the trends in the preceding decade. The cost projections were updated in 2025 regarding currency values (for US Dollar and Euro) from 2015 to 2025 values.

For renewable power production, we used investment costs from the IEA WEO 2025[129] projections for the Stated Policies Scenario (STEP). For technologies not distinguished in the IEA report (such as geothermal combined heat and power [CHP]), we used cost assumptions based on our research (Teske et al. 2015) with updated currency values.

Table 38 summarises the cost trends for power technologies derived from the assumptions discussed above. It is important to note that the cost reductions are not a function of time but of cumulative capacity (production of units), so dynamic market development must achieve a significant reduction in specific investment costs. Therefore, overall, we might underestimate the costs of renewables in scenarios with low market growth rates and/or implementation rates.

However, our approach is conservative when we compare conservation renewable energy uptake scenarios with the more ambitious renewable energy scenarios under identical cost assumptions. Fossil-fuel power plants have limited potential for cost reductions because they are at advanced stages of their technology and market development.

In contrast, several renewable technologies have seen considerable cost reductions over the last decade. This is expected to continue if renewables are deployed extensively. Hydropower and biomass have remained stable in terms of costs. Tremendous cost reductions are still expected for solar energy and wind power, even though they have experienced significant reductions already. Whereas CSP might deliver dispatchable power at half its current cost in 2050, variable photovoltaic costs could drop to almost half of the 2024 costs.

Table 38: Investment cost assumptions for power generation plants in Euro per kilowatt installed (Euro/kW) until 2050 – all scenarios

Technology	2024 Euro/kW	2030 Euro/kW	2035 Euro/kW	2040 Euro/kW	2045 Euro/kW	2050 Euro/kW
Coal power plants	1,800	1,800	1,800	1,800	1,800	1,800
Diesel generators	1,120	1,120	1,120	1,120	1,120	1,120
Gas power plants	900	900	900	900	900	900
Oil power plants	1,157	1,107	1,087	1,067	950	834
Hydropower plants*	3,297	3,297	3,297	3,297	3,297	3,297
photovoltaic power plants	684	547	432	411	390	369
Concentrated Solar Power						
Onshore Wind	1,458	1,419	1,386	1,377	1,368	1,359
Offshore Wind	3,114	2,574	2,124	2,022	1,920	1,818
Geothermal power plant	19,467	17,749	16,317	15,897	15,477	15,057
Bioenergy power plants	2,923	2,861	2,799	2,737	2,681	2,625

* Values apply to both run-of-the-river and reservoir hydropower.

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[129] IEA (2025), World Energy Outlook 2025, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2025, Licence: CC BY 4.0 (report); CC BY NC SA 4.0 (Annex A)

5.8.2 Heating technologies

Assessing the costs in the heating sector is even more challenging than in the power sector. Costs for new installations differ significantly between regions and are interlinked with construction costs and industrial processes, which are not addressed in this study. Moreover, no data are available to allow the comprehensive calculation of the costs for existing heating appliances in all regions. Therefore, we have concentrated on the additional costs of new renewable applications in the heating sector.

Our cost assumptions are based on the authors' research about renewable heating technologies in Europe, which focused on solar collectors, geothermal energy, heat pumps, and biomass applications. Biomass and simple heating systems in the residential sector are already mature. However, more-sophisticated technologies that can provide higher shares of the heat demand from renewable sources are still under development and rather expensive. Market barriers will slow the further implementation and cost reductions of renewable heating systems, especially for heating networks. Nevertheless, significant learning rates can be expected if renewable heating is increasingly implemented, as projected in all scenarios.

Table 39 presents the investment cost assumptions for heating technologies, disaggregated by sector. Geothermal heating shows the same high costs in all sectors. In Europe, deep geothermal applications are being developed for heating purposes at investment costs ranging from 500 €/kW$_{\text{thermal}}$ (shallow) to 3,000 €/kW$_{\text{thermal}}$ (deep), with the costs strongly dependent on the drilling depth. The cost-reduction potential is assumed to be around 30% by 2050 However; geothermal power and heating plants are not assumed to be built under any scenario.

Heat pumps typically provide hot water or space heat for heating systems with relatively low supply temperatures, or they supplement other heating technologies. Therefore, they are currently mainly used for small-scale residential applications. Costs currently cover a large bandwidth and are expected to decrease by only 20% to 1,450 €/kW by 2050.

We assume the appropriate differences between the sectors for biomass and solar collectors. There is a broad portfolio of modern technologies for heat production from biomass, ranging from small-scale single room stoves to heating or CHP plants on an MW scale. Investment costs show similar variations: simple log-wood stoves can be run for 100 €/kW, but more sophisticated automated heating systems that cover the whole heat demand of a building are significantly more expensive to run. The running costs of logwood or pellet boilers are 500–1,300 €/kW, and large biomass heating systems are assumed to reach their cheapest in 2050 at around 480 €/kW for industry. For all sectors, we assume a cost reduction of 20% by 2050.

In contrast, solar collectors for households are comparatively simple and will become cheap, at US$680/kW, by 2050. The cost of simple solar collectors for service water heating may have been optimised already, whereas their integration into large systems is neither technologically nor economically mature. For larger applications, especially in heat-grid systems, the collectors are large and more sophisticated. Because there is not yet a mass market for such grid-connected solar systems, we assume there will be a cost-reduction potential until 2050.

Table 39: Specific investment cost assumptions for heating plants in Euro per kilowatt installed (Euro/kW) until 2050 – all scenarios

Investment Costs for Heat Generation Plants							
		2024 Euro/kW	2030 Euro/kW	2035 Euro/kW	2040 Euro/kW	2045 Euro/kW	2050 Euro/kW
Solar collectors	Industry	1,011	900	851	801	740	678
	In heat grids	1,196	1,196	1,196	1,196	1,196	1,196
	Residential	1,245	1,122	1,054	986	912	838
Geothermal		2,799	2,503	2,361	2,219	2,090	1,960
Heat pumps		2,145	2,022	1,960	1,899	1,843	1,788
Biomass heat plants		715	678	653	629	610	592
Commercial biomass heating systems	Commercial scale	999	937	912	888	863	838
Residential biomass heating stoves	Small scale/Rural	136	136	136	136	136	136

5.8.3 Fuel cost projections

Fossil Fuels

Although fossil fuel price projections have seen considerable variations, as described above, we based our fuel price assumptions for 2035 and 2050 on *World Energy Outlook 2025* (IEA WEO 2025). Price developments for 2040 and 2045 are extrapolated based on values for 2035 and 2050 (Table 40). Although these price projections are highly speculative, they provide prices consistent with our investment assumptions. Fuel prices for nuclear energy are based on the values of (Teske et al. 2019)[130] corrected by the cumulative inflation rate of the USD 2015 to the USD 2025 of 37% and converted to Euro.

Biomass prices

Biomass prices depend on the quality of the biomass (residues or energy crops) and the regional supply and demand. The global variability is large. Lamers et al. (2015)[131] reported a price range of €4–4.8/GJ for forest residues in Europe in 2020, whereas agricultural products might cost €8.5–12/GJ. IRENA modelled a cost supply curve on a global level for 2030, ranging from US$3/GJ for a potential of 35 EJ/yr up to US$8–10/GJ for a potential of up to 90–100 EJ/yr (IRENA 2014) (and up to US$17/GJ for a potential extending to 147 EJ).

Table 40: Development projections for fossil fuel prices in Euro 2025 based on (IEA 2025 and Teske 2019)

Development Projections for Fossil-Fuel Prices – all scenarios		**2024**	**2030**	**2035**	**2040**	**2045**	**2050**
Crude oil	Euro/GJ	11.62	11.69	11.77	11.57	11.37	11.18
Natural gas	Euro/GJ	9.76	7.96	6.16	6.76	7.36	7.96
Hard coal	Euro/GJ	3.54	3.00	2.46	2.34	2.21	2.08
Brown coal	Euro/GJ	3.34	4.35	4.20	4.53	4.88	5.25
Uranium	Euro/GJ	1.20	1.45	1.59	1.75	1.92	2.12
Biomass	Euro/GJ	10.27	10.27	10.27	10.27	10.27	10.27
Biofuel	Euro/GJ	13.22	13.01	12.47	11.64	10.00	8.22
Synthetic fuels & hydrogen	Euro/GJ	20.55	11.78	12.63	13.54	10.69	8.45
Fossil Fuel Prices in Historical Units		**2024**	**2030**	**2035**	**2040**	**2045**	**2050**
Crude oil	Euro/barrel	71	71.55	72.00	70.80	69.60	68.40
Natural gas import	Euro/Mbtu	9.3	7.56	5.85	6.42	6.99	7.56
Steam coal	Euro/tonne	101	85.50	70.20	66.60	63.00	59.40

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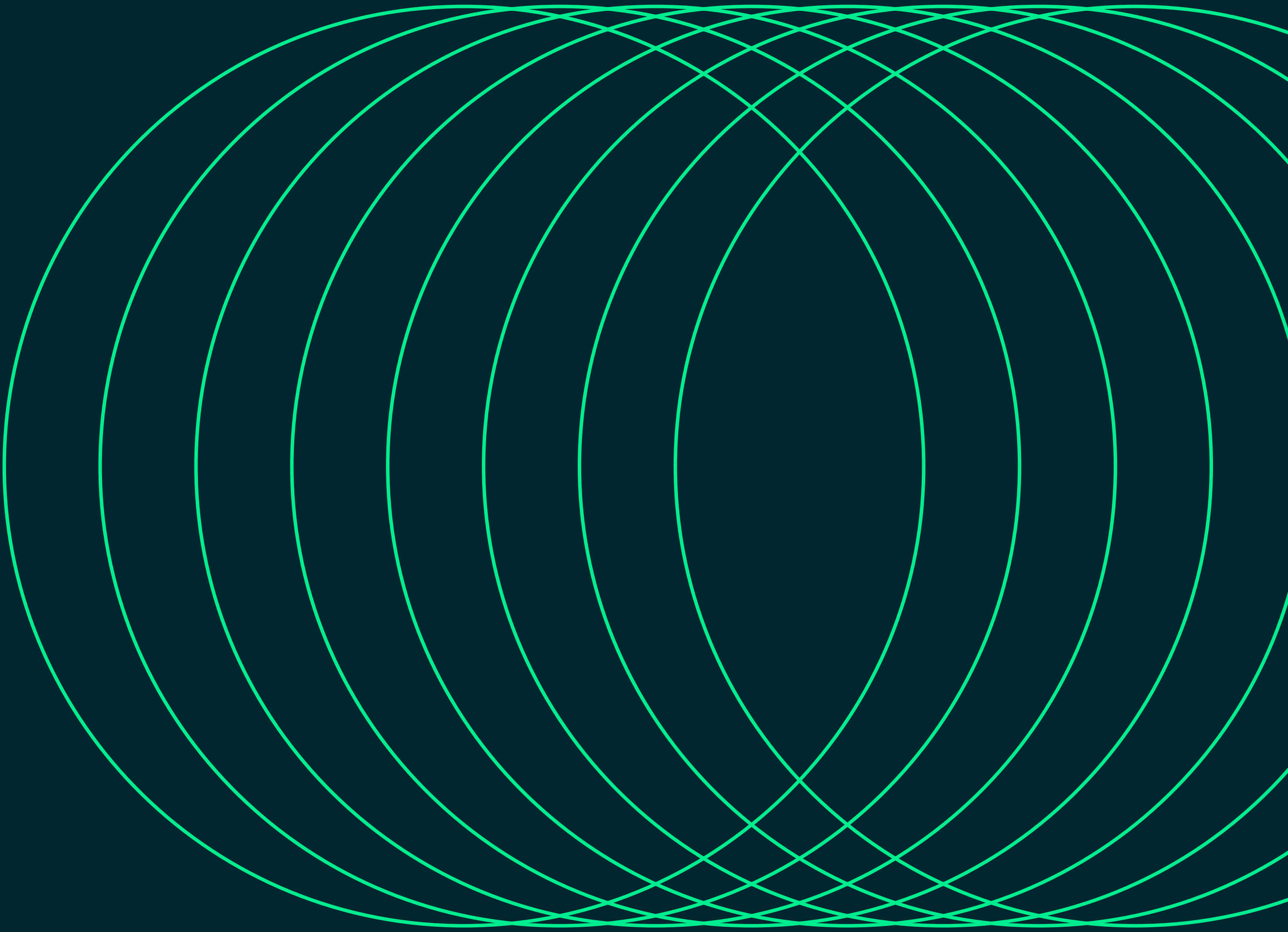
[130] Pregger, T., Simon, S., Naegler, T., Teske, S. (2019). Main Assumptions for Energy Pathways. In: Teske, S. (eds) Achieving the Paris Climate Agreement Goals. Springer, Cham. https://doi.org/10.1007/978-3-030-05843-2_5

[131] Lamers P, Hoefnagels R, Junginger M, Hamelinck C, Faaij A (2015) Global solid biomass trade for energy by 2020: an assessment of potential import streams and supply costs to North-West Europe under different sustainability constraints. GCB Bioenergy 7 (4):618–634. doi: https://doi.org/10.1111/gcbb.12162

6 Key Results



This section provides an overview of the key results for the three calculated energy pathways for the Iberian Peninsula: BAU, E 4.0 and E 4.1. The key results for the Iberian Peninsula are the sum of the three country specific scenarios (BAU, 4.0 and 4.1) for Spain and Portugal, which is presented as well.

Results regarding the 24/7 modelling of the Iberian Peninsula's electrical system are left for chapter 6. Note the 2020 values are on average lower that in the years before, due to the reductions caused by COVID-19 both in Spain and Portugal, and therefore as a sum for the Iberian Peninsula. The 2025 values are estimated with (partly) available statistical values for 2023 and 2024.

6.1 Primary Energy Demand

Section '4.3.1 Primary Energy – Oil, Gas and Coal' provides an overview of the primary energy associated with fossil fuel used across the Iberian Peninsula (crude oil, natural gas, hard coal). Primary energy is a commonly used metric when discussing fossil fuels as it does not account for the conversion efficiency of fuel-to useful-energy output (e.g. internal combustion vehicles, coal power plants), thus provides a metric for fossil fuel producers who extract, pump, and mine the carbon-intensive fuels currently used in these sectors. It should be noted, however, that this creates a 'primary energy fallacy' such that fossil fuels appear to be a much larger portion of the energy mix because the primary energy content in the fuel is measured and not the useful energy that comes from the combustion of said fuel. For this reason, the primary energy statistics are only shown in Figure 6-1 and Figure 6-2, and the remainder of the results are displayed using final energy (i.e. considering conversion efficiency).

Figure 6-1: Primary energy demand by fuel type for the Iberian Peninsula under each scenario

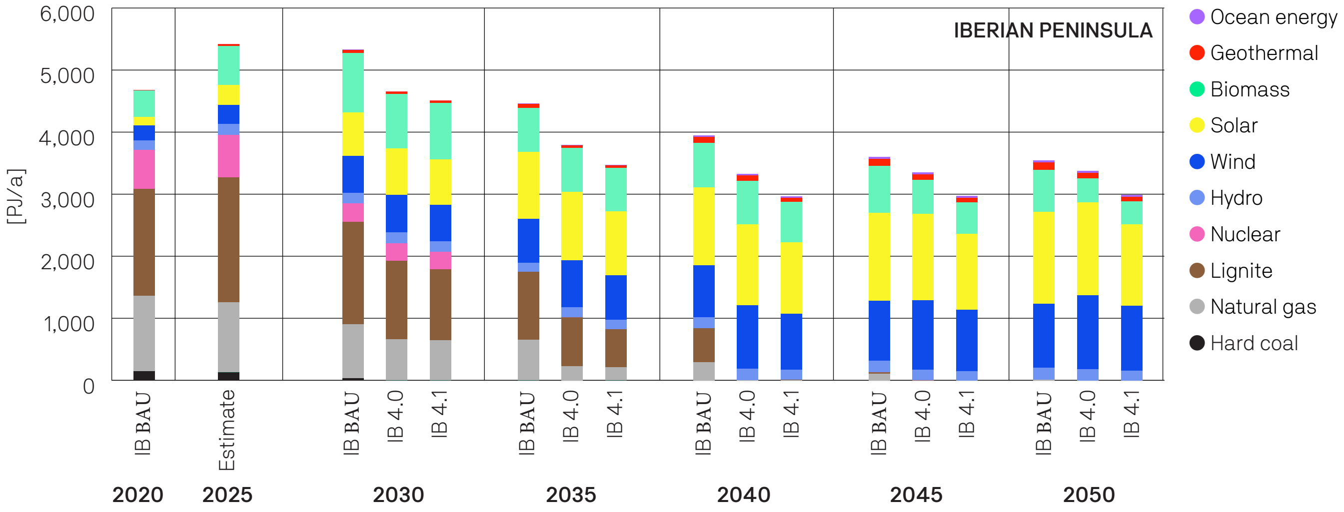
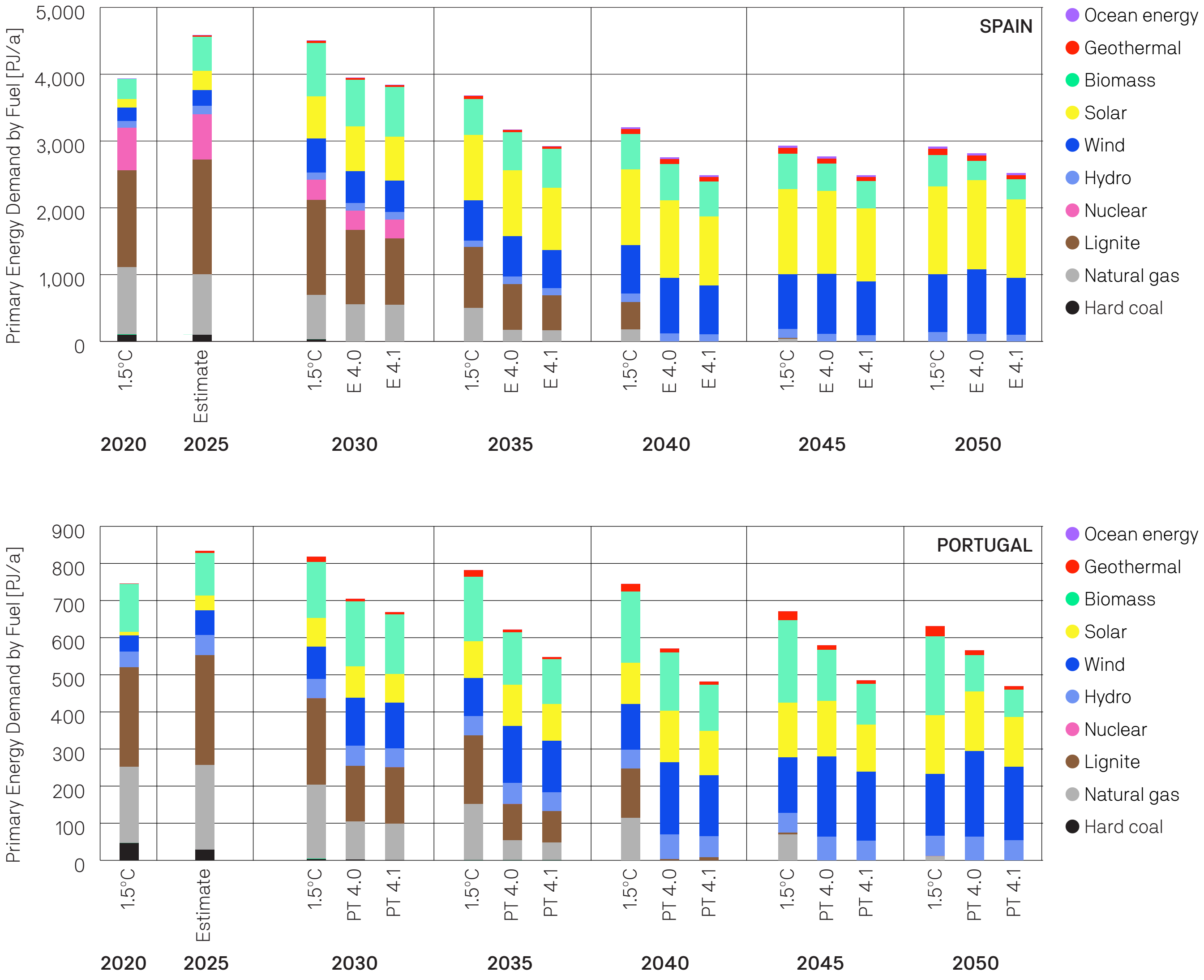


Figure 6-2: Primary energy demand by fuel type for the Spain (top) and Portugal (bottom) under each scenario



In 2020, all scenarios are calibrated with a total primary energy consumption of 5,400 PJ/a, which is aligned with IEA statistics. All 2025 values in this section are estimation based on preliminary statistics for 2023 published in 2024[132]. The primary energy consists of ***70% fossil fuels*** (45% crude oil and 23% natural gas).[133] The BAU scenario for the Iberian Peninsula shows a 7% increase during the first decade (2020–2030). However, it is projected that this trend will reverse and that reductions of 26% are achieved in the following decade (2030–2040), and 11% per year reduction in the following decade (2040–2050).

The IB4.0 scenario shows reductions in primary energy demand between 2020 and 2050, achieving a reduction of 5% in the first decade, then a reduction of 29% in the next decade. The IB 4.1 scenario leads to more substantial decreases in the Iberian Peninsula's primary energy demand, 8% in the first decade, followed by reductions of 36% between 2030 and 2040. These values for the Iberian Peninsula, Spain and Portugal are summarised in Table 41.

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[132] IEA Advanced energy balances, 2024

[133] Including contributions from each fuel type to the electricity sector

Table 41: Percent change in primary energy demand between each decade (compared to the same scenario across time periods)

Change in Primary Energy	2020–2030	2030– 2040	2020–2040 cumulative change
Iberian Peninsula			
IB BAU	+14%	-26%	-1%
IB 4.0	-5%	-29%	-33%
IB 4.1	-8%	-36%	-41%
Spain			
ES BAU	+6%	-29%	-19%
ES 4.0	-4%	-30%	-34%
ES 4.1	-6%	-37%	-41%
Portugal			
PT BAU	+10%	-9%	0%
PT 4.0	-11%	-19%	-27%
PT 4.1	-16%	-28%	-39%

6.2 Final Energy Demand

Final energy consumption is the total energy consumed by end users, such as households, industry and agriculture. It is the useful energy that reaches the end use to power, heat or fuel the relevant application, and excludes energy which is used by the energy sector itself in transformation and delivery. The pattern of energy consumption follows a similar trend to that primary energy regarding the percentage changes seen in a scenario over time, as can be seen in Figure 6-3 and Figure 6-4.

Figure 6-3: Final Energy Demand under each scenario for the Iberian Peninsula

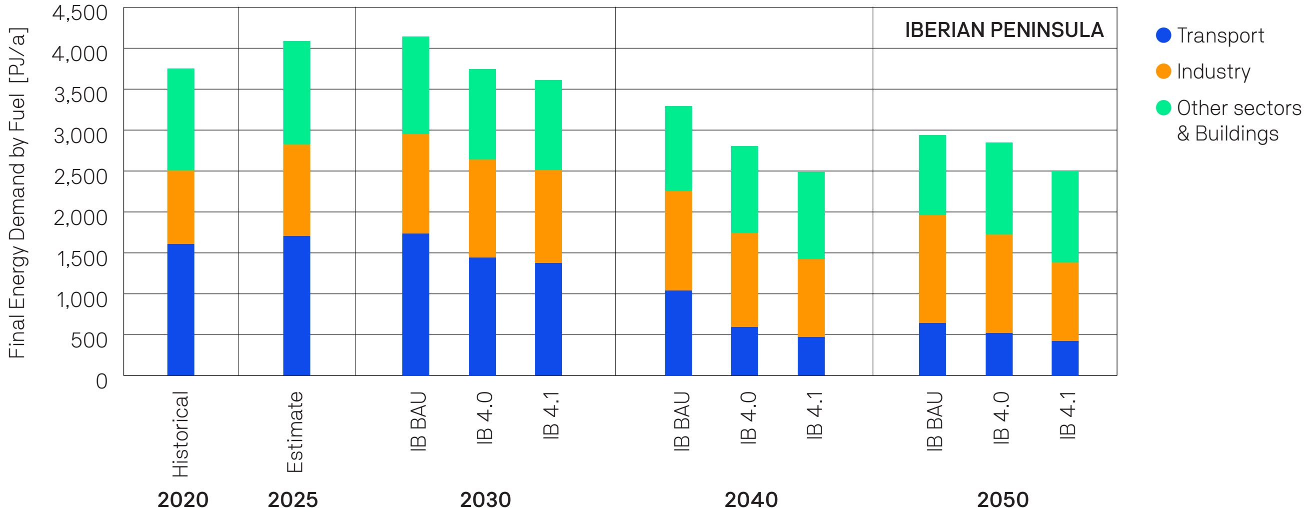


Figure 6-4: Final energy demand by fuel type for the Spain (top) and Portugal (bottom) under each scenario

In 2020, all scenarios are calibrated with a total final energy consumption of 4,180 PJ/a, which is aligned with IEA statistics. The BAU scenario shows a 10% increase per year during the first decade (2020–2030). However, it is projected to shift to a reduction of 21% in the next decade (2030–2040) and a 11% reduction the following decade (2040–2050). The IB 4.0 scenario shows reductions in final energy demand between 2020 and 2050: a reduction of 1% in the first decade and a reduction of 25% in the following decade. The IB 4.1 scenario leads to a more substantial decrease in the Iberian Peninsula's final energy demand of 4% in the first decade, followed by a substantial reduction of 31% in the following decade. These values are summarised in Table 42.

Table 42: Change of final energy demand under each scenario for Iberian Peninsula, Spain and Portugal

Change in Final Energy	2020–2030	2030–2040	2040–2050
Iberian Peninsula			
IB BAU	10%	-21%	-11%
IB 4.0	-1%	-25%	1%
IB 4.1	-4%	-31%	1%
Spain			
ES BAU	6%	-29%	-9%
ES 4.0	-4%	-30%	1%
ES 4.1	-6%	-37%	0%
Portugal			
PT BAU	10%	-9%	-16%
PT 4.0	-11%	-19%	-2%
PT 4.1	-16%	-28%	-2%

The reduction of primary energy associated with crude oils fuels, such as petrol and kerosene, can be seen in the significant reductions achieved in the final energy demand of transport sector by 2040 (less so in the BAU scenario, which retains these fuels until 2050). The reduction in final energy of the transport sector caused by electrification is only enhanced by the shift from private vehicles to public transport and active forms of transport such as walking and cycling in urban areas. While section '4.5.3 Transport' provides a detailed breakdown of transport demand in terms of passenger-km and tonne-km, the following section shows the energy results of these scenarios for the transport sector.

As discussed in section '4.3.5 Demand from Data Centres and AI', the scenarios account for the growth in electrical demand associated with these end uses and this provides context as to why the aggregate sector of other sectors and buildings does not show the substantial reductions of energy use that the transport sector does (particularly in the 4.0 and 4.1 scenarios). In addition to the growing final energy associated with this energy use, the scenarios also account for population and GDP growth as discussed in previous chapters, and this also provides context as to why less dramatic shifts are seen in both the industry and other sectors and buildings sectors. An exception to this would be the 4.1 scenarios, where the change in socio-economic assumptions alongside the sufficiency measures lead to reductions in both GDP and the final energy demand. A breakdown of final energy demand across the sectors are shown below in Table 43.

Table 43: Sectoral breakdown of final energy demand under the scenarios

		2020	2025	2030			2040			2050		
Iberian Peninsula		**Historical**	**Estimate**	**IB BAU**	**IB 4.0**	**IB 4.1**	**IB BAU**	**IB 4.0**	**IB 4.1**	**IB BAU**	**IB 4.0**	**IB 4.1**
Transport	[PJ/a]	1,605	1,703	1,735	1,443	1,374	1,040	592	469	644	523	424
Industry	[PJ/a]	903	1,122	1,215	1,192	1,135	1,213	1,149	957	1,318	1,198	957
Other Sectors & Buildings	[PJ/a]	1,246	1,260	1,193	1,109	1,105	1,041	1,066	1,061	974	1,126	1,119
Total	**[PJ/a]**	**3,754**	**4,086**	**4,143**	**3,744**	**3,614**	**3,293**	**2,807**	**2,487**	**2,936**	**2,847**	**2,500**
Spain		**Historical**	**Estimate**	**ES BAU**	**ES 4.0**	**ES 4.1**	**ES BAU**	**ES 4.0**	**ES 4.1**	**ES BAU**	**ES 4.0**	**ES 4.1**
Transport	[PJ/a]	1,357	1,463	1,498	1,261	1,195	875	506	403	573	447	368
Industry	[PJ/a]	732	907	998	964	929	972	930	798	1,052	975	804
Other Sectors & Buildings	[PJ/a]	1,041	1,053	1,010	928	927	871	876	875	807	911	909
Total	**[PJ/a]**	**3,130**	**3,423**	**3,505**	**3,153**	**3,052**	**2,718**	**2,311**	**2,075**	**2,431**	**2,332**	**2,081**
Portugal		**Historical**	**Estimate**	**PT BAU**	**PT 4.0**	**PT 4.1**	**PT BAU**	**PT 4.0**	**PT 4.1**	**PT BAU**	**PT 4.0**	**PT 4.1**
Transport	[PJ/a]	248	240	238	182	179	164	87	67	71	76	55
Industry	[PJ/a]	171	215	218	228	206	241	218	159	267	223	154
Other Sectors & Buildings	[PJ/a]	205	207	183	182	177	170	191	186	167	216	210
Total	**[PJ/a]**	**623**	**663**	**638**	**592**	**562**	**575**	**496**	**412**	**504**	**515**	**419**

The increasing electrification of end uses increases the proportion of final energy demand that is supplied by electricity. As this trend is not easily seen in the above analysis, Table 44 illustrates the increasing electricity demand across the scenarios. The electricity demand under the 4.0 and 4.1 scenario continues to increase due to the overall growths of energy demand across the Iberian Peninsula because of population and economic growth beyond 2040. For the Iberian Peninsula, electricity demand doubles by 2040 under the 4.0 scenario, relative to 2020 baseline. This increase for both Spain and Portugal is similar. The electricity demand growth in both the BAU and the 4.1 scenario by 2040 is lower than that of the 4.0 scenario, by approximately 10%. This aligns with the lower rates of electrification under the BAU scenario, and the efficiency and sufficiency measures of the 4.1 scenario.

Table 44: Electricity demand by sector under each scenario for the Iberian Peninsula, Spain and Portugal

		2020	2025	2030			2040			2050		
Iberian Peninsula		**Historical**	**Estimate**	**IB BAU**	**IB 4.0**	**IB 4.1**	**IB BAU**	**IB 4.0**	**IB 4.1**	**IB BAU**	**IB 4.0**	**IB 4.1**
Transport	[PJ/a]	12	22	127	115	117	339	427	323	471	381	295
Industry	[PJ/a]	297	425	631	592	563	842	752	624	959	855	681
Other Sectors & Buildings	[PJ/a]	626	684	719	726	722	770	870	866	826	1,005	999
Total	**[PJ/a]**	**935**	**1,131**	**1,477**	**1,433**	**1,402**	**1,952**	**2,049**	**1,813**	**2,256**	**2,240**	**1,975**
Spain		**Historical**	**Estimate**	**ES BAU**	**ES 4.0**	**ES 4.1**	**ES BAU**	**ES 4.0**	**ES 4.1**	**ES BAU**	**ES 4.0**	**ES 4.1**
Transport	[PJ/a]	10	19	116	93	93	314	365	273	415	328	247
Industry	[PJ/a]	241	345	494	478	460	677	608	520	763	692	569
Other Sectors & Buildings	[PJ/a]	521	559	586	591	591	629	700	699	676	803	802
Total	**[PJ/a]**	**772**	**923**	**1,196**	**1,162**	**1,144**	**1,620**	**1,673**	**1,492**	**1,855**	**1,822**	**1,618**
Portugal		**Historical**	**Estimate**	**PT BAU**	**PT 4.0**	**PT 4.1**	**PT BAU**	**PT 4.0**	**PT 4.1**	**PT BAU**	**PT 4.0**	**PT 4.1**
Transport	[PJ/a]	2	3	11	23	24	25	62	51	55	53	48
Industry	[PJ/a]	56	80	137	113	103	166	144	105	196	163	112
Other Sectors & Buildings	[PJ/a]	104	125	133	135	132	141	171	166	150	202	197
Total	**[PJ/a]**	**162**	**208**	**282**	**272**	**258**	**332**	**376**	**322**	**401**	**418**	**357**

6.3 Transport Demand

The overall final energy demand decreases significantly by 2040. With the reductions in energy demand relative to a 2020 baseline listed in Table 45 for each of the scenarios.

