Documentation - The European Commission's "A Clean Planet for all" scenarios modelled in EnergyPLAN

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The European Commission's "A Clean Planet for all" scenarios modelled in EnergyPLAN

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Introduction

This report documents all steps and assumptions in the process of replicating the European Commission's (EC) "A Clean Plant for All" scenarios in the EnergyPLAN tool. Accompanying this report is a matrix (Appendix 1, found online) that presents all the required data extracted from the EC's documentation, as well as a brief note documenting the origin of each value. The goal of this report is to make the replication of the scenarios transparent in order to strengthen the academic quality of the work. Within the RE-INVEST research project, the replicated scenarios will form the basis of the development of new scenarios.

The first chapter of this report introduces the EC scenarios, including their background and the context, in which they are created. Furthermore, it explains the relevance of replicating these scenarios in EnergyPLAN within the context of the RE-INVEST project. Finally, the chapter describes the overall methodology for how the replication is performed, also touching upon some of the challenges that were met in this process and how these were overcome.

Following the first chapter, the report presents a series of chapters, each focused on how each individual sector of the energy system is replicated in terms of energy demands, supply technologies, technology efficiencies and costs.

Finally, having documented how the input data for the replicated EnergyPLAN models are identified, the two final chapters compare the outputs of the EnergyPLAN modelling and the outputs of the EC modelling using the PRIMES model and discusses the accuracy of the replicated scenarios as well the implications of any inaccuracies.

1 The European Commission's scenarios

In November 2018, the European Commission (EC) published a report titled: "*A clean planet for all - strategic long-term vision for a prosperous, modern, competitive and climate-neutral economy by 2050*" [1]. Accompanying this report, the EC published a substantial report about the energy system modelling that forms the basis for the EC's vision. This background report is called "*Supplementary information - In-depth Analysis in Support of the Commission Communication COM(2018) 773*" [2]. As such, this report it is the Commissions latest contribution to the debate on how the future European energy system should look like, factoring in the transition to a climate-neutral economy.

As detailed in [2], the EC scenarios are modelled using the PRIMES model [3]. Table 1 highlights the different "A Clean Planet for All" scenarios calculated in PRIMES.

Table 1:The long term strategy options as presented by the European Comission

Long Term Strategy Option								
	Electrification (ELEC)	**Hydrogen (H2)**	**Power-to-X (P2X)**	**Energy Efficiency (EE)**	**Circular Economy (CIRC)**	**Combination (COMBO**	**1.5°C Technical (1.5TECH)**	**1.5°C Sustainable Lifestyles (1.5LIFE)**
Main Drivers	Electrification in all sectors	Hydrogen in industry, transport and buildings	E-fuels in industry transport and buildings	Pursuing deep energy efficiency in all sectors	Increased resource and material efficiency	Cost-efficient combination of options from 2°C scenarios	Based on COMBO with more BECCS, CCS	Based on COMBO and CIRC with lifestyle changes
GHG target in 2050	-80% GHG (excluding sinks) ["well below 2°C ambition]					-90% GHG (incl. sinks)	-100% GHG (incl. sinks) ["1.5°C" ambition]	
Major Common Assumptions	• Higher energy efficiency post 2030 • Development of sustainable, advanced biofuels • Moderate circular economy measures • Digitalisation • Market coordination for infrastructure development • BECCS present only post 2050 in 2°C scenarios • Significant learning by doing for low carbon technologies • Significant improvements in the efficiency of the transport system							
Power sector	Power is near decarbonised by 2050. Strong penetration of RES facilitated by system optimization (demand-side response, storage, interconnections, role of prosumers). Nuclear still plays a role in the power sector and CCS deployment faces limitations.							
Industry	Electrification of processes	Use of H2 in targeted applications	Use of e-gas in targeted applications	Reducing energy demand via Energy Efficiency	Higher Recycling rates, material substitution, circular measures	Combination of most Cost-efficient options from "well below 2°C" scenarios with targeted application (excluding CIRC)	COMBO but stronger	CIRC+COMBO but stronger
Buildings	Increased deployment of heat pumps	Deployment of H2 in targeted applications	Deployment of e-gas for heating	Increased renovation rates and depth	Sustainable buildings			CIRC+ COMBO but stronger
Transport sector	Faster electrification for all transport modes	H2 deployment for HDV's and some for LDV's	E-fuels deployment for all modes	Increased model shift	Mobility as a service			• CIRC+COMBO but stronger • Alternatives to air travel
Other drivers		H2 in gas distribution grid	E-gas in gas distribution grid				Limited enhancement natural sink	• Dietary changes • Enhancement natural sink

1.1 Relevance of replicating the EC scenarios in EnergyPLAN

The EC scenarios are modelled on an annual basis in the PRIMES tool. In the RE-INVEST project the intention is to model alternative scenarios based on smart energy system. These scenarios will be developed utilising the EnergyPLAN model, which is why a comparison requires the utilisation of the same model. Hence a replication of the PRIMES models is necessary. EnergyPLAN has the ability to perform a complete hour-by-hour energy system analysis for a full year for all energy sectors with the aid of time series. This is required to complete a smart energy system analysis. In comparison the EC scenarios modelled in PRIMES are not conducted on an hourly level. Time series for the supply side include wind, photovoltaics or other variable energy sources, whilst the demand side includes electricity demand, heating or transport demands.

EnergyPLAN was developed to model both traditional energy systems based on fossil fuels as well as 100% renewable energy systems. Hence, it can represent/model radical technological changes in all energy sectors, which is a key requirement for replicating the PRIMES scenarios.

The PRIMES data is aggregated on a European level including all its 28 members (Report was published in 2018), so the aim is to replicate both the "copper plate" model that includes all countries as well as the individual countries. This will allow at a later stage to model and understand better the role of gas and electricity interconnections between the EU members. This documentation describes the development of the "copper plate" replication of the PRIMES data into a single EnergyPLAN file. Within this single system there is free flow of energy, however this entire European energy system is seen as closed from other potential export and import areas.

1.2 Methodology

General methodology:

- The PRIMES report makes a general presentation of the assumptions and inputs to the analysis. Most of the input data is presented in figures throughout this report. The EC background report [2] details the data found in these figures in significantly more detail.
- First, we use the data found directly where applicable, e.g. the capacity of the power plants or a fuel consumption.
- We convert Mtoe to TWh at a conversion factor of 1 Mtoe = 11.630 TWh

- Where direct values are not presented, values are calculated from totals using the available data in the figures
- Finding historic data in relevant cases, mostly 2005 data from Eurostat
- Limitations:
  - Rounded-up mtoe numbers in the figures from the PRIMES documentation reports may lead to round-up decimals after the conversion to TWh
  - Specific inputs in EnergyPLAN could not be found in the EC report (e.g. mass-energy balances for the production of e-fuels)
  - Knowledge on technology and capacity used (e.g. several different heat pump technology data sets are presented for different geographical regions, but no indication of which heat pumps or regions are used in the model)
- Application and identification of other possible assumptions and reference, when none is given the PRIMES documentation report.

2 Replicating the heating sector

This chapter describes how the heating sector of the EC scenarios is replicated in EnergyPLAN.

In EnergyPLAN, the heating sector is split into individual heating and district heating. Furthermore, the individual heating demand is determined by the fuel input and boiler efficiency, while the district heating demand is determined by the demand for district heating plus the losses of the grid. Therefore, to replicate the heating sector of the EC scenarios in EnergyPLAN, the following is required:

- For individual heating:
  - Fuel consumption for individual boilers, including coal, oil, natural gas and biomass.
  - Efficiencies of the fuel boilers.
  - Heat demand from electric heating, including a split between electric boilers and heat pumps.
  - Efficiency of electric boilers and heat pumps.
- For district heating:
  - Heat demand from district heating.
  - Losses of the district heating grid.
  - Capacity of available district heating producing technologies and their efficiencies.

Section 2.1 describes the individual heating sector and Section 2.2 describes the district heating sector.

2.1 Individual heating

This section describes how the individual heating sector was replicated.

2.1.1 Fuel demands for individual boilers

Figure 1 shows the non-electricity fuel consumption in buildings in the EC scenarios.

Figure 44: Non-electricity fuel consumption in buildings

		oil & coal	natural gas	biogas	e-gas	hydrogen	solid biomass	district heating	other RES
	2015	60.5	143.2	1.8	0.0	0.0	45.0	30.0	2.8
	2030	8.4	113.7	0.0	0.0	0.0	30.2	24.8	6.5
2050	Baseline	0.6	71.5	0.0	0.0	0.0	13.9	19.9	9.6
	EE	0.4	34.8	7.3	0.0	0.0	9.8	14.3	6.2
	CIRC	0.5	37.0	15.6	0.0	0.0	12.4	16.8	8.1
	ELEC	0.4	28.4	6.0	0.0	0.0	11.1	17.8	8.8
	H2	0.5	30.4	5.4	0.0	35.4	12.7	17.2	8.7
	P2X	0.5	23.8	12.4	37.2	0.0	12.8	17.2	8.7
	COMBO	0.5	10.6	8.5	18.7	6.8	11.3	15.9	6.9
	1.5TECH	0.5	6.2	6.3	20.1	6.4	10.5	14.3	6.6
	1.5LIFE	0.4	6.1	6.1	19.7	6.2	9.3	13.6	6.1

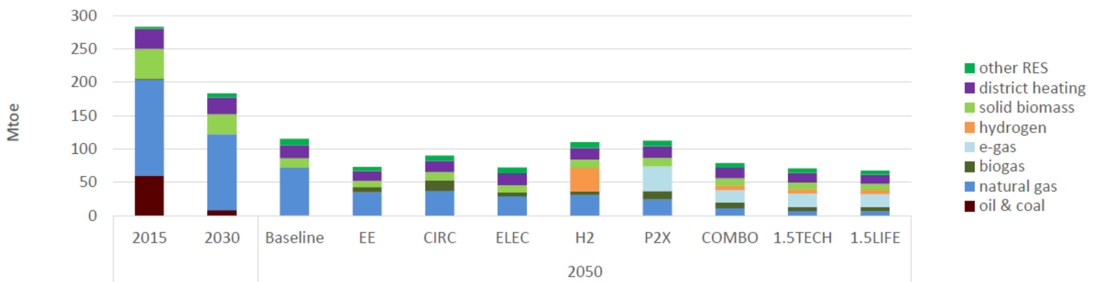

Figure 1: Non-electricity fuel consumption in buildings, interpreted as fuel for individual heating boilers and district heating demand. (Figure 44 in [2]*)*

The non-electricity fuel consumption presented in Figure 1 is interpreted as fuels for individual heating and cooking, while the numbers presented for district heating are assumed to be de demand for district heating (excluding losses).

Since the demands for oil and coal are grouped together in Figure 1, and since [2] has no account of the two individually, assumptions are required for separating oil and coal. In the data gathered for Heat Roadmap Europe 4 [4], between the two, oil boilers account for about 80% in 2015, while in 2050, they account for 100%. This same assumption is applied here for the 2015 Reference scenario.

Hydrogen is presented as a fuel for individual heating. However, hydrogen boilers are not included as a category per se, but rather, it is assumed that hydrogen-blends in the natural gas distribution grids will increase[1]. To account for the hydrogen consumption in individual heating, hydrogen is added as *H2 micro CHP* in EnergyPLAN, with the thermal efficiency of gas boilers and with an electric efficiency of zero, thus functioning as a boiler.

[1] This assumption is not stated in the EC background report *[2]*. However, it was confirmed by a representative from the EC in an e-mail correspondence dated March 28th, 2019.

Furthermore, Since EnergyPLAN does not distinguish between natural gas, biogas, and e-gas on the input side, these are all considered to be natural gas.

Based on these assumptions, Table 2 presents the fuel demands for individual boilers for each of the replicated scenarios.

Table 2 Fuel demands for individual boilers in TWh.

	2015 Reference	2050 Baseline	COMBO	1.5TECH	1.5 LIFE
Coal	140.7	1.4	1.2	1.2	0.9
Oil	562.9	5.6	4.6	4.6	3.7
Natural gas	1,686.4	831.5	439.6	379.2	370.1
Biomass	523.4	161.7	131.4	122.1	108.2
Hydrogen	0.0	0.0	79.1	74.4	72.1

2.1.2 Efficiencies of individual fuel boilers

The efficiencies of the individual fuel boilers are provided by the Technology Pathways report [5]. In some cases, [5] includes two datasets for each fuel-based boiler (*e.g.* Gas Boilers and *Condensing* Gas Boilers). In such cases, the average efficiency between the two types is used for the 2015 Reference scenario, while only condensing boilers are used in the 2050 scenarios, based on a sentence on page 94 in [2] saying that energy consumed by heaters can be significantly reduced, thanks to a "*… replacement of the most inefficient segments with more efficient alternatives, which range from condensing boilers to heat pumps…*". The efficiencies of individual fuel boilers in the replicated scenarios are presented in Table 3.

Table 3: Efficiencies of individual fuel boilers, based on [5].

	2015 Reference	2050 Baseline	COMBO	1.5 TECH	1.5 LIFE
Coal	80%	97%	97%	97%	97%
Oil	80%	97%	97%	97%	97%
Natural gas	83%	98%	98%	98%	98%
Biomass	72%	79%	79%	79%	79%
Hydrogen	83%	98%	98%	98%	98%

For hydrogen, the efficiency of natural gas boilers is used, due to the assumption that hydrogen will be blended in the gas distribution grid.

2.1.3 Electric heating: heat generation and technology efficiencies

To identify the demand covered by individual electric heating, the EC background report [2] identifies the share of electricity in space heating in buildings. This is documented in Figure 43 in [2] shown below in Figure 2.

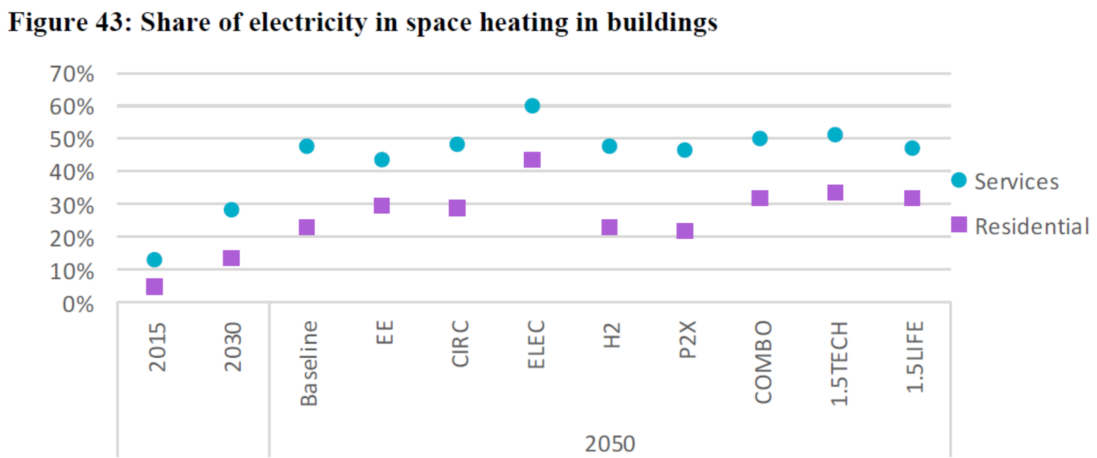

Figure 2: Share of electricity in space heating in buildings.

From the tables in section 2.1.1 and 2.1.2 it is possible to identify the heating demand without heat demand covered by electricity. Table 4 highlights the calculated heat demands excluding electricity.

Table 4: Heat demand for various units in the EC scenarios.

TWh	2015 Reference	2050 Baseline	COMBO	1.5 TECH	1.5 LIFE
Heat demand for boilers excluding electric heating	2,710	1,240	840	750	720
Heat demand covered by renewables	32	112	80	76	72
Total heat demand excluding electricity	2,742	1,352	920	826	792

The electricity demand from heating must be added on top of these heating demands. Based on the shares in Figure 43 in [2] and split between energy demands and services, the share of heat demand supplied by electricity is shown in Table 5.

Table 5: Share of heat demand estimated to be supplied by electricity

	2015 Reference	2050 Baseline	COMBO	1.5 TECH	1.5 LIFE

Share of heat demand supplied for electricity	8.12%	34.8%	40.55%	41.65%	39.2%

Thus, the heat demand covered by electric heating is shown in Table 6 below:

Table 6: Resulting heat demand covered by electric heating

TWh	2015 Reference	2050 Baseline	COMBO	1.5 TECH	1.5 LIFE
Demand covered by electric heating	242	722	628	590	511

The EC background report [2] mentions, that both electric boilers and electric heat pumps provide heating in their scenarios. However, it does not mention, how the electric heating production is split between the two technologies. However, in several places, [2] mentions that electrification is mostly due to heat pumps (*e.g.* p. 46, 94, 103 and 104). Therefore, it is assumed, that electric boilers provide 10% of the heating supplied through electricity, while heat pumps provide 90%. This assumption is also based on the rationale, that pumps serve the base load and electric boilers are only used for peak demands. In 2015, the historic split between heat pumps and electric boilers from Eurostat is used.

The efficiencies of electric boilers and heat pumps are provided in the Technology Pathways report [5]. Based on [5], the efficiency of electric boilers is assumed to be 100%. For heat pumps, however, [5] includes seven different datasets (including gas-, ground- and water-based heat pumps, as well as air-based heat pumps for South, Middle south, Middle north and North countries). Furthermore, each dataset includes a high, a medium and a low efficiency assumption. Since neither [2] nor [5] provides any logical way of calculating a weighted average between the datasets, the heat pumps are assumed to have a coefficient of performance (COP) of 3. Table 7 sums up these efficiencies.

Table 7: Assumed efficiencies of electric boilers and heat pumps.

	2015 Reference	2050 Baseline	COMBO	1.5 TECH	1.5 LIFE
Electric boilers	100%	100%	100%	100%	100%
Heat pumps	300%	300%	300%	300%	300%

Combining these assumptions, with heat demand the following heat delivered from electric boilers and heat pumps and the associate electricity is identified in Table 8.

Table 8: Heat production the different heating technology.

TWh	2015 Reference	2050 Baseline	COMBO	1.5 TECH	1.5 LIFE
Heat from EB	242	72	63	59	51
Heat from HP	3	649	565	531	460
Total electricity for heating	236	289	251	236	204

The 'Other RES' category includes solar thermal and geothermal heat. Since no other information is provided, these are assumed split equally. In the 2015 Reference scenario, solar thermal is added as input to buildings with electric boilers, while in the 2050 scenarios, solar thermal is added as input to buildings with individual heat pumps. Geothermal is added to the district heating demand in all scenarios. The geothermal is included as district heating production via absorption heat pumps (see Table 13), while the solar thermal is presented in Table 9.

Table 9: Solar thermal, added as input to buildings with electric boilers (2015 Reference) and individual heat pumps (2050 scenarios). (TWh)

	2015 Reference	2050 Baseline	COMBO	1.5 TECH	1.5 LIFE
Solar thermal	16.30	55.80	40.15	38.40	35.50

2.2 District heating

This section describes how the district heating was replicated.

2.2.1 District heating demand

Figure 1 includes the demand for district heating, and this demand is reproduced in TWh in Table 10 for the replicated scenarios, together with the assumed district heating grid losses. The grid losses are not included in the EC background report [2]. Therefore, the losses are assumed based on data from Eurostat [6].

Table 10: District heating demand and grid losses

	2015 Reference	2050 Baseline	COMBO	1.5 TECH	1.5 LIFE
District heating demand (TWh)	365.2	287.2	225.1	204.7	193.7
District heating losses	14%	14%	14%	14%	14%

2.2.2 District heating production technologies

The technologies that produce district heating in the EC scenarios are:

- CHP plants
- District heating boilers
- Waste incineration plants
- Geothermal stations

The EC background report does not mention large scale compression heat pumps as part of the district heating supply mix, even though this technology is already being used in many places and its potential in future district heating systems has been shown to be significant.

The following sections describe the different district heating supply technologies.

CHP Plants

The assumed CHP plant capacity and efficiency is described in Section 3.2.2 and presented in Table 34.

District heating boilers

The district heating boiler capacity is presented in Table 11:. The capacity corresponds to the peak district heating demand plus 20% (to account for security of supply during extreme peaks). The peak demand is assessed based on the annual demand for district heating and the district heating time series in EnergyPLAN. The efficiency of district heating boilers is set as the weighted average efficiency of the used fuel boilers, based on technology data provided in the Technology Pathways report [5].

Table 11: Assumed district heating boiler capacity and efficiency.

	2015 Reference	2050 Baseline	COMBO	1.5 TECH	1.5 LIFE
DH boiler capacity (MW)	79,000	90,000	60,000	55,000	50,000
DH boiler efficiency	84%	94%	94%	94%	94%

Waste incineration plants

The EC background mentions that waste is used in the scenarios. However, waste is always presented together with biomass. A consequence of this way of conveying the data is that the report neither provides any information about how much waste is used, nor what it is used for. Therefore, to account for some waste incineration, some assumptions had to made. Figure 3 shows the available bioenergy feedstock (including waste) in the EC scenarios, while Figure 4 shows the use of bioenergy in the EC scenarios.