Table 45: Overall Final Energy Demand reduction under each scenario for Iberian Peninsula, Spain and Portugal

	2020–2040
Iberian Peninsula	
IB BAU	60% (excl. BUNKER)
IB 4.0	55%
IB 4.1	67%
Spain	
ES BAU	62% (excl. BUNKER)
ES 4.0	55%
ES 4.1	65%
Portugal	
PT BAU	47%
PT 4.0	58%
PT 4.1	73%

The above results highlight the benefits from the electrification of transportation and the mode shift, which were described in the previous chapters. These results also quantify the additional energy reductions caused by the efficiency and sufficiency measures used in the 4.0 and 4.1 scenarios. Figure 6-5 illustrates the final energy demand in the transport sector across the varying categories of transportation for the Iberian Peninsula, while Figure 6-7 provides a breakdown by fuel source.

Figure 6-5: Final Energy Demand by transport mode under each scenario for the Iberian Peninsula

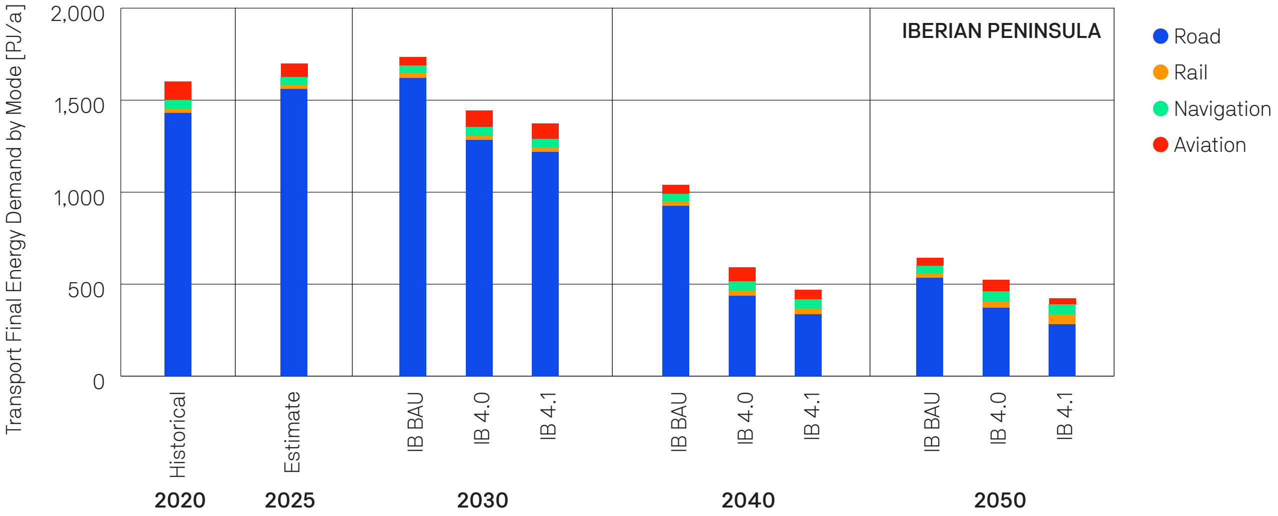
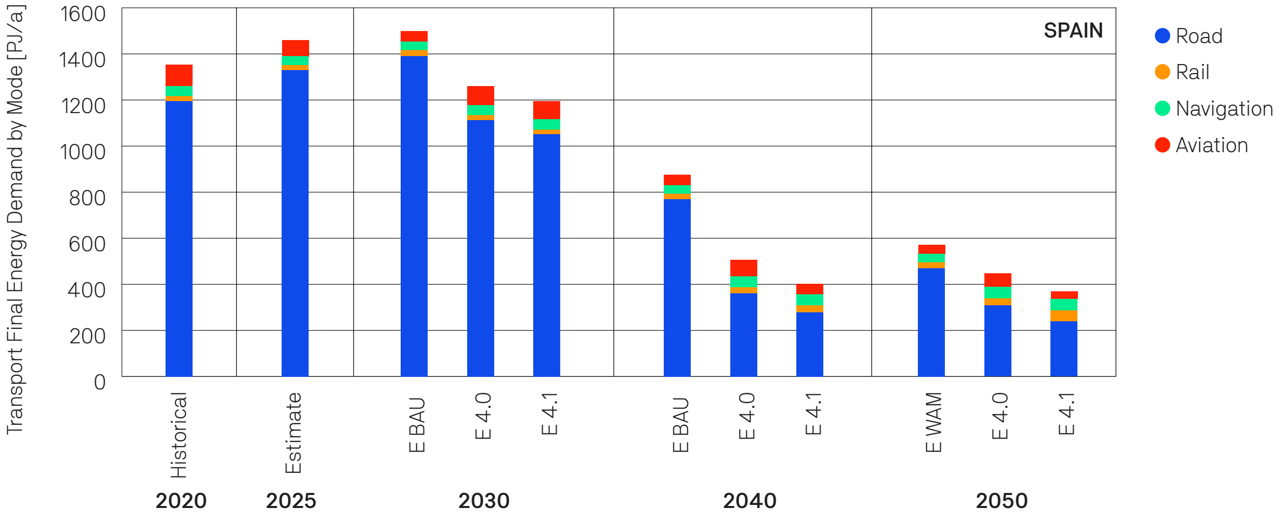


Figure 6-6: Final energy demand by fuel type for the Spain (top) and Portugal (bottom) under each scenario



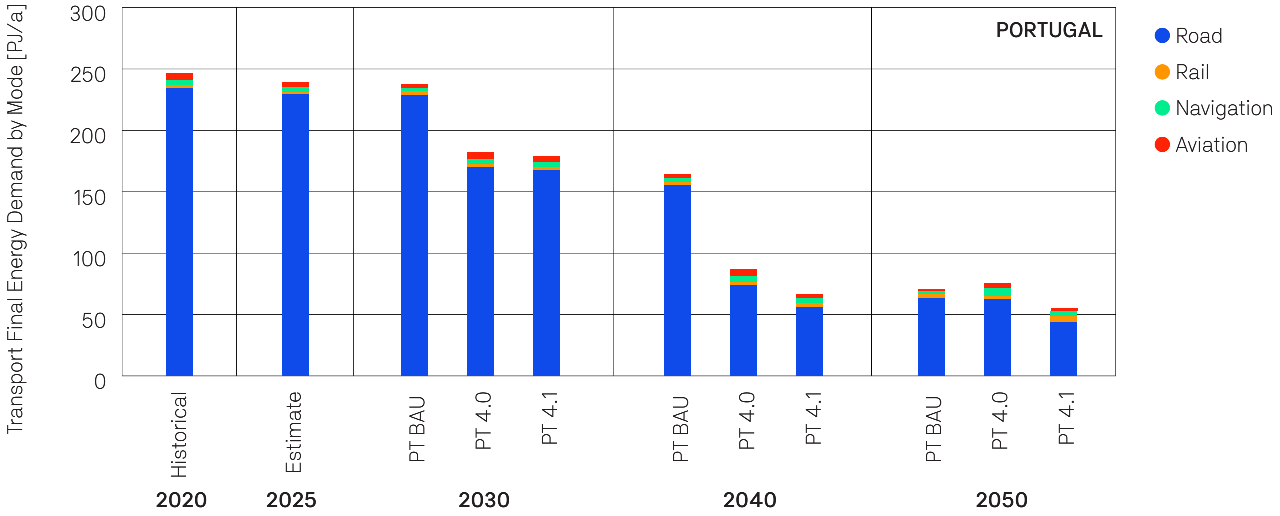


Figure 6-7: Final transport energy demands by fuel for all transport modes for the Iberian Peninsula

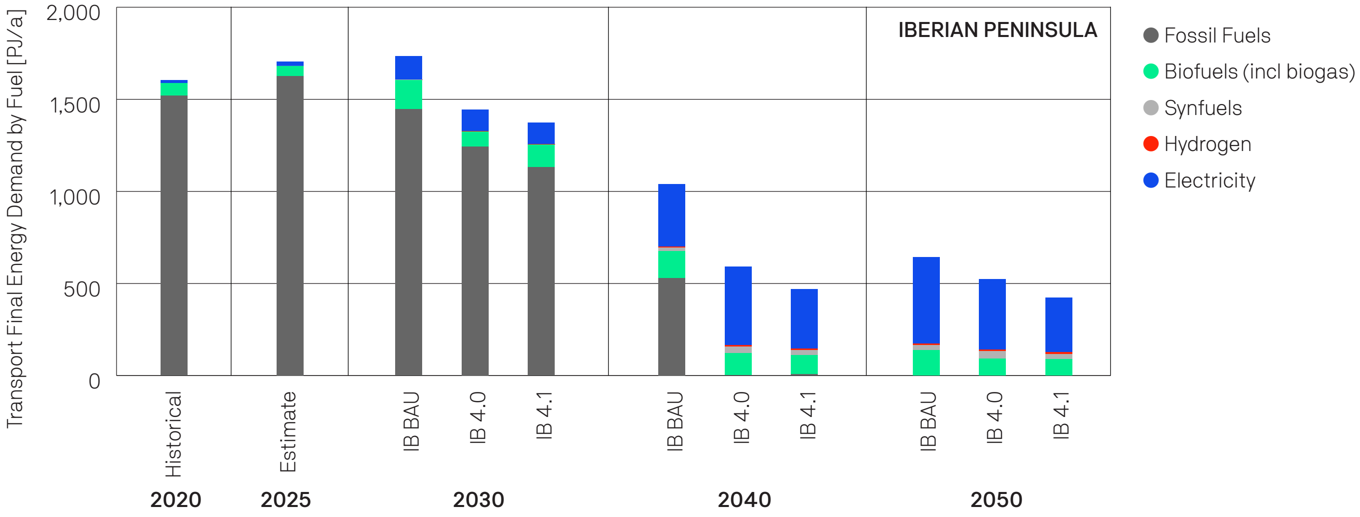
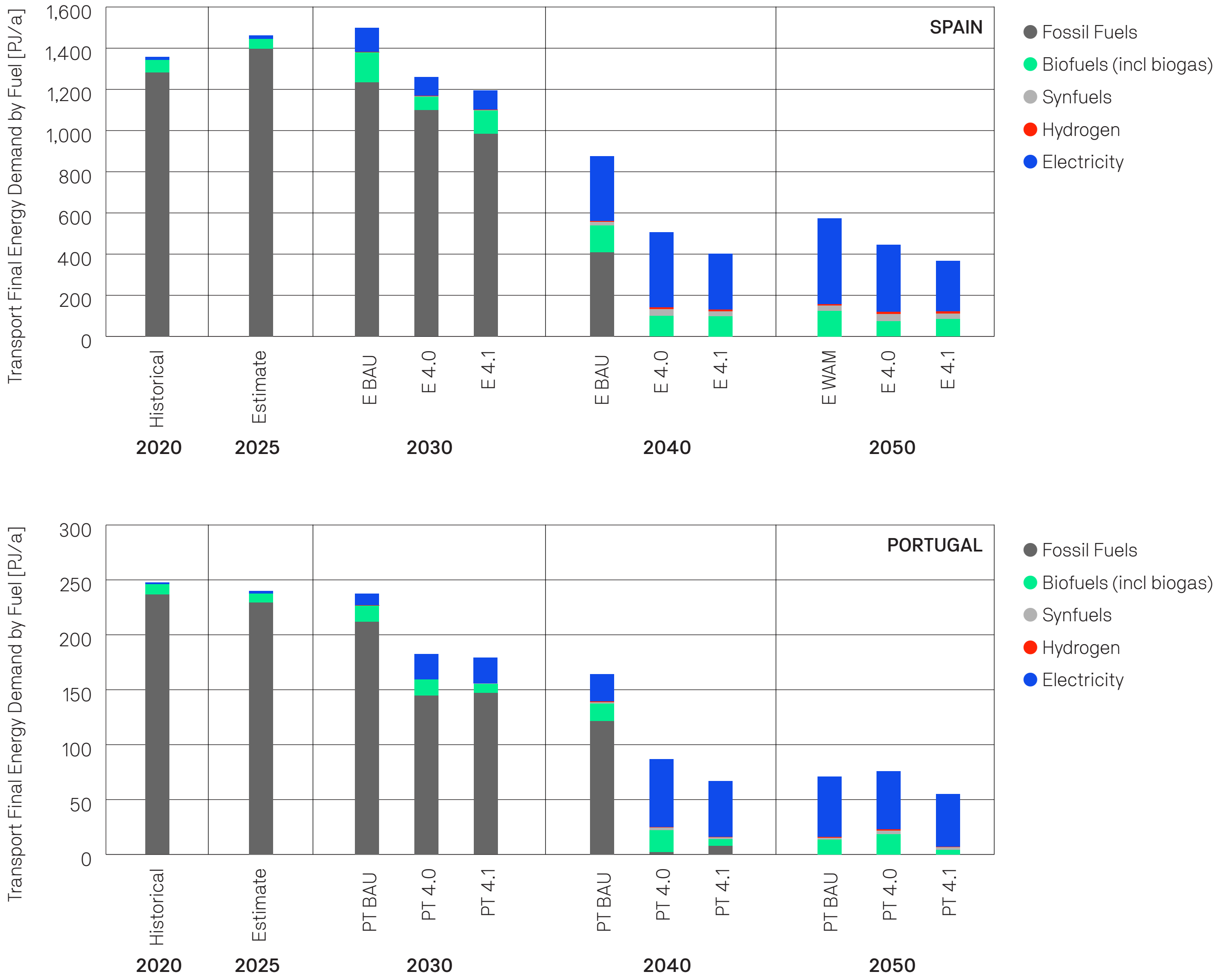


Figure 6-8: Final transport energy demands by fuel for all transport modes for Spain (top) and Portugal (bottom)



Final Energy Demand by Fuel for the entire transport sector for all scenarios across the region is shown in Figure 6-7 and Figure 6-8. Electricity dominates the transport sector, the remaining biofuels in 2040 and 2050 are on today's level and mainly used for aviation, shipping and for heavy-duty transport and working vehicles.

6.4 Power Sector

Electrification in conjunction with the continued decarbonisation of the Iberian Peninsula's power sector is vital in all three scenario narratives. New renewable power generation – predominantly solar photovoltaic systems and onshore wind – will not only replace existing gas power plant capacities and the phase-out of nuclear energy, they will also have to meet increasing electricity demand as transport, buildings and industry increasingly electrify. Sector-coupling in conjunction with modernisation of power system management, will enable the electrical power system to couple with transport and heating sector, and create for improved outcomes such as system flexibility.

Figure 6-9: Development of electricity generation structure under three scenarios for the Iberian Peninsula

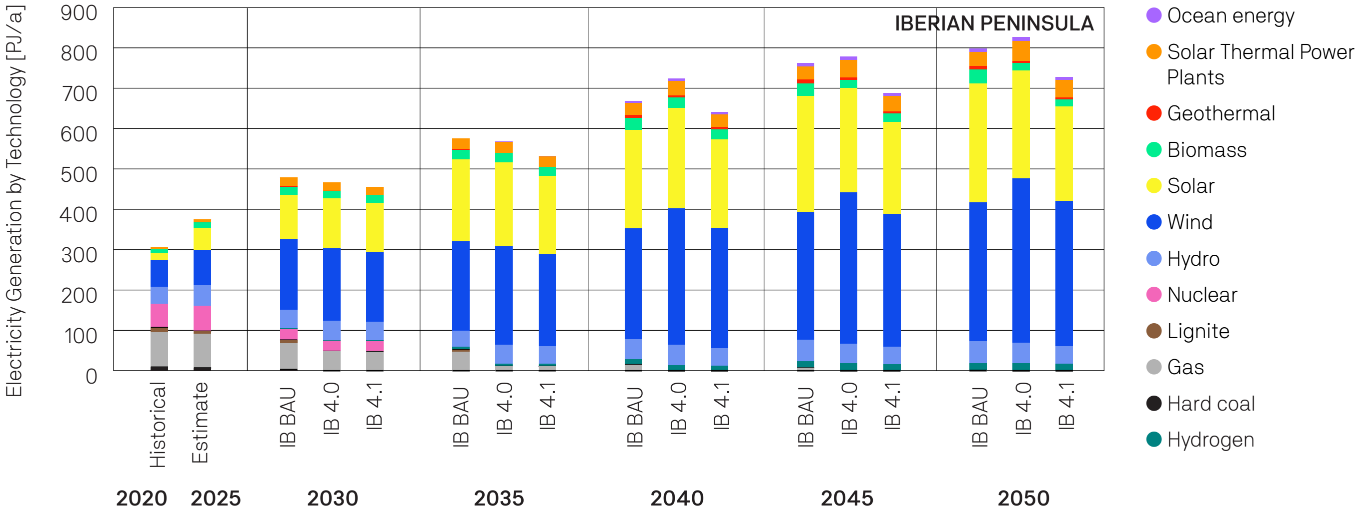


Figure 6-10: Development of electricity generation structure under three scenarios for Spain (top) and Portugal (bottom)

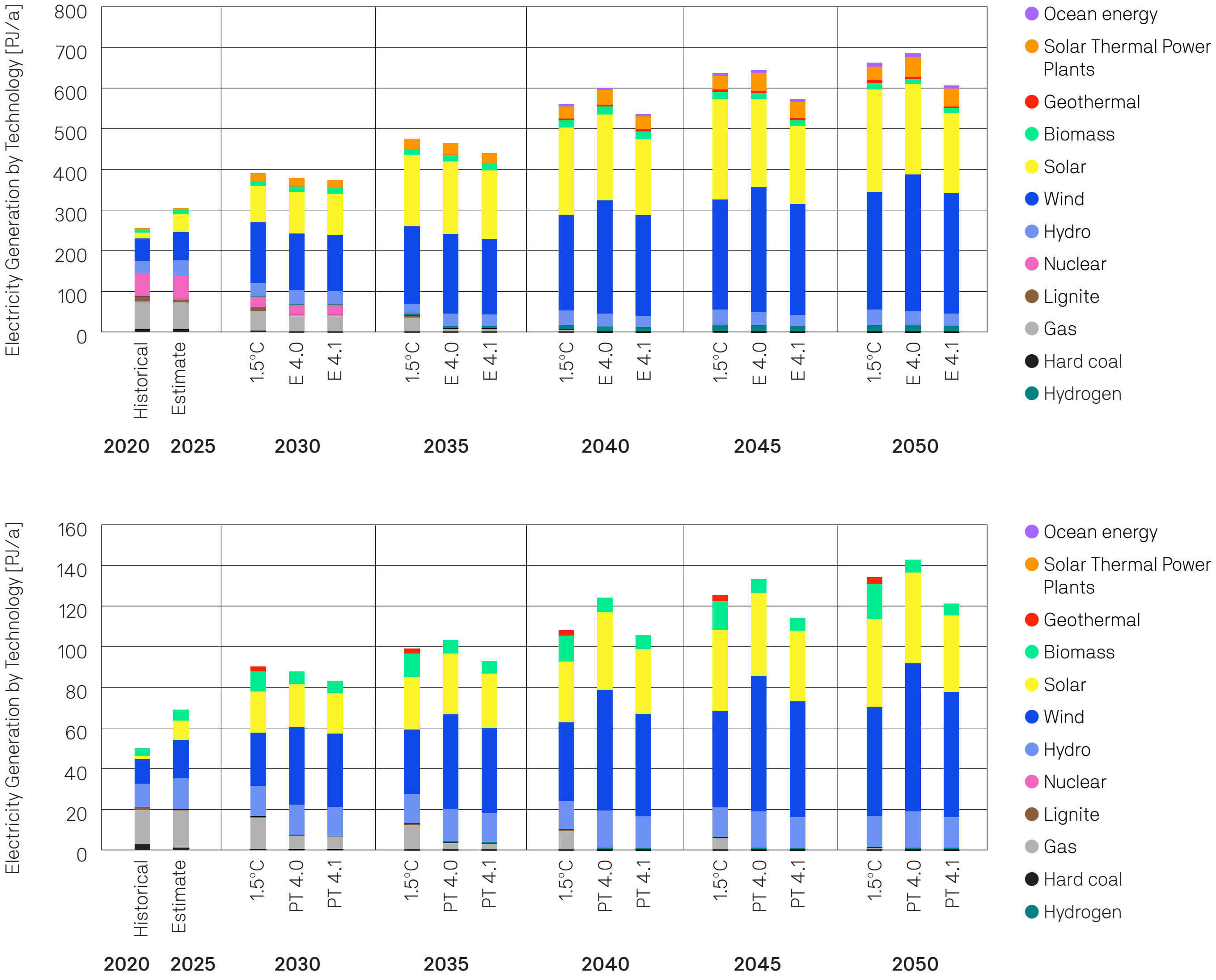


Figure 6-9 shows the development of the electricity sector across all three scenarios until 2050 in terms of energy generation in TWh/a, while Table 46 and Table 47 show the percentage of electricity supply in five-year increments, which is sourced from renewables for the period of 2020–2040 (including and excluding hydropower respectively). These values show that all scenarios have a strong staring point with a renewable energy share of 46% including hydropower, thanks both to the investment in renewables which has occurred to date, as well as the previous development of hydropower across both Spain and Portugal (share of 32% excluding hydro). By 2030 the share of renewables develops substantially across all scenarios, achieving ~80% of electricity generation including hydropower. In the period of 2020–2030, the share of renewables excluding hydropower, more than doubles across all scenarios thanks to the level of large-scale solar and wind projects which can be expected to materialise in the near-term future.

Table 46: Renewable electricity share – including hydropower – under three scenarios and regions

Renewable Energy Share [%]	2020 Historical	2025 Estimate	2030	2035	2040
Iberian Peninsula					
IB BAU	46%	57%	78%	91%	98%
IB 4.0			84%	98%	100%
IB 4.1			84%	98%	100%
Spain					
ES-BAU	43%	54%	78%	92%	99%
ES 4.0			82%	98%	100%
ES 4.1			82%	98%	100%
Portugal					
PT-BAU	58%	72%	82%	87%	91%
PT 4.0			92%	97%	100%
PT 4.1			92%	97%	100%

Table 47: Renewable electricity share – excluding hydropower – under three scenarios and regions

Renewable Energy Share [%]	2020 Historical	2025 Estimate	2030	2035	2040
Iberian Peninsula					
IB BAU	32%	45%	69%	84%	90%
IB 4.0			74%	90%	93%
IB 4.1			74%	90%	93%
Spain					
ES-BAU	32%	44%	70%	86%	93%
ES 4.0			74%	92%	95%
ES 4.1			73%	92%	95%
Portugal					
PT-BAU	35%	49%	65%	73%	78%
PT 4.0			75%	81%	85%
PT 4.1			75%	81%	85%

Table 48: Required renewable electricity generation capacity under three scenarios and regions in [GW]*

		2020 Historical	2025 Estimate	2030	2035	2040
Iberian Peninsula						
Wind	IB-BAU	33	36	71	87	105
	IB 4.0			71	94	130
	IB 4.1			69	89	115
Photovoltaic	IB-BAU	17	50	98	184	223
	IB 4.0			92	154	184
	IB 4.1			89	145	162
Total Renewable Capacity	IB-BAU	74	109	205	301	367
	IB 4.0			198	281	356
	IB 4.1			193	264	314
Spain						
Wind	ES-BAU	27	29	62	75	92
	ES 4.0			58	79	111
	ES 4.1			57	75	98
Photovoltaic	ES-BAU	15	41	80	160	196
	ES 4.0			76	132	156
	ES 4.1			75	125	139
Total Renewable Capacity	ES-BAU	60	87	169	258	319
	ES 4.0			163	237	301
	ES 4.1			160	225	267
Portugal						
Wind	PT-BAU	6	7	10	11	13
	PT 4.0			13	15	19
	PT 4.1			12	14	16
Photovoltaic	PT-BAU	2	9	19	24	27
	PT 4.0			16	22	28
	PT 4.1			15	20	24
Total Renewable Capacity	PT-BAU	13	22	36	42	48
	PT 4.0			35	44	55
	PT 4.1			33	40	46

*The values for photovoltaic capacity in this table reflects total solar capacity i.e. utility and rooftop scale.

Following on from the above results, the renewable energy generation capacity increases significantly until 2050 in all scenarios. The capacity for wind (onshore and offshore), solar and total renewables for 2020 to 2040 is presented above in Table 48 in five-year increments to show the increase in capacity as the scenarios move towards the 2040 net-zero target. The capacity increase is due to higher electricity demand and the lower capacity factors of solar and wind power plants compared to coal or gas power plants.

Table 49 below specifies the development of electricity generation related to the production of H_2 under each of the scenario and for each region. With the values for current production reflecting the reality that currently the vast majority of H_2 production is 'grey' and thus comes from natural gas, as opposed to 'green' H_2 which is modelled in these scenarios and thus requires additional generation from renewable electricity. The H_2 production modelled under these scenarios are linked to the demand requirements of the scenario transition based on the uses across industry and other sectors.

Table 49: Development of electricity generation related to the production of H_2 under three scenarios and regions [TWh]

Power for H_2 Production [TWh]	2020 Historical	2025 Estimate	2030	2035	2040
Iberian Peninsula					
IB BAU	0	0	15	37	60
IB 4.0			16	49	81
IB 4.1			15	46	72
Spain					
ES-BAU	0	0	12	32	53
ES 4.0			12	43	72
ES 4.1			12	40	65
Portugal					
PT-BAU	0	0	3	5	7
PT 4.0			3	6	8
PT 4.1			3	5	7

6.5 Heating Sector

This section focusses on the modelling outcomes of the three scenarios in terms of the heating sector, both in terms of the useful heat energy delivered to end users for the needs of their heating applications (final energy – output heat) and the amount of final energy associated with supplying the heat for those end uses (final energy – input energy). This distinction is important even though both forms of energy are in terms of final/useful energy, because heat pumps have an efficiency greater than one. As mentioned in section '4.3.4 Buildings', heat pumps are assumed to have a COP of 3.5, which means that 3.5 units of output heat energy is delivered for every unit of (final) electrical energy input.

Figure 6-11: Heat supply by energy carrier under three different scenarios for the Iberian Peninsula

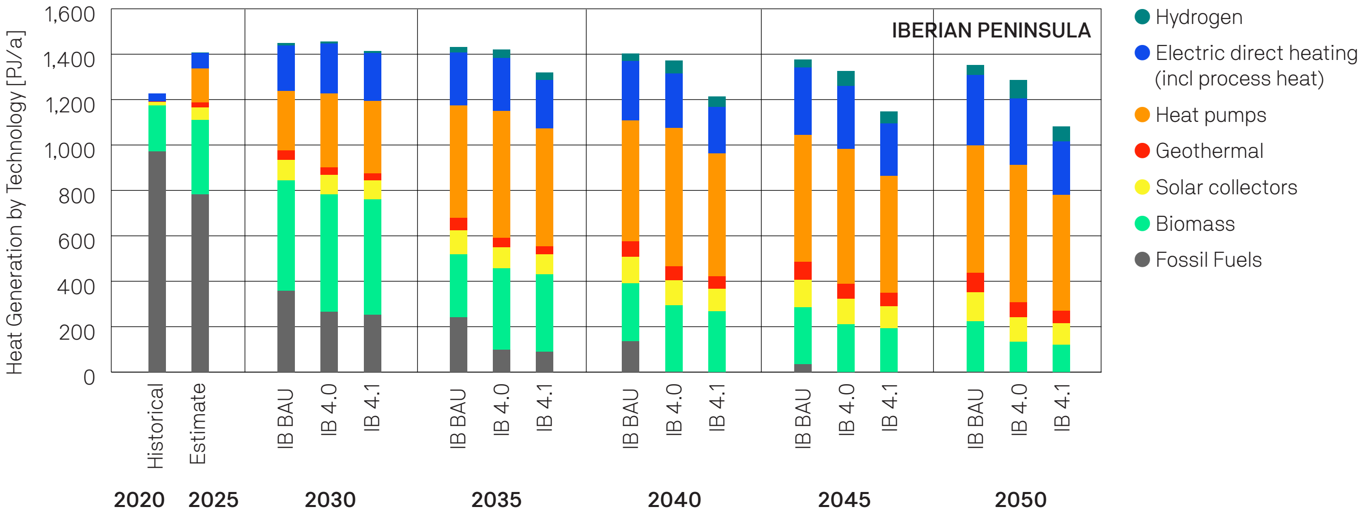


Figure 40: Heat supply by energy carrier under three different scenarios for Spain (top) and Portugal (bottom)

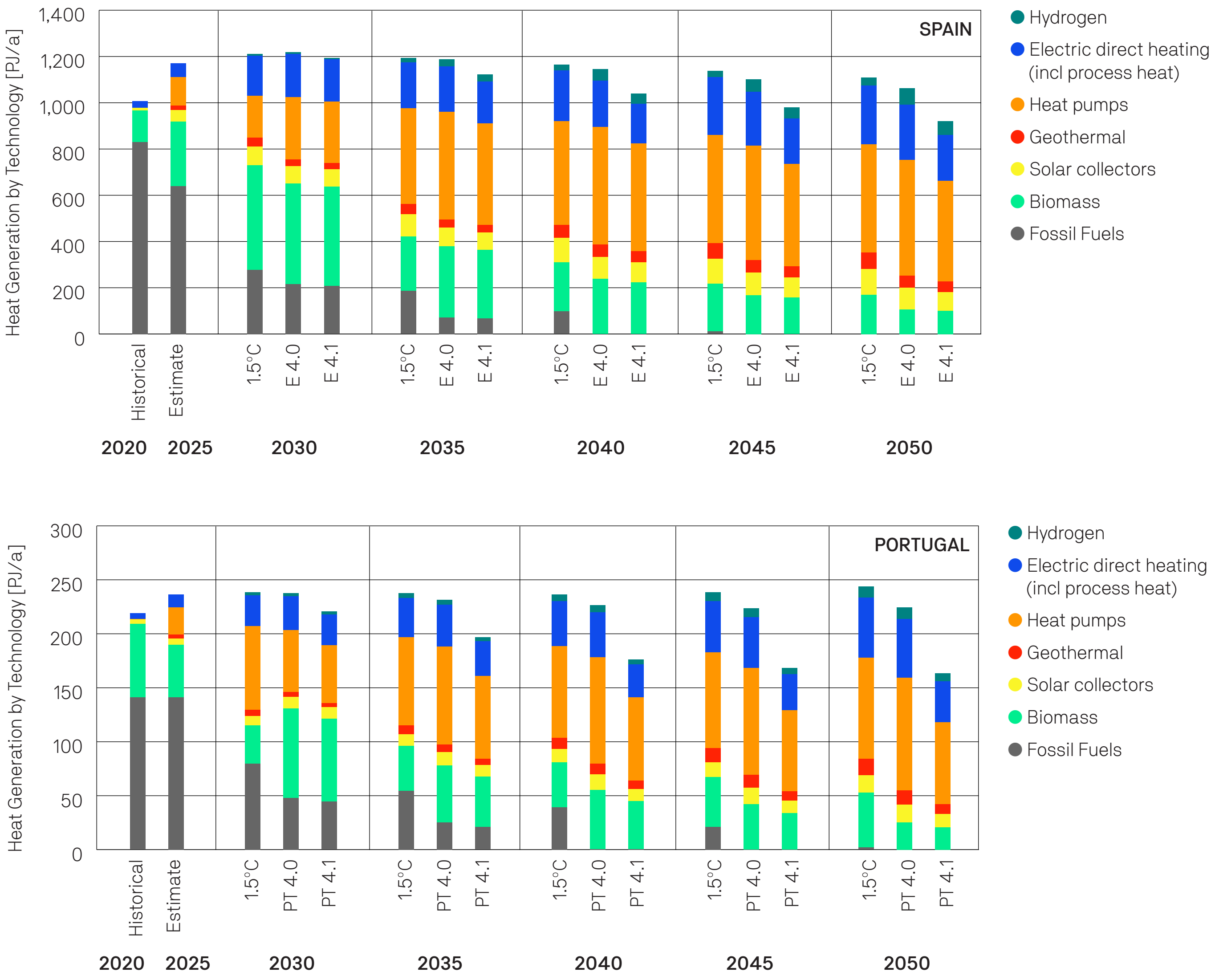


Figure 6-11 shows a breakdown of the first category of heat demand, that which is delivered to end users for the needs of their heating applications (output heat). This form of heat energy was chosen as the main category to be displayed in the results as it provides a fair comparison of the type of technology used to supply the heating end uses across the Iberian Peninsula. This avoids misrepresenting the energy that heat pumps provides to residential households, business and industry – as the fact that heat pumps supply useful heat energy 3.5 times better than a 100% efficient heater – does not mean they are producing 3.5 times less heat energy. Which is to say that output heat results include the heat energy taken from ambient environment through thermodynamic cycle that is driven by heat pumps.