Figure 84: Break down of bioenergy feedstock in 2050

	2015	Baseline	ELEC	H2	P2X	EE	CIRC	COMBO	1.5TECH	15LIFEa	1.5LIFE	1.5LIFE-LB
Food crops	17	4	3	4	4	3	3	4	3	3	2	2
Lignocellulosic grass	0	18	66	72	76	45	87	79	85	79	68	31
Short rotation coppice	0	4	13	15	21	10	21	13	24	14	13	7
Agriculture residues	18	17	33	34	32	31	35	34	33	34	34	18
Forest stemwood	28	28	33	33	33	29	34	33	34	33	32	29
Forest residues	15	30	32	32	32	31	33	32	32	32	32	30
Waste	59	90	96	96	98	92	93	97	96	93	92	85
Paper and pulp residues	14	15	15	15	15	15	13	15	15	13	13	13

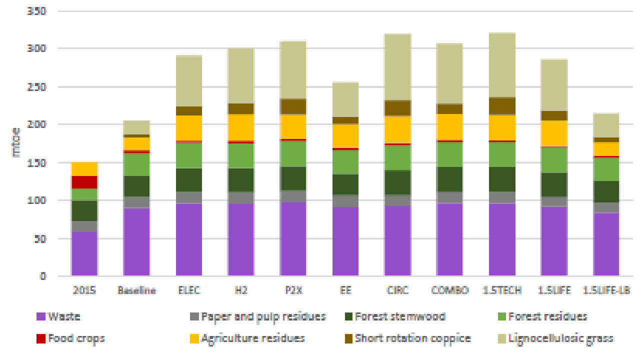

Figure 3: Break down of bioenergy feedstock in 2050, according to [2]. *(Figure 84 in* [2]*)*

Figure 83: Use of bioenergy by sectors and by scenario in 2050

	2015	2020	Baseline	ELEC	H2	P2X	EE	CIRC	COMBO	15TECH	15LIFEa	15LIFE	15LIFE-LB
Power	49	62	89	105	106	121	79	93	115	155	120	100	126
Industry	26	33	43	47	47	52	45	52	41	35	35	35	11
Road Transport	16	21	14	25	24	24	24	31	27	18	22	22	12
Air Transport	0	0	2	13	13	5	13	15	12	14	23	23	8
Service & Agriculture	6	7	6	11	10	12	11	14	11	10	10	10	7
Residential	41	44	12	14	15	21	14	23	16	14	13	13	2
Other	1	1	3	4	5	5	5	5	5	5	6	5	4

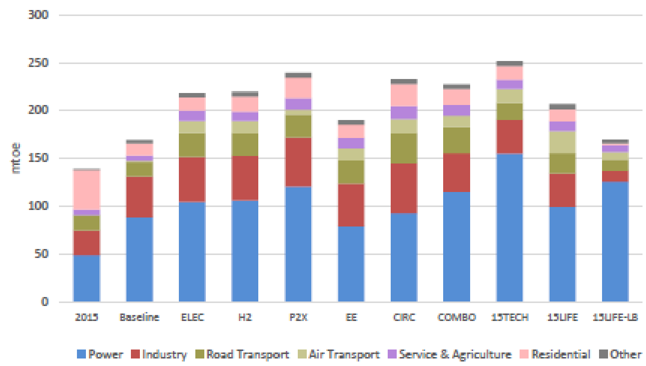

Figure 4: Use of bioenergy by sectors and by scenario in 2050 (Figure 83 in [2]*)*

To identify the waste incineration for district heating, the following assumptions are applied:

1. Summing up the figures shows that there are more resources available than used. However, there is no way of knowing which resources are not used. In a lack of better knowledge, all available waste is assumed used in each scenario.
2. The bioenergy of Figure 4 is assumed to consist of the different residue-types in Figure 3. These are considered one pool of fuel, meaning that all residues go to all end-uses in Figure 4, according to their share of the total.
3. District heating from waste incineration is only assumed to go to the Residential and industry end-uses.

Based on these assumptions, the share of waste that goes to district heating is equal to the share of the total bioenergy that goes to Residential and Industrial uses. The shares and the resulting waste incineration are presented in Table 12, together with the assumed thermal and electrical efficiencies.

Table 12: Waste incineration assumed for the replicated scenarios.

	2015 Reference	2050 Baseline	COMBO	1.5 TECH	1.5 LIFE
Available waste (TWh)	686	1,047	1,128	1,116	1,070
Residential and Industry share of total bioenergy use	48%	33%	25%	20%	23%
Waste for district heating (TWh)	331	341	283	226	247
Electricity production efficiency	30%	34%	34%	50%	50%
Heat production efficiency	20%	5%	5%	5%	5%

The electricity production efficiency is based on the Technology pathways report [5], while the heat production efficiency is the authors' assumption. It is set rather low, due to there being rather few waste incineration plants, which produce electricity and heat.

Geothermal

The Other RES category in Figure 1 includes solar thermal and geothermal. The geothermal is included in the district heating supply mix via absorption heat pumps, and the annual heating production is presented in Table 13.

Table 13: District heating from Geothermal (TWh)

	2015 Reference	2050 Baseline	COMBO	1.5 TECH	1.5 LIFE

Geothermal DH	16	56	40	38	36

3 Replicating the Electricity sector

This chapter describes how the electricity sector of the EC scenarios is replicated in EnergyPLAN. Firstly, the different demands for electricity are identified. Secondly, the power generation technologies are identified, together with their capacity and efficiency.

3.1 Demands

When modelling in EnergyPLAN, the electricity demand that is put into the model is the main parameter that decides how and when electricity is produced. Therefore, accurately replicating this part of the EC scenarios in EnergyPLAN is very important.

In EnergyPLAN, the following electricity demands are needed as inputs:

- Regular electricity demand, including:
  - Residential and tertiary sector demands, excluding electricity for heating, cooling[2] and flexible demand.
  - Transmission and distribution losses. In EnergyPLAN, these will only be treated separately, if they are added as an additional demand. Else it is assumed that electricity demands are stated in ex-work thus including transmission and distribution grid losses.
- Electricity demand for heating and cooling.
- Flexible electricity demand.
- Electricity demand for transportation.
- Grid-supplied electricity demand for the industry sector.

Furthermore, electricity demands for electrolysis are included in EnergyPLAN. These are obtained as an output from the model based on the demand for hydrogen from electrolysis. Therefore, the demand for electrolysis is also needed as input.

Since the EC data from the PRIMES model is not conveyed in these exact categories, replicating the electricity demands requires using a combination of the data in EC background report [2]. Note that the numbers behind all figures in [2] are presented as tables in the "*Supplementary information*" report [7]. The following sub-sections describe how the different electricity demands were replicated.

[2] Cooling is described in the EC background report [2], however there is no mentioning of cooling being included in the EC scenarios.

3.1.1 Total final electricity demand for each scenario

Figure 20 in the EC background report [2] presents the final energy consumption by energy carrier in all scenarios of the report. The figure is reproduced as Figure 5, below. The light-blue fraction of the bars in the lower panel is the electricity share of the total final energy demand. The upper panel depicts the total final demand in units of Mtoe. The table in the top of the figure presents the numbers behind the charts.

Figure 20: Share of energy carriers in final energy consumption

		solids	fossil liquids	e-liquids	natural gas	e-gas	hydrogen	heat distributed	biomass	other RES	electricity	total
	2000	63	490	0	268	0	0	45	48	1	217	1132
	2015	49	430	0	237	0	0	46	84	3	237	1086
	2030	38	368	0	235	0	0	49	106	7	261	1064
	Baseline	10	228	0	155	0	6	41	78	14	349	881
	EE	1	112	0	77	0	8	31	109	11	323	672
	CIRC	1	111	0	73	0	9	41	138	13	352	738
	ELEC	1	115	0	72	0	10	42	112	12	415	779
2050	H2	2	116	0	55	0	133	38	111	13	341	809
	P2X	3	107	54	58	85	15	38	115	14	342	831
	COMBO	3	91	19	29	49	42	36	109	11	355	744
	1.5TECH	1	35	41	15	45	68	32	94	10	343	684
	1.5LIFE	1	38	20	13	41	61	31	106	10	307	628

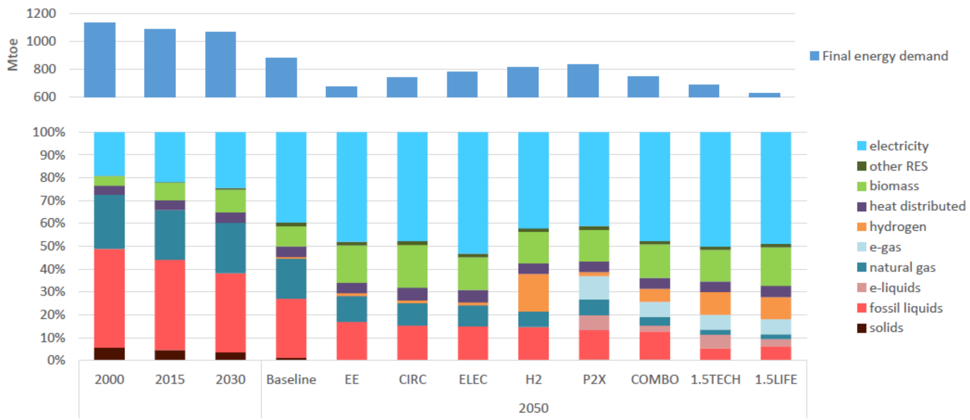

Figure 5: Final energy consumption by energy carrier as a share of the total final energy demand in all EC scenarios. (Figure 20 in [2]).

These numbers are converted to TWh as used by EnergyPLAN, and are presented in Table 14, which shows the final electricity demand in the replicated scenarios.

Table 14 Final electricity demand in the replicated scenarios (TWh)

	2015 Reference	2050 Baseline	COMBO	1.5 TECH	1.5 LIFE
Final electricity demand	2,756	4,059	4,129	3,989	3,570

Before these electricity demands can be modelled in EnergyPLAN, the setup of the model requires these are separated into the categories mentioned previously and that transmission and distribution losses are added as explained in Section 1.1.1, below. However, before separating the final electricity demand between the different sectors, it is necessary to first identify the total final energy demand of each sector. This was done using Figures 9, 19, 42, 57 and 69 in [2]. This process is described in Section 3.1.2, below.

3.1.2 Separating the total final energy demand into sectoral demands

Figure 6, below represents Figure 9 in [2]. It shows the total final energy demand of the four mentioned sectors in the Baseline scenario.

Figure 9: Final Energy demand by sector

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Industry	291	276	294	284	258	255	253	253	254
Residential	320	276	293	265	224	202	195	197	192
Tertiary	189	176	188	175	151	143	144	153	156
Transport	364	358	359	341	321	302	290	282	280

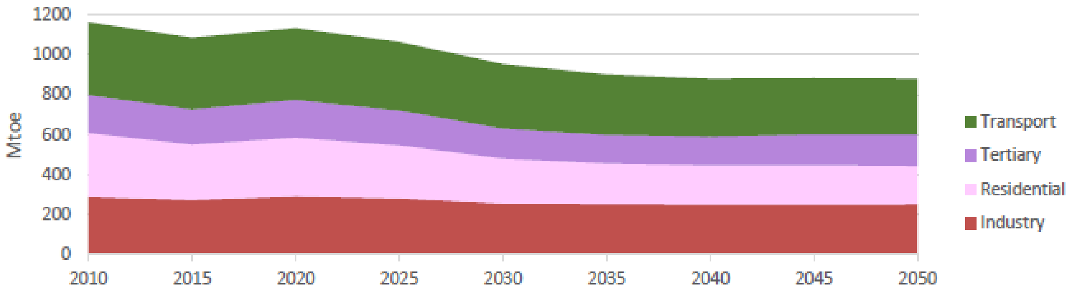

Figure 6: Final energy demand by sector

Table 15 Final energy demand in the 2015 Reference and 2050 Baseline scenario (TWh/year) shows the sectoral and total final energy demands of the replicated 2015 Reference and 2050 Baseline scenario identified by converting the numbers in Figure 6.