The predominant story from Figure 40 is the important role that heat pump technologies are assumed to have across all future scenarios. As discussed in section '4.3.4 Buildings', the principles utilised in the 'Net Zero' heat supply scenario endorsed by Greenpeace Spain in the 'Hoja De Ruta De La Calefacción Renovable' (accounting for the fact that this report does not consider the heating needs of industry).[134]

A summary of how heat pumps grow to play a substantial role in the supply of final heat energy output is provided in Table 50. Noting that heat pumps can rapidly increase their share of total final energy outputted, thanks to the fact that each unit installed is able to deliver 3.5 times the heat energy relative to the electrical energy input. In addition to this, heat pumps have significant potential to be installed a high rate for the remainder of the decade thanks to maturing of the technology, alongside the economic benefits this produces from a cost of production perspective. Furthermore, heat pumps provide good economic outcomes for consumers thanks to their high efficiencies, low operating costs and ability to avoid the fuel costs associated with fossil fuel processes for low- and medium-temperature heating needs. For these reasons, the large increase between 2020 and 2030 in share of heat supply is seen as achievable, even in the BAU scenario.

Table 50: Heat pump share of final energy output heat supply

Heat Pump Share [%]	2020 Historical	2025 Estimate	2030	2035	2040	2045	2050
Iberian Peninsula							
IB BAU	0%	10%	18%	35%	38%	41%	42%
IB 4.0			22%	39%	44%	45%	47%
IB 4.1			23%	40%	46%	47%	50%
Spain							
ES-BAU	0%	11%	15%	35%	38%	41%	42%
ES 4.0			22%	39%	44%	45%	47%
ES 4.1			22%	40%	47%	47%	50%
Portugal							
PT-BAU	0%	7%	33%	34%	36%	37%	38%
PT 4.0			24%	39%	44%	44%	46%
PT 4.1			25%	40%	45%	46%	49%

Heat pumps can be used for both heating and cooling in building climate control and are highly efficient. Furthermore, they are electrically powered and therefore advantageous for integrating variable solar and wind power. The market for heat pumps is growing rapidly internationally and is one of the most important climate-control technologies not only for residential buildings but also increasingly for office buildings and for providing process heat to the industrial sector.

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[134] La Plataforma por la Descarbonización de la Calefacción y el Agua Caliente (Rivas et al.), Hoja De Ruta De La Calefacción Renovable',

Table 51: Comparison of the total heat energy generation across the scenarios in [PJ/a]

Heat Energy Demand [PJ/a]	2020 Historical	2025 Estimate	2030	2035	2040	2045	2050
Iberian Peninsula							
IB BAU	1,237	1,411	1,448	1,430	1,402	1,376	1,353
IB 4.0			1,456	1,420	1,371	1,326	1,286
IB 4.1			1,405	1,285	1,168	1,095	1,016
Spain							
ES-BAU	1,018	1,177	1,210	1,192	1,166	1,138	1,109
ES 4.0			1,218	1,189	1,145	1,102	1,062
ES 4.1			1,187	1,092	996	932	860
Portugal							
PT-BAU	219	234	238	237	236	238	244
PT 4.0			238	232	226	224	225
PT 4.1			218	193	172	163	156

Table 51 shows the total heat demand of residential and commercial buildings as well as industrial process heat. The crucial measure for decreasing heat demand for buildings is refurbishing existing building stock to improve insulation of the building envelope and double- and triple-glazing windows. Furthermore, the replacement of thermal heating systems with electric heat pumps and solar collectors reduces losses in heat generation.

6.6 Energy-Related CO_2 emissions

Energy demand reduction, and the deployment of renewable energy to phase-out fossil-fuel based energy supply across all sectors are key to decarbonising the entire energy system. Furthermore, the absorption of CO_2 by natural sinks neutralises the remaining energy-related CO_2 emissions by 2040.

An overview of these results is shown in Figure 6-12, in which the remaining CO_2 emissions in 2045 and 2050 relate to the production of synthetic fuels, such as SAF for aviation and methanol for navigation. These emissions range from 6 to 11 $MtCO_2$ from the 4.1 to the BAU scenarios respectively. The CO_2 required to produce synthetic fuels is derived from natural sinks in the 4.0 and 4.1 scenarios. The source of CO_2 for these synthetic fuels can be from biomass or from technically captured CO_2. However, the carbon source analysis for synthetic fuels was outside the scope of this research. 50% of the emissions for international transport (aviation, shipping rail and road) have been added to the national emission balance for Spain and Portugal. It is assumed that the decarbonisation of international travel applied to domestic AND international travelling under the 4.0 and 4.1 scenarios.

Figure 6-12: Sectoral energy-related CO_2 emissions for the Iberian Peninsula under each scenario (excl. negative emissions from sinks)

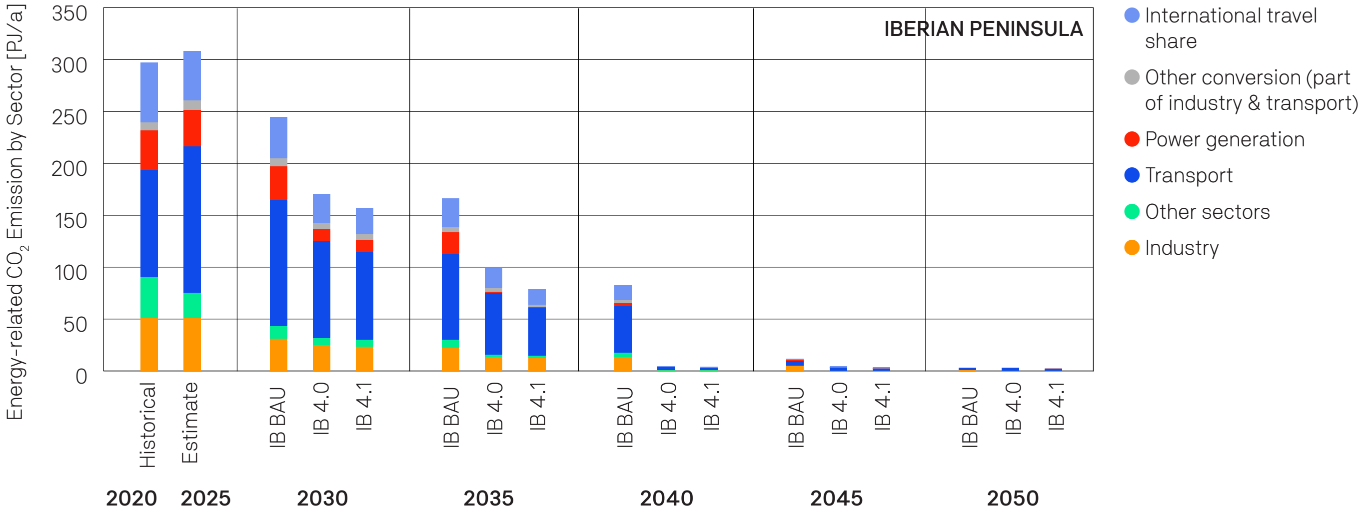
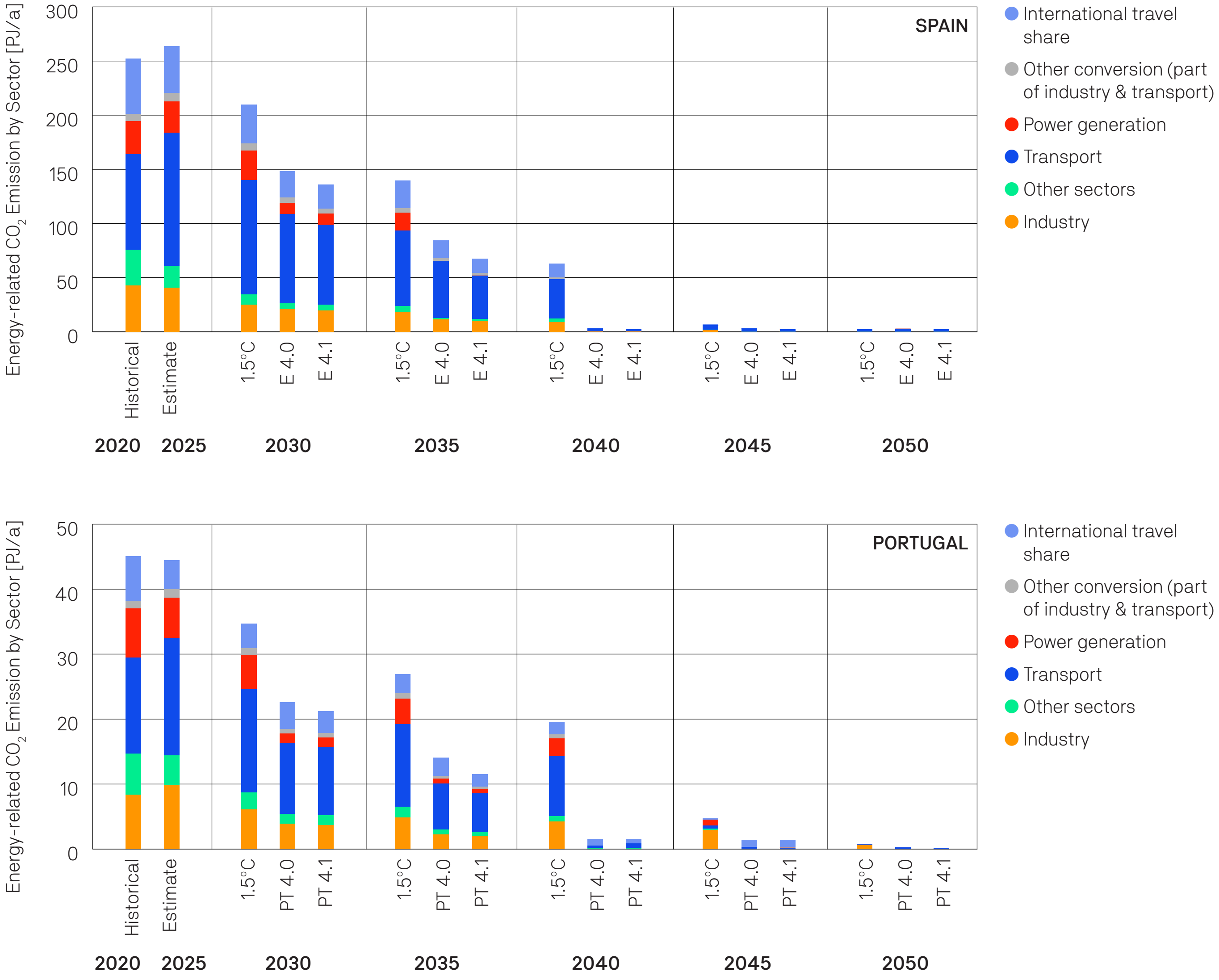


Figure 6-13: Sectoral energy-related CO_2 emissions Spain (top) and Portugal (bottom) under each scenario (excl. negative emissions from sinks)



As discussed in section 1 ‘Introduction and Scope of Research’ the NECPs state their emission-reductions target relative to a 1990 baseline, with Spain and Portugal separating their updated NECP documents independently of each other, as European Member States abiding by the requirements of EU climate policy and the Paris Agreement. For this reason, the results of the annual carbon emissions of Spain and Portugal are shown separately in Table 52 and Table 53.

The previous chapters discussing carbon emissions targets also outlined that both the 4.0 and 4.1 scenarios beating the targets set out in the updated NECP 2030 documents, as well as the proposed EU target of a 90% reduction of emissions relative to 1990 (by 2040). The results shown below clearly demonstrate these outcomes. The data below in Table 54 also details the emissions for each scenario on a per capita basis for the Iberian Peninsula, while the data presented in Table 55 provides insight into the energy intensity of the Iberian economy on a per GDP basis.

Table 52: Analysis of the Change in Gross CO_2 Mt/a Relative to 1990 Baseline for Spain, shown as a percentage change

Change in CO_2 Mt/a Relative to 1990 Baseline	2025	2030	2035	2040	2045	2050
ES-BAU	-25%	-43%	-61%	-80%	-94%	-97%
ES 4.0		-50%	-71%	-97%	-97%	-97%
ES 4.1		-52%	-75%	-98%	-98%	-98%

Table 53: Analysis of the Change in Gross CO_2 Mt/a Relative to 1990 Baseline for Portugal, shown as a percentage change

Change in CO_2 Mt/a Relative to 1990 Baseline	2025	2030	2035	2040	2045	2050
PT-BAU	-29%	-42%	-52%	-66%	-90%	-97%
PT 4.0		-64%	-77%	-96%	-97%	-98%
PT 4.1		-65%	-81%	-97%	-98%	-99%

Table 54: Emissions per capita for the Iberian Peninsula [t CO_2.eq/person]

Per Capita Emissions T CO_2 .eq/person	2025	2030	2035	2040	2045	2050
IB-BAU	4.6	3.4	2.4	1.3	0.4	0.2
IB 4.0		2.8	1.7	0.2	0.2	0.2
IB 4.1		2.7	1.4	0.1	0.1	0.1

Table 55: Emissions per capita for the Iberian Peninsula [grams CO_2 eq\€] (note: change of units from kg to grams)

GDP Emission Intensity grams CO_2 eq\€	2025	2030	2035	2040	2045	2050
IB-BAU	135	97	64	32	9	4
IB 4.0		80	45	5	4	3
IB 4.1		78	39	3	3	2

Table 52 and Table 53 reflect the differences in ambition of the three scenarios for Spain and Portugal relative to the 1990 baseline, where it can be seen the 4.1 scenario makes marginal improvements upon the emissions reductions achieved between 2040–2050, with more noticeable emission reductions occurring between 2030 and 2040 such that aggregate emissions do differentiate throughout the extended modelling period (until 2050 to calculate emissions and compare them to the carbon budget limits).

These tables also clearly indicate the slower decarbonisation rates set out in the BAU scenarios. The BAU scenario for Spain shows a much slower rate relative to the 4.0 scenario particularly in the medium term where emissions in 2035 and 2040 decrease in line with technological changes which can be expected under current trends in Spain and the EU more broadly. Likewise, the Portuguese BAU scenario shows a slow transition towards a decarbonised future under the trends set for this scenario, which are reflective of the Portuguese context discussed in section one ‘Energy & Emissions Context of the Iberian Peninsula’.

The impacts of both the faster decarbonisation pathway of the E 4.1 scenarios, as well as the slower decarbonisation rate of the BAU scenario are not fully contextualised in this chapter. This is because the aggregate emissions released between 2020 and 2050 are not compared to the ultimate test of the scenario, which is whether the emissions in this time frame conform to the limit of a fairly allocated CO_2 budget. The following chapter analyses the CO_2 emission outcomes with respect to the 2020–2050 CO_2 budget.

6.7 Comparison of CO_2 Budget and Scenario Emissions

The preceding chapters reference the a 'fair allocation' carbon budget for the Iberian Peninsula, which aligns with the Paris Agreement and Greenpeace's principles of climate justice. Greenpeace Spain provided a methodology for the calculation of a fair allocation budget for Spain in their report 'Spanish Climate Action: Highest Ambition is Necessary and Possible' using a 400 $GtCO_2$-e global carbon budget – which provides a 67% likelihood of maintaining global warming to 1.5°C. Given the population data used for the entirety of Spain in this report, the 'fair allocation' carbon budget was determined to be 2.04 $GtCO_2$-e between 2020 and 2050.[135] The same principles used by Greenpeace Spain in this report were used to calculate fair allocation carbon budgets for the geographical regions modelled in this study (note the excluded regions specified in section '1.1 Context for this research'). The results are presented below in Table 56.

Table 56: Fair allocation carbon budget limits

	Share of the World Population 2020–2050	Carbon Budget 2020–2050 ($GtCO_2$-e)
Global	100%	400
Spain	0.51%	2.04
Portugal	0.11%	0.45
Total Iberian Peninsula	**0.62%**	**2.49**

The results from section '6.6 Energy-related CO_2 emissions' form the basis for the emissions results shown in this chapter. An additional step is taken in this chapter to calculate the absorption of carbon by natural sinks such as through the net absorption of LULUCF (i.e. no absorption of carbon through CCS), as this carbon is absorbed naturally the CO_2 emission results of this section can be described as energy emissions minus natural sinks and for this reason the data is presented as 'including CO_2 sinks'.

The absorption of CO_2 by sinks was calculated using official data from EU national emission accounts, such that the difference between historical net and gross emissions was used to produce an average absorption value for the period of 1990 to 2023.[136] The difference between these two values provides an accurate historical value for CO_2 absorbed by sinks, and was hence used as an estimate for the average absorption of sinks which will occur per year until 2050 (absorption of 45.5 $MtCO_2$/yr for Spain and 1.8 $MtCO_2$/yr for Portugal).

The results of the carbon budget comparative analysis for the whole of the Iberian Peninsula are displayed in Figure 6-14, with a country breakdown provided in Figure 6-15 – with the emissions caused from the accounting for 50% of international travel shown as shaded sections of the emission figures.

The results demonstrate that:

- The BAU scenario exceeds carbon budget by a large margin with the consideration of international travel.
- All BAU scenarios exceed the carbon budget without the consideration of international travel.
- Both the E 4.0 & E 4.1 scenarios meet the carbon budget for the Iberian Peninsula.
- Spain easily remains within the carbon budget under the E 4.0, while Portugal slightly exceeds the budget under these scenarios (irrespective of the inclusion of international travel).
- Both Spain and Portugal remain under the fairly allocated carbon budget under the E 4.1 scenario.
- Although the E 4.1 scenario makes significant reductions in demand as per results discussed in this chapter – it does not equate to a large reduction in emissions as the economy is already largely decarbonised in the 2030s under E 4.0.

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[135] Greenpeace Spain, 'Spanish Climate Action: Highest Ambition is Necessary and Possible' (10/06/2024)

[136] European Environment Agency, EEA greenhouse gases – data viewer, <https://www.eea.europa.eu/en/analysis/maps-and-charts/greenhouse-gases-viewer-data-viewers> (modified 16/05/2025)

Figure 6-14: Comparison of carbon budget to total scenario emissions (2020–2050), for the Iberian Peninsula (incl. CO_2 sinks)

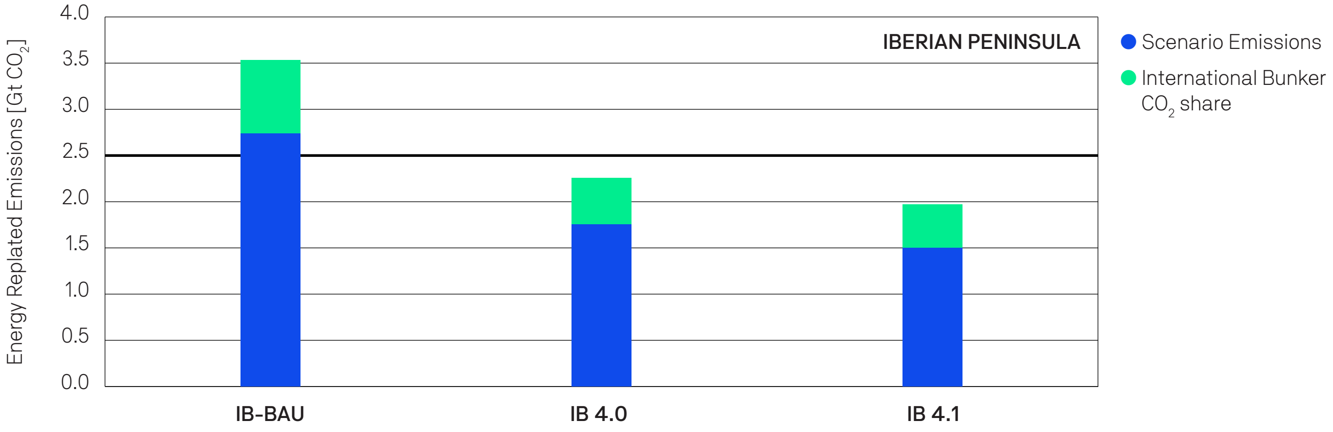
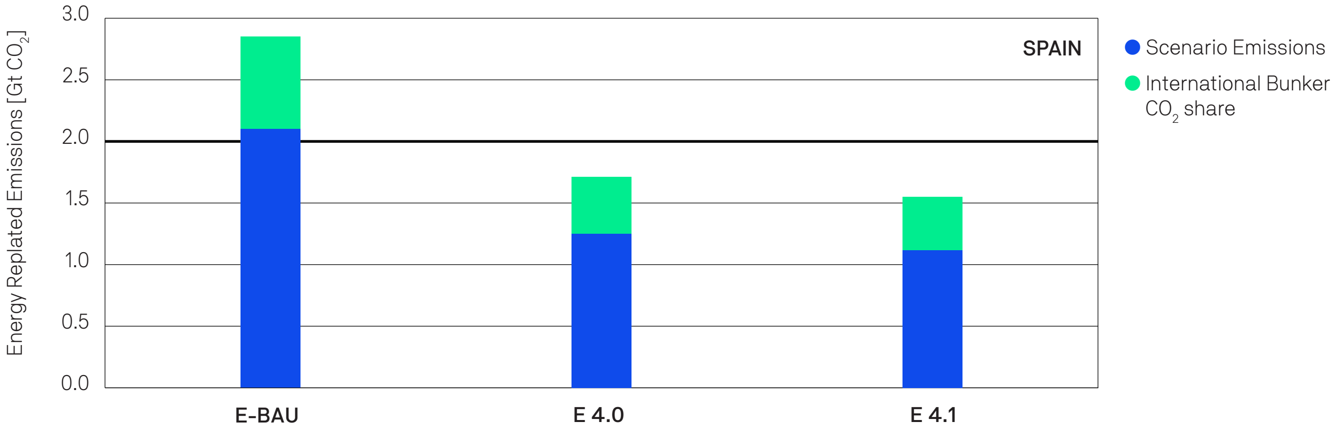
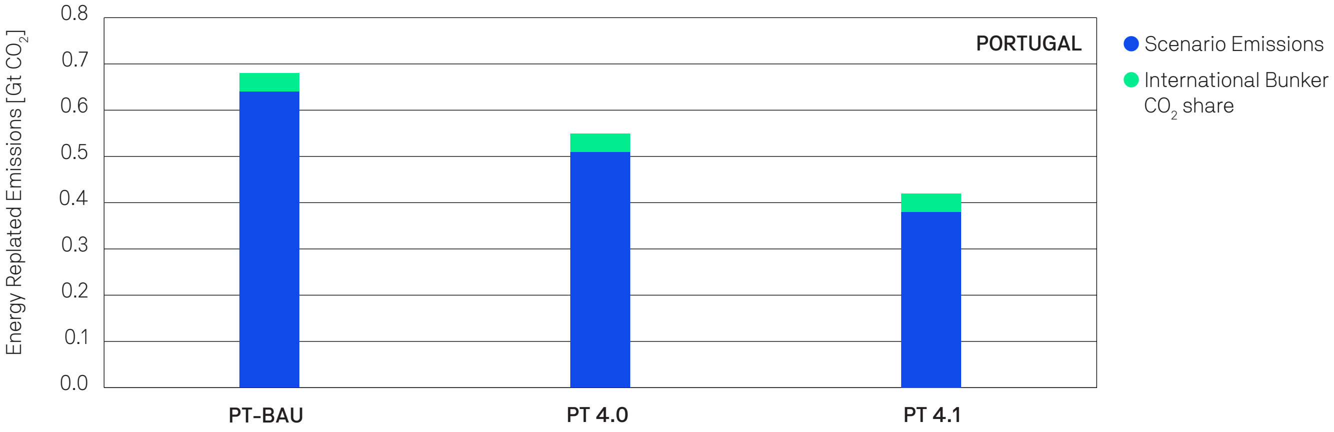


Figure 6-15: Comparison of carbon budget to total scenario emissions (2020–2050), for Spain & Portugal (incl. CO_2 sinks)





6.8 Cost analysis

6.8.1 Investments in power generation

The total investment in the Iberian Peninsula between 2020 and 2040 would invest Euro 402 billion (around Euro 20 billion annually) in new power generation under the IB BAU pathway until 2040. In comparison, the IB 4.0 scenario will require a total investment of Euro 426 billion, whereas the IB 4.1 scenario will lead to an investment of Euro 373 billion. Most of this investment will go into solar photovoltaic, followed by onshore wind. None of the calculated scenarios will invest in new nuclear power plants due to the significant cost advantages of renewable power generation. The infrastructure for renewables is also much faster to build and can therefore follow the increasing electricity demand from year 1 onwards, whereas nuclear power plants require a construction period of well over 12 years. During this time, no electricity is produced, whereas significant costs are incurred during the early phase of construction. The Iberian Peninsula has significant solar and wind potential, both within Spain and Portugal. Roof-top solar photovoltaics generate electricity close to the consumer and – in connection with storage and flexible demand measures – boost resilience of the regional electricity supply while being cost effective for consumers. Therefore, solar electricity systems are the premier choice to provide access to modern energy services. However, wind energy – both onshore and offshore – plays a vital role for bulk electricity supply. The generation pattern is different from that of solar and will therefore reduce the energy storage requirements because electricity generation is distributed throughout the day and is not limited to daylight hours.

Figure 6-16: Iberia: Cumulative investment shares in power generation

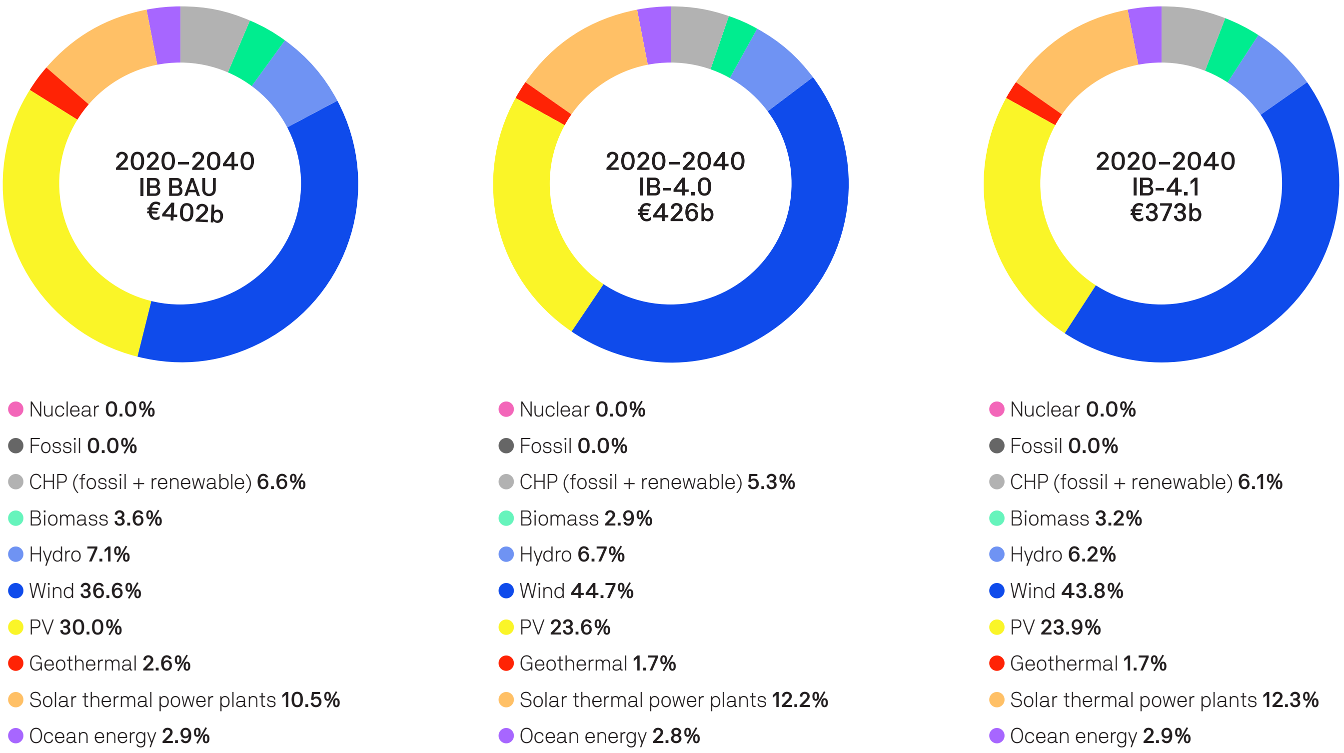


Figure 6-17: Spain: Cumulative investment shares in power generation

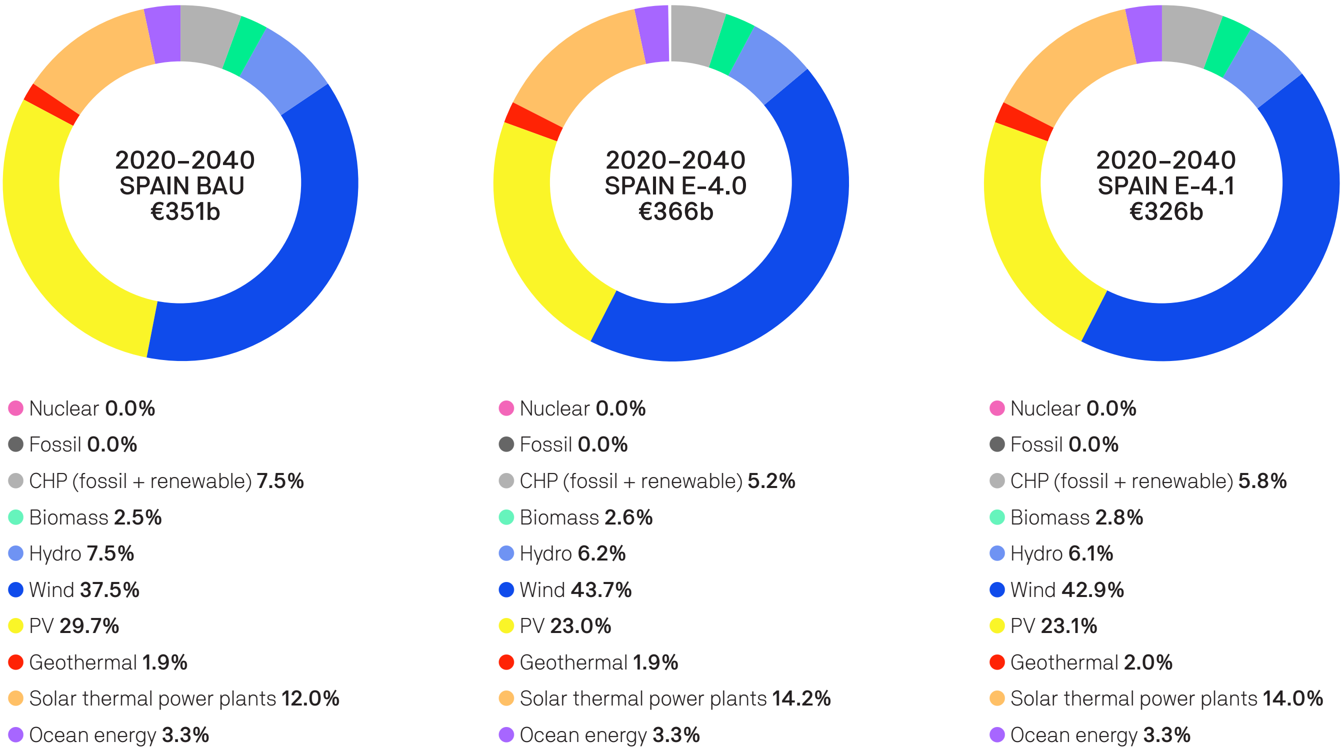


Figure 6-18: Portugal: Cumulative investment shares in power generation

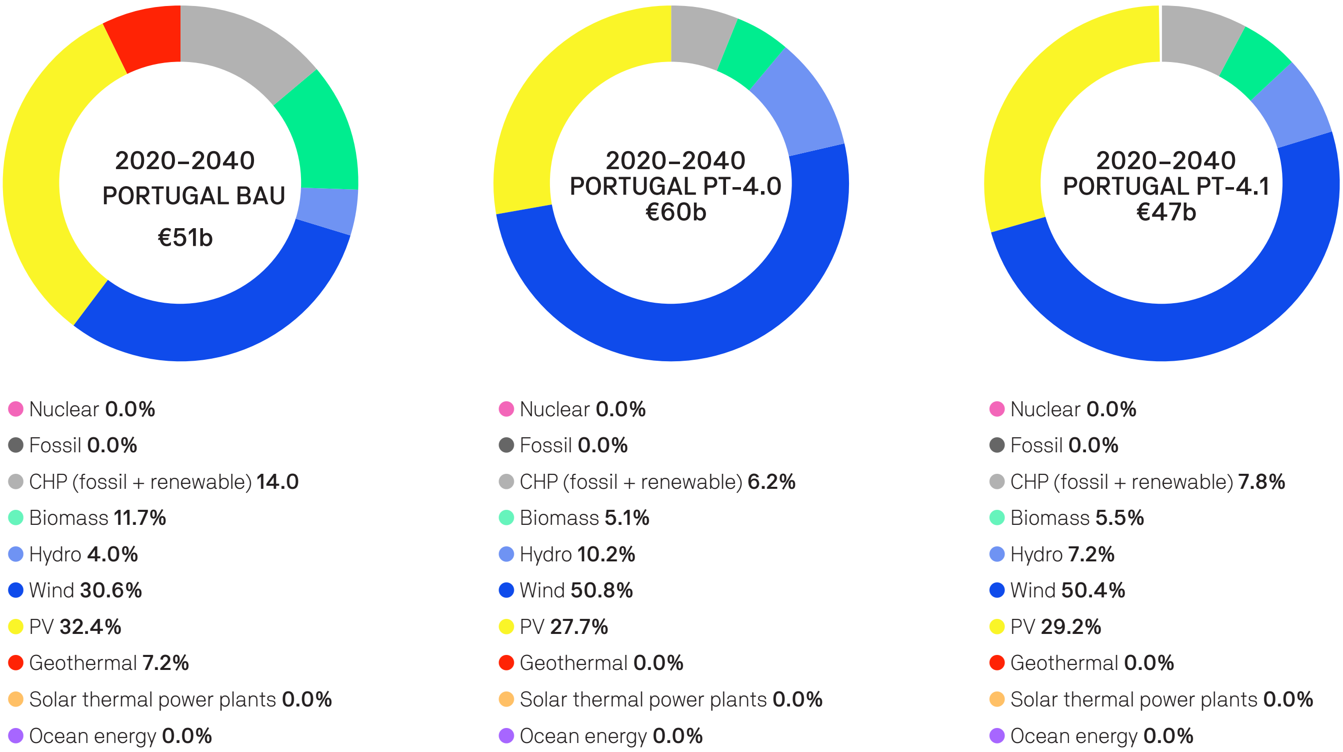


Table 57: Iberian Peninsula – Cumulative investment in power generation under each scenario

Cumulative investment in power generation	2020–2030	2031–2040	2041–2050	2020–2040 [billion Euro]	Average annual [billion Euro/a]
IB BAU					
Fossil	0.0	0.0	0.0	0.0	0.0
Nuclear	0.0	0.0	0.0	0.0	0.0
CHP (fossil + renewable)	10.6	16.1	9.4	26.6	1.3
Biomass	9.0	5.6	8.8	14.6	0.7
Hydro	18.9	9.6	6.3	28.5	1.4
Wind	77.4	69.9	48.0	147.3	7.4
photovoltaic	56.9	63.7	19.4	120.6	6.0
Geothermal	3.0	7.5	2.1	10.5	0.5
Solar thermal power plants	30.3	11.9	6.3	42.3	2.1
Ocean energy	0.3	11.2	3.7	11.5	0.6
Total investment	**IB BAU**			**402.0**	**20.1**
IB 4.0					
Fossil	0.0	0.0	0.0	0.0	0.0
Nuclear	0.0	0.0	0.0	0.0	0.0
CHP (fossil + renewable)	9.0	13.6	2.5	22.6	1.1
Biomass	7.9	4.6	3.3	12.5	0.6
Hydro	23.1	5.6	3.1	28.7	1.4
Wind	80.2	110.0	49.7	190.1	9.5
photovoltaic	52.9	47.6	6.0	100.5	5.0
Geothermal	0.2	6.9	0.6	7.1	0.4
Solar thermal power plants	29.1	22.8	16.0	51.9	2.6
Ocean energy	0.3	11.8	3.2	12.1	0.6
Total investment	**IB 4.0**			**426.0**	**21.3**
IB 4.1					
Fossil	0.0	0.0	0.0	0.0	0.0
Nuclear	0.0	0.0	0.0	0.0	0.0
CHP (fossil + renewable)	9.0	13.6	2.5	22.6	1.1
Biomass	7.7	4.1	3.3	11.8	0.6
Hydro	21.9	1.3	2.9	23.2	1.2
Wind	77.0	86.4	44.1	163.4	8.2
photovoltaic	51.4	37.6	5.0	89.0	4.4
Geothermal	0.2	6.3	0.5	6.5	0.3
Solar thermal power plants	28.5	17.2	14.1	45.7	2.3
Ocean energy	0.3	10.4	2.8	10.7	0.5
Total investment	**IB 4.1**			**373.0**	**18.7**

6.8.2 Future investments in the heating sector

The main difference between the BAU scenarios for Spain and Portugal (and the sum of those for the Iberian Peninsula) and the E.0 and 4.1 scenarios for the same region is the significant investment in heat pumps and the diversification of heating technologies/shift away from fossil fuels, especially gas. The Iberian BAU and the 4.1 scenarios led to investment in heating generation of around Euro 160 billion, while the 4.0 pathway requires a higher investment on Euro 170 billion between 2020 and 2040. Both the 4.0 and the 4.1 pathways implement renewable energy technologies faster to achieve zero emissions by 2040, while the BAU pathway aims to decarbonise by 2050.