Table 15 Final energy demand in the 2015 Reference and 2050 Baseline scenario (TWh/year)

Sector	2015 Reference	2050 Baseline
Industry	3,210	2,954
Residential	3,210	2,233
Tertiary	2,047	1,814
Transport	4,164	3,256
Total	12,630	10,258

In order to identify the final energy demands for each sector in the remaining scenarios, Figure 19 in [2] is used. This figure shows the changes in sectoral final energy consumption as a percentage difference from 2005 historic values to the modelled 2050 scenarios.

Figure 19: Changes in sectoral final energy consumption (% change vs 2005)

		Services	Industry	Transport	Residential	Total
2030		-18%	-22%	-13%	-28%	-20%
	Baseline	-15%	-23%	-24%	-38%	-26%
	EE	-39%	-35%	-43%	-56%	-44%
	CIRC	-25%	-33%	-43%	-46%	-38%
	ELEC	-22%	-23%	-42%	-46%	-35%
2050	H2	-20%	-24%	-38%	-41%	-32%
	P2X	-21%	-25%	-31%	-41%	-30%
	COMBO	-28%	-31%	-38%	-50%	-38%
	1.5TECH	-36%	-33%	-45%	-54%	-43%
	1.5LIFE	-39%	-41%	-50%	-57%	-47%

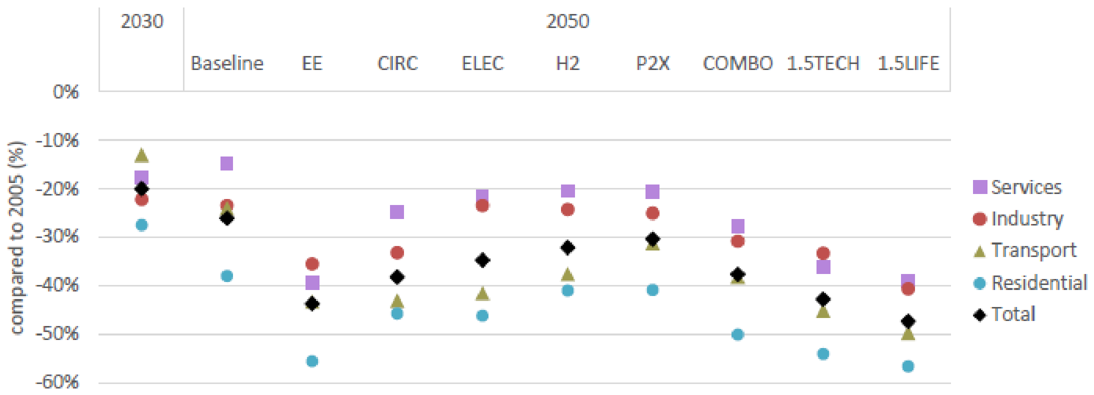

Figure 7: Final energy consumption by energy carrier as a share of the total final energy demand in all EC scenarios. (Figure 20 in [2]).

In order to convert the percentages of the figure to units of energy, the 2005 historic final energy demands of each sector have to be found. This can be done by either: A) Calculating back from the 2050 Baseline final energy demand, which was already identified in Table 15 or B) By looking up historic values from Eurostat [6]. To replicate the EC scenarios as accurately and self-consistently as possible, method A is chosen. However, the values derived from this method are also compared with the historic values from EUROSTAT.

For each sector, the values of the 2050 Baseline (Table 15) are divided with the corresponding percentage reductions compared to 2005 (Figure 7) using the following formula:

$$2005\ Baseline\ demand_{sector} = \frac{2050\ Baseline\ demand_{sector}}{(1 + \%\ change\ from\ 2005_{sector})} \quad \text{Equation 1}$$

From this calculation, the sectoral demands are identified for 2005. See Table 16, below:

Table 16: Sectoral final energy demands in 2005, based on Figures 9 and 19 from [2] (TWh/year).

Sectors	2005 demands from EC
Industry	3,836
Residential	3,602
Tertiary	2,134
Transport	4,285
Total	13,857

In order to check the accuracy of the 2005 sectoral final energy demands identified above, these are compared to the historic values documented by EUROSTAT in their annually published Energy Balances spreadsheet, which is available from [6]. This comparison shows that the total final energy demand fits very well, with 13.86 PWh based on the EC scenarios and 13.87 PWh in EUROSTAT EU Energy Balances.

Once the 2005 sectoral final energy demands are identified, the sectoral demands of the remaining 2050 scenarios can be found, using the percentages of Figure 7. The resulting sectoral final energy demands of the 2050 scenarios are presented in Table 17, together with the previously identified demands of the 2050 Baseline and the 2015 Reference scenarios.

Table 17: Sectoral final energy demand in the replicated scenarios, based on Figures 9 and 19 from [2] (TWh/year).

Sector	2015 Reference	2050 Baseline	COMBO	1.5 TECH	1.5 LIFE
Industry	3,210	2,954	2,647	2,570	2,263
Residential	3,210	2,233	1,801	1,657	1,549
Tertiary	2,047	1,814	1,537	1,366	1,302
Transport	4,164	3,256	2,657	2,357	2,142
Total	12,630	10,258	8,641	7,950	7,257

3.1.3 Identifying sectoral final electricity demands

Services and Residential sector

The final electricity demands of the Services and the Residential sectors are identified, using Figure 42 in [2] (below). It shows the share of electricity in the final energy demand in these two sectors.

Figure 42: Share of electricity in final energy demand buildings

		Services	Residential
	2015	49%	25%
	2030	64%	39%
2050	Baseline	79%	54%
	EE	78%	61%
	CIRC	80%	60%
	ELEC	83%	68%
	H2	79%	54%
	P2X	78%	53%
	COMBO	81%	63%
	1.5TECH	80%	64%
	1.5LIFE	79%	64%

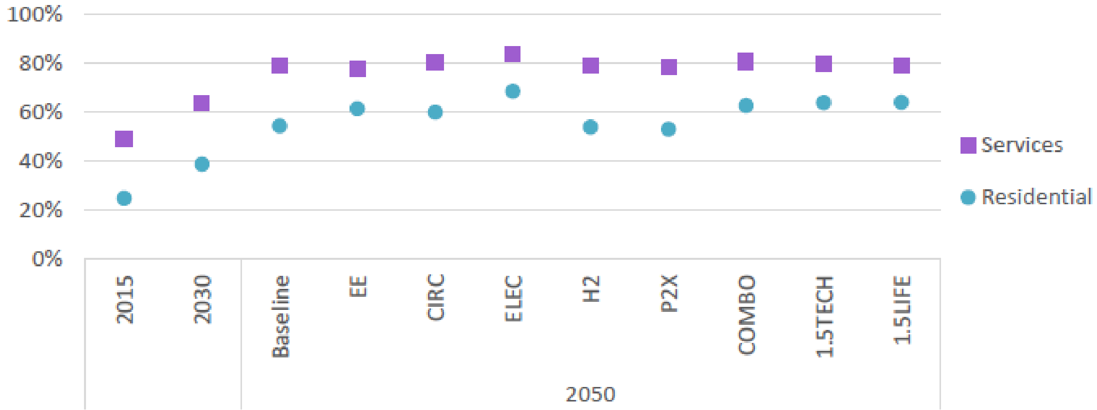

Figure 8: Final energy consumption by energy carrier as a share of the total final energy demand in all EC scenarios. (Figure 20 in [2]).

Multiplying the values in Table 17 with the corresponding percentages in Figure 8 above results in the final electricity demands in the Services and Residential sector listed in Table 18.

Table 18: Final electricity demand of the Services and Residential sectors, based on figures 9, 19 and 42 in [2] (TWh/year)

Sector	2015 Reference	2050 Baseline	COMBO	1.5 TECH	1.5 LIFE
Services	1,003	1,433	1,245	1,093	1,029
Residential	802	1,206	1,134	1,060	991

Transport sector

The final electricity demand of the transport sector is identified using Figure 57 in [2] (Figure 9 below). It presents the fuels consumed in the transport sector in all the EC scenarios. Here, electricity is presented as a fuel consumed, and this is considered the final electricity demand for transport.

Figure 57: Fuels consumed in the transport sector in 2050

Mtoe

		oil products	e-liquids	liquid biofuel	natural gas	biogas	e-gas	hydrogen	electricity
2015		337.8	0.0	16.4	1.7	0.1	0.0	0.0	4.8
2030		279.0	0.0	18.1	8.6	0.3	0.0	0.4	12.2
2050	Baseline	207.5	0.0	15.7	15.2	2.3	0.0	5.7	31.4
	EE	105.9	0.0	39.3	0.9	0.3	0.0	7.8	52.9
	CIRC	103.4	0.0	48.6	1.0	0.6	0.0	8.8	45.4
	ELEC	106.7	0.0	39.7	0.8	0.3	0.0	10.2	55.8
	H2	102.8	0.0	37.4	3.4	1.6	0.0	48.1	35.0
	P2X	93.5	54.3	24.1	10.4	7.4	16.3	9.1	36.5
	COMBO	80.1	19.0	34.6	7.0	6.9	11.9	19.8	46.6
	1.5TECH	25.7	40.7	28.2	4.2	6.0	12.2	31.7	51.9
	1.5LIFE	29.7	19.6	44.5	2.5	3.5	7.6	28.1	48.4

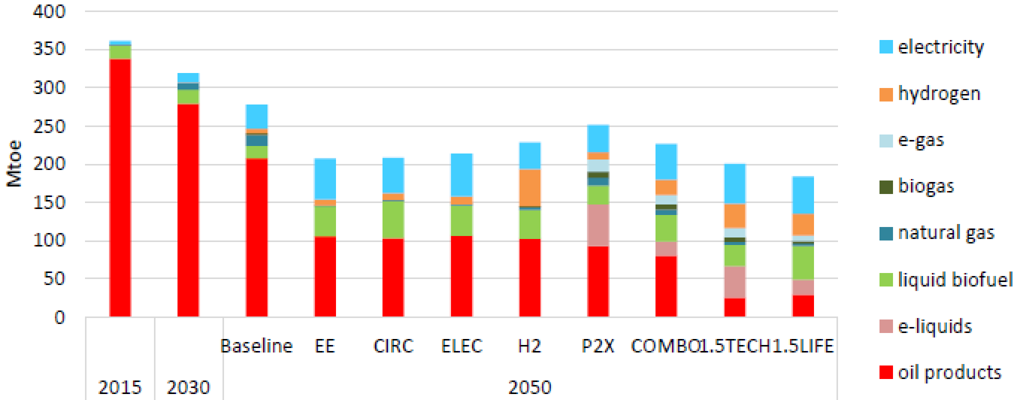

Figure 9: Fuels consumed in the transport sector. Final electricity demand for transport is expressed by the light-blue fraction of the bars. (Figure 57 in [2]).

Using this data, the following final electricity demands of the transport sector are identified in Table 19.

Table 19: Final electricity demand of the Transport sector. (TWh)

Sector	2015 Reference	2050 Baseline	COMBO	1.5 TECH	1.5 LIFE
Transport	56	365	542	604	563

With the final electricity demands of the first three sectors identified, the only remaining sector is the industry sector. Section 3.1.4 presents how the electricity demand of this sector is identified.

3.1.4 Identifying the final electricity demand of the industry sector

This sub-section explains, how the EC background report [2] documents the final electricity demand of the industrial sector. Two slightly different demands are presented in [2], and based on a discussion of the two presented demands, a decision is made regarding which particular demand is considered to be the correct one to use in the replication of the EC scenarios.

- **The first demand** derives directly from the information that has been collected so far in this chapter. Since the total final electricity demand has been identified together with the sectoral final electricity demands of three sectors, it seems reasonable to assume, that subtracting the demand of the first three sectors from the total demand would result in the exact demand of the only remaining sector: the industrial sector.
- **The second demand** derives from a specific sentence in the report. On page 155, the EC background report [2] mentions:

  "The scenario with the highest electricity demand in industry in PRIMES is 1.5TECH. Electricity demand for industrial sectors (including refineries), as well as for the production of hydrogen and e-fuels consumed by all sectors, reach 4808 TWh, of which 1344 TWh is final electricity demand in industry, not related to hydrogen or e-fuel production.

  With the information that the industrial final electricity demand in the 1.5 TECH scenario is 1,344 TWh, it is possible to find out the demands of the remaining scenarios using Figure 69 in [2] (Figure 10 below). This shows the differences in final energy consumption in industry compared to the 2050 Baseline by energy carrier in Mtoe.

Figure 69: Differences in final energy consumption in industry compared to Baseline in 2050

	ELEC	H2	P2X	EE	CIRC	COMBO	1.5TECH	1.5LIFE
Egas	0.0	0.0	29.8	0.0	0.0	17.2	10.7	11.7
Hydrogen	0.0	48.2	5.5	0.0	0.0	14.8	29.1	25.8
Electricity	35.6	1.6	3.1	7.4	4.7	13.5	15.8	-5.9
Biomass	4.2	3.7	8.6	1.9	9.5	-2.3	-7.6	-8.2
Reduced Demand	0.1	2.7	5.2	39.8	32.1	24.4	32.7	56.9
Natural Gas (incl. coal gas)	-24.4	-44.5	-41.2	-25.9	-31.2	-53.2	-60.1	-59.8
Steam	2.6	-1.1	-1.0	-4.7	2.4	-1.1	-3.9	-3.7
Solids	-9.1	-7.3	-7.2	-8.8	-9.3	-7.2	-8.8	-9.0
Fossil Based Liquids	-7.9	-3.3	-2.8	-9.6	-8.2	-5.1	-6.9	-7.2
Other (solar, geothermal)	-1.0	0.0	0.0	-0.1	-0.1	-0.9	-1.0	-0.6

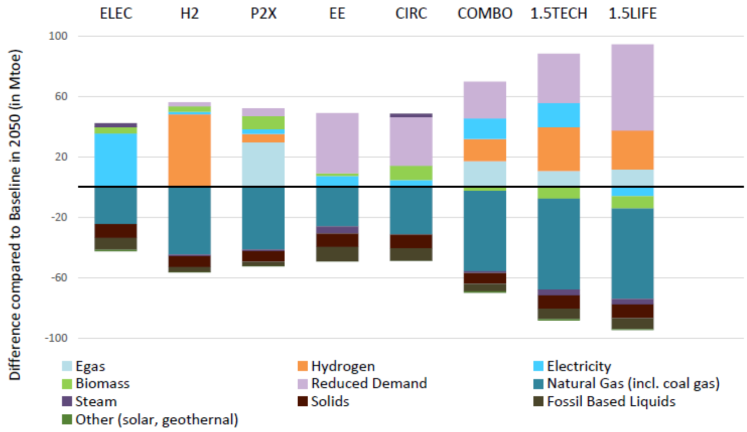

Figure 10: Differences in final energy consumption per energy carrier in industry compared to Baseline 2050 (Mtoe). (Figure 69 in [2]).

Knowing that the final electricity demand in the 1.5 TECH scenario is 1,344 TWh, the demand of the 2050 Baseline scenario must be 1,344 TWh minus the difference between the Baseline 2050 and the 1.5 TECH scenario; *i.e.* 1,344 TWh minus 184 TWh (15.8 Mtoe) which equals 1,160 TWh.

With the industrial final electricity demand of the 2050 Baseline scenario identified, the demand of the remaining 2050 scenarios can be found using their differences compared to the 2050 Baseline as presented by Figure 10 (Figure 69 in [2]). However, here the demand in the 2015 Reference scenario is not included. If using this demand, then the historic demand of the industry sector as documented by EUROSTAT could be applied.

The two different industrial final electricity demands presented in [2], which have been described in the points above, are presented in Table 20.

Table 20: Overview of the two different industrial final electricity demands inferred from [2] for each of the replicated scenarios (TWh)

	2015 Reference	2050 Baseline	COMBO	1.5 TECH	1.5 LIFE
The first demand (remaining)	895	1,055	1,207	1,232	988

The second demand (from text)	1,008	1,160	1,317	1,344	1,092

In the table above it is clear, that it is not possible to consistently establish the electricity demand of the industrial sector from the EC background report [2]. An explanation could be the found in the fact that (Figure 20 in [2]) presents the final electricity demand in Mtoe in whole numbers. When converting these numbers to TWh, this can lead to a margin of error of more than 10 TWh (0.5 Mtoe to 1.49 Mtoe). Furthermore, multiplying these numbers with shares in various figures, also without any decimals, inevitably cause differences that factor into the differences seen in Table 20.

Of the two different demands that may be inferred from the EC background report [2], only one is selected for the replication in EnergyPLAN. However, since both demands are identified from [2], there is no obvious "correct" demand to replicate. Nonetheless, a choice must be made.

Since there have been identified some inconsistencies between the figures regarding industry, it is decided to go with the wording in the report, i.e. the second demand described above.

3.1.5 Final electricity demand of all sectors

Based on the descriptions above, the Table 21 sums up the final electricity demand of each sector.

Table 21: Breakdown of the sectoral final electricity demands. (TWh)

	2015 Reference	2050 Baseline	COMBO	1.5 TECH	1.5 LIFE
Services	1,003	1,433	1,245	1,093	1,029
Residential	802	1,206	1,134	1,060	991
Transport	56	365	542	604	563
Industry	1,008	1,160	1,317	1,344	1,092
Total FED calculated	2,869	4,165	4,239	4,101	3,674

Considering the structure of EnergyPLAN, the demands of the Transport and Industry sectors are ready to be inputted to the model. However, as previously explained, EnergyPLAN requires that electricity for heating and flexible demand is subtracted from the regular electricity demand of the Household and Tertiary sectors. Therefore, the following two sub sections describe how this is accounted for.

3.1.6 Flexible electricity demand (1 day)

The EC background report [2] does not mention specifically, whether the PRIMES model includes any flexible electricity demand. However, it describes in detail a future, where smart buildings can "*effectively adapt operation to the needs of the occupants, while ensuring optimal energy performances and being able to interact with energy grids*" ([2] p. 96). Therefore, it is decided to include flexible demands in the replicated scenarios.

Since there is no way of knowing exactly how much flexible demand is included in the EC scenarios, it is decided to use data from the JRC-EU-TIMES model [8], which was also used for the modelling in the Heat Roadmap 4 project [9]. This model is somewhat similar to the PRIMES model, as it models the future European energy system in a yearly time resolution based on partial equilibrium modelling.

Based on the authors' previous work with the JRC-EU-TIMES and on the knowledge of the replicated scenarios from EC, the following assumptions are made regarding flexible electricity demand in the replicated scenarios (see Table 22).

Table 22: Share of flexible demand assumed for the replicated scenarios, based on the authors' previous experience from the JRC-EU-TIMES model

	2015 Reference	2050 Baseline	COMBO	1.5 TECH	1.5 LIFE
Share of conventional electricity demand	0%	10%	10%	12%	13%
TWh	0	225	198	214	222
Max power for flexible electricity demand (1 day) (GW)	0	24.96	20.64	21.97	23.25

In EnergyPLAN, flexible electricity is modelled using two main characteristics. The share that may be shifted according to dispatch requirements within a number of time periods and the maximum power of the shifted demand. In this case, we only include flexible loads that may be allocated within the 24 hours of the day. Secondly, a maximum power is applied. This is to ensure that all flexible load cannot simply be moved from 23 hours to one single hour.

As neither the flexible energy demand nor the maximum capacity for this demand is provided in [2], these values are identified using EnergyPLAN. This is achieved by combining the EU28 domestic electricity demand with the estimated flexible demands in Table 22 in EnergyPLAN as sole inputs. The tool can then calculate the maximum capacity for flexible demands, which is subsequently used in the scenarios.

3.1.7 Electricity for heating

The electricity demand for heating is identified in Section 2.1.3 and presented in Table 8.

Having identified how much the flexible electricity demand and the electricity demand for heating is of the total electricity demand, the only remaining electricity demand to identify in the replication of the EC scenarios is the electricity demand from electrolysis.

3.1.8 Electricity demand for electrolysis

In the most ambitious decarbonisation scenarios, fossil fuels are replaced by biofuels and electrofuels. Between the two, the production of electrofuels as e-gas and e-liquids requires vast amounts of electricity.

Figure 30: Consumption of e-gas by sector in 2050

	Power	Industry	Residential & services	Transport
P2X	6	30	39	16
COMBO	1	17	20	12
1.5TECH	0	11	22	12
1.5LIFE	0	12	21	8

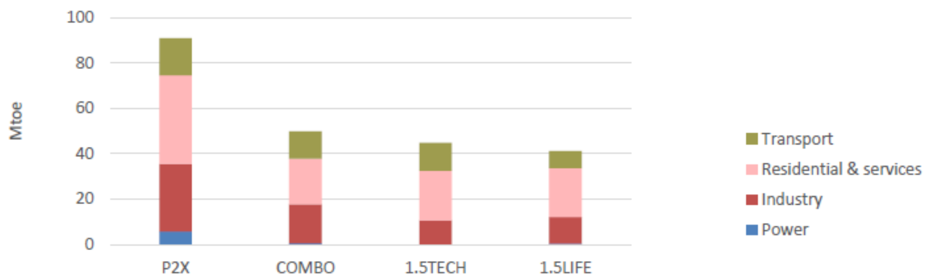

Figure 11: Consumption of e-gas by sector in the three decarbonised PRIMES scenarios. (Figure 30 in [2]).

The e-gas (methane) is used as a supplement or replacement for natural gas across all energy sectors as shown in Figure 3.11. This e-gas is produced through the process of methanation, where molecules of carbon are combined with molecules of hydrogen to form methane in the following reaction:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \qquad \text{Equation 2}$$

The carbon comes from carbon capture, whilst hydrogen comes from the electrolysis. The balance between the two is dictated by the stoichiometry of the chemical reaction. The overall process efficiency is ~50% from electricity to methane, with most of the electricity demand coming from electrolysis. The energy demands are presented in Table 24.

Table 23: Energy demands for e-gas production

	COMBO	1.5TECH	1.5 LIFE
e-gas demand (TWh)	580	520	450
CO2 (Mt)	0.10	0.09	0.07
Hydrogen (TWh)	630	570	490
Electricity for electrolysis (TWh)	990	890	760

In the case of e-liquids, the EC background report [2] does not clarify which types of liquid fuels are used in the scenarios. Since in the case of aviation it is clear that a jet fuel type is used, in the case of the other types of transport the report does not mention which e-fuels are used. These can be methanol, DME, diesel, gasoline or other blends, making it more difficult to define the energy efficiency of the pathways. Like in the case of e-gas production, [2] neither mentions what type of electrolysis is used in the process of producing these fuels; hence some assumptions have to be made in this sense.