Electrical heat pumps, geothermal heat pumps, and solar thermal applications for space and water heating and drying will lead to a considerable reduction in the use of biogas and solid biomass and therefore reduce the fuel costs. Figure 6-19, Figure 6-20 and Figure 6-21 shows the shares of cumulative investments in the heating sector between 2020 and 2050.

Figure 6-19: Iberian Peninsula – Cumulative investment in the heating technologies (generation) under the scenarios

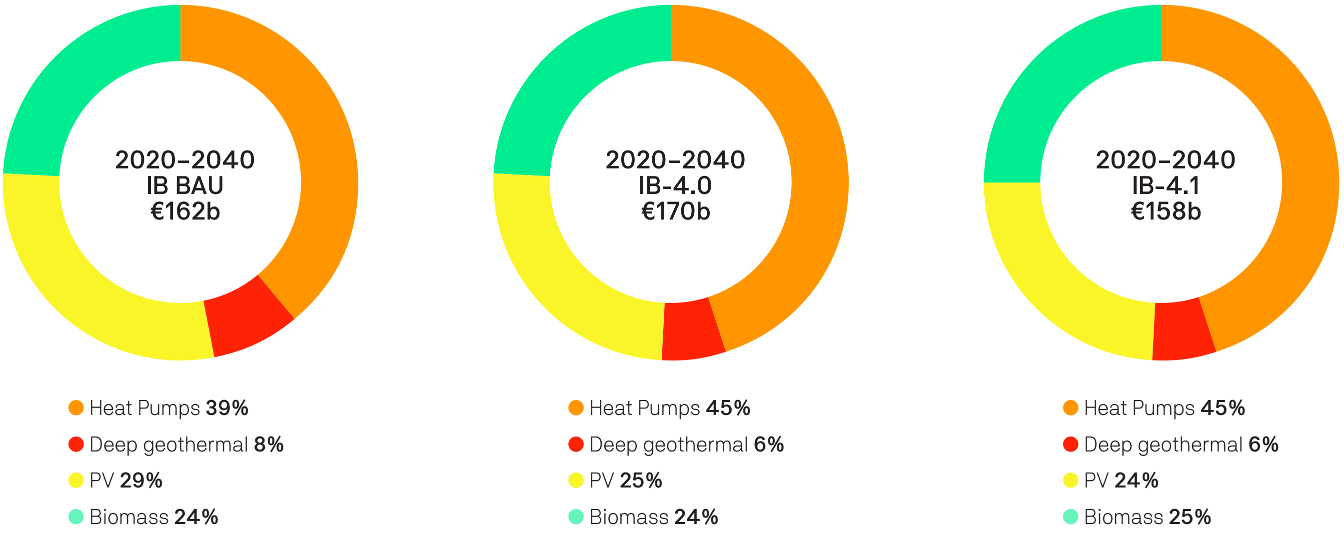


Figure 6-20: Spain – Cumulative investment in the heating technologies (generation) under the scenarios

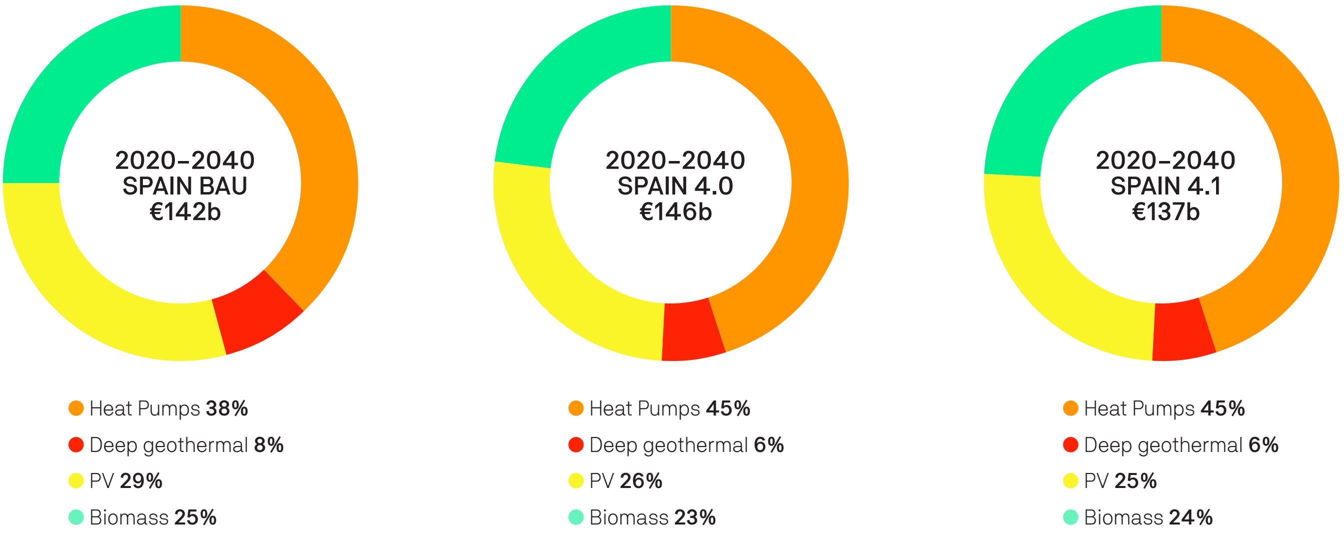


Figure 6-21: Portugal – Cumulative investment in the heating technologies (generation) under the scenarios

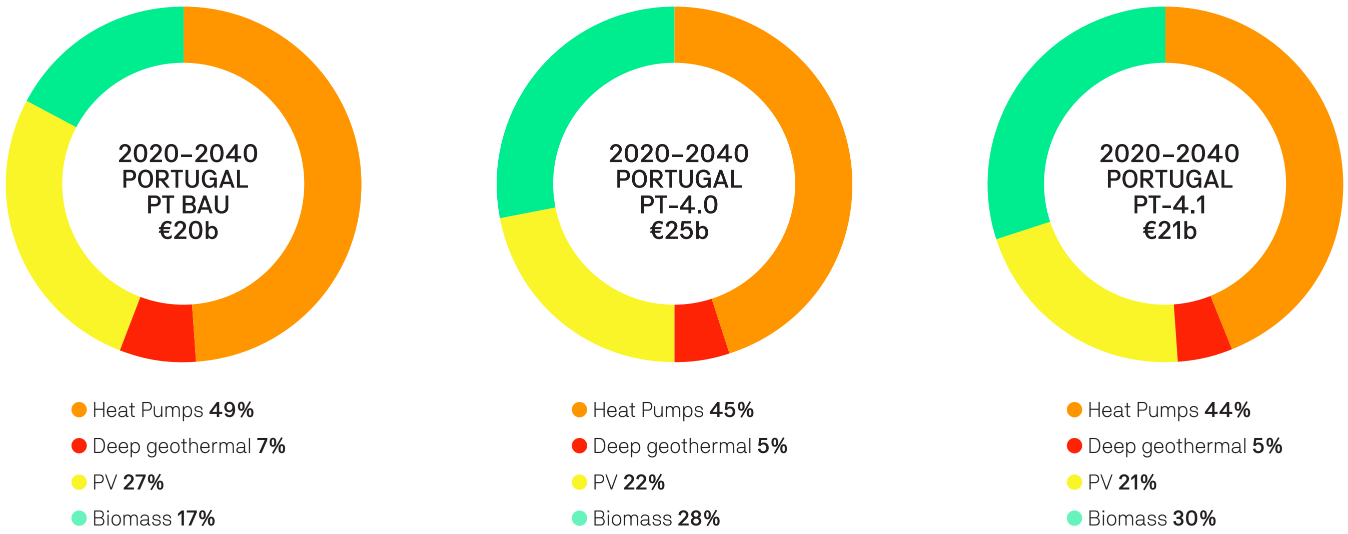


Table 58, Table 59 and Table 60 shows the cumulative investment in heat generation for Spain and Portugal and the sum for the Iberian Peninsula under all three analysed scenarios. The investments are in favour of electrification (heat pumps) – and 'fuel-less technologies' (solar thermal), while bio energy is used to replace fossil fuels in co-generation and for the supply of industrial process heat. However, fuel costs will decrease and refinance that investment over the technical lifetimes.

Table 58: Iberian Peninsula – Accumulated investment costs for heat generation under three scenarios

	Cumulative Investment Costs in billion Euro 2020–2040			Average annual investment costs in billion Euro/a		
	IB BAU	IB 4.0	IB 4.1	IB BAU	IB 4.0	IB 4.1
Heat pumps	63.8	76.4	70.9	3.2	3.8	3.5
Deep geothermal	12.4	10.0	9.4	0.6	0.5	0.5
Solar thermal	46.6	43.4	38.4	2.3	2.2	1.9
Biomass	39.7	40.5	39.4	2.0	2.0	2.0
Total	**162.0**	**170.0**	**158.0**	**8.1**	**8.5**	**7.9**

Table 59: Spain – Accumulated investment costs for heat generation under three scenarios

	Cumulative Investment Costs in billion Euro 2020–2040			Average annual investment costs in billion Euro/a		
	ES BAU	ES 4.0	ES 4.1	ES BAU	ES 4.0	ES 4.1
Heat pumps	53.8	65.4	61.7	2.7	3.3	3.1
Deep geothermal	10.9	8.8	8.4	0.5	0.4	0.4
Solar thermal	41.1	37.8	34.1	2.1	1.9	1.7
Biomass	36.2	33.5	33.2	1.8	1.7	1.7
Total	**142.0**	**146.0**	**137.0**	**7.1**	**7.3**	**6.9**

Table 60: Portugal – Accumulated investment costs for heat generation under three scenarios

	Cumulative Investment Costs in billion Euro 2020–2040			Average annual investment costs in billion Euro/a		
	PT BAU	PT 4.0	PT 4.1	PT BAU	PT 4.0	PT 4.1
Heat pumps	9.9	11.0	9.2	0.5	0.6	0.5
Deep geothermal	1.5	1.2	1.0	0.1	0.1	0.0
Solar thermal	5.4	5.5	4.3	0.3	0.3	0.2
Biomass	3.5	7.0	6.2	0.2	0.3	0.3
Total	**20.0**	**25.0**	**21.0**	**1.0**	**1.3**	**1.1**

6.8.3 Investments and fuel cost savings

Finally, the fuel costs for the power, heating, and transport sectors are presented. All three scenarios have very low fuel costs for the power sector because generation is based mainly on solar and wind power, which need no fuels. The average annual fuel costs of the Iberian BAU case – the sum of Spain and Portugal – will add up to Euro 105 billion between 2020 and 2040 and drop to Euro 87.8 billion between if the period is extended to 2050. The IB 4.0 scenario has a cost advantage of around 21.9 billion per year (for the period until 2040) and Euro 15.1 billion per year (2020-2050) and the 4.1 case has even further costs advantages of Euro 31.9 billion respectively Euro 32.9 billion per year.

Table 61: Iberian Peninsula – Total fuel costs across all sectors between 2020 and 2050 under three difference scenario

IB BAU	**Unit**	**2020–2040**	**2020–2050**	**Unit**	**Annual average 2020–2040**	**Annual average 2020–2050**
Oil	billion Euro	1,709	2,162	[billion Euro/a]	85.5	72.1
Gas	billion Euro	317	379	[billion Euro/a]	15.8	12.6
Coal	billion Euro	4	4	[billion Euro/a]	0.2	0.1
Lignite/Brown coal	billion Euro	0	0	[billion Euro/a]	0.0	0.0
Biomass	billion Euro	69	83	[billion Euro/a]	3.4	2.8
Synthetic Fuels	billion Euro	1	5	[billion Euro/a]	0.1	0.2
Total Fuel Costs	**billion Euro**	**2,100**	**2,633**	**[billion Euro/a]**	**105.0**	**87.8**
IB 4.0	**unit**	**2020–2040**	**2020–2050**	**Unit**	**Annual average 2020–2040**	**Annual average 2020–2050**
Oil	billion Euro	1,367	1,567	[billion Euro/a]	68.3	52.2
Gas	billion Euro	220	221	[billion Euro/a]	11.0	7.4
Coal	billion Euro	3	3	[billion Euro/a]	0.2	0.1
Lignite/Brown coal	billion Euro	0	0	[billion Euro/a]	0.0	0.0
Biomass	billion Euro	70	81	[billion Euro/a]	3.5	2.7
Synthetic Fuels	billion Euro	2	10	[billion Euro/a]	0.1	0.3
Total Fuel Costs	**billion Euro**	**1,663**	**1,882**	**[billion Euro/a]**	**83.1**	**62.7**
IB 4.1	**Unit**	**2020–2040**	**2020–2050**	**Unit**	**Annual average 2020–2040**	**Annual average 2020–2050**
Oil	billion Euro	1,172	1,341	[billion Euro/a]	58.6	44.7
Gas	billion Euro	216	217	[billion Euro/a]	10.8	7.2
Coal	billion Euro	3	3	[billion Euro/a]	0.2	0.1
Lignite/Brown coal	billion Euro	0	0	[billion Euro/a]	0.0	0.0
Biomass	billion Euro	69	80	[billion Euro/a]	3.5	2.7
Synthetic Fuels	billion Euro	2	6	[billion Euro/a]	0.1	0.2
Total Fuel Costs	**billion Euro**	**1,463**	**1,647**	**[billion Euro/a]**	**73.1**	**54.9**

Table 62: Spain –Total fuel costs across all sectors between 2020 and 2050 under three difference scenario

ES BAU	**Unit**	**2020–2040**	**2020–2050**	**Unit**	**Annual average 2020–2040**	**Annual average 2020–2050**
Oil	billion Euro	1,433	1,789	[billion Euro/a]	71.7	59.6
Gas	billion Euro	247	280	[billion Euro/a]	12.3	9.3
Coal	billion Euro	3	3	[billion Euro/a]	0.2	0.1
Lignite/Brown coal	billion Euro	0	0	[billion Euro/a]	0.0	0.0
Biomass	billion Euro	54	64	[billion Euro/a]	2.7	2.1
Synthetic Fuels	billion Euro	1	4	[billion Euro/a]	0.0	0.1
Total Fuel Costs	**billion Euro**	**1,739**	**2,141**	**[billion Euro/a]**	**86.9**	**71.4**
ES 4.0	**Unit**	**2020–2040**	**2020–2050**	**Unit**	**Annual average 2020–2040**	**Annual average 2020–2050**
Oil	billion Euro	1,141	1,293	[billion Euro/a]	57.0	43.1
Gas	billion Euro	181	181	[billion Euro/a]	9.0	6.0
Coal	billion Euro	2	2	[billion Euro/a]	0.1	0.1
Lignite/Brown coal	billion Euro	0	0	[billion Euro/a]	0.0	0.0
Biomass	billion Euro	54	62	[billion Euro/a]	2.7	2.1
Synthetic Fuels	billion Euro	2	7	[billion Euro/a]	0.1	0.2
Total Fuel Costs	**billion Euro**	**1,380**	**1,546**	**[billion Euro/a]**	**69.0**	**51.5**
ES 4.1	**Unit**	**2020–2040**	**2020–2050**	**Unit**	**Annual average 2020–2040**	**Annual average 2020–2050**
Oil	billion Euro	999	1,134	[billion Euro/a]	49.9	37.8
Gas	billion Euro	178	179	[billion Euro/a]	8.9	6.0
Coal	billion Euro	2	2	[billion Euro/a]	0.1	0.1
Lignite/Brown coal	billion Euro	0	0	[billion Euro/a]	0.0	0.0
Biomass	billion Euro	55	63	[billion Euro/a]	2.8	2.1
Synthetic Fuels	billion Euro	1	6	[billion Euro/a]	0.1	0.2
Total Fuel Costs	**billion Euro**	**1,236**	**1,385**	**[billion Euro/a]**	**61.8**	**46.2**

Table 63: Portugal –Total fuel costs across all sectors between 2020 and 2050 under three difference scenario

PT BAU	Unit	2020–2040	2020–2050	Unit	Annual average 2020–2040	Annual average 2020–2050
Oil	billion Euro	276	373	[billion Euro/a]	13.8	12.4
Gas	billion Euro	70	99	[billion Euro/a]	3.5	3.3
Coal	billion Euro	1	1	[billion Euro/a]	0.0	0.0
Lignite/Brown coal	billion Euro	0	0	[billion Euro/a]	0.0	0.0
Biomass	billion Euro	14	19	[billion Euro/a]	0.7	0.6
Synthetic Fuels	billion Euro	0	0	[billion Euro/a]	0.0	0.0
Total Fuel Costs	**billion Euro**	**361**	**492**	**[billion Euro/a]**	**18.1**	**16.4**
PT 4.0	**Unit**	**2020–2040**	**2020–2050**	**Unit**	**Annual average 2020–2040**	**Annual average 2020–2050**
Oil	billion Euro	226	274	[billion Euro/a]	11.3	9.1
Gas	billion Euro	40	40	[billion Euro/a]	2.0	1.3
Coal	billion Euro	1	1	[billion Euro/a]	0.0	0.0
Lignite/Brown coal	billion Euro	0	0	[billion Euro/a]	0.0	0.0
Biomass	billion Euro	16	19	[billion Euro/a]	0.8	0.6
Synthetic Fuels	billion Euro	1	3	[billion Euro/a]	0.0	0.1
Total Fuel Costs	**billion Euro**	**283**	**336**	**[billion Euro/a]**	**14.1**	**11.2**
PT 4.1	**Unit**	**2020–2040**	**2020–2050**	**Unit**	**Annual average 2020–2040**	**Annual average 2020–2050**
Oil	billion Euro	174	207	[billion Euro/a]	8.7	6.9
Gas	billion Euro	38	38	[billion Euro/a]	1.9	1.3
Coal	billion Euro	1	1	[billion Euro/a]	0.0	0.0
Lignite/Brown coal	billion Euro	0	0	[billion Euro/a]	0.0	0.0
Biomass	billion Euro	14	16	[billion Euro/a]	0.7	0.5
Synthetic Fuels	billion Euro	0	0	[billion Euro/a]	0.0	0.0
Total Fuel Costs	**billion Euro**	**226**	**262**	**[billion Euro/a]**	**11.3**	**8.7**

Table 64, Table 65 and Table 66 show cumulative investment costs in power and heat generation versus cumulative fuel costs for the three scenarios for Spain, Portugal and as a sum for the Iberian Peninsula between 2020 and 2040 and 2050.

The 4.1 scenario have the highest overall cost savings followed by the 4.0 scenario in comparison to the BAU both in Spain and Portugal.

Table 64: Iberian Peninsula – Cumulative investment costs in power and heat generation and fuel costs between 2020 and 2040 and 2050

	2020–2040 [billion Euro]	Average annual [billion Euro/a]	2020–2050 [billion Euro]	Average annual [billion Euro/a]
Iberian Peninsula IB BAU				
Cumulative Investment in renewable power generation (with no fuel demand)	399	20	855	29
Cumulative heating investment: 2020–2040	162	8	233	8
Cumulative fuel costs: 2020–2040	2,100	105	2,633	88
Total cumulative costs: 2020–2040	**2,661**	**113**	**3,721**	**124**
Iberian Peninsula IB 4.0				
Cumulative Investment in renewable power generation (with no fuel demand)	422	21	874	29
Cumulative heating investment: 2020–2040	171	9	222	7
Cumulative fuel costs: 2020–2040	1,663	83	1,882	63
Total cumulative costs: 2020–2040	**2,255**	**92**	**2,978**	**99**
Costs Savings: IB4.0 versus IB BAU	**405**	**21**	**743**	**25**
Iberian Peninsula IB 4.1				
Cumulative Investment in renewable power generation (with no fuel demand)	371	19	779	26
Cumulative heating investment: 2020–2040	158	8	202	7
Cumulative fuel costs: 2020–2040	1,463	73	1,647	55
Total cumulative costs: 2020–2040	**1,992**	**81**	**2,628**	**88**
Costs Savings: IB 4.1 versus IB BAU	**669**	**32**	**1,093**	**36**

Table 65: Spain – Cumulative investment costs in power and heat generation and fuel costs between 2020 and 2040 and 2050

	2020–2040 [billion Euro]	Average annual [billion Euro/a]	2020–2050 [billion Euro]	Average annual [billion Euro/a]
Spain ES BAU				
Cumulative Investment in renewable power generation (with no fuel demand)	352	18	428	14
Cumulative heating investment: 2020–2040	142	7	201	7
Cumulative fuel costs: 2020–2040	1,739	87	2,141	71
Total cumulative costs: 2020–2040	2,233	94	2,770	92
Spain				
Cumulative Investment in renewable power generation (with no fuel demand)	365	18	437	15
Cumulative heating investment: 2020–2040	146	7	188	6
Cumulative fuel costs: 2020–2040	1,380	69	1,546	52
Total cumulative costs: 2020–2040	**1,891**	**76**	**2,171**	**72**
Costs Savings: ES 4.0 versus ES BAU	**342**	**18**	**599**	**20**
Spain				
Cumulative Investment in renewable power generation (with no fuel demand)	325	16	389	13
Cumulative heating investment: 2020–2040	137	7	174	6
Cumulative fuel costs: 2020–2040	1,236	62	1,385	46
Total cumulative costs: 2020–2040	**1,699**	**69**	**1,948**	**65**
Costs Savings: ES 4.1 versus ES BAU	**535**	**25**	**822**	**27**

Table 66: Portugal – Cumulative investment costs in power and heat generation and fuel costs between 2020 and 2040 and 2050

	2020-2040 [billion Euro]	Average annual [billion Euro/a]	2020-2050 [billion Euro]	Average annual [billion Euro/a]
Portugal PT BAU				
Cumulative Investment in renewable power generation (with no fuel demand)	46	2	428	14
Cumulative heating investment: 2020-2040	20	1	31	1
Cumulative fuel costs: 2020-2040	361	18	492	16
Total cumulative costs: 2020-2040	**427**	**19**	**951**	**32**
Portugal				
Cumulative Investment in renewable power generation (with no fuel demand)	56	3	437	15
Cumulative heating investment: 2020-2040	25	1	34	1
Cumulative fuel costs: 2020-2040	283	14	336	11
Total cumulative costs: 2020-2040	**364**	**15**	**807**	**27**
Costs Savings: PT 4.0 versus PT BAU	**63**	**4**	**144**	**5**
Portugal				
Cumulative Investment in renewable power generation (with no fuel demand)	46	2	389	13
Cumulative heating investment: 2020-2040	21	1	28	1
Cumulative fuel costs: 2020-2040	226	11	262	9
Total cumulative costs: 2020-2040	**293**	**12**	**679**	**23**
Costs Savings: PT 4.1 versus PT BAU	**134**	**7**	**271**	**9**

6.8.4 Key result Investments and fuel cost savings

For Spain, the cumulative costs of investment in new power and heat generation and total fuel costs between 2020 and 2040 are calculated with Euro 2,233 billion Euro or Euro 94 billion annually on average (Table 65).

In comparison, the ES 4.0 scenario decreases cumulative costs for the same time span by Euro 18 billion per year to Euro 76 billion annually on average.

The ES 4.1 pathway decreases cost even further to Euro 69 billion per year – a cost advantage compared to the ES 4.0 of Euro 7 billion/a and Euro 25 billion per year to ES BAU.

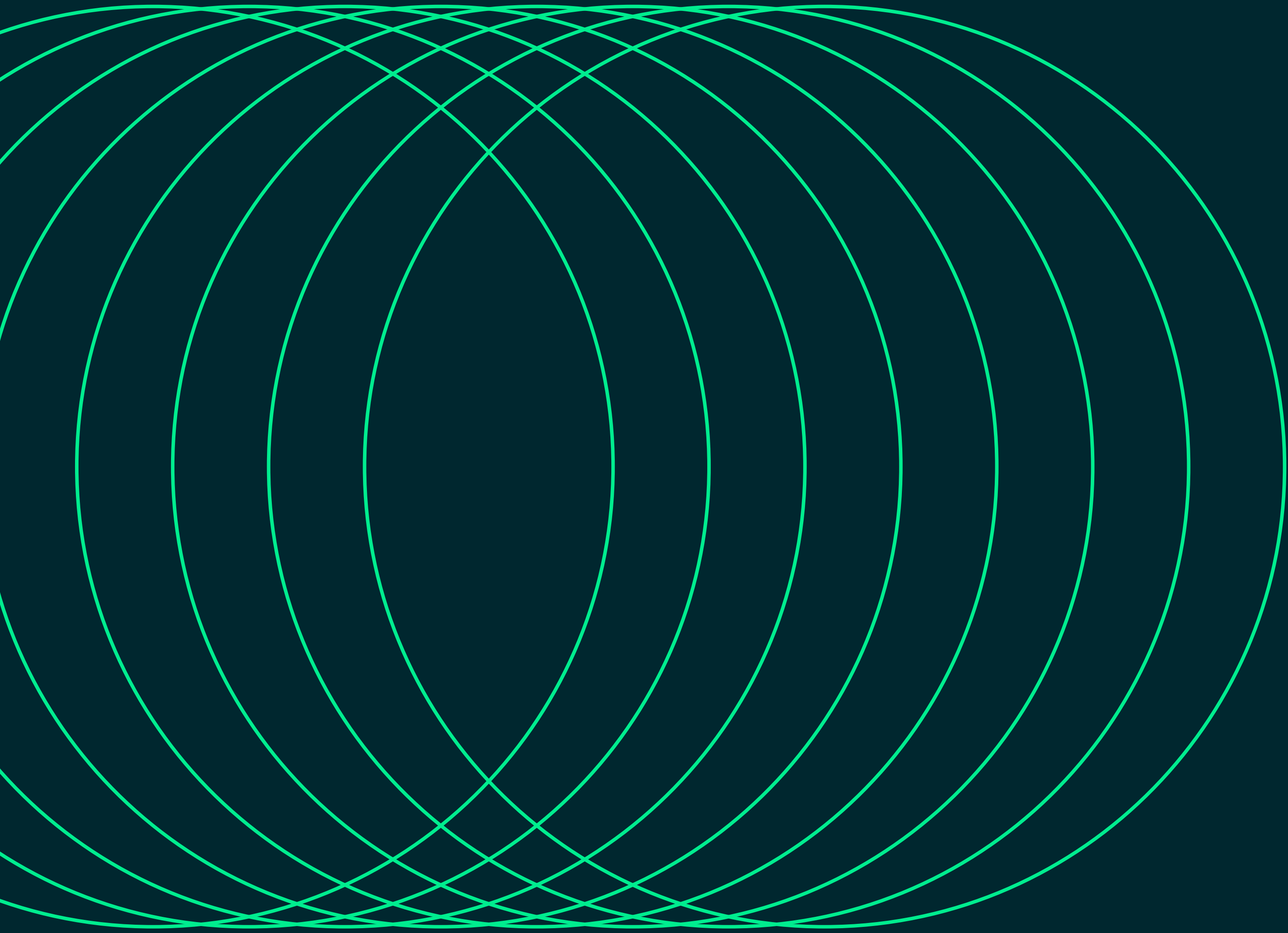
The results for Portugal are similar with annual savings of Euro 7 billions for the PT 4.0 case and Euro 9 billion annually respectively for the PT 4.1 in comparison to the PT BAU case (Table 66).

For the whole Iberian Peninsula, the cost advantage for the IB 4.0 pathway adds up to Euro 405 billion between 2020 and 2040 and Euro 669 billion- Euro 32 billion annually – for the IB 4.1.

The fuel costs savings can finance the entire investment in new power generation across the whole Iberian Peninsula.

7

Iberian Peninsula: Power Sector Analysis



As discussed in section 2 in the 'methodology overview', the energy demand development was calculated with a detailed bottom-up analysis for 20 industry and service sectors, alongside the residential and the transport sector. Based on the demand energy projection, the three energy scenarios were developed using the supply narratives and assumptions outlined. The forecasted levels of solar and wind generation were assessed against the different land use scenarios outlined in section 3, with the analysis demonstrating that there is ample potential to power the Iberian Peninsula across all scenarios. This section analyses the power sector of the Iberian Peninsula with a focus on security of supply and requirements for infrastructural changes and storage requirements, using a regional analysis of demand and supply by region (see section '2.4 Power Sector Analysis – Methodology').

The electricity market of Spain and Portugal experienced significant levels of integration in the early 2000s thanks to several agreements which led to the formation of the 'Mercado Ibérico de Electricidad' in 2007 (MIBEL). The Iberian Peninsula market is in dynamic development with rapidly increasing shares of solar photovoltaic and wind power generation, in addition there have also been recent measures undertaken to help decouple the price of natural gas from electricity.[137] Furthermore, this evolving market context has also been paired with additional policy and technical developments, such as push to modernise the grid and grid management practices, alongside ambitions to expand the level of interconnection the MIBEL has to the rest of Europe.