EnergyPLAN requires the user to input the fuel pathway efficiency, hydrogen and carbon demands. In the case of e-liquids the energy balances for methanol are used, the simplest liquid fuel often proposed for the transport sector. To better simulate the variety of end-fuels that can be produced, additional losses are considered: 20% for jet fuel production and 14% for the road/sea transport fuels. These losses are not covered by the EC background report [2], making it difficult to estimate a production efficiency considering the variety of end-fuels covered by the "e-liquids". In the case of road transport fuels, the production is more straight-forward, and it involves a well-known process called MTG (methanol-to-gasoline), for which the efficiency is estimated in [10]. Jet fuels require other processing stages as Fischer-Tropsch synthesis and upgrading, all of which are all known large-scale refining processes, but which have not been combined and demonstrated together with non-fossil feedstocks. The 20% losses have been extrapolated from the available literature [11,12].

For the electrolysis, an efficiency of 64.2% is considered for both e-gas and e-liquid production, which is based on the efficiency of alkaline electrolysis used in [13], onto which additional 5% losses for storage are added. The energy demands of the pathway are presented in Table 25.

Table 24: Energy demands for e-fuel production

	COMBO	1.5TECH	1.5 LIFE
e-liquid demand (TWh)	220	470	230
e-liquid demand with losses (TWh)	260	570	270
CO2 (Mt)	0.06	0.14	0.07

Hydrogen (TWh)	290	660	310
Electricity for electrolysis (TWh)	460	1,020	480

Table 26 presents the total electricity demand of electrolysis for P2G and P2L:

Table 25: Total electricity demand from electrolysis for e-fuel production. (TWh)

	2015 Reference	2050 Baseline	COMBO	1.5 TECH	1.5 LIFE
Electricity demand for Electrolysis	0	0	1,450	1,910	1,240

3.1.9 Summary of all electricity demands

Table 27 summarises all the electricity demands that are identified in the previous sub-sections.

Table 26: Summary of all the electricity demands that have been identified in this chapter. (PWh).

	2015 Reference	2050 Baseline	COMBO	1.5TECH	1.5 LIFE
Fixed electricity demand (household and tertiary sector, excluding heating and flexible demand)	1,563	2,115	1,915	1,687	1,579
Electricity for heating	242	289	251	236	204
Flexible electricity demand (1 day)	0	235	213	230	236
Industry	1,008	1,160	1,317	1,344	1,092
Transport	56	365	542	604	563
Electrolysis	0	0	1,450	1,910	1,240
Total	**2,869**	**4,165**	**5,689**	**6,011**	**4,914**

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3.2 Power generation capacity and efficiencies

This section describes how the power generation technologies that are included in the EC scenarios are replicated in EnergyPLAN, including how the capacities and efficiencies of the different technologies are identified.

Figure 24: Power generation capacity

GW		Wind onshore	Wind offshore	Solar	Other renewables	Nuclear	Fossil fuels	Fossil fuel (CCS)	BECCS
	2000	12.7	0.0	0.2	150.0	136.6	381.4	0.0	0.0
	2015	130.4	11.0	94.7	196.1	122.0	430.6	0.0	0.0
	2030	262.9	88.4	320.5	197.7	96.5	302.7	0.0	0.0
2050	Baseline	440.9	142.9	441.5	209.6	86.8	254.2	1.1	0.0
	EE	457.3	222.5	492.6	211.1	99.3	166.4	0.0	1.1
	CIRC	501.4	253.0	543.8	217.4	106.7	200.2	1.0	1.3
	ELEC	560.2	304.6	683.0	226.6	112.9	248.5	0.3	1.9
	H2	635.3	362.2	803.9	225.8	114.1	166.4	0.4	1.1
	P2X	753.2	423.3	966.4	244.0	116.9	161.1	4.2	1.3
	COMBO	684.9	373.6	828.4	235.2	116.9	160.1	1.1	3.2
	1.5TECH	758.7	451.4	1,029.8	244.8	121.3	118.2	16.7	49.1
	1.5LIFE	693.8	396.1	769.8	237.2	114.8	119.1	2.5	2.6

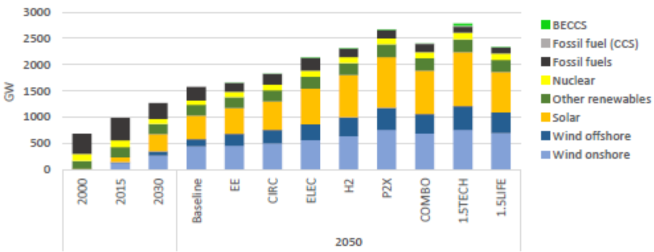

Figure 12: Power generation capacities of the technologies included in each scenario. (Figure 24 in [2]). (GW)

Figure 12 shows the power generation capacities of most of the technologies that are used in the different scenarios. However, since some of the categories presented in the figure are aggregations of several technologies, it is necessary to disaggregate these categories using other figures in the report. Furthermore, the efficiencies of the different technologies are presented in a separate report also published by the European Commission, called “Technology Pathways in decarbonisation scenarios” [5]. However, due to the aggregation in some of the categories in the Figure 3.12, using the provided technology data also entails making assumptions. Therefore, to explain how both the capacities and the efficiencies of each technology is identified, the following sub-sections separately deal with the following technology groups:

- Section 3.2.1: Renewable energy sources, including
  - Onshore wind
  - Offshore wind
  - Photovoltaics
  - Dammed hydro and biomass
  - Geothermal

- Section 3.2.2: Thermal power production technologies, including
  - Nuclear power plants
  - Condensing power plants
  - Cogeneration plants
- Section 3.2.3: Electricity storage
  - Pumped hydro
  - Batteries

3.2.1 Renewable energy sources

Wind and PV

Figure 12 provides the capacities for the variable renewable energy sources, *i.e.* Onshore wind, Offshore wind and photovoltaics. The following capacities are identified for these technologies from that figure (See Table 29).

Table 27 Capacities of On- and Offshore wind and PV, from figure 24 in [2]. (GW). Note that the table includes more decimals than the figure above. This is because some additional numbers were provided from the EC upon request, which included slightly more detailed numbers.

Technology	2015 Reference	2050 Baseline	COMBO	1.5TECH	1.5 LIFE
Onshore Wind	130.416	440.867	684.883	758.727	693.834
Offshore Wind	11.066	142.859	373.629	451.383	396.142
Photovoltaic	94.864	441.490	828.420	1,029.767	769.768

The power output of these technologies is determined by their capacity factors, *i.e.* the ratio between the actual annual production and annual production if operating at full capacity. Since PRIMES and EnergyPLAN simulate different temporal resolutions, *i.e.* PRIMES in yearly intervals and EnergyPLAN in hourly intervals, the hourly time series used in EnergyPLAN determine, whether the VRES technologies above generate the same power in the two tools.

The time series representative for onshore and offshore wind capacity factors have been modelled using the Global Renewable Energy Atlas (REatlas) from Aarhus University [14]. The capacity layout corresponding to 2015 is considered, that is, it is assumed that in 2050 the ratios (but not necessarily the installed capacities) among European countries would be similar to what they are to- day. To model onshore wind time series, the current turbines are substituted by *Gamesa G128* turbines, whose rated power is 5 MW, at a hub height of 80 m. To model offshore wind time series, the current turbines are substituted by *Vestas V164* turbines, whose rated power is 8 MW, at a hub height of 100 m. In both cases, a Gaussian smoothing with σ=2.5m/s is applied. Wind velocity data corresponding to 2015 has been used. The modelled annually-averaged capacity factor is 0.32 for onshore wind and 0.54 for offshore wind.

For 2050, the Baseline scenario in the EC background report [2] assumes a cumulative installed capacity of 440.9 GW and 142.9 for onshore and offshore wind respectively (See Figure 12). Calculating the capacity-weighted average capacity factor with the modelled time series, we obtain an annual wind capacity factor of 0.374. This is in very good agreement with the annual wind capacity factor used in [2] and estimated by dividing the electricity produced by wind in the Baseline scenario (Figure 8 in [2]) and the installed capacity, that is, 0.374.

For solar photovoltaics (PV), the time series representative for Europe in 2050 is calculated as the average of the time series for southern countries (Portugal, Spain, Italy, Bulgaria, Croatia, Cyprus, Malta). This represents both installations in southern countries and those in the sunny areas of northern countries. Calculating the average capacity factor with the modelled time series, we obtain an annual solar capacity factor of 0.165. This is in very good agreement with the annual solar capacity factor used in the EU Commission report and that can be estimated by dividing the electricity produced by solar PV by wind in the Baseline scenario (Figure 8 in [2]) and the installed capacity (Figure 12), that is, 0.166.

Dammed hydro and biomass

As mentioned above, some of the categories in Figure 12 require disaggregation to identify the capacity of the technologies. One of these categories is the one called "*Other Renewables*". On page 78 in [2] it is stated, that the Other Renewables category covers "*mostly hydro and biomass*".

Since the EC background report [2] does not provide any account of the split between dammed hydro and biomass power plants, the historic capacity of dammed hydro from EUROSTAT [6] is assumed as the capacity in 2015. With this assumption, the dammed hydro capacity can be subtracted from the Other Renewables capacity, in order to provide the capacity of Biomass power plants.

Having found the capacities of Dammed hydro and biomass power plants for the 2015 Reference scenario, some other assumptions are needed in order to find the capacities of the 2050 scenarios. Also on page 78 in [2] it is stated that the biomass capacity is 60 GW in 2030, and that it "*either stabilises (in EE) or grows very moderately - up to 83 GW (P2X)*". Based on this sentence, and considering the total capacity of the Other

Renewables group in each scenario, it is assumed that the Biomass power plant capacity is 56 GW in the 2050 Baseline scenario, 80 GW in the COMBO scenario, 82 GW in the 1.5 TECH scenario and 81 GW in the 1.5 LIFE scenario. Subtracting these values from the total capacity of the Other Renewables category leads to the following capacities for Dammed Hydro and Biomass power plants, see Table 30.

Table 28: Disaggregation of the Other Renewables category in Figure 3.12. Note that Biomass PP includes renewable waste, biogas and other bioenergy. (GW)

Technology	2015 Reference	2050 Baseline	COMBO	1.5TECH	1.5 LIFE
Dammed hydro	152	154	155	163	156
Biomass PP	44	56	80	82	81

The efficiency of dammed hydro is assumed to be 95%, based on the Danish Energy Agency's Technology Data Catalogue on Energy Storage [15]. The efficiency of biomass power plants is described in Section 3.2.2.

Geothermal

Figure 12 illustrates some geothermal power production in the 2050 Baseline scenario. However, this is the only place in the report, where geothermal power production is mentioned. Most likely, the power producing capacity of geothermal is included in the Other Renewables category of Figure 12, however, since the electricity production from this technology comprises only 0.4% of the gross electricity production in Baseline 2050, it was decided to omit this technology from the mix in all scenarios.