Section '3.4 Power Utilities' provides an overview of the blackout event that impacted the Iberian Peninsula on the 28th of April 2025. This analysis is valuable in regard to expelling the myths spread about renewable energy in the fallout of the blackout, however, the lasting impact of the blackout will be less about these myths and will be felt more so in the policy and actions which will be undertaken to remedy the system vulnerabilities which provided the underlying conditions for a blackout to occur. This can be seen in the 'report of the committee for the analysis of the circumstances surrounding the electricity crisis of the April 28, 2025' – which highlighted the importance grid modernisation and increasing the strength of interconnection.[138] The report has a number of measures proposed by the Grupo de Trabajo de Operación del Sistem Eléctrico (GTOSE)[139], with a selection of the recommendations listed below:

- **Reinforcement of bodies charged with the supervision of the electrical system** (including regulatory compliance, particularly with voltage and power factor control). This includes the accelerating the re-establishment of the Comisión Nacional de Energía (CNE) which was closed in 2013 as an independent body when it was amalgamated into the Comisión Nacional de los Mercados y la Competencia (CNMC).[140]
- **Technical measures to reinforce the capacities for voltage control and protection against oscillations in the system.** This includes a modification to the legislation of 'procedimiento de operación 7.4' released in June, which is the regulation behind how the complementary service of voltage control is provided in the transmission network.
- **Continue to promote the increase of interconnections with the European system.** With the report highlighting the benefits of interconnection in providing system strength and resilience, e.g. assist with avoiding oscillations and with supply replenishment. The report also highlights that the Iberian Peninsula only has an interconnection capacity of 3% of its installed capacity, which is a far cry from the 15% target established in European regulations.
- **Increased robustness and flexibility of the electric power system.** Including the boosting electric storage across the Iberian Peninsula, promotion of demand flexibility.

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[137] Direção Geral de Energia e Geologia (DGEG), 'Markets and Capacity Mechanisms – MIBEL', <https://www.dgeg.gov.pt/en/transversal-areas/markets-and-capacity-mechanisms/mibel/> , (first accessed 10/6/25)

[138] Spanish Government – Committee for the Analysis of Circumstances that Concurred in the Electricity Crisis, 'Non-confidential version of the report of the committee for the analysis of the circumstances surrounding the electricity crisis of the April 28, 2025', 17th June 2025

[139] The GTOSE is composed of the Secretary of State for Energy, the Director of Energy Policy and Mines, the Director General of Energy Planning and Coordination, the Deputy Director of Electric Energy and the Director of the Institute for Energy Diversification and Saving, with the Director of Energy and the Deputy Director of Electric Energy of the CNMC acting as guests.

[140] MITECO, 'El Gobierno aprueba el Proyecto de ley de restablecimiento de la Comisión Nacional de Energía y lo remite al Congreso para seguir su tramitación' (25/09/240

While the exact implications of the blackout and the subsequent recommendations made by the GTOSE are yet to be seen, it can be envisioned that the electricity system of the Iberian Peninsula will continue to remain an integrated system (between Spain and Portugal), with increased levels of modernisation, regulation, interconnectionand storage. Even though 2040 is only 15 years away, there is a large degree of uncertainty of the extent which the above policy and technology changes will eventuate across the Iberian Peninsula. The following section '7.1 Power Sector Analysis – Modelling Framework and Key Assumptions', provide justification and details regarding the key inputs utilised in the development of the power sector scenarios and the regional power sector modelling. While the following sections details the results of the 24/7 modelling.

7.1 Power Sector Analysis – Modelling Framework and Key Assumptions

Throughout this report a plurality of scenarios were assessed across the mapping of renewable energy potential, as well as the results of the three E4BL scenarios for the Iberian Peninsula: BAU, IB 4.0, IB 4.1. With the Iberian Peninsula results consisting of the summated results of two detailed national scenario assessments for Spain and Portugal. As discussed in section '2.4 Power Sector Analysis – Methodology', the 24/7 power system simulation takes in a range of inputs from the energy scenarios, the renewable energy potential mapping, as well as meteorological data and interconnection constraints.

Beyond this, the 24/7 modelling considers hourly data for a simulated year alongside more granular regional data than the national energy scenarios. Due to these considerations, 24/7 modelling utilises specialised in-house software such as the dispatch engine described in the methodology. This process is more computationally involved, particularly when many regions are considered due to the processing of localised data alongside regional constraints. This process provides rich data on the simulated electricity system and the modelled regions. For the above reasons it is necessary to hone into a select combination of inputs for the 24/7 modelling simulation – both due to the complexity of the modelling task, and to be able to present the array of results in a manner which enables the relevant results to be highlighted. The following paragraphs outline the rationale for the modelling framework utilised for the 24/7 power sector modelling, with the proceeding sub-sections describing an array of inputs and assumptions that also feed into the power sector analysis.

There are a variety of aspects to the 24/7 modelling framework, one of them being the consideration of regions within the modelling boundaries. Sections '1.1.2 Geographic Territory' and '2.4 Power Sector Analysis – Methodology' indicates how modelling undertaken in this study is able to treat the Iberian Peninsula as an integrated region, with Portugal being treated as one of the 18 modelled regions in this study (and thus not treated as a separate international region from an electrical system perspective). This provides one level of integration for the different E4BL scenarios modelled in this report, as it allows the energy scenarios for Spain and Portugal to be simultaneously considered within the same modelling framework. Furthermore, this choice provides more accurate representation of the modelling of the Iberian Peninsula as an integrated electricity system, which aligns with the earlier of integration of the Spanish and Portuguese electricity systems and the common MIBEL energy market.

Another aspect of the modelling framework for the 24/7 simulation is the distribution of the renewable energy capacity. As discussed in section '4 Iberian Peninsula – Renewable Energy Potential', a number of GIS mapping frameworks were used to assess renewable energy potential, namely: technical potential (scenario one), nature compatible (scenario two), nature and agriculture compatible (scenario three). The technical potential outlined by mapping scenario one, provides the maximum possible renewable capacity based solely on a limited number of technical constraints – thus the distribution or renewable capacity in this scenario does not consider the nature of the land classes in which capacity is developed and hence is not consistent with the principles of ecological development of renewables. However, scenario two takes into consideration the land classes of possible renewable development alongside the environmental sensitivity of the land. Thus, scenario two provides a more constrained potential provides both a more accurate and preferable placement of renewable energy generation. As mentioned in section 3 of the report, agricultural land is a vital part to the Iberian Peninsula for several reasons, such as: food production, food sovereignty, export markets, economic activity and GDP, and jobs. Thus, one possible consideration of the 24/7 modelling would be to compare and contrast the differences caused by aligning the distribution of utility solar capacity in line with the mapping of scenario three as opposed to scenario two.

The comparison of the above two distributions of utility solar capacity constitutes a sensitivity test. The contrasting distribution of these cases are shown in appendix '9.3 Renewable Energy & Storage Distribution Used in 24/7 Modelling' alongside a brief description of how the distribution differ. As can be seen by the percentage distribution of utility solar across mapping scenario two and three, there is negligible variation between the principal and sensitivity test simulations This is the case as majority of regions experience a similar reduction in terms of proportion of suitable land under scenarios two and three. For this reason, the ‘Nature and Agriculture Compatible Sensitivity Test’ did not produce novel results relative to the baseline and thus was not included in the 24/7 modelling framework.

In addition to the above choices for the combination of inputs selected for inclusion in the final 24/7 modelling framework, the IB 4.0 scenario for the Iberian Peninsula was selected as the pathway for inclusion in the power sector modelling. The IB 4.0 scenario was selected as it represents the primary pathway for the Iberian Peninsula to achieve its overall carbon budget target without the need for additional sufficiency measures reducing the energy demand associated with transportation and mobility, or to economic sectors. In addition to the pathway’s ability to meet its carbon reduction target, it also serves as a better limiting case for assessing the electricity sector due to its higher electrical demand. Thus, the IB 4.0 scenario will highlight any possible future strain on the electrical network through its modelling of higher demand and capacity e.g. constraints on inter-regional connections within the Iberian Peninsula to transport surplus renewable energy, as well as the international capacity constraints for both exports and imports.

Given the above, two separate 24/7 modelling simulations were included in the final modelling framework for the 24/7 modelling exercise, both leveraging the main pathway to achieve the carbon budget, the E 4.0 scenario. With the simulation being undertaken for the year 2040, to align with the net-zero target being achieved in this timeframe under this scenario. The two simulations are as follows and are summarised in Table 67: (1) Principal Simulation – utilising the IB 4.0 scenario alongside an Iberian Peninsula electrically interconnected to its neighbouring countries, (2) Islanded Iberian Peninsula Sensitivity Test – utilising the same framework as the first 24/7 simulation, with the removal of all international connections to neighbouring countries.

Table 67: Final Modelling Framework for 24/7 Simulation

Simulation Name	Scenario	Year	International Interconnections	Utility Solar & Wind Distribution	Rooftop Solar Distribution
Principal Simulation	IB 4.0	2040	Interconnections as per Section 7.1.2	GIS Scenario 2	Rooftop Potential
Islanded Iberian Peninsula			Interconnection Capacity Removed		

It is noted here that the 24/7 power system modelling excludes the generation capacity and demand associated with H_2, because there is uncertainty as to the extent that these operations would be connected to the electrical system of the Iberian Peninsula (as opposed to off-grid systems), the extent to which H_2 will develop storage capacity alongside renewable energy capacity, as well as the load profile of these operations seen by the grid.

7.1.1 Iberian Peninsula – Regions and Internal Interconnector Limits

The Spanish and Portuguese governments and grid operators do not provide publicly available data on the interconnector limits between states or provide a detailed map of the electricity system. The ‘European Network of Transmission System Operators for Electricity’ (ENTSO-E), does provide a map of high voltage transmission infrastructure across the European continent for lines rated higher than 220 kV.[141] The data from this map provides the basis for the calculation of the internal interconnector limits within the Iberian Peninsula, with the data being represented in a high-level schematic in Figure 7-1, and the details of the interconnection presented in Appendix ‘7.6 List of Internal Line Limits (kV)’. The data from the ENTSO-E map reflects all transmission infrastructure which currently exists, or projects were already under-construction. As the modelling year of 2040 provides sufficient time for the projects currently under-development to be completed, all current interconnections shown in the map were accounted for.

While Figure 7-1 in conjunction with the detailed list of interconnections in Appendix 9.4 List of Internal Line Limits & Reinforcement Assessment (kV), provides a good overview of the internal transmission connections across the Iberian Peninsula, it is not sufficient for the completion of the power sector analysis undertaken in this chapter.

Firstly, not all regions are directly interconnected by network infrastructure, and thus the weakest link in the chain needs to be identified in the interconnection of any two given regions to account for the constraining interconnection limiting the possible power flow between the two areas. This was mapped out for all combinations of regions, such that the maximal possible interconnection value between two regions were taken. Mapping out all interconnections in this way provides

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[141] ENTSO-E, Transmission System Map, <https://www.entsoe.eu/data/map/>

a basis for power sector modelling, however, there are two remaining considerations which need to be accounted for to undertake an accurate simulation of the power system in the Iberian Peninsula:

1. Consideration of the high voltage network between regions not mapped by ENTSO-E (e.g. 66 kV and 132 kV lines)
2. Line ratings conversion factors providing information on the limits of power flow in MW that a single line can carry

This study uses the line ratings outlined in, based on information provided grid operators across both Australian and European contexts, and as used in previous power sector modelling.[142] The values had minor adjustments to ensure alignment with statistics on Spain's and Portugal's interconnections amongst each other and with other nations. With these values specified in Table 68.

Figure 7-1: Schematic of the transmission system interconnections across the Iberian Peninsula

The authors of this report also note that the power carrying capacity of a powerline varies over time and is dependent on several parameters including the outside temperature, the utilisation of the line, the frequency, the physical characteristics of the line, the length of the line and power generation capacity connected to the line. The conversion factors used in this study provide a generalised conversion factor, which was determined to be appropriate for the Iberian Peninsula given the adjustments taken to ensure alignment between the conversion factors and data on the power capacity exchange between countries (given the relevant ENTSO-E data).[143,144]

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[142] Teske, S., Rispler J., Miyake, S. (2024) 'Australia: Aim High, Go Fast: Why Emissions Need to Plummet this Decade. Limiting global warming to 1.5 C', prepared for the Climate Council. by the University of Technology Sydney, Institute for Sustainable Futures; March 2024

[143] ENTSO-E, Transmission System Map, <https://www.entsoe.eu/data/map/>

[144] Red Electrica, 'Interconexión eléctrica subterránea España-Francia', <https://www.ree.es/es/transporte-electricidad/proyectos-transporte/interconexion-electrica-subterranea-espana-francia>,

Table 68: Conversion factors between line rating conversion and limits of power flow in MW

Line Rating (kV)	Max Power Rating per Circuit (MW)
66	75
132	150
220	250
400	455

To deal with the first question, a review of local data was undertaken to see what information on 66kV and 132kV interconnections was publicly available in the Iberian Peninsula. Data from 'Agencia Andaluza de la Energía' (AAE) was found which provided a higher level of information on transmission infrastructure than the ENSTO-E maps. In particular, the 'Mapa de Infraestructuras Energéticas de Andalucía', provided information between Andalucía and the surrounding regions including lines rated at 66kV and 132kV.[145] This data was used to calculate the interconnection limits, and compare them to the constraints based solely on ENTSO-E map in Table 69 (with the ENTSO-E map consisting of 220kV and 400 kV lines).

Table 69: Comparison of Andalucía interconnection limits based on ENTSO-E and AAE maps

Connected 24/7 Regions	Interconnection (MW) Based on ENTSO-E	Interconnection (MW) Based on AAE Map	Percent Increase (%)
Andalucía – Extremadura	2980	3280	10.1%
Andalucía – Castilla-La Mancha	2570	2870	11.7%
Andalucía – Región de Murcia	1365	1515	11%

The data shown in Table 68 demonstrates that accounting for the additional 66kV and 132 kV lines, leads to an increase of at least 10% power flow capacity across Andalucía. This assumption was carried through to the remaining modelled regions on the Iberian Peninsula mainland, excluding Ceuta and the Islas Baleares as the interconnection limits for these regions are well defined. The results of these final calculations are shown in Appendix '9.5 Table of Power Flow Constraints (MW)'.

In addition to the above considerations , initial testing was undertaken to assess possible power flow constraints on the mapped network. This analysis is summarised in Appendix '9.4 List of Internal Line Limits & Reinforcement Assessment (kV)', with the outcomes being reinforcement of three regional interconnections:

- Aragón – Cataluña by 800 MW.
- Comunidad Valenciana – Islas Baleares by 200 MW.
- Andalucía – Ceuta by 100 MW.

It is noted that these reinforcements are not extensive relative to the existing capacity and, furthermore, could be mitigated by a variety of measures in practice. Firstly, the exact development of regional generation and load utilised in this study are merely forecasts based on the IB 4.0 scenario and high-level regional statistics.

Thus, these reinforcements may not actually be required in future (e.g. in a lower demand scenario such as IB 4.1). In addition to this, grid planning bodies such as Red Electrica alongside other regional bodies would look to ensure that each region would have sufficient power supply, and thus investments in targeted generation assets alongside efficiency measures and demand management could also defer the need for the above grid reinforcement. Demand management and optimisation of consumption patterns, such that regional demand coincides with regional renewable generation, would also alleviate the utilisation of inter-regional electrical connections. Furthermore, grid improvements such as upgrades, thermal management, and dynamic line ratings, all could help defer the need for grid reinforcements.

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[145] Agencia Andaluza de la Energía, 'Mapa de Infraestructuras Energéticas de Andalucía', <https://www.agenciaandaluzadelaenergia.es/MapMiea/> (last updated 30/06/2025)

7.1.2 Iberian Peninsula – International Interconnector Limits

The previous section details the internal interconnections within the Iberian Peninsula. However, as discussed by the GTOSE in the 'report of the committee for the analysis of the circumstances surrounding the electricity crisis of the April 28, 2025', international interconnections play an important role in avoiding the circumstances which led to the blackout event. The report also states that there needs to be a marked increase in interconnection capacity for the Iberian Peninsula to approach the levels set out by European targets (3% of installed capacity, relative to 15% target).

Given the above context, the handling for international energy exchanges in the 24/7 model were improved to increase the accuracy of how the model accounts for the interconnections and constraints of the interconnections with neighbouring countries. In addition to improving the model, the ENTSO-E's 'Ten-Year Network Development Plan' (TYNDP) was reviewed to assess what transmissions projects have the potential to be developed between now and 2040 (the year chosen for the power sector analysis).[146] A summary of the existing international interconnection is provided in Table 70 while transmission projects currently under development under the TYNDP are detailed in Table 71.

Table 70: Existing international interconnections

Connected 24/7 Regions	Capacity/Rating (incl. multiple circuits)
Andalucía – Morrocco	1400 MW
País Vasco – France	1x 135 kV 1x 220 kV 1x 400 kV
Aragón – France	1 x 220 kV
Cataluña – France	1x 400 kV 1400 MW DC

It is assumed that all transmission infrastructure in Table 70 gets built by 2040, given the need for the Iberian Peninsula to expand its interconnection capacity. Given the strong level of domestic interconnection within the Iberian Peninsula, the main assumption is not whether a specific project is built by 2040, but more so that the Iberian Peninsula is able to achieve the increase in interconnection capacity in this time frame (e.g. if the 'Apollo Link' project does not get built, but another 2 GW international interconnector is established, then the results of the power sector modelling would still be applicable).

Table 71: International interconnections under development

Project Name	Connected 24/7 Regions	Capacity/Rating (incl. multiple circuits)	Expected Completion
Interconexión con Andorra	Cataluña – Andorra	2x 220 kV	~ 2026
TR 16 – Biscay Gulf	País Vasco – France	2000 MW	~ 2028
TR 1210 – APOLLO-LINK	Cataluña & Italy	2091 MW	~ 2032
Interconexión con Marruecos (3rd)	Andalucía – Morrocco	700 MW	~ 2026
TR 276 – FR-ES project – Navarra-Landes	Foral de Navarra – France	2000 MW	~2036
TR 270 – FR-ES project – Aragón-Atlantic Pyrenees	Aragón – France	2000 MW	~2040

As noted in section '2.4 Power Sector Analysis – Methodology' there are limitations to the dispatch engine of the 24/7 model:

1. Dispatchable power is only called upon to fill supply gaps in the Iberian Peninsula and thus does not get dispatched in cases where there is a supply gap in a neighbouring country (e.g. France).
2. Utility storage only interacts with its nearest neighbouring regions, both in regard to storage of surplus generation and dispatch of stored energy (within the boundaries of the Iberian Peninsula)
3. Demand reduction is the only form of demand response modelled in the power sector analysis, and thus other forms such as shifting usage to another period are not modelled here.

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[146] ENTSO-E, TYNDP 2024 Project Sheets, <https://tyndp2024.entsoe.eu/projects-map/transmission>

Given the above limitations in the export from the Iberian Peninsula to its neighbours (dispatchable and utility storage), the full levels of export are underestimated relative to the potential of export as we are not replicating the ability of hydropower or utility batteries to export across the border to France (as an example). The export of stored power across international connections could occur and would happen under the relevant technical or economic conditions. However, as this does not occur in the 24/7 dispatch engine, the model does not produce the energy balance which would naturally occur between the Iberian Peninsula and its neighbouring countries, such that imports and exports would be a similar order of magnitude with a similar sized nation such as France. This is explored in more detail in section '7.7 Results – International Energy Exchanges'.

A positive outcome of this limitation of the dispatch engine, is that it maximises energy independence of the Iberian Peninsula, as excess power generated and stored in the Iberian Peninsula is then saved for consumption later (for example when there is a supply gap within the borders of the peninsula).

7.1.3 Installed Capacity – Solar/Wind Ratio

The key results chapter '6.4 Power Sector', provides an overview of the development of the electricity sector under the three scenarios. In particular Table 48 details the solar and onshore wind capacity which is expected to be needed under each scenario. Behind these values of assumed renewable capacity installation, lie assumptions regarding the solar/wind ratio which will be developed across the Iberian Peninsula. Where the solar/wind ratio is determined by adding both rooftop and utility solar together with onshore wind, to determine the percentage of each onshore variable generator type as a proportion of the total solar and wind installed generation capacity. Offshore wind plays an important role as part of the energy mix of the E4BL scenarios, only onshore wind was chosen for these calculations for several reasons: (1) to allow direct comparison between existing onshore renewable resources and future projections, (2) to allow comparison of scenarios which do not include offshore wind in their projections, (3) to provide a calculation which enables the alignment of land-based wind and solar capacity with projections in the literature based on national trends and other forecast sources. Data from 2023 demonstrates that solar capacity has continued to close the gap that it previously had with wind capacity in Spain, while wind capacity remains dominant in Portugal.[147,148] The values are summarised below in Table 72:

Table 72: Amount of installed solar and wind generation capacity across Spain & Portugal in 2023 [GW]

Country	Solar Capacity [GW]	Wind Capacity [GW]	Solar/Wind Ratio
Spain	32.4	32.1	50%/50%
Portugal	2.6	5.4	33%/67%

Although the data from 2023 serves as usual reference point, the solar/wind ratios are not fixed, and as mentioned the proportion of solar capacity has increased in recent years in Spain. Given that 2040 is less than 15 years away from the present date, there is scope for the solar/wind ratios across both Spain and Portugal to continue to change in line with recent trends (and further, for example if rooftop solar markets can be unlocked across the Iberian Peninsula). A variety of literature sources were reviewed to inform an appropriate selection for the solar/wind ratios used across our scenarios for both Spain and Portugal. [149,150] The results of the literature review is summarised below in Table 73 and Table 74.

Table 73: Literature review of solar and wind capacity installed in Spanish scenarios for 2040

Scenario Name	Solar Capacity [GW]	Wind Capacity [GW]	Solar/Wind Ratio
ENTSOE-E: National Trend	139	80	63%/37%
ENTSOE-E: Distributed Energy	129	91	59%/41%
Climact: Long Term Strategy	134	80	62%/38%

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[147] Red Electrica, 'Installed Capacity 2023', <https://www.sistemaelectrico-ree.es/en/spanish-electricity-system/generation/installed-capacity>

[148] Statista, 'Power capacity installed in Portugal as of December 2023, by source', Original data from REN, (published August 2024)

[149] ENTSO-E, 'TYNDP Visualization Platform', <https://2024.entsos-tyndp-scenarios.eu/visualisation-platform/>

[150] Climact, 2050 Pathways Explorer, <https://pathwaysexplorer.climact.com/pathways>

Table 74: Literature review of solar and wind capacity installed in Portuguese scenarios for 2040

Scenario Name	Solar Capacity [GW]	Wind Capacity [GW]	Solar/Wind Ratio
ENTSOE-E: National Trend	30	13	70%/30%
ENTSOE-E: Distributed Energy	29	13	69%/31%
Climact: Long Term Strategy	25	12	67%/33%

As can be seen in the above tables, the literature and modelling undertaken by other organisations is consistent in the growth of solar energy continuing well beyond its current levels and beyond the values forecasted for 2030 by the official government NECP documents. Based on the above, the scenarios in this study have aligned the solar/wind ratios with the current literature instead of aligning the forecast with the likes of those seen in the 2030 NECPs.

7.1.4 Installed Capacity – Rooftop Solar

Chapters '3.4 Power Utilities and '7.1.3 Installed Capacity – Solar/Wind Ratio' discuss the assumptions and results behind the level of solar capacity installed in the three scenarios. One point not yet discussed is what proportion of solar is expected to be distributed (i.e. rooftop solar – being the most prominent form of this technology). Section '3.3.1 Solar Potential' shows the results from the calculation of the technical potential of rooftop solar using a variety of urban areas:

- Continuous urban fabric (land cover class 1.1.1).
- Discontinuous urban fabric (landcover class 1.1.2).
- Industrial or commercial units (C&I units) and public facilities (land cover class 1.2.1).
- Road and rail networks and associated land (land cover class 1.2.2).

The technical potential from this assessment of technical potential led to a result of ~71 GW across the Iberian Peninsula. This value represents the technical potential based purely on spatial analysis and does not account for limitations on rooftop installation such as local design constraints (e.g. structures and shading), roof space and layout, angle considerations of each rooftop, or the practicality of some installations related to land classes 1.2.1 and 1.2.2. The technical potential also does not account for the determination of which rooftop systems are worth investing from an economic perspective for the buyer, as the economic potential would require assessment of financial benefits of a project to see if there was sufficient payback time for the purchaser. This potential calculation also does not account for the short-medium term barriers of the installation of solar in high-density residential areas such as apartment buildings with shared ownership of rooftop space.

Given the relatively short time horizon of the modelling period (2040), there exists many barriers to the utilisation of rooftop space across the four land classes (practical, design, legal, economic etc.). Given the above, the discontinuous urban areas which mainly consist of low-density residential areas acts as the most readily available area for the continued growth of distributed in the next 15 years (alongside several classes of landcover class 1.2.1 – noting that this land class category also includes 'energy production and distribution facilities).

A potential of 30.3 GW was calculated for the discontinuous urban areas. Utilising this value of ~30 GW as the assumption for the modelling of the Iberian Peninsula's power system in the year 2040 (and excluding solar for H_2 generation), would lead to a ratio of rooftop solar: utility solar of 18%/82% under the IB 4.0 scenario. This value aligns with the available literature, with SolarPower Europe stating that photovoltaic systems <1,000 kW accounted for a similar level of total installed solar capacity in Spain in 2018.[151] While the most recent data from SolarPower Europe shows that in 2024, 14% of the photovoltaic capacity installed in Spain was from rooftop solar.[152]

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[151] SolarPower Europe, 'Global Market Outlook for Solar Power 2019 – 2023'

[152] SolarPower Europe, 'Global Market Outlook for Solar Power 2025 – 2039'

Furthermore, internal modelling undertaken based on Statista data and analysis of previous installation rates of rooftop systems, shows that distributed rooftop solar is not likely surpass 30-35 GW of capacity before 2040 under a medium-high growth assumption.[153] For this reason the contribution of rooftop solar was restrained to ~30 GW despite the fact that it the total potential of distributed generation is much as higher (noting, that of course the same could be said of utility solar as it has a potential many times greater than installed in the IB 4.0 scenario). This is not to discount the distributed solar potential from continuous urban fabric areas or non-rooftop space in discontinuous areas (e.g. green spaces such as community gardens, small paddocks in semi-urban areas or holdings of land which may be suitable for the deployment of small-scale solar). For this reason, the rooftop solar modelled in the 24/7 simulation follows a distribution of the potential mapped using all land classes (1.1.1, 1.1.2, 1.2.1, 1.2.2).

7.1.5 Storage Capacity and Demand Flexibility

As mentioned in earlier sections of the report, the operation and management of the Iberian electricity system will need to be upgraded and modernised with increasing penetration of variable renewable energy. The importance of this was acknowledged by the GTOSE in their analysis of the blackout event. In addition to this, the GTOSE also acknowledges the importance of having sufficient levels of energy storage as well as demand flexibility in the system. Table 75 below summarises the assumed levels of storage capacity under the IB 4.0 scenario in 2040, and the reference for the assumption.

For the projection of utility storage capacity, data was taken from the NECPs and from Red Electrica, to provide a basis for existing capacity and forecasted storage capacity by 2030. For the projection until 2040, two steps were undertaken:

(1) assume that all utility storage capacity which is currently under development or has a project proposal under review is built by 2035 (2) apply the same growth rate between the 2030 & 2035 capacity values, for the calculation of the 2040 capacity. Where the values were based on the Energía 3.0 report, appropriate scaling was undertaken to reflect the potential for the Iberian Peninsula. For the distributed storage associated with EVs, both population and uptake of EVs amongst the population was considered. For the demand response category, scaling was undertaken to reflect the underlying driver in terms of statistical data (population, GDP) alongside considerations of the initial study and the proportion of each technology relative to total capacity.

Table 75: Assumed levels of storage capacity under the IB 4.0 scenario in 2040*

Technology	Storage/Flexibility Type	Capacity [GW]	Source
Residential Battery	Distributed	1.9	Compound growth calculation154
Electric Vehicle (V2G)	Distributed	120	E 3.0 report calculation155
Utility Scale Battery	Utility	40	Aligned with Red Electrica Data156
Hydro Pump Storage	Utility	13	Red Electrica Data & NECPs157
Buildings Demand Response	Flexibility	42	E 3.0 report calculation158
Industry Demand Response	Flexibility	16	E 3.0 report calculation159

*The distribution of the main sources of storage are shown in appendix 9.3, with other categories distributed according to relevant parameters i.e. population, land distribution, GDP.

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153 Statista, ‘Cumulative capacity of residential solar photovoltaic systems in Spain from 2017 to 2024’,

154 McKinsey, ‘How Europe’s residential BESS industry can navigate global competition’, <https://www.mckinsey.com/industries/industrials-and-electronics/our-insights/how-europes-residential-bess-industry-can-navigate-global-competition>

155 Greenpeace Spain, ‘Energía 3.0 – un sistema energético basado en inteligencia, eficiencia y renovables 100%’ (September 2011)

156 Red Electrica, ‘datos de capacidad de accesso de instalaciones (MW)’, accessed via El Periodico de la Energia, https://elperiodicodelaenergia.com/boom-de-baterias-en-espana-mas-de-22-gw-de-proyectos-han-pedido-conectarse/ (note: this data does not include Portuguese Capacity)

157 Ibid., (in conjunction with previously referenced NECPs for Spain and Portugal)

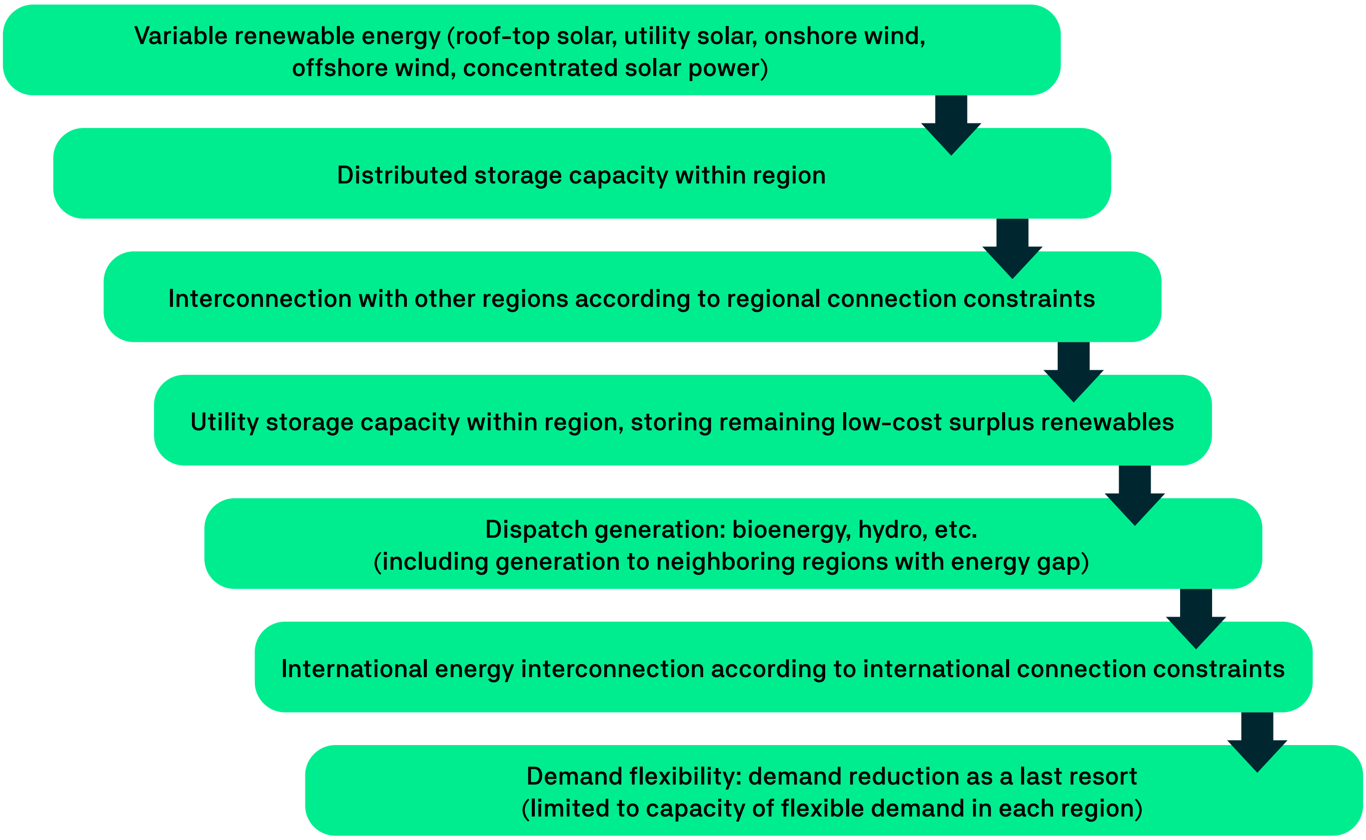
158 Greenpeace Spain, ‘Energía 3.0 – un sistema energético basado en inteligencia, eficiencia y renovables 100%’ (September 2011)

159 Greenpeace Spain, ‘Energía 3.0 – un sistema energético basado en inteligencia, eficiencia y renovables 100%’ (September 2011)

It is noted here that demand response category acts for a load which can be reduced or turned off when given the appropriate signal by a grid operator, electricity retailer or third-party aggregator. This is the only form of demand response modelled in the power sector analysis, and thus forms of demand response such as shifting usage to another period are not modelled here. Demand flexibility is used as a last option and is only implemented in line with the limits listed above, with the proportion based on a regional allocation of buildings and industry.