3.2.2 Thermal power production

Nuclear Power Plants

Figure 12 illustrates the power generation capacity of Nuclear power plants in the EC scenarios. The capacities are presented in Table 31. The table also shows the assumed efficiency of nuclear power plants. The Technology Pathways report [5] states, that the efficiency of nuclear power plants is 38% from the year 2020 until 2050. However, with this efficiency, power production and PES do not add up in the 2050 Baseline scenarios, which, as stated previously, is the only 2050 scenario for which we know the power production split between the power generating technologies. Therefore, the efficiency was adjusted to 38.6% to make both PES and power production fit with PRIMES. The technology Pathways report does not include an efficiency for the year 2015, but by

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dividing the gross electricity production by the final energy demand for nuclear (Figures 8 and 7 in [2] respectively) it was possible to identify the efficiency of 33.4%.

Furthermore, [5] also states, that Nuclear has a capacity factor of 0.85 from the year 2020 to 2050. However, the time series used in EnergyPLAN have a capacity factor of 0.83. Therefore, the *correction factor* is adjusted to make the electricity production fit with PRIMES in the 2050 baseline, and then to make the PES fit in the remaining 2050 scenarios. The resulting correction factors used are presented in Table 31. More details of how the correction factor is used can be found in the EnergyPLAN Model Documentation Version 15 [16].

Table 29: Power generation capacity, efficiency, and correction factor for Nuclear power plants in each of the replicated scenarios.

	2015 Reference	2050 Baseline	COMBO	1.5TECH	1.5 LIFE
Nuclear capacity (GW)	122.0	86.8	116.9	121.3	114.8
Nuclear efficiency	33.4%	38.6%	38.6%	38.6%	38.6%
Nuclear Correction Factor	0.97	1.09	1.04	1.08	1.01

Condensing Power Plants

The power generation capacities of condensing power plants are presented in Figure 12 n certain groups; the groups are:

- Power plants running on bioenergy (identified above from the Other renewables category)
- Power plants running on fossil fuels
- Power plants running of fossil fuels with CCS
- Powerplants running on bioenergy with CCS

The structure of the EnergyPLAN tool requires, that all power plants are aggregated when put into the model. Therefore, Table 32 presents the aggregated capacity of the power plants together with the efficiency and the minimum power plant operation, which are described below the table.

Table 30: Power generation capacity, efficiency, and minimum operation capacity of fossil fuelled power plants

	2015 Reference	2050 Baseline	COMBO	1.5TECH	1.5LIFE
Total Condensing power plant capacity (GW)	480.1	310.9	244.4	266.0	205.2
Condensing power plant electric efficiency	39%	55%	49%	43%	50%
Minimum power plant operation (GW)	0.00	0.83	3.22	49.35	3.08

The efficiency of the power plants is based on the Technology Pathways report, which includes technology data for several power plant technologies. The efficiency of the power plants is adjusted to match the level of CCS. Thus, since there is much more CCS in the 1.5 TECH scenario (see Table 50), the efficiency of the power plants is lower than in the other scenarios.

In EnergyPLAN, there is an option of setting a fixed minimum capacity of power plants, that is forced to operated constantly. This option is used in the replicated 2050 scenarios. The selected minimum power plant operation is set at 75% of the capacity of power plants that have CCS. It is assumed, that most of these plants need to work constantly, since otherwise the investments into CCS cannot be used or explained.

Cogeneration Plants

The EC background report [2] mentions, that CHP plants are included in the EC scenarios. However, there is no presentation of the actual capacity of this technology. Therefore it is assumed that the CHP plants generate approximately 40% of the total district heating energy, and based on this assumption, the capacity of CHP plants are adjusted to the levels presented in Table 33.

Table 31: Assumed Combined Heat and Power plant capacities, including power and heat efficiencies.

	2015 Reference	2050 Baseline	COMBO	1.5TECH	1.5 LIFE
CHP Electric Capacity (GW)	38	30	30	25	20
CHP Electric efficiency	35%	40%	40%	40%	40%
CHP Thermal Efficiency	40%	45%	45%	45%	45%

The efficiency of the CHP plants are assumed based on the authors best knowledge and backed up by the Danish Energy Agency's Technology data catalogue on Energy Plants for Generation of Electricity and District Heating [17].

3.2.3 Electricity storage

Figure 13 below, presents the different types of electricity storages that are included in the EC scenarios, as well as their annual usage in TWh.

Figure 26: Electricity storage in 2050

	Pumped hydro	Batteries	Hydrogen	e-gas
2030	37	34	0	0
Baseline	56	119	0	0
EE	73	151	77	0
CIRC	74	171	74	0
ELEC	76	198	65	0
H2	46	126	185	0
P2X	60	160	166	60
COMBO	60	145	95	1
1.5TECH	48	128	105	0
1.5LIFE	44	113	88	0

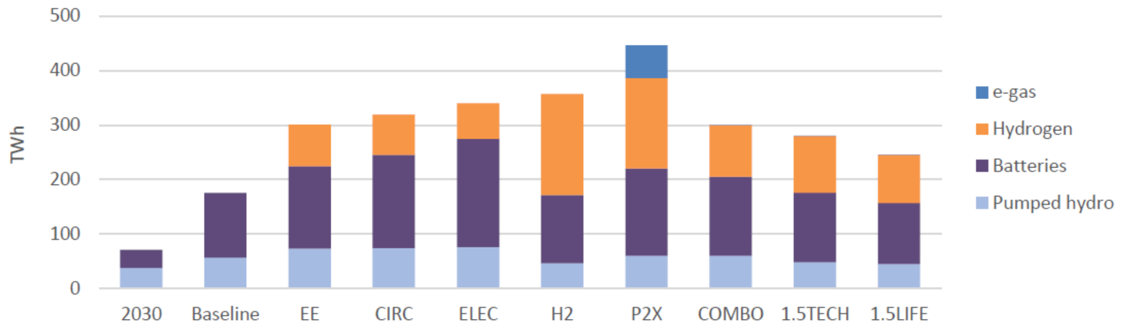


Figure 13: Annual usage of the different storages in each scenario. (Figure 26 in [2])

Furthermore, Figure 14 presents the charge/discharge capacity of the storages in GW.

Figure 27: Electricity storage and new fuel production capacities (2050)

	Pumped hydro	Batteries	Hydrogen	PtG	PtL
2015	47				
2030	51	29	2	0	0
Baseline	59	139	18	0	0
EE	64	109	57	0	0
CIRC	66	124	56	0	0
ELEC	70	178	64	0	0
H2	54	97	341	0	0
P2X	56	91	454	142	79
COMBO	58	99	352	76	28
1.5TECH	51	69	511	80	59
1.5LIFE	53	54	403	71	29

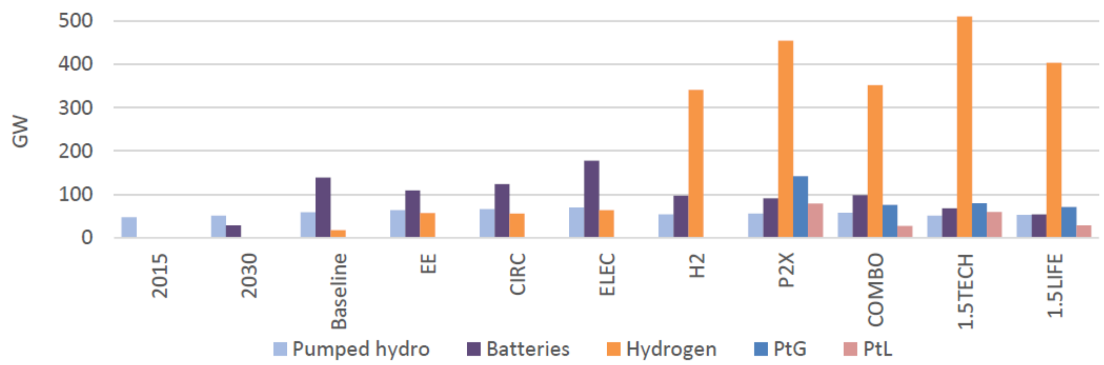


Figure 14: Charge/discharge capacities of the different storage technologies in each scenario. (Figure 27 in [2]).

The following two sub-sections describe the Pumped Hydro and Battery storages. Figure 13 and Figure 14 present Hydrogen, PtG and PtL as electricity storages. However, in this documentation report, these technologies are described elsewhere (see Section 6.2 for hydrogen and Section 3.1.8 for PtG and PtL).

Pumped Hydro

EnergyPLAN requires, that an energy storage capacity is provided. However, since [2] does not provide such a capacity, but only provides the annual usage and charge/discharge capacities, some assumptions are required.

As a rule of thumb, it is assumed that it takes 8 hours to fully charge the pumped hydro storages[3]. Therefore, by multiplying the charge/discharge capacity with 8, the energy storage capacity of the pumped hydro is identified. This capacity, together with the

[3] The assumption of 8 hours to fully charge/discharge the pumped hydro storages was confirmed by a representative of the EC in an e-mail correspondence dated October 1st 2019.

charge/discharge capacity identified from Figure 3.14 and the efficiency are presented in Table 34.

Table 32: Energy storage capacity, charge/discharge capacity and efficiency of pumped hydro in the replicated scenarios. Note that the annual usage in 2015 is not provided in Figure 3.13, however, this value is mentioned in the text surrounding the figure in [2].

	2015 Reference	2050 Baseline	COMBO	1.5TECH	1.5 LIFE
Pumped hydro (TWh)	0.38	0.47	0.46	0.41	0.42
Pumped hydro capacity (GW)	47.46	58.99	57.86	51.35	52.85
Pumped hydro efficiency	80%	80%	80%	80%	80%

The round-trip efficiency of 80% is assumed based on the Danish Energy Agency's Technology Data Catalogue on Energy Storage [15].

Batteries

To identify the energy storage capacity of batteries, the same methodology is applied as for the pumped hydro, also assuming a charge/discharge time of 8 hours[4]. The resulting energy storage capacity is presented in Table 35, together with the charge/discharge capacity presented in Figure 3.14 and the efficiency, which is based on [15].

Table 33: Energy storage capacity, charge/discharge capacity and efficiency of batteries in the replicated scenarios.

	2015 Reference	2050 Baseline	COMBO	1.5TECH	1.5 LIFE
Batteries (TWh)	0.00	1.11	0.79	0.55	0.43
Batteries (GW)	0.00	139.12	98.64	68.68	54.31
Battery efficiency (%)	98%	98%	98%	98%	98%

[4] The assumption of 8 hours to fully charge/discharge the batteries was confirmed by a representative of the EC in an e-mail correspondence dated October 1st 2019.

4 Replicating the Transport sector

This chapter describes how the transport sector of the EC scenarios is replicated in EnergyPLAN.

In EnergyPLAN, the transportation demand is determined by the amount of fuel used and the assumed efficiency of the vehicles, expressed in km/kwh. Therefore, this chapter describes, how the fuels consumed in the EC scenarios are identified. First, the consumption of liquid and gas fuels is identified. Secondly, the consumption of electricity for transportation is identified, also distinguishing between the fraction going to *Dump* charge and the fraction going to *Smart* charge.

4.1 Liquid and gas fuel consumption

Figure 9 presented previously shows the fuels consumed in the transport sector in the EC scenarios. This includes fuels for all modes of transport, including aviation, navigation, light road transport and heavy-duty road transport.