Demand reduction is implemented as the last option in the 24/7 model and can thus be viewed as an additional last step in the dispatch order in the event there is a demand mismatch within flexibility limits. With the consideration of demand flexibility, the final dispatch order is depicted in Figure 7-2:

Figure 7-2: Depiction of dispatch order used in 24/7 modelling



7.2 Results – Maximum Load, Generation, Residual Load

The table below shows maximum, minimum and average load in GW for the year 2040, alongside annual demand in GWh for each region.

Table 76: Demand summary for the IB 4.0 scenario

Region Names	Annual Demand [GWh]	Max Demand [GW]	Min Demand [GW]	Average Demand [GW]
Cas. y León	41,596	6.3	3.9	4.7
Galicia	26,627	4.3	2.5	3.0
Asturias	9,757	1.6	0.9	1.1
Cantabria	5,502	0.9	0.5	0.6
País Vasco	20,674	3.4	1.9	2.3
La Rioja	3,782	0.6	0.4	0.4
Navarra	8,215	1.3	0.8	0.9
Aragón	22,982	3.5	2.1	2.6
Cataluña	72,172	11.6	6.7	8.2
Valenciana	42,982	7.2	3.9	4.9
Baleares	10,973	1.8	1.0	1.2
Murica	13,747	2.3	1.2	1.6
Cas. Mancha	34,930	5.3	3.2	4.0
Madrid	64,390	10.5	5.9	7.3
Extremadura	17,689	2.7	1.6	2.0
Portugal	100,292	16.0	9.3	11.4
Andalucía	79,563	12.8	7.2	9.1
Ceuta	527	0.1	0	0.1

The table below summarises maximum demand and generation. Peak load and peak generation events do not appear at the same time, so the values cannot be simply compared or added to provide a total maximum value. Moreover, the timing of peak loads varies across all regions. Residual load is the load remaining after local variable renewable generation within the analysed region is exhausted (i.e. load – wind – solar generation, for a given region in a given time interval). The maximum residual load shows the maximum undersupply in a region and indicates the gap which would be filled through storage, dispatchable power sources (i.e. hydropower or bioenergy), or through interconnection.

Table 77: Maximum demand and generation, alongside residual load

Region Names	Max Demand [GW]	Max Generation [GW]	Max Residual Load [GW]	Dispatchable & Utility Storage Capacity [GW]*
Cas. y León	6.3	37.4	5.6	10.2
Galicia	4.3	7.7	3.6	4.3
Asturias	1.6	1.6	1.3	0.6
Cantabria	0.9	1.4	1.1	0.9
País Vasco	3.4	1.8	3.9	0.4
La Rioja	0.6	1.9	0.5	0.4
Navarra	1.3	3.9	1.1	0.7
Aragón	3.5	14.9	3.1	4.1
Cataluña	11.6	10.4	10.4	4.0
Valenciana	7.2	9.2	5.9	5.4
Baleares	1.8	2.7	1.5	0.5
Murcia	2.3	5.4	2.3	1.2
Cas. Mancha	5.3	23.6	4.7	7.1
Madrid	10.5	3.3	10.2	0.5
Extremadura	2.7	7.1	2.4	4.3
Portugal	16.0	32.9	13.6	17.8
Andalucía	12.8	30.0	10.3	8.2
Ceuta	0.1	0.1	0.4	0.0

*Excluding distributed storage.

There are some cases in the above where the residual load left after the supply of variable renewables is greater than sum of the dispatchable and utility storage capacity provided by hydropower and utility scale batteries (e.g. Cataluña with a maximum residual load of 10.4 GW and dispatchable power reserves of 4 GW). This does not imply that Cataluña experiences issues with supply adequacy in terms of the region having enough power for its demand. Although Cataluña is more reliant on neighbouring regions during periods of low renewable supply, it needs to be remembered that there is also significant amount of distributed storage resources in regions (particularly from EVs with V2G capacity), with Cataluña having distributed storage capacity of 17 GW. As these low renewable periods may also coincide with limited stored energy, Cataluña will also rely on the 5.8 GW of import capacity between neighbouring regions of Aragón & Valenciana to have sufficient capacity to cover this load in periods of high demand and low local renewable generation. In addition to dispatchable storage, local distributed storage capacity, and imports from neighbouring regions – Cataluña also has ~ 2 GW of international exchange capacity with France to support its demand needs when required.

As the Principal Simulation does not have unserved supply gaps, it can be concluded that the above-mentioned forms of generation, storage, power exchange – in conjunction with demand flexibility – is sufficient to power the Iberian Peninsula. Thus, the residual load of regions is not an indication of risk of blackout, but a consequence of having an interconnected Iberian power system reliant on variable renewables and the storage of said generation across both the utility and distributed sectors.

7.3 Results – Additional Analysis of Generation

As discussed in earlier chapters, the IB 4.0 scenarios provides the overall pathway for the Iberian Peninsula to achieve net-zero emissions by 2040, and at the same time achieve a fair-allocation carbon budget. From the bottom-up modelling of demand, it is possible to develop a forecast of electrical demand and based on this demand develop supply scenarios. Section '6.4 Power Sector' outlines the supply scenario developed for the IB 4.0 scenario. The supply scenario was developed with several considerations such as having a solar/wind ratio aligned with the literature to reflect the direction the Iberian Peninsula system can be expected to take under an accelerate net-zero transition, alongside the need to have sufficient diversity of generation sources to ensure an adequate supply.

In respect to the last point, the capacity in GW is developed based on assumptions of capacity factors for each generation type alongside the allocation of expected generation under the scenario. With either capacity [GW] or generation [GWh] able to be adjusted according to the required parameters. This step is completed without an assumption regarding the contribution's battery storage will be able to make in the scenario, as the level of storage is dependent on a number of factors: load profile, variable generation profile (weather dependent), and the dynamic interplay of these two factors alongside the regional storage capacity and transmission constraints. Thus, an energy scenario cannot 'know' *a priori* the role of storage.

Given the above context, the full results of the Principal Simulation 24/7 are presented in Table 78. Reflecting the total capacity assumed under the 4.0 scenario alongside the extent to which they are called upon to generate power for households and businesses in the generation column. Noting that this generation includes power which is exported outside of the Iberian Peninsula regarding variable renewable energy.

Table 78: Total Capacity and generation across the Iberian Peninsula under the Principal Simulation

Technology	Total Capacity [GW]	Generation [GWh]
Rooftop photovoltaic	30	46,372
Utility photovoltaic	134	210,109
Onshore Wind	103	355,629
Offshore Wind	9.4	38,602
CSP	16	1,853
Hydropower	15	21,639
Geothermal	0.7	323
Bioenergy	1.4	1,030
Other Renewables (e.g. Ocean, Fuel Cell)	7.7	1,219
Co-Generation	3.8	1,117
Distributed Battery	1.9	1,572
Electric Vehicle – V2G	120	30,593
Hydro Pump Storage	13	3,868
Utility Battery	40	3,908

Table 78 addresses concerns which may be raised regarding the inclusion of a variety of dispatchable renewable sources such as geothermal power or biomass generation in section '6.4 Power Sector'. Particularly as the standard capacity factor approach utilises assumptions about the run time of each generator type and thus the generation which would occur throughout the year in GWh. This chapter is thus provided to negate to the concerns relating to the utilisation of these forms of power which may not be considered as desirable from either a techno-economic perspective or an environmental perspective.

The 24/7 model can shine light on this matter, as it captures the role of stored surplus energy from solar and wind generators alongside and collates the generation across each generator type throughout the year (given the dispatch order). In short, both geothermal and biomass power generation play a negligible role in supply demand throughout the year under the IB 4.0 scenario. Geothermal power was called upon to provide 323 GWh throughout the year, which equates to <0.1% of the required generation throughout the year. Likewise, biomass was only called upon to supply 1,030 GWh throughout the year, which equates to <0.2% of the required generation throughout the year.

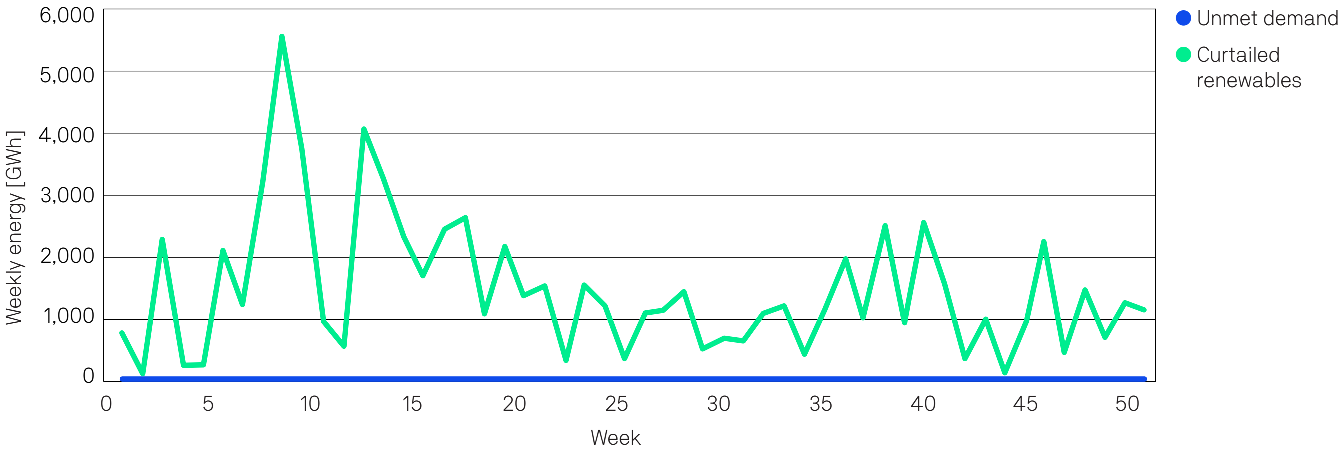
7.4 Results – Analysis of Supply Adequacy

While the tables in section '7.2 Results – Maximum Load, Generation, Residual Load' provides an overview of the maximal values of demand, generation, and the residual load for each region, it does not indicate the level of supply adequacy of the IB4.0 scenario (supply adequacy being the extent to which the scenario ensures that regional demand is met throughout the year).

As discussed above, peak load and generation events are not concurrent and thus do not provide an accurate insight into supply adequacy. Furthermore, the maximal values do not provide insight into what is occurring outside these edge case periods. For this reason, the below figures were plotted. Figure 7-3 provides insight into the hourly modelling simulation, by summing the values of unmet demand and that of curtailed renewables for every week in the year. Where unmet demand is demand not able to be met through generation, interconnection with other regions or countries, or through demand flexibility measures. Curtailed renewables reflect the value of renewable energy which cannot be stored or exported.

It should be noted that availability of storage is restrained in the 24/7 mode such that distributed storage capacity is only available to store excess generation in the region of origin (i.e. EVs with V2G technology cannot store surplus generation from a neighbouring region). For this reason the large capacity of V2G EVs is rarely utilised to a significant extent as EV ownership coincides with population, and thus with electrical demand (making surpluses less likely in populated areas).

Figure 7-3: Weekly Values of Unmet Demand and Curtailed Renewables



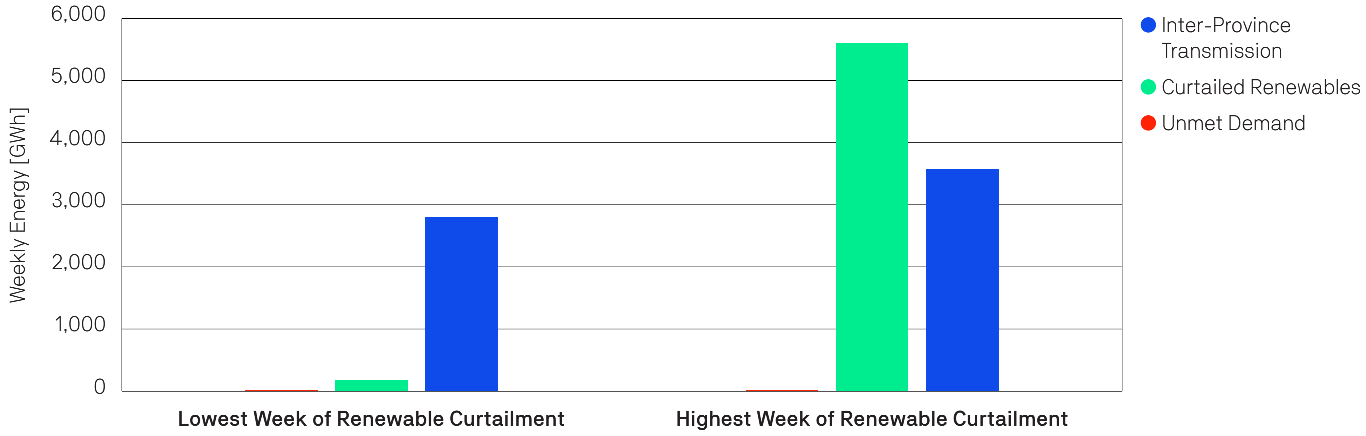
As can be seen in Figure 7-3, the IB 4.0 scenario has no unmet demand and thus provides a complete coverage of the demand across all regions for each week in the 2040 simulation. This occurs thanks to a combination of all generation sources, storage, interconnection and demand flexibility. As shown, there are several weeks of noticeably high surplus renewables which are unable to be stored or exported (equivalent to curtailed renewables in the model).

Throughout the year 11.5% of total generation is curtailed in this scenario, which is a good outcome for a completely decarbonised system relying primarily on variable renewables and storage (particularly when considering that limited forms of demand management explicitly modelled – only demand reduction, as opposed to other forms of shifting).

Furthermore, the curtailment is primarily driven by a handful of weeks with consistently high wind speeds, such that storage capacity is not significantly called upon to cycle between generation and storage (remaining full), which thus leads to spilling of excess renewables. Figure 7-4 shows the variance across the year regarding the curtailment of renewables. As discussed in section '6.1.5 Storage Capacity & Demand Flexibility' other forms of demand response such as shifting usage to another period are not modelled here.

As mentioned earlier in this section, distributed storage provides an untapped opportunity to store this surplus generation but is constrained from doing so in the 24/7 model. This was assumed because a significant level of co-ordination of distributed storage services would be required to achieve the absorption of surplus utility generation, and this would require business model arrangements such as 'virtual power plants' to facilitate the co-ordination. It was outside the scope of this study to accurately the assess the potential for energy retailers, and third-party aggregators to co-ordinate distributed storage in a manner that would help to absorb surplus renewables from across the Iberian Peninsula.

Figure 7-4: Lowest and Highest Weeks of Renewable Curtailment



The above figure also shows that in weeks of higher surplus generation there is more inter-province transmission of energy within the boundaries of the Iberian Peninsula, conversely, this shows that there exist spare transmission capacities in the lower periods of surplus.

Furthermore, the inter-province values do not include the transmission capacities of international interconnections. It should also be noted that not all curtailment is inherently negative, and in fact there are levels of economic curtailment which are beneficial to a system with high levels of variable renewable energy. This is because other forms of generation and storage are more costly than wind or solar energy, either from a capital cost or operational cost perspective (recalling that the marginal generation cost of wind and solar are effectively zero given there are no fuel costs associated with generation).

7.5 Detailed Supply Balance Analysis – Lowest and Highest Curtailment Weeks

While Figure 7-3 demonstrates the differences in weekly levels of generation and demand, it does so only for surplus generation and unmet demand. The hourly level supply balance for the lowest and highest curtailment week are shown below in Figure 7-5 and Figure 7-6, for the weeks of lowest and highest curtailment, respectively.

Figure 7-5: Hourly supply balance – lowest week of renewable curtailment

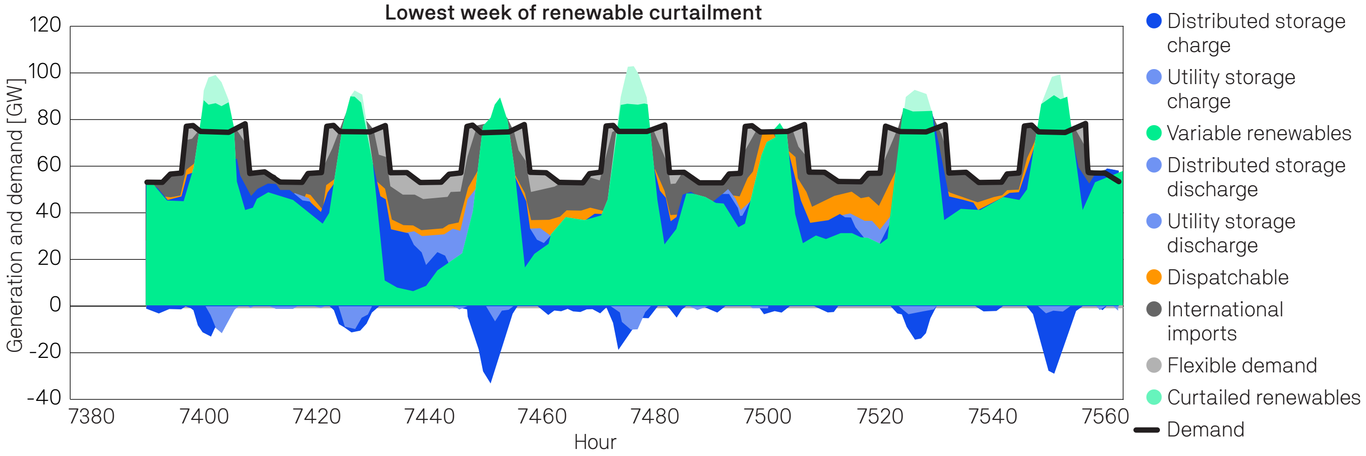
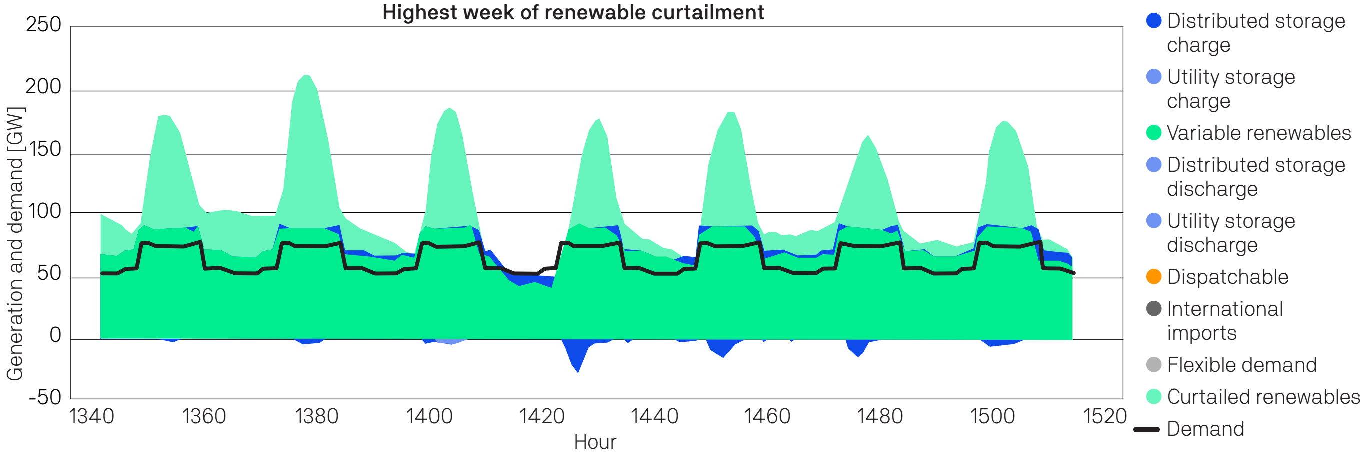


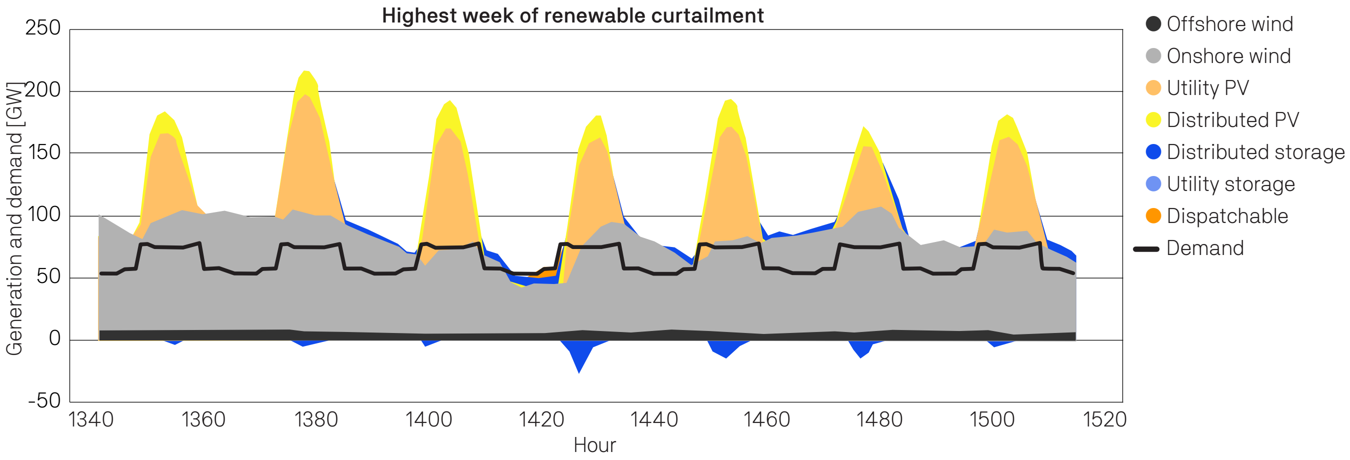
Figure 7-6: Hourly supply balance – highest week of renewable curtailment



A comparison of Figure 7-5 and Figure 7-6 reveals the stark differences between periods of high solar irradiation and wind speeds relative to weeks with the opposite conditions. In Figure 7-5, storage generation, alongside international imports, and demand flexibility are all used to a significant extent to cover for a week of poor wind speeds. Any further reduction of generation in this period would lead to levels of demand reductions beyond that forecasted to be available and thus require brown outs by grid operators (the forced reduction of load in a controlled manner to avoid widespread blackouts). For this reason, there are high levels of surplus generation in other weeks when there are high wind speeds.

As can be seen in Figure 7-3, the week with the highest curtailment comes after several consecutive weeks of high curtailment. This is reflected in Figure 7-6, where battery storage remains more or less full for the first three days in the week, prior to any storage dispatch being required mid-week. This finding also demonstrates that significant amounts of curtailment may be required in a given week as it would be uneconomic to have excess storage capacity which would be redundant apart from its ability to absorb surplus in weeks of consistently high wind speeds and good solar irradiance. Noting: that the levels of storage modelled in the IB 4.0 scenario already provide coverage of the load across the Iberian Peninsula (alongside international interconnections and demand flexibility). It should be noted here that although it looks there is excessive solar production during this week, it actually caused by a week with very strong and consistent very high wind speeds, as can be seen in Figure 7-7

Figure 7-7: Hourly supply balance with breakdown of renewable generation – highest week of renewable curtailment



The above figures provide some insight into the extent of energy exchange internationally. However, it does not provide insight into regional transmission or provide detail of international exchanges, which is explored in the following two sections.

7.6 Results – Inter-Regional Energy Exchanges

Figure 7-8 shows weekly summed value of energy exchange across the 18 modelled regions, while Figure 7-9 provides a breakdown by region, and by import/export values. Figure 7-9 clearly demonstrates the regions which are high net-exporters to other regions due to high potential and low load (i.e., Castilla y León, Castilla-La Mancha, and Aragón), as well as the regions of the Iberian Peninsula which import electricity from these regions (e.g. Madrid, Cataluña).

Figure 7-8: Weekly values of inter-province transmission

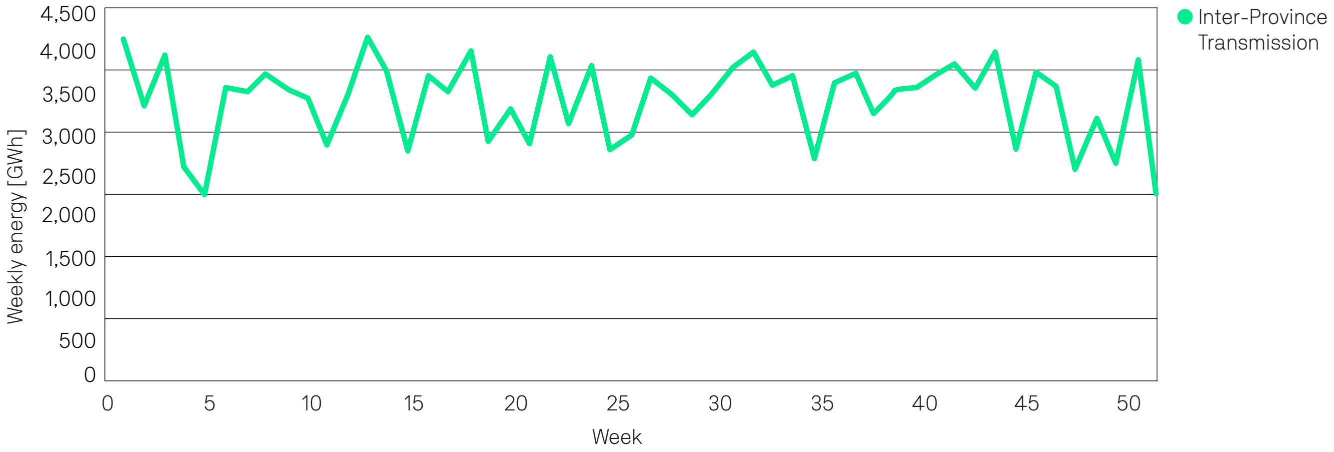
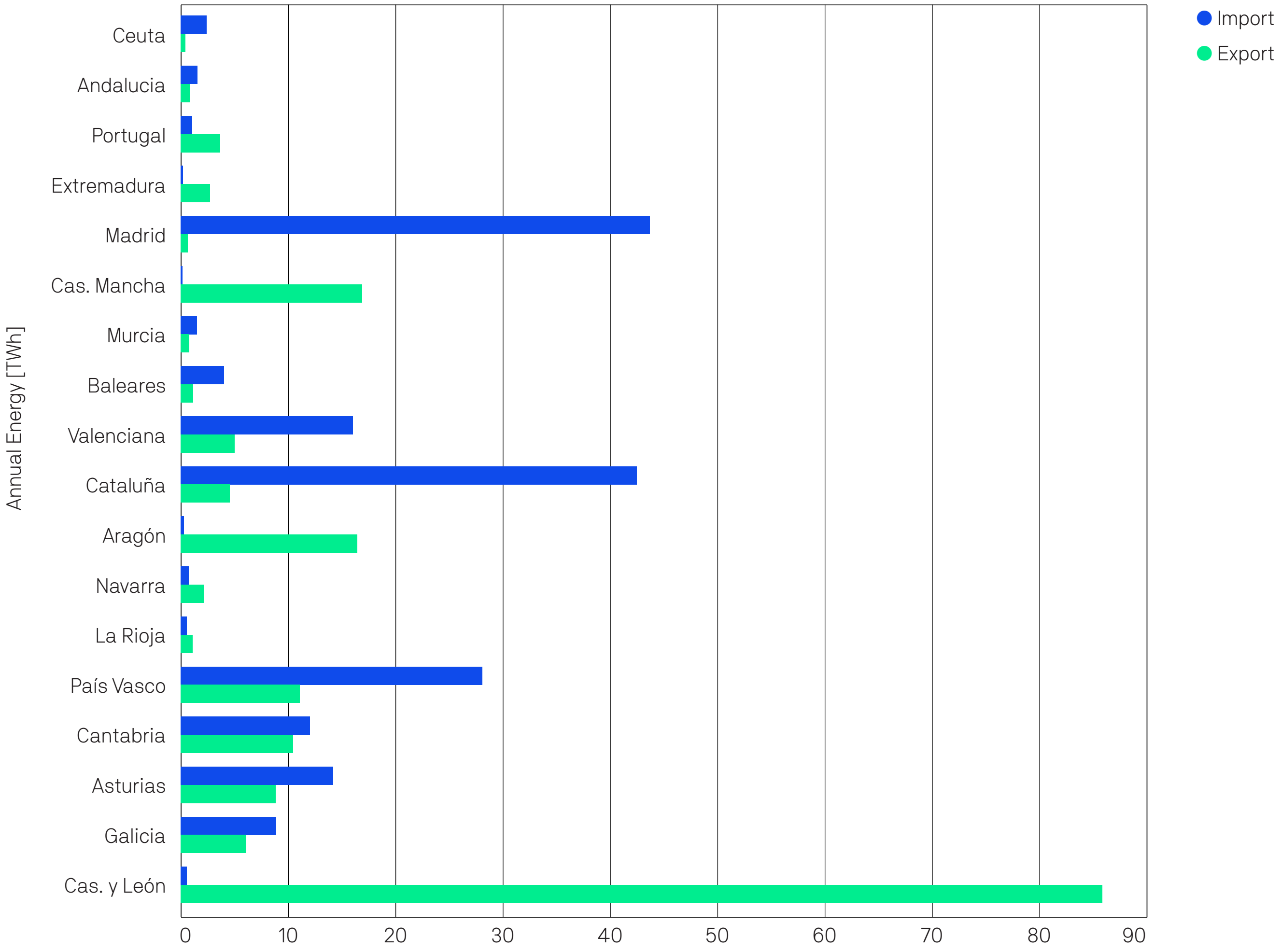


Figure 7-9: Annual values of inter-province transmission – broken down by region, and by import/export values



7.7 Results – International Energy Exchanges

As discussed by the GTOSE in the 'report of the committee for the analysis of the circumstances surrounding the electricity crisis of the April 28, 2025', international interconnections play an important role in avoiding the circumstances which led to the blackout event. For this reason, the handling of international interconnections was improved for this report to disaggregate international exchanges amongst the different nations and improve the accuracy of how exchange limits were handled for each interconnection.

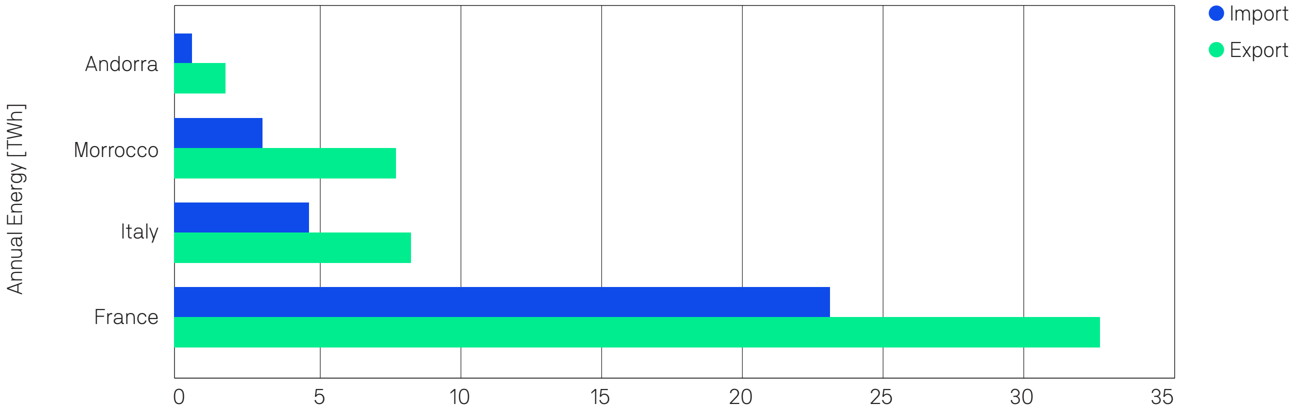
Prior to discussing these results, it should be remembered that the fixed dispatch order for the 24/7 modelling undertaken for the IB 4.0 scenario was (Figure 7-2):

1. Variable Renewable Energy (rooftop solar, utility solar, onshore wind).
2. Distributed Storage.
3. Inter-Province Interconnection.
4. Utility Storage.
5. Dispatch Generation (Hydropower, Bioenergy).
6. International Interconnection.
7. Demand Flexibility.

This was chosen to represent how a future renewable Iberian Peninsula could interact with an increasingly renewable world, aiming to maximise the use of variable renewable energy generation across regions and across countries, before calling on the dispatchable supply such as bioenergy.

While Portugal is a net-exporter to its neighbouring Spanish regions, it can be seen that Spain is also a net-exporter to neighbouring countries outside of the Iberian Peninsula thanks to its large renewable energy potential and the forecasted upgraded exchange capacity. This is reflected in Figure 7-10, where it can be seen that the Iberian Peninsula as a whole has a positive export balance to all four interconnected countries:

Figure 7-10: Annual international transmission flows



The total value for energy imports into the Iberian Peninsula was calculated to be 31.18 TWh for 2040, while the value for total exports was calculated to be 50.08 TWh. This equates to the Iberian Peninsula exporting 160% of the energy it imported from its European neighbours over the course of the year. As mentioned, this level of exports possible due to the large renewable energy potential and the forecasted upgraded exchange capacity available to the Iberian Peninsula – alongside a strong build out of renewable energy capacity which includes over capacity to account for lulls in production during low wind periods.

This level of export represents a large increase relative to current levels of export, on the order of double current levels.[160] It is not guaranteed that this will eventuate, the Iberian Peninsula becoming a 'renewable energy superpower' is dependent on investments in local renewable energy generation capacity as well as investments in international transmission infrastructure.

Much like exports, imports also experiences an increase by 2040 under the IB 4.0 scenario. Like exports, the growth of imports is also dependent on the necessary international transmission infrastructure being financed and built in this time frame. While imports grow substantially under thIB 4.0 scenario, it is important to contextualise the value of import relative to the demand of the Iberian Peninsula, noting that the demand of the Iberian Peninsula also grow significantly in this same period.

Figure 7-11, shows that level is on the same order of magnitude of historical levels of import (4.9% vs 5.4%). As discussed in previous sections, this increase in imports is in line with EU policy recommendations and those made by the GTOSE in the aftermath of the blackout i.e. that the Iberian Peninsula should continue to strengthen its international connections, and more from the current level of 3% of installed capacity towards EU targets of 15%.

Figure 7-11: Comparison of levels of import on a percentage basis relative to electrical demand – historical 2023 values vs 2040 projection under the IB 4.0 scenario[161]

While the imports in the above section are deemed to be acceptable under the high demand growth IB 4.0 scenario alongside increasing levels of interconnection capacity, the question of energy independence may still be raised by some within Spain and Portugal.

The idea of energy sovereignty or electricity independence is at odds with calls for greater connectivity for the Peninsula's electricity network which is already quite isolated relative to other European nations regarding its transmission capacity.

The 'Islanded Iberian Peninsula' scenario was modelled to explore what would occur to the Peninsula's electricity system based under the same set of conditions of the 'Principal Simulation' modelled above – with the only parameter adjusted being the removal of international interconnections. The key results from this simulation are shown below in section '7.8 Results – Islanded Iberian Peninsula'.

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[160] Red Eléctrica Summary Cross-Border Electricity Exchanges 2023, https://www.sistemaelectrico-ree.es/en/2023/spanish-electricity-system/exchanges/cross-border-electricity-exchanges.

[161] *Ibid.*

7.8 Results – Islanded Iberian Peninsula

Table 79 summarises the outcomes of islanding the Iberian Peninsula relative to the Principal Simulation. Several points can be clearly seen through the table, namely that under the Islanded Simulation there is a supply gap which cannot be met using renewables, storage, or demand flexibility. The islanded scenario experiences an overall unmet demand of 124 GWh throughout the year, or 0.02% of annual demand. This value appears to be negligible; however, this does not consider the prominent role that demand reduction through demand flexibility plays in the Islanded Simulation.

Under the Principal Simulation, demand reduction through flexible demand enabled devices and businesses accounts for only 0.8% of demand (4,756 GWh throughout the year). Thus, under the Principal Simulation, demand flexibility plays a negligible role which helps to scales back demand in periods of time when some regions experience high load simultaneously with poor generation conditions for renewables.

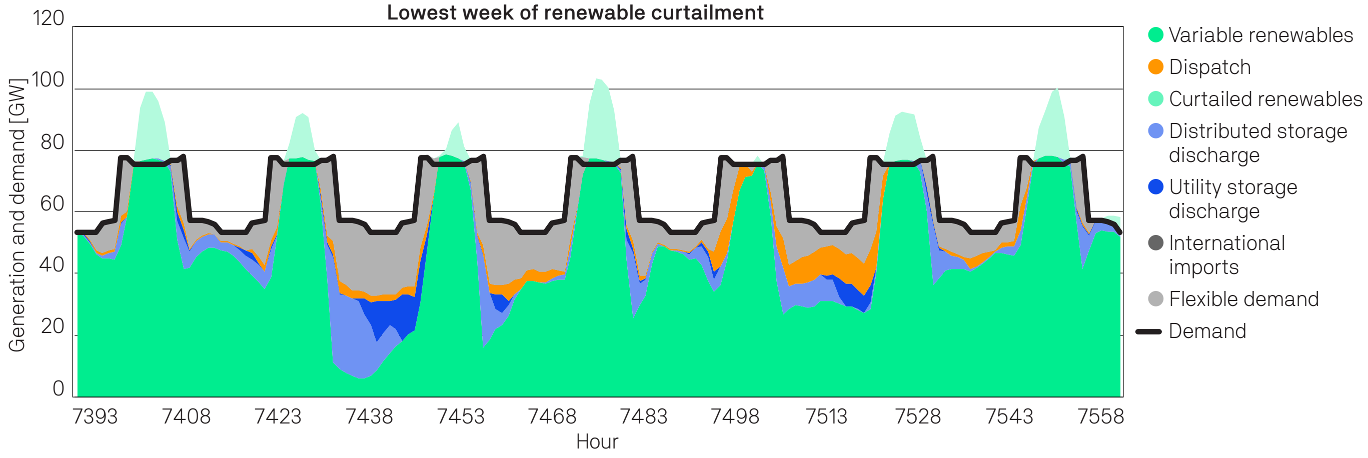
The same cannot be said about the Islanded Simulation, where demand flexibility grows by a factor of 7.5 times, to a value of 35,833 GWh throughout the year. This value of demand reductions accounts for 6.2% of demand in the Iberian Peninsula. This moves beyond the spirit of demand flexibility as a tool available to grid operators and retailers to help manage the grid in edge cases of supply and demand mismatch – or by aggregators and consumers responding to price signals provided through retail contracts and the electricity market. Under the Islanded Scenario more than six out of every 100 hundred units of electrical demand must be suppressed because there is insufficient generation in the Islanded Simulation. The substantial role that 'demand flexibility' plays in compensating for the lack of international imports can be clearly seen in Figure 7-12.

Table 79: Comparison of Islanded and Principal Simulations

Parameter	Islanded Simulation	Principal Simulation
Annual Unmet Demand [GWh]	124	0
Unmet/Total Demand	0.02%	0%
Maximum Unmet Demand Value [GW]*	2.5	0
Reliance on Demand Flexibility [GWh]	35,833	4,756
Reliance on Demand Flexibility [%]	6.2%	0.8%
Curtailed Renewables/Generation	19.0%	11.5%
International Import [GWh]	0	31,183
Import/Demand	0%	5.4%

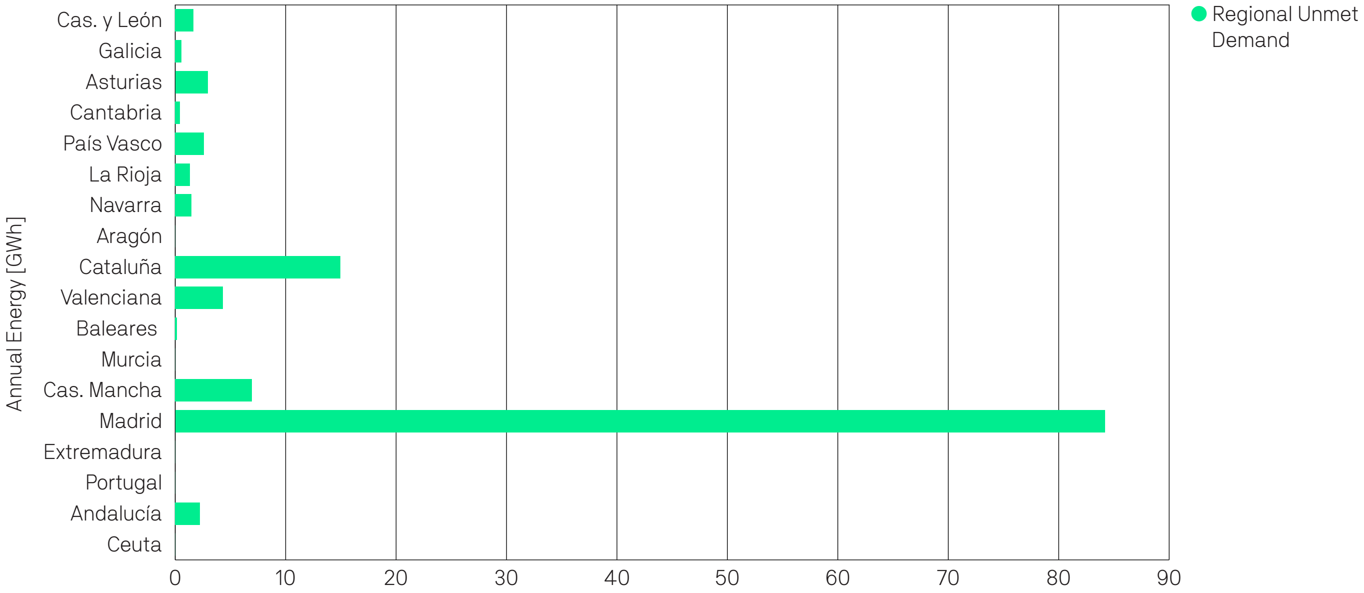
*This demand is what remains after demand flexibility is utilised in the dispatch order, it represents the maximum of the sum of regional values.

Figure 7-12: Hourly supply balance – lowest week of renewable curtailment



The regional distribution for unmet demand (excluding demand reductions through demand flexibility), is shown below in Figure 7-13. It can be seen quite clearly that Madrid, as a large population and demand centre, experiences the highest levels of unmet demand throughout the year:

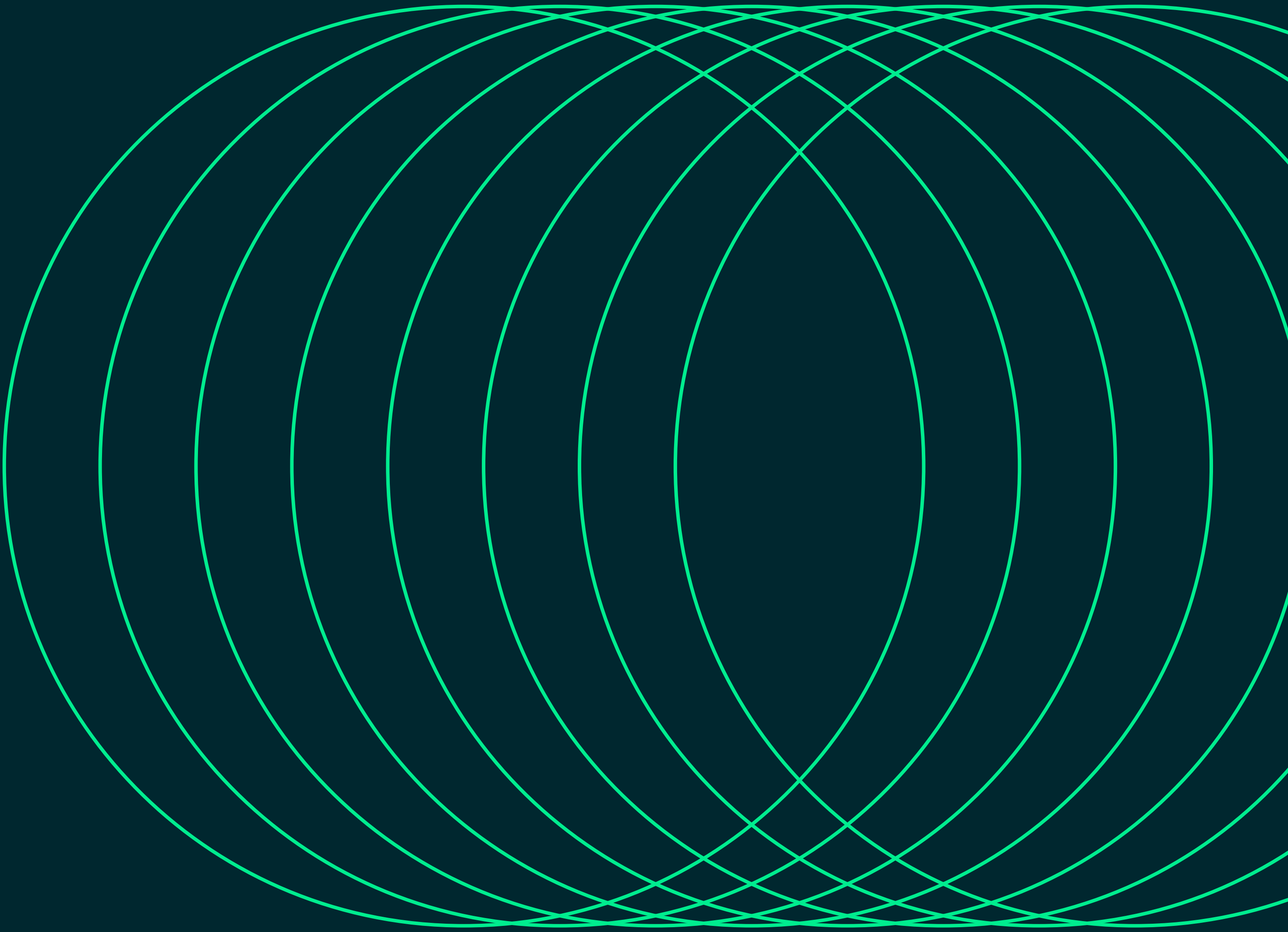
Figure 7-13: Regional distribution of unmet demand under the Islanded Simulation



In addition to the Islanded Simulation requiring 6% of demand throughout the year to be suppressed at the expense of end users using electricity under the forecasted usage patterns, the Islanded Simulation also has a negative impact on the levels of renewables curtailed across the Iberian Peninsula. By blocking off the opportunity to export excess renewables to other countries, the percentage of curtailment jumps from 11.5% to 19% (of total supplied generation from renewables and dispatchable sources of power).

This value of curtailment exceeds the range of curtailment which could be considered economic and thus would be unlikely to eventuate. If the Iberian Peninsula would be developed with the objective of working under islanded conditions, investments which would have been made in variable renewable energy capacity would instead need to go to other forms of dispatchable power, energy storage, or perhaps internal connections such that load centres like Madrid could import power from other regions within the Iberian Peninsula.

8 Mineral Demand for Energy Transition Technologies



8.1 Interdisciplinary Research: Responsible Resources, Circular Economy and 1.5°C Paris-aligned pathways

The One Earth Climate Model is not only focused on energy and emission pathways but provides a holistic approach which takes resource requirements into account too. In 2016, UTS-ISF published the first research that investigates required metal resource requirements for a global 100% renewable energy-based pathway[162].

A second analysis investigated responsible resourcing of minerals and was published in 2019[163] examines the intersection of future demand for metals and available supply in the context of a renewable energy future. Metals with increasing demand that might be subject to future mining operations have been considered in this analysis to understand the likely increase in demand and possible implications for mining – both on land as well as the suggested deep-sea mining. These insights can also inform consideration of the ways to reduce the demand by increasing the intensity of use and recycling.

The different metals considered include:

- Copper
- Cobalt
- Graphite
- Dysprosium
- Lithium
- Manganese
- Neodymium
- Nickel
- Vanadium.

This report focuses on the above listed minerals as these are all needed in the key energy transition technologies and potentially mined in deep-sea operations. Rare earths and specialty metals are also important in the development of renewable energy technologies; and future demand for these materials is expected to be significant.

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[162] Teske, S., Florin, N., Dominish, E. and Giurco, D. (2016) Renewable Energy and Deep-Sea Mining: Supply, Demand and Scenarios. Report prepared by ISF for J.M.Kaplan Fund, Oceans 5 and Synchronicity Earth, July 2016, https://opus.lib.uts.edu.au/bitstream/10453/67336/1/DSM%20-%20RE%20resource%20Report_9_FINAL%20DRAFT-NEWTITLE-ANDNAME.pdf

[163] Dominish, E., Florin, N. and Teske, S., 2019, Responsible Minerals Sourcing for Renewable Energy. Report prepared for Earthworks by the Institute for Sustainable Futures, University of Technology Sydney.

8.2 Methodology – Mineral Resource Calculation module

The mineral resource requirements for the energy pathways, developed under the Paris Agreement to limit warming to 1.5°C, include the 'OECM Net-zero (OECM-NZS) – E-Mobility', 'OECM Progressive – E-Mobility', and the 'Accelerated Na-ion Scenario'. The pathways are calculated based on the following main parameters:

1. Technology sector: Generation, Storage, Application
2. Technology group: Generation technologies, storage technologies, electric mobility (application)
3. Technology type
4. Quantity of technology
5. Resource intensity per unit for quantity.

Table 81 shows the calculation matrix for mineral resource requirement assessments of energy scenarios. While not all technology groups are listed, it shows all parameters.

8.2.1 Assumed recycling rates

The recycling rates are assumed for all minerals included in the technology (see Table 80). It is assumed that, on average globally, 70% of all EV and BESS batteries are recycled, and that all minerals are recovered at the same percentage. This is a simplification, as not all minerals are always returned to the recycling loop (= 'yield rates') in equal proportions. However, the 'yield rates' of minerals are in practice not 100%.

Table 80: Assumed recycling rates

Recycling rates at end-of-life for renewable energy technologies		**Recycling for Technology**		
Technology		**OECM**	**SUF**	**SUF High NA**
Batteries	Current	70%		
	2030–2040	70%	85%	85%
	2041–2050	90%	95%	95%
	Potential	95%		
Electric vehicles	Current–2029	70%		
	2030–2040	70%	85%	85%
	2041–2050	90%	95%	95%
	Potential	95%		
Solar photovoltaic	Current–2029	70%		
	2030–2040	70%	70%	70%
	2041–2050	81%	81%	81%
	Potential	81%		
Wind	Current–2029	90%		
	2030–2040	90%	90%	90%
	2041–2050	95%	95%	95%
	Potential	95%		

Furthermore, the assumed recycling rates and yield rates – so the material that is reused from the recycling collection – has been considered under the IEA scenario, but not under the OECM/SUF scenarios.

Table 81: Calculation matrix for mineral resource requirement assessments of energy scenarios (example)

Technology				Market share of technology variation		Quantity of technology			Resource Intensity – Base year			Projected future Resource Intensity			Total required material under calculated scenario		
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
Sector	Technology Group	Technology Type	Technology Type variation and/or component	Status Quo [%]	Estimation development until 2030/2050 [%]	by quantity [1]	by capacity [GW]	by energy unit [GWh/a]	by quantity [t/unit]	by capacity [t/GW]	by energy unit [t/GWh]	by quantity [t/unit]	by capacity [t/GW]	by energy unit [t/GWh]	Base year [t/year]	2050 [t/year]	Development [%/a]
Storage	Batteries	Lithium-ion	Mobile storage applications	X%	X% +/- Y%			●		●	●	+/- X%	+/- X%	+/- X%		●	+/- X%
		Lithium-ion phosphate	Mobile storage applications	X%	X% +/- Y%			●		●	●	+/- X%	+/- X%	+/- X%		●	+/- X%
		Lithium Nickel-Cobalt-Aluminium-Oxide	Mobile storage applications	X%	X% +/- Y%			●		●	●	+/- X%	+/- X%	+/- X%		●	+/- X%
		Vanadium redox flow	Stationary storage	X%	X% +/- Y%			●		●	●	+/- X%	+/- X%	+/- X%		●	+/- X%
		Lithium sulphur	Stationary storage	X%	X% +/- Y%			●		●	●	+/- X%	+/- X%	+/- X%		●	+/- X%

8.2.2 Assumed Technical lifetime for analysed applications

The assumed technical lifetime for the calculation of mineral resource requirements for the key energy transition technologies has a significant impact on the results. For the material demand, it is essential how many applications are manufactured. After the end of the assumed technical lifetime, the products will be replaced, the replacement two main effects on the material calculation:

1. The material can be recycled.
2. The overall product quantity required to implement the energy transition scenario will increase.

Although, the experience of the past indicates that technical lifetimes of wind turbines, solar photovoltaic generator, CSP plants and EV are higher than the assumed lifetimes we have chosen those industry standards as a precautionary principle to avoid underestimation of mineral resources.

Table 82: Assumed technical lifetimes for the analysed technologies

Technology	Assumed average technical lifetime
Solar Photovoltaics	20 years
Concentrated Solar Power Plants (CSP)	20 years
Wind (Onshore & Offshore)	20 years
EV (incl. batteries)	12 years
Battery electric storage Systems (BESS)	12 years

8.2.3 Battery chemistries and properties

In this research, we are considering different battery chemistries and their characteristics relevant for the electrification of the energy sector. These include currently available and applied battery types, and battery types projected to increase in their market share and commercial applications until 2050, while others are phased out.

Our research differentiates between two battery applications: batteries used for mobility and energy storage. Electric mobility includes passenger and commercial electric vehicles and the electrification of 2-and 3-wheelers. Batteries used for energy storage systems include in-front-of-the-meter systems, i.e. utility-scale battery storage systems with capacities of several megawatt (MW) and durations of megawatt hours (MWh), and behind-the-meter applications such as home battery systems, which range in units of kilowatts (kW) and smaller durations measured in units of kilowatt hours (kWh).

In 2020, lithium battery types dominated the mobility and energy storage sector. Traditionally, high nickel-based lithium-ion batteries (NMC, NCA) provided the largest market share for both sectors; however, other battery types predominately manufactured in China (Lithium Iron Phosphate (LFP)) have been increasing their global market share from 7% in 2018 to 27% in 2022.·For EV applications, LFP reached a global market share of 48% in 2024. We assessed the currently applied battery chemistries, trends, costs, and demands to understand what a global future battery chemistry mix can look like.

NMC and NCA batteries

High nickel-based lithium-ion batteries, including Nickel Manganese Cobalt (NMC) and Nickel Cobalt Aluminium (NCA) chemistries, have played a central role in the electrification of the energy sector (IEA 2022) due to their high energy density and suitability for electric vehicles and stationary storage. NMC batteries have various ratios, like NMC 111, which uses equal parts nickel, manganese, and cobalt. Others, such as 622 and 811, have an increased Nickel content to boost energy density. Tesla used NCA batteries in earlier models, offering even higher energy density but rely more heavily on cobalt and aluminium.

LFP batteries

Electrification of mobility and energy storage is driven by the commercialisation, mass-manufacturing, and increasing uptake of battery types. Lithium Iron Phosphate (LFP) batteries have rapidly gained prominence as a cost-effective and durable lithium-ion chemistry, particularly suited for electric vehicles and stationary storage. LFP batteries have benefited from the broader 'battery domino effect', where falling costs and rising energy density across battery technologies have accelerated adoption across sectors. While LFP cells typically offer lower energy density than Nickel-based chemistries highlight the potential for improved energy density based on changes in battery chemistry), LFP's excel in thermal stability, safety, and longevity, making them ideal for applications where volume is less constrained. LFP's affordability and long cycle life are key to its growing role in displacing fossil fuels, especially in grid storage and entry-level EVs, with continued innovation expected to further improve performance and expand market share. Future projections indicate that nickel-based chemistries may be increasingly replaced by Lithium Iron Phosphate (LFP) batteries, which offer greater affordability, safety, and longer cycle life.

Sodium-ion (Na-ion) batteries

Sodium-ion batteries are rechargeable and use sodium as the main carrier for charging. Sodium ion batteries are similar to lithium-ion batteries, and can include critical minerals such as copper, nickel, and manganese. Sodium-ion batteries are on as mature as LFP batteries and gaining a greater market share, the application is particularly growing for 2-and 3 wheelers (micromobility) and passenger EVs.

The increased application of sodium ion in passenger EVs will lead to a further reduction of the cost of EVs and will increase the uptake of EVs. The IEA's 2025 Global EV Outlook states that while "NMC batteries still provide an energy density advantage, the gap has narrowed in recent years.[164] The energy density of LFP battery packs is about one-fifth lower by mass (Wh/kg) and about one-third lower by volume (Wh/L) than that of NMC packs". Considering the recent developments related to improved energy density of LFP batteries, this report develops a scenario which assumes an increased uptake of sodium ion batteries for all vehicle types from 2030, including commercial EVs such as heavy duty EVs.

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[164] Timo Möller, Clemens Cepnik, Marcelo Azevedo, Nicolò Campagnol, and Yunjing Kinzel, "The Battery Chemistries Powering the Future of Electric Vehicles," McKinsey & Company, December 17, 2024, https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/the-battery-chemistries-powering-the-future-of-electric-vehicles

Lithium sulphur

Lithium sulphur (Li-S) battery technologies are using sulphur as the negative battery electrode and lithium as the positive electrode. Li-S batteries are rechargeable, light and have a high energy density, and a lower reliance on critical minerals. IEA's Global EV Outlook projects that by 2030, lithium sulphur batteries will be commercialised and could find applications in commercial road transport (long distance trucks), shipping (short-distance boats) and the aviation sector. Other future applications might include large-scale grid energy storage solutions due to a breakthrough and improvement of Li-S's ability to charge and discharge fast, while current state-of-the-art lithium-sulphur batteries show slow charge-discharge rates. Lithium sulphur batteries currently face challenges including "improving volumetric energy density (Wh/L), enhancing durability, and addressing safety concerns related to the use of lithium metal anodes.

8.3 Key Results

Base on the methodology documented in the previous chapters, the resource requirement for nine important mineral was calculated. The selected minerals are key for the leading energy transition technologies in the following sectors:

Power generation, solar photovoltaics, onshore and offshore wind clearly dominate the market for new power generation. The significant cost benefits compared to all other power generation technologies in combination with relatively short installation times and low operation costs due to no fuel needs will make those technologies the backbone of future power generation with a very high likelihood.

Storage adapts the variable power generation of solar and wind power plants to the temporal needs of different consumption sectors. Batteries – along with pumped hydro and molten salt – are a key technology for the energy transition and for electrification, and thus urgently needed for sector-coupling in sectors currently dominated by oil (vehicles) and gas (space heating). Furthermore, batteries are the 'core' of any electric vehicle. The mining extraction activities for minerals that are required for electric mobility replaces the extraction for oil. But as opposed to oil that will simply be burned, the battery mineral stores the energy required for driving and can be recharged for at least a decade. After the technical lifetime of batteries, the minerals can be recycled.

Table 83: Spain – 4.0 scenario – development of annual mineral demand

Material Demand		**Annual Material Demand**							
		2024	**Current global mining**	**Share Global Energy Transition Materials**		**Increase Annual Material Demand: 2024 to 2030**	**Increase Annual Material Demand: 2024 to 2050**	**2030**	**2050**
Spain 4.0		**[t/a]**	**[t/a]**	**[%]**		**[1]**	**[1]**	**[t/a]**	**[t/a]**
Cobalt	Co	1,116	290,000	0%	No Recycling	1.7	3.0	1,881	3,349
					With Recycling	0.9	0.4	1,024	493
Copper	Cu	23,053	23,000,000	0%	No Recycling	3.2	7.2	74,314	165,405
					With Recycling	1.5	3.1	33,844	72,536
Graphite	Gr	14,499	1,600,000	1%	No Recycling	3.3	11.3	48,140	163,497
					With Recycling	2.6	5.2	37,630	75,791
Dysprosium	Dy	15	1,800	1%	No Recycling	5.5	4.2	85	64
					With Recycling	1.2	-1.0	18	-15
Lithium	Li	1,753	240,000	1%	No Recycling	4.1	13.8	7,177	24,178
					With Recycling	2.3	7.5	4,056	13,108
Manganese	Mn	4,666	20,000,000	0%	No Recycling	3.6	11.3	16,750	52,605
					With Recycling	1.2	6.3	5,505	29,363
Neodymium	Nd	81	16,000	1%	No Recycling	7.3	1.4	593	113
					With Recycling	1.5	-5.2	119	-421
Nickel	Ni	8,816	3,700,000	0%	No Recycling	2.8	7.3	24,625	63,979
					With Recycling	0.9	4.1	8,018	36,239

Table 84: Spain – 4.1 scenario – development of annual mineral demand

Material Demand		Annual Material Demand							
		2024	Current global mining	Share Global Energy Transition Materials		Increase Annual Material Demand: 2024–2030	Increase Annual Material Demand: 2024–2050	2030	2050
Spain 4.1		[t/a]	[t/a]	[%]		[1]	[1]	[t/a]	[t/a]
Cobalt	Co	1,116	290,000	0%	No Recycling	1.6	1.8	1,746	2,054
					With Recycling	0.8	-0.1	944	-61
Copper	Cu	23,053	23,000,000	0%	No Recycling	3.1	4.5	70,235	103,071
					With Recycling	1.4	1.3	31,803	29,644
Graphite	Gr	14,499	1,600,000	1%	No Recycling	3.1	6.9	45,053	99,884
					With Recycling	2.4	2.4	35,200	34,933
Dysprosium	Dy	15	1,800	1%	No Recycling	5.3	2.8	81	43
					With Recycling	1.1	-2.0	17	-30
Lithium	Li	1,753	240,000	1%	No Recycling	3.8	8.4	6,665	14,749
					With Recycling	2.2	3.7	3,778	6,539
Manganese	Mn	4,666	20,000,000	0%	No Recycling	3.4	6.9	15,660	32,170
					With Recycling	1.1	3.0	5,134	14,191
Neodymium	Nd	81	16,000	1%	No Recycling	7.1	1.3	576	103
					With Recycling	1.4	-5.1	115	-416
Nickel	Ni	8,816	3,700,000	0%	No Recycling	2.6	4.5	22,912	39,268
					With Recycling	0.8	2.0	7,425	17,911

Table 85: Portugal – 4.0 scenario – development of annual mineral demand

Material Demand		Annual Material Demand							
		2024	Current global mining	Share Global Energy Transition Materials		Increase Annual Material Demand: 2024–2030	Increase Annual Material Demand: 2024–2050	2030	2050
Portugal 4.0		[t/a]	[t/a]	[%]		[1]	[1]	[t/a]	[t/a]
Cobalt	Co	185	290,000	0%	No Recycling	2.5	4.3	467	803
					With Recycling	1.5	0.6	278	111
Copper	Cu	4,401	23,000,000	0%	No Recycling	3.8	8.7	16,556	38,236
					With Recycling	1.9	4.0	8,377	17,392
Graphite	Gr	2,396	1,600,000	0%	No Recycling	5.2	16.3	12,437	38,983
					With Recycling	4.2	7.3	10,118	17,569
Dysprosium	Dy	4	1,800	0%	No Recycling	4.2	3.3	17	14
					With Recycling	0.9	-0.6	4	-2
Lithium	Li	291	240,000	0%	No Recycling	6.1	19.2	1,765	5,583
					With Recycling	3.6	10.1	1,061	2,938
Manganese	Mn	720	20,000,000	0%	No Recycling	4.1	16.6	2,957	11,938
					With Recycling	1.5	10.0	1,102	7,208
Neodymium	Nd	26	16,000	0%	No Recycling	4.4	0.7	115	20
					With Recycling	0.9	-3.2	23	-84
Nickel	Ni	1,491	3,700,000	0%	No Recycling	3.6	9.5	5,328	14,107
					With Recycling	1.3	5.4	1,901	8,055

Table 86: Portugal – 4.1 scenario – development of annual mineral demand

Material Demand		Annual Material Demand							
		2024	Current global mining	Share Global Energy Transition Materials		Increase Annual Material Demand: 2024–2030	Increase Annual Material Demand: 2024–2050	2030	2050
Portugal 4.1		[t/a]	[t/a]	[%]		[1]	[1]	[t/a]	[t/a]
Cobalt	Co	185	290,000	0%	No Recycling	2.2	2.5	404	457
					With Recycling	1.3	-0.1	233	-12
Copper	Cu	4,401	23,000,000	0%	No Recycling	3.5	5.2	14,619	22,049
					With Recycling	1.7	1.7	7,235	7,068
Graphite	Gr	2,396	1,600,000	0%	No Recycling	4.5	9.2	10,712	21,900
					With Recycling	3.6	3.1	8,616	7,449
Dysprosium	Dy	4	1,800	0%	No Recycling	4.3	2.3	15	8
					With Recycling	0.9	-1.5	3	-5
Lithium	Li	291	240,000	0%	No Recycling	5.3	10.9	1,532	3,181
					With Recycling	3.1	4.7	907	1,377
Manganese	Mn	720	20,000,000	0%	No Recycling	3.6	9.5	2,587	6,862
					With Recycling	1.3	5.0	953	3,609
Neodymium	Nd	26	16,000	0%	No Recycling	4.8	0.7	105	15
					With Recycling	1.0	-3.6	21	-80
Nickel	Ni	1,491	3,700,000	0%	No Recycling	3.2	5.6	4,676	8,212
					With Recycling	1.1	2.7	1,631	3,925

Figure 8-1: Spain 4.0 Material demand decrease with Recycling

		Material Reduction with Recycling			
		2030		2050	
Spain 4.0		[t/a]	[%]	[t/a]	[%]
Cobalt	Co	857.1	46%	2855.4	85%
Copper	Cu	40469.2	54%	92868.8	56%
Graphite	Gr	10510.1	22%	87706.5	54%
Dysprosium	Dy	66.9	79%	79.0	123%
Lithium	Li	3,121	43%	11,070	46%
Manganese	Mn	11,246	67%	23,243	44%
Neodymium	Nd	475	80%	534	472%
Nickel	Ni	16,607	67%	27,740	43%

Figure 8-2: Spain 4.1 Material demand decrease with Recycling

		Material Reduction with Recycling			
		2030		2050	
Spain 4.1		[t/a]	[%]	[t/a]	[%]
Cobalt	Co	802.2	46%	2115.5	103%
Copper	Cu	38431.6	55%	73427.2	71%
Graphite	Gr	9852.5	22%	64950.7	65%
Dysprosium	Dy	64.4	79%	72.9	171%
Lithium	Li	2,887	43%	8,210	56%
Manganese	Mn	10,526	67%	17,979	56%
Neodymium	Nd	461	80%	519	503%
Nickel	Ni	15,487	68%	21,357	54%

Figure 8-3: Portugal 4.0 Material demand decrease with Recycling

		Material Reduction with Recycling			
		2030		2050	
Portugal 4.0		[t/a]	[%]	[t/a]	[%]
Cobalt	Co	189.6	41%	691.2	86%
Copper	Cu	8178.7	49%	20844.6	55%
Graphite	Gr	2319.8	19%	21414.2	55%
Dysprosium	Dy	13.3	79%	15.8	117%
Lithium	Li	704	40%	2,645	47%
Manganese	Mn	1,855	63%	4,730	40%
Neodymium	Nd	92	80%	103	530%
Nickel	Ni	3,427	64%	6,053	43%

Figure 8-4: Portugal 4.1 Material demand decrease with Recycling

		Material Reduction with Recycling			
		2030		2050	
Portugal 4.1		[t/a]	[%]	[t/a]	[%]
Cobalt	Co	171.0	42%	468.4	103%
Copper	Cu	7384.1	51%	14981.1	68%
Graphite	Gr	2096.5	20%	14451.3	66%
Dysprosium	Dy	12.2	79%	13.7	165%
Lithium	Li	625	41%	1,804	57%
Manganese	Mn	1,634	63%	3,254	47%
Neodymium	Nd	84	80%	95	617%
Nickel	Ni	3,046	65%	4,287	52%

8.3.1 Achieved Material Demand Decrease with Recycling in Spain and Portugal

The material demand for energy transition technologies can decrease significantly with recycling measures. As shown in Figure 8-1 and Figure 8-2 the material demand for both scenarios between 2024 and 2030 in Spain can be reduced by 20% for graphite, 50% for copper and up to 80% for the rare earth metals dysprosium and neodymium. Similar values are calculated for Portugal (Figure 8-3 and Figure 8-4) for the 4.0 and 4.1 scenarios as well.

Five key interventions are required for a green and just energy transition with less minerals:

1. Reduce mineral demand through investment and delivery of shared mobility systems like improved public transport and smaller, more efficient cars.

Shifting towards shared mobility systems is one of the most effective ways to reduce the need for mineral-intensive electric vehicles and the batteries that power them. Expanding high-quality public transport, car-sharing schemes and other forms of convenient mobility can significantly decrease reliance on individual car ownership. Complementary measures such as right-sizing batteries, avoiding unnecessarily large vehicles (e.g. SUVs in cities) and improving vehicle efficiency, also contribute to reduced mineral demand.

2. Incentivise battery technology substitution towards alternatives requiring less lithium, cobalt, or nickel.

Technological innovation over the last decade has transformed the mobility and energy storage battery markets. Lithium iron phosphate (LFP) batteries, now widely commercialised, eliminate the need for cobalt and nickel, reducing pressure on these supply chains. At the same time, sodium-ion (Na-ion) batteries are advancing rapidly, and because they do not require lithium or cobalt, they offer a pathway to significantly reduce mineral demand for lithium. Further market growth of these and other emerging chemistries (e.g. redox flow batteries) in the coming years, as outlined in the Progressive- Battery scenarios, can significantly reduce supply gaps and ease potential development pressures for new mines. Innovative energy storage systems that do not require these key minerals, could further reduce the need for batteries in the electricity grid.

3. Design for circularity and scale up recycling.

By maximising collection and the recovery of transition minerals from end-of-life renewable technologies, recycling can significantly reduce the need for new extraction. Investing in advanced recycling technologies and collection systems, alongside policy incentives that reward high recycled mineral content, can ensure that transition minerals re-enter the supply chain. All scenarios in the study show significant reductions in primary demand when ambitious recycling assumptions are included. Additional circularity measures like extending technologies' lifespans, improving repairability, incentivising reuse, designing products for easy disassembly, standardising components, and enforcing extended producer responsibility (EPR), while not part of the mineral resources' calculation model, could also contribute to reducing overall mineral demands.

4. Prioritise mineral use for essential energy transition needs.

Minerals are finite resources, and mining for them carries significant social and environmental risks. Therefore, the use of mineral resources should be prioritised where they matter most – with renewable energy applications to phase out fossil fuels being a major part of that. This study focuses on the mineral demands for energy transition, however demand from other uses often compete for the same limited supply. Governments and industries must steer minerals toward critical energy transition infrastructure and other vital uses. Coupled with supply chain transparency, prioritising minerals for energy transition ensures finite minerals are used to advance climate goals that benefit all people and the planet.

5. Protect 'Restricted Areas' from mining development.

Protecting human rights and ecological integrity is a non-negotiable foundation of a just and green transition. Restricted Areas (RA) have critical environmental, ecological and natural values, and Indigenous Peoples and Local Community (IP&LC) territories. Defining and protecting these RAs is a crucial step in ensuring that mining of transition minerals does not compromise the safeguarding of biodiversity, ecosystem services, natural carbon storage, freshwater systems, oceans and respecting the rights of IP&LC. Protecting these areas is essential to staying within the Earth's planetary boundaries[165] and to prevent the energy transition from repeating the injustices of past extractive models, with Free, Prior and Informed Consent from IP&LC as a key prerequisite of any mining development.

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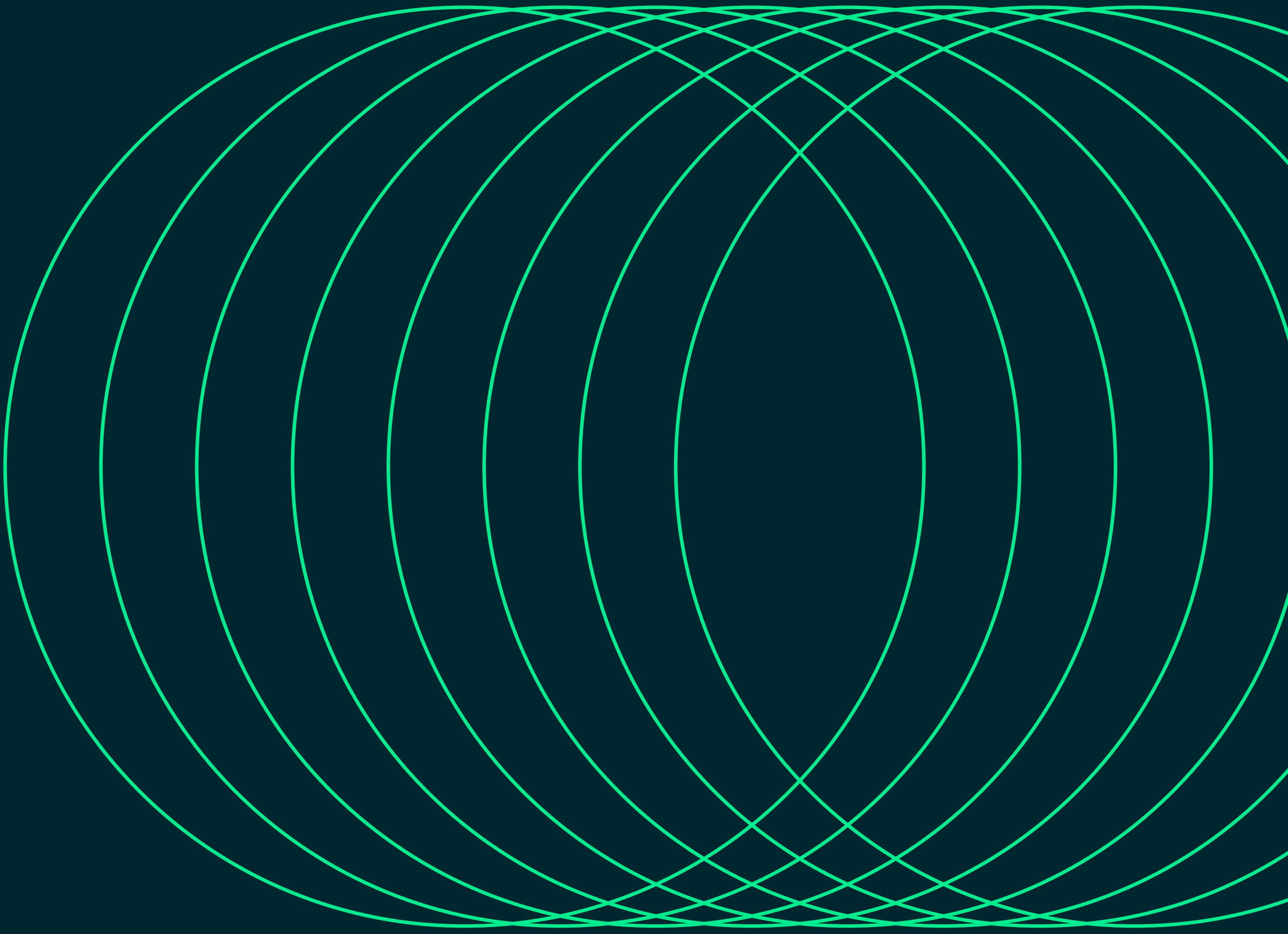
[165] Planetary Boundaries Science (PBScience). 2025. Planetary Health Check 2025. Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany. https://publications.pik-potsdam.de/rest/items/item_32589_5/component/file_33151/content

9 Appendix



9.1 OECM Literature

Publications: One Earth Climate Model Methodology

Publisher and link	Title
Springer Book (Open Access):	The 'Global Stocktake' and the remaining carbon budgets for G20 countries to limit global temperature rise to +1.5 °C
Springer Book (Open Access):	A Net-zero 1.5 °C sectorial pathways for G20 countries: energy and emissions data to inform science-based decarbonisation targets
Springer Book (Open Access):	Achieving the Paris Climate Agreement Goals – Part 2: Science-based Target Setting for the Finance industry – Net-Zero Sectoral 1.5˚C Pathways for Real Economy Sectors
Springer Nature (Open Access):	Global sector-specific Scope 1, 2, and 3 analyses for setting net-zero targets: agriculture, forestry, and processing harvested products
Springer Nature (Open Access):	1.5 °C pathways for the Global Industry Classification (GICS) sectors chemicals, aluminium, and steel
Journal (Open Access):	One Earth Climate Model – Integrated Energy Assessment Model to Develop Industry-Specific 1.5 °C Pathways with High Technical Resolution for the Finance Sector
Journal (Open Access):	It Is Still Possible to Achieve the Paris Climate Agreement: Regional, Sectoral, and Land-Use Pathways
Springer Book (Open Access):	Achieving the Paris Climate Agreement Goals – Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5°C and +2°C

9.2 Land cover classes considered for developing solar and onshore wind potential maps

Land cover classes included for solar and onshore wind energy potential areas (Scenario 1 and 2)

Data	Solar energy	Onshore Wind energy
CORINE Land Cover 2018 (Europe)	– Discontinuous urban fabric (1.1.2) – Industrial or commercial units and public facilities (1.2.1) – Port areas (1.2.3) – Airports (1.2.4) – Mineral extraction sites (1.3.1) – Dump sites (1.3.2) – Construction sites (1.3.3) – Green urban areas (1.4.1) – Sport and leisure facilities (1.4.2) – Non-irrigated arable land (2.1.1) – Permanently irrigated arable land (2.1.2) – Rice fields (2.1.3) – Vineyards (2.2.1) – Fruit tree and berry plantations (2.2.2) – Olive groves (2.2.3) – Pastures, meadows and other permanent grasslands under agricultural use (2.3.1) – Annual crops associated with permanent crops (2.4.1) – Complex cultivation patterns (2.4.2) – Land principally occupied by agriculture, with significant areas of natural vegetation (2.4.3) – Agro-forestry areas (2.4.4) – Natural grassland (3.2.1) – Sclerophyllous vegetation (3.2.3) – Transitional woodland/shrub (3.2.4) – Bare rock (3.3.2) – Sparsely vegetated areas (3.3.3)	– Port areas (1.2.3) – Dump sites (1.3.2) – Non-irrigated arable land (2.1.1) – Permanently irrigated arable land (2.1.2) – Rice fields (2.1.3) – Pastures, meadows and other permanent grasslands under agricultural use (2.3.1) – Annual crops associated with permanent crops (2.4.1) – Complex cultivation patterns (2.4.2) – Land principally occupied by agriculture, with significant areas of natural vegetation (2.4.3) – Agro-forestry areas (2.4.4) – Natural grassland (3.2.1) – Sclerophyllous vegetation (3.2.3) – Transitional woodland/shrub (3.2.4) – Sparsely vegetated areas (3.3.3) – (Sea and Ocean) (5.2.3)

Land cover classes included for solar and onshore wind energy potential areas (Scenario 3

Data	Solar energy	Onshore Wind energy
CORINE Land Cover 2018 (Europe)	– Discontinuous urban fabric (1.1.2) – Industrial or commercial units and public facilities (1.2.1) – Port areas (1.2.3) – Airports (1.2.4) – Mineral extraction sites (1.3.1) – Dump sites (1.3.2) – Construction sites (1.3.3) – Green urban areas (1.4.1) – Sport and leisure facilities (1.4.2) – Pastures, meadows and other permanent grasslands under agricultural use (2.3.1) – Agro-forestry areas (2.4.4) – Natural grassland (3.2.1) – Sclerophyllous vegetation (3.2.3) – Transitional woodland/shrub (3.2.4) – Bare rock (3.3.2) – Sparsely vegetated areas (3.3.3)	– Port areas (1.2.3) – Dump sites (1.3.2) – Pastures, meadows and other permanent grasslands under agricultural use (2.3.1) – Agro-forestry areas (2.4.4) – Natural grassland (3.2.1) – Sclerophyllous vegetation (3.2.3) – Transitional woodland/shrub (3.2.4) – Sparsely vegetated areas (3.3.3) – (Sea and Ocean) (5.2.3)

9.3 Renewable Energy and Storage Distribution used in 24/7 Modelling

The following table outlines how the nature and agricultural sensitivity test differs in regard to a principal simulation using the mapping from scenario two. This table reflects that previous methodological choices made in chapter three, in which wind capacity was assessed to not have sufficient incompatibility with a number of agricultural production types due to the ability of wind farm design and spacing being adjustable such that can co-exist with a variety of agriculturally productive activities. Meanwhile, solar does not have this ability, and thus attracts more political scrutiny due to concerns by industry and some sections of the community.

Comparison of distribution between the principal simulation and the nature and agricultural sensitivity test

Simulation Name	Wind Distribution	Rooftop Solar Distribution	Utility Solar Distribution
Principal Simulation	Mapping Scenario 2	Mapping Of Rooftop Potential	Mapping Scenario 2
Nature & Agricultural Sensitivity Test			Mapping Scenario 3

The below tables contain rounded figures for the overall renewable potential mapped in Section 3, and it should be noted that where a potential in GW is non-zero, so too is the percentage of capacity which is distributed to that region.

Comparison of the Potential and Distribution of Utility Solar – Scenario 2 and Scenario 3

	Scenario 2		Scenario 3		
Region	GW	Percentage	GW	Percentage	% Delta (Scenario 3 vs 2)
Andalucía	976	17%	198	15%	-1.5%
Aragón	390	7%	102	8%	1.2%
Asturias, Principado de	39	1%	5	0%	-0.3%
Cantabria	30	1%	6	1%	0%
Castilla-La Mancha	923	16%	192	15%	-1.1%
Castilla y León	1,134	20%	254	20%	0.1%
Cataluña	261	5%	53	4%	-0.4%
Ceuta	0	0%	0	0%	0%
Extremadura	231	4%	48	4%	-0.3%
Galicia	180	3%	41	3%	0%
Islas Baleares	58	1%	8	1%	-0.4%
La Rioja	54	1%	14	1%	0.2%
Madrid, Comunidad de	80	1%	35	3%	1.3%
Murcia, Región de	159	3%	35	3%	0%
Navarra, Comunidad Foral de	93	2%	16	1%	-0.3%
País Vasco	49	1%	10	1%	0%
Valenciana, Comunidad	220	4%	70	5%	1.6%
Portugal	867	15%	193	15%	0%
Total	**5,745**	**100%**	**1,280**	**100%**	**-**

Potential and Distribution of Onshore Wind*

Region	GW	Percentage
Andalucía	48	10%
Aragón	48	10%
Asturias, Principado de	1	0%
Cantabria	1	0%
Castilla-La Mancha	91	18%
Castilla y León	140	28%
Cataluña	8	2%
Ceuta	0	0%
Extremadura	24	5%
Galicia	12	2%
Islas Baleares	5	1%
La Rioja	4	1%
Madrid, Comunidad de	4	1%
Murcia, Región de	10	2%
Navarra, Comunidad Foral de	11	2%
País Vasco	2	0%
Valenciana, Comunidad	11	2%
Portugal	75	15%
Total	**497**	**100%**

*Offshore wind was also utilised in this modelling but did not rely on internal GIS mapping as data was only available for Spain and not Portugal. Thus offshore wind was proportioned on an estimate of projects which could be running by 2040 for the purposes of the 24/7 modelling.

Potential and Distribution of Rooftop Solar

Region	GW	Percentage
Andalucía	12	17%
Aragón	2	3%
Asturias, Principado de	1	1%
Cantabria	1	1%
Castilla-La Mancha	6	8%
Castilla y León	5	7%
Cataluña	8	11%
Ceuta	0	0%
Extremadura	3	4%
Galicia	3	4%
Islas Baleares	1	2%
La Rioja	0	1%
Madrid, Comunidad de	5	7%
Murcia, Región de	2	3%
Navarra, Comunidad Foral de	1	1%
País Vasco	2	2%
Valenciana, Comunidad	8	11%
Portugal	13	18%
Total	**71**	**100%**

Distribution of Electric Vehicle – V2G

Region	GW	Percentage
Andalucía	18.1	15%
Aragón	2.8	2%
Asturias, Principado de	2.1	2%
Cantabria	1.2	1%
Castilla-La Mancha	4.4	4%
Castilla y León	5.0	4%
Cataluña	16.9	14%
Ceuta	0.2	0%
Extremadura	2.2	2%
Galicia	5.7	5%
Islas Baleares	2.6	2%
La Rioja	0.7	1%
Madrid, Comunidad de	14.9	12%
Murcia, Región de	3.3	3%
Navarra, Comunidad Foral de	1.4	1%
País Vasco	4.7	4%
Valenciana, Comunidad	11.3	9%
Portugal	22.2	19%
Total	**120**	**100%**

Distribution of Hydro Pump Storage

Region	GW	Percentage
Andalucía	0.6	5%
Aragón	0.6	5%
Asturias, Principado de	0.1	1%
Cantabria	0.3	2%
Castilla-La Mancha	0.3	2%
Castilla y León	1.0	8%
Cataluña	1.0	8%
Ceuta	0.0	0%
Extremadura	1.2	9%
Galicia	1.4	11%
Islas Baleares	0.0	0%
La Rioja	0.0	0%
Madrid, Comunidad de	0.0	0%
Murcia, Región de	0.0	0%
Navarra, Comunidad Foral de	0.0	0%
País Vasco	0.0	0%
Valenciana, Comunidad	1.8	14%
Portugal	4.7	36%
Total	**13**	**100%**

Distribution of Utility Battery Storage

Region	GW	Percentage
Andalucía	6.6	17%
Aragón	2.8	7%
Asturias, Principado de	0.3	1%
Cantabria	0.2	1%
Castilla-La Mancha	6.5	16%
Castilla y León	8.1	20%
Cataluña	1.8	5%
Ceuta	0.0	0%
Extremadura	1.6	4%
Galicia	1.2	3%
Islas Baleares	0.4	1%
La Rioja	0.4	1%
Madrid, Comunidad de	0.5	1%
Murcia, Región de	1.1	3%
Navarra, Comunidad Foral de	0.7	2%
País Vasco	0.3	1%
Valenciana, Comunidad	1.5	4%
Portugal	6.0	15%
Total	**40**	**100%**

9.4 List of Internal Line Limits and Reinforcement Assessment (kV)

List of Internal Line Limits Based on Literature discussed in section 7.1.1

Connected 24/7 Regions	Capacity/Rating (incl. multiple circuits)
Comunidad Valenciana – Islas Baleares	800 MW (250kV DC)
Andalucía – Ceuta	2x 132 KV
Andalucía – Extremadura	1x 220 kV; 6x 400kV
Andalucía – Castilla-La Mancha	3x 220 kV; 4 x 400kV
Andalucía – Región de Murcia	3 x 400kV
Extremadura – Castilla y León	1x 220 kV; 2x 400kV
Extremadura – Castilla-La Mancha	1x 220 kV; 6x 400 kV
Castilla-La Mancha – Castilla y León	5x 220 kV; 1x 400 kV
Castilla-La Mancha – Madrid	19x 220 kV; 2x 400 kV
Castilla-La Mancha – Aragon	3x 220 kV; 2x 400 kV
Castilla-La Mancha – Comunidad Valenciana	8x 400 kV
Castilla-La Mancha – Murcia	2x 400 kV
Castilla y León – Galicia	6x 220 kV; 4x 400kV
Castilla y León – Asturias	3x 220 kV; 2x 400kV
Castilla y León – Cantabria	3x 220 kV; 4x 400kV
Castilla y León – País Vasco	10x 220 kV; 3x 400kV
Castilla y León – La Rioja	2x 220 kV; 1x 400kV
Castilla y León – Aragón	2x 220 kV; 4x 400kV
Castilla y León – Madrid	16x 220 kV; 4x 400kV
Galicia – Asturias	4x 400kV
Asturias – Cantabria	2x 220 kV; 1x 400kV
Cantabria – Pais Vasco	3x 220 kV; 2x 400kV
Pais Vasco – La Rioja	5x 220 kV
Pais Vasco – Comunidad Foral de Navarra	3x 220 kV; 1x 400kV
La Rioja – Navarra	5x 220 kV; 3x 400kV
Navarra – Aragón	3x 220 kV; 3x 400kV
Aragón – Cataluña	11x 220 kV; 3x 400kV
Aragón – Comunidad Valenciana	2x 220 kV; 2x 400kV
Cataluña – Comunidad Valenciana	1x 400kV
Comunidad Valenciana – Murcia	1x 220 kV; 6x 400kV
Andalucía – Portugal	4x 400 kV
Extremadura – Portugal	1x 400 kV
Castilla y León – Portugal	3x 220 kV; 1x 400kV
Galicia –ß Portugal	3x 400 kV

Identification of regional constraints based on above line limits:

Region Names	**Max Residual Load [GW]**	**Dispatchable & Utility Storage Capacity [GW]***	**Import Capacity from within IB [GW]**	**Possible IB Supply Gap [GW]***
Cataluña	9.8	4.0	5.0	0.8
Baleares	1.5	0.5	0.8	0.2
Ceuta	0.4	0.0	0.3	0.1

*Excluding distributed storage.

Table of Power Flow Constraints (MW)

	Galicia	**Asturias**	**Cantabria**	**País Vasco**	**La Rioja**	**Navarra**	**Aragón**	**Cataluña**	**Valenciana**	**Baleares**	**Murcia**	**Cas. Mancha**	**Madrid**	**Extremadura**	**Portugal**	**Andalucía**	**Ceuta**
Cas. y León	3652	1826	2827	4252	1051	1326	2552	2552	1876	1000	1820	1876	6402	1276	1600	1876	400
Galicia		2002	1051	3652	1051	1326	2552	2552	1876	1000	1820	1876	3652	1276	1456	1876	400
Asturias			1051	1826	1051	1051	1826	1826	1826	1000	1820	1826	2002	1276	1600	1826	400
Cantabria				1826	1375	1326	2552	2552	1876	1000	1820	1876	2827	1276	1600	1876	400
País Vasco					1375	1326	2552	2552	1876	1000	1820	1876	4252	1276	1600	1876	400
La Rioja						2877	2327	2327	1551	1000	1436	1439	1051	1051	1051	1051	400
Navarra							2327	2327	1551	1000	1820	1826	2327	1061	1061	1826	400
Aragón								5327	1551	1000	1820	1826	2552	1826	1600	1826	400
Cataluña									501	1000	1820	1826	2552	1826	1600	1158	400
Valenciana										1000	3278	4004	4004	3278	1600	1515	400
Baleares											1000	1000	1000	1000	1000	1000	400
Murica												1820	3278	1820	1515	1515	400
Cas. Mancha													6226	3278	2002	2870	400
Madrid														3278	2002	3228	400
Extremadura															1331	3228	400
Portugal																2002	400
Andalucía																	400

* Grey shading identifies power flow constraints which were increased through reinforcement.

9.6 Annex Cost Calculation

Cumulative investment in power generation	2020–2030	2031–2040	2041–2050	2020–2040 [billion Euro]	Average annual [billion Euro/a]
IB BAU					
Fossil	0.0	0.0	0.0	0.0	0.0
Nuclear	0.0	0.0	0.0	0.0	0.0
CHP (fossil + renewable)	10.6	16.1	9.4	26.6	1.3
Biomass	9.0	5.5	8.7	14.4	0.7
Hydro	17.0	8.6	5.7	25.6	1.3
Wind	73.1	64.9	44.0	138.0	6.9
photovoltaic	54.7	59.3	17.2	114.0	5.7
Geothermal	3.0	7.2	1.9	10.2	0.5
Solar thermal power plants	28.7	10.4	5.2	39.1	2.0
Ocean energy	0.3	10.5	3.3	10.8	0.5
Total investment IB BAU				**378.6**	**18.9**
IB 4.0					
Fossil	0.0	0.0	0.0	0.0	0.0
Nuclear	0.0	0.0	0.0	0.0	0.0
CHP (fossil + renewable)	9.0	13.6	2.5	22.6	1.1
Biomass	7.9	4.7	3.3	12.5	0.6
Hydro	23.3	5.9	3.0	29.2	1.5
Wind	81.0	115.9	49.2	196.9	9.8
photovoltaic	50.8	52.0	5.6	102.8	5.1
Geothermal	0.2	7.1	0.5	7.3	0.4
Solar thermal power plants	29.3	24.6	16.1	53.9	2.7
Ocean energy	0.3	12.2	3.2	12.5	0.6
Total investment IB 4.0				**437.8**	**21.9**
IB 4.1					
Fossil	0.0	0.0	0.0	0.0	0.0
Nuclear	0.0	0.0	0.0	0.0	0.0
CHP (fossil + renewable)	9.0	13.6	2.5	22.6	1.1
Biomass	7.6	4.1	3.2	11.7	0.6
Hydro	22.3	1.3	2.8	23.6	1.2
Wind	77.0	92.9	43.3	169.8	8.5
photovoltaic	50.1	43.6	4.8	93.8	4.7
Geothermal	0.2	6.5	0.5	6.7	0.3
Solar thermal power plants	28.9	19.1	14.2	48.0	2.4
Ocean energy	0.3	10.9	2.8	11.2	0.6
Total investment IB 4.1				**387.4**	**19.4**

Cumulative investment in power generation	2020–2030	2031–2040	2041–2050	2020–2040 [billion Euro]	Average annual [billion Euro/a]
ES BAU					
Fossil	0.0	0.0	0.0	0.0	0.0
Nuclear		0.0	0.0	0.0	0.0
CHP (fossil + renewable)	6.8	12.8	4.7	19.6	1.0
Biomass	4.8	3.8	4.6	8.6	0.4
Hydro	16.9	9.6	4.7	26.5	1.3
Wind	69.1	62.7	40.0	131.8	6.6
photovoltaic	45.0	59.3	14.1	104.2	5.2
Geothermal	0.2	6.7	0.9	6.8	0.3
Solar thermal power plants	30.3	11.9	6.3	42.3	2.1
Ocean energy	0.3	11.2	3.7	11.5	0.6
Total investment ES BAU				**351.0**	**17.6**
ES 4.0					
Fossil	0.0	0.0	0.0	0.0	0.0
Nuclear		0.0	0.0	0.0	0.0
CHP (fossil + renewable)	7.0	11.9	2.0	19.0	0.9
Biomass	5.8	3.6	2.9	9.4	0.5
Hydro	20.5	2.1	2.6	22.6	1.1
Wind	62.6	97.3	42.4	159.9	8.0
photovoltaic	43.0	41.0	3.8	84.0	4.2
Geothermal	0.2	6.9	0.6	7.1	0.4
Solar thermal power plants	29.1	22.8	16.0	51.9	2.6
Ocean energy	0.3	11.8	3.2	12.1	0.6
Total investment ES 4.0				**366.0**	**18.3**
ES 4.1					
Fossil	0.0	0.0	0.0	0.0	0.0
Nuclear		0.0	0.0	0.0	0.0
CHP (fossil + renewable)	7.0	11.9	2.0	19.0	0.9
Biomass	5.8	3.4	2.9	9.2	0.5
Hydro	19.8	0.0	2.5	19.8	1.0
Wind	61.0	78.6	38.2	139.6	7.0
photovoltaic	42.2	33.0	3.3	75.2	3.8
Geothermal	0.2	6.3	0.5	6.5	0.3
Solar thermal power plants	28.5	17.2	14.1	45.7	2.3
Ocean energy	0.3	10.4	2.8	10.7	0.5
Total investment ES 4.1				**326.0**	**16.3**

Cumulative investment in power generation	2020–2030	2031–2040	2041–2050	2020–2040 [billion Euro]	Average annual [billion Euro/a]
PT BAU					
Fossil	0.0	0.0	0.0	0.0	0.0
Nuclear	0.0	0.0	0.0	0.0	0.0
CHP (fossil + renewable)	3.8	3.3	4.7	7.0	0.4
Biomass	4.2	1.8	4.2	5.9	0.3
Hydro	2.0	0.0	1.7	2.0	0.1
Wind	8.3	7.2	8.1	15.5	0.8
photovoltaic	12.0	4.4	5.2	16.4	0.8
Geothermal	2.8	0.8	1.2	3.7	0.2
Solar thermal power plants	0.0	0.0	0.0	0.0	0.0
Ocean energy	0.0	0.0	0.0	0.0	0.0
Total investment PT BAU				**51.0**	**2.6**
PT 4.0					
Fossil	0.0	0.0	0.0	0.0	0.0
Nuclear		0.0	0.0	0.0	0.0
CHP (fossil + renewable)	2.0	1.7	0.5	3.7	0.2
Biomass	2.1	1.0	0.4	3.1	0.2
Hydro	2.6	3.5	0.5	6.1	0.3
Wind	17.6	12.6	7.3	30.2	1.5
photovoltaic	9.9	6.6	2.2	16.5	0.8
Geothermal	0.0	0.0	0.0	0.0	0.0
Solar thermal power plants	0.0	0.0	0.0	0.0	0.0
Ocean energy	0.0	0.0	0.0	0.0	0.0
Total investment PT 4.0				**60.0**	**3.0**
PT 4.1					
Fossil	0.0	0.0	0.0	0.0	0.0
Nuclear		0.0	0.0	0.0	0.0
CHP (fossil + renewable)	2.0	1.7	0.5	3.7	0.2
Biomass	1.9	0.7	0.4	2.6	0.1
Hydro	2.1	1.3	0.4	3.4	0.2
Wind	16.0	7.8	6.0	23.8	1.2
photovoltaic	9.2	4.6	1.8	13.8	0.7
Geothermal	0.0	0.0	0.0	0.0	0.0
Solar thermal power plants	0.0	0.0	0.0	0.0	0.0
Ocean energy	0.0	0.0	0.0	0.0	0.0
Total investment PT 4.1				**47.0**	**2.4**

Notes

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