The EC background report does not provide a separation of the fuel demands for each mode of transport. However, it does provide the fuel consumption in aviation, consumption of hydrogen for transportation, as well as the consumption of gas for transportation. Therefore, the next subsection describes the fuel consumption in aviation and Section 4.1.2 describes the consumption of hydrogen for transportation, Section 4.1.3 describes the consumption of gas for transportation, while Section 4.1.4 describes the fuel consumption in all other transport modes.

4.1.1 Fuel for aviation

In EnergyPLAN, fuel for aviation is denoted as “jet fuel”. Furthermore, in EnergyPLAN jet fuel can be based on fossil fuel, biofuel or electrofuel. Therefore, in order to replicate the fuel consumption in aviation, the fuel mix for jet fuel is required.

Figure 4.2 presents the fuels that are used for aviation in the EC scenarios.

Figure 52: Aviation fuels mix in the Baseline and scenarios reaching -80% to net zero emissions by 2050 in 2050

Mtoe

		jet fuels	e-liquids	liquid biofuel	electricity
2015		53.3	0.0	0.0	0.0
2030		57.3	0.0	0.0	0.0
2050	Baseline	63.2	0.0	1.8	0.0
	EE	46.6	0.0	12.7	0.5
	CIRC	46.2	0.0	15.1	0.1
	ELEC	46.8	0.0	12.7	0.5
	H2	47.5	0.0	12.9	0.0
	P2X	46.8	8.5	5.1	0.0
	COMBO	44.6	3.3	11.9	0.4
	1.5TECH	23.9	19.8	13.7	1.2
	1.5LIFE	22.4	5.0	23.0	0.3

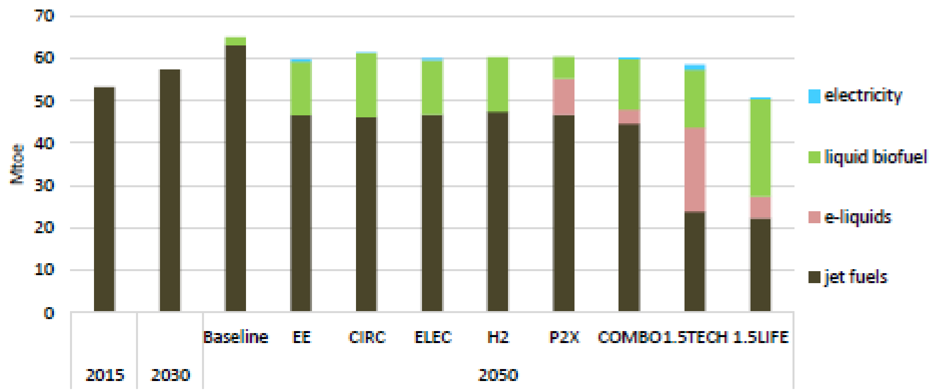


Figure 15: Aviation fuel mix in the EC scenarios (Figure 52 in [2]*)*

Note, that the "jet fuels" category is assumed to be fossil-based, "biofuels" are represented by the Fischer-Tropsch fuels and "e-liquids" correspond to the Electrofuel category in EnergyPLAN. Thereby, Figure 15 provides the necessary numbers to model the fuel consumption in aviation in EnergyPLAN and the numbers are converted to TWh in Table 36, which shows the jet fuel mix in the replicated scenarios.

Table 34: JP (Jet fuel) in the replicated scenarios (TWh)

	2015 Reference	2050 Baseline	COMBO	1.5TECH	1.5 LIFE
Fossil	620	735	519	278	261
Biofuel	0	21	138	159	268
Electrofuel	0	0	38	230	58

Figure 15 also provides the electricity consumption in aviation. However, EnergyPLAN does not include this as an option directly. Therefore, the electricity used for aviation is added to electricity for transportation, which is described in Section 4.2.

4.1.2 Hydrogen consumption for transportation

The consumption of hydrogen for transportation is presented in Figure 9. This consumption is converted to TWh and presented in Table 37.

Table 35: Hydrogen consumption for transportation in the replicated scenarios (TWh)

	2015 Reference	2050 Baseline	COMBO	1.5TECH	1.5 LIFE
Hydrogen for transportation	0	66	230	369	327

4.1.3 Gas consumption for transportation

Gas consumption for transportation is included in Figure 9, and consists of the natural gas, e-gas and biogas categories. The sum of these is converted to TWh and presented in Table 38.

Table 36: Gas consumption in the replicated scenarios. Includes natural gas, e-gas and biogas (TWh)

	2015 Reference	2050 Baseline	COMBO	1.5TECH	1.5 LIFE
Gas consumption	21	204	300	261	158

4.1.4 Remaining fuel consumption for transportation

In order to identify the remaining fuel consumption for transportation, the liquid fuels consumed in aviation (Table 36) are subtracted from the total consumption of liquid fuels (Figure 9). The resulting fuel consumption used for transportation in the replicated scenarios is presented in Table 39.

Table 37: Remaining fuels used for transportation in the replicated scenarios. (TWh).

	2015 Reference	2050 Baseline	COMBO	1.5TECH	1.5 LIFE
Fossil	3,309	1,678	413	21	85
Biofuel	191	162	264	169	250
Electrofuel	0	0	183	243	170

4.2 Electricity for transportation

The EC background report [2] states, that battery electric vehicles (BEV) cover approximately 80% of the transport demands for cars, vans, busses and coaches in all the decarbonisation scenarios. A significant part of the other means of transport as rail, inland navigation and aviation are also converted towards electricity. The EC report describes in a detailed way the shares and demand changes for all means of transport, but it is very general in terms of explaining the final demands per type of vehicles. Furthermore, it does not explain whether the electrified demands are flexible, can participate in the grid stabilisation process or include any V2G (Vehicle-to-grid) capabilities.

EnergyPLAN provides the option to split demands in dump (regular) charge, smart charge, or smart charge with V2G. The smart charge allows the battery electric powertrains to charge outside the peak hours or in times of high renewable electricity production. Not the least, the smart charge with V2G can contribute to supplying electricity to the grid, working as dispatchable energy storage. This type of differentiation between BEVs is not mentioned in the report, but it was reported as accounted for in the scenarios[5].

The total electricity used for transport is presented in Figure 9 for all the replicated scenarios. This electricity is then split in dump charge and smart charge (including V2G) and presented in Table 40.

Table 38: Electricity for transport. (TWh)

	2015 Reference	2050 Baseline	COMBO	1.5TECH	1.5 LIFE
Electrified transport	55.8	365.2	542.0	603.6	562.9
Dump charge	55.8	135.1	165.1	174.0	165.4
Smart charge	0	230.1	376.3	429.6	397.5

To determine the demands between the two types of charging, several assumptions are made. To start with, it is assumed that non-road transport, such as rail, inland navigation and aviation, can only operate as dump charge, due to their specific operational schedule, while the remaining demands (road transport) were assumed to operate as smart charge.

[5] This was explained by a representative of the European Commission in an e-mail correspondence dated March 29th 2019.

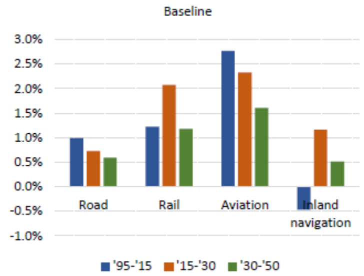
Deviations from this assumption can exist, but due to the lack of data, this approach is used across the scenarios.

The dump charge for non-road transportation is calculated using the Mpkm (million person-kilometres) and Gtkm (giga tonne-kilometres) from the EU Reference Scenario for the year 2015 [18], onto which the demand increases from the EC report were added (Figure 16, Figure 17). Combined with average vehicle demand data from [19], the total dump charge demand was replicated, while the remaining demand is considered smart charge and smart charge with V2G. The V2G charging capacity is estimated to be 5% of the total charging capacity, as in [19].

Figure 45: Passenger transport activity in the Baseline (average growth rates per year) and in the -80% to net zero scenarios (% changes to the Baseline in 2050)

Passenger transport	Annual growth rates		
	'95-'15	'15-'30	'30-'50
Road	1.0%	0.7%	0.6%
Rail	1.2%	2.1%	1.2%
Aviation	2.8%	2.3%	1.6%
Inland navigation	-0.5%	1.2%	0.5%

Passenger transport				
EE	Road	Rail	Aviation	Inland navigation
CIRC	-5%	11%	-3%	8%
ELEC	-3%	4%	-2%	5%
H2	-1%	1%	-3%	3%
P2X	-2%	2%	-3%	3%
COMBO	-3%	2%	-3%	4%
1.5TECH	-1%	5%	-3%	5%
1.5LIFE	-3%	2%	-3%	3%
	-4%	9%	-18%	7%



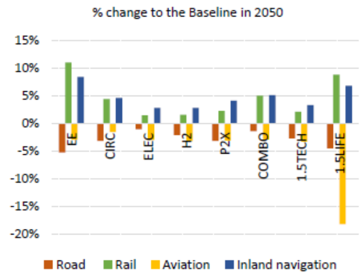
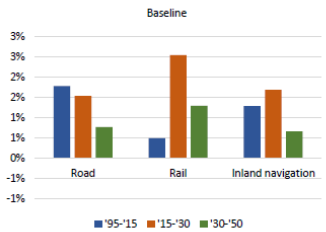


Figure 16: Passenger transport growth rates from 2015 Reference to 2050 scenarios. (Figure 45 in [2]*).*

Figure 46: Inland freight transport activity in the Baseline (average growth rates per year) and in the scenarios reaching -80% to net zero emissions by 2050 (% changes to the Baseline in 2050)

	'95-'15	'15-'30	'30-'50
Road	1.8%	1.5%	0.8%
Rail	0.5%	2.5%	1.3%
Inland navigation	1.3%	1.7%	0.7%

	Road	Rail	Inland navigation
EE	-10.6%	15.1%	13.5%
CIRC	-6.0%	5.7%	2.7%
ELEC	-2.1%	3.4%	2.1%
H2	-1.0%	2.5%	2.1%
P2X	-2.6%	2.5%	1.9%
COMBO	-3.2%	8.3%	5.5%
1.5TECH	-4.8%	4.4%	2.4%
1.5LIFE	-6.2%	9.4%	6.7%



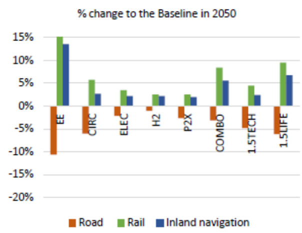


Figure 17 Freight transport growth rates from the 2015 Reference to 2050 scenarios. (Figure 46 in [2]*).*

5 Replicating the Industry sector

This chapter describes how the industrial sector of the EC scenarios was replicated in EnergyPLAN.

5.1 Fuels used in industry and refineries

To model the industry and refineries sectors, EnergyPLAN requires that the fuels used within these industries to be provided, including:

- Coal
- Oil
- Natural gas
- Biomass
- Hydrogen

Furthermore, these sectors have an electricity demand. Section 3.1.3, above, describes how this is identified.

The industrial sector is challenging to replicate, since the data presented in [2] are not very detailed. Therefore, several assumptions are required. For most fuels, it is possible to identify the consumption for the 2050 scenarios. However, for the 2015 Reference scenario, no practical way has been identified to accurately replicate the fuel consumption from the EC report. Therefore, the 2015 Reference is based on historical data from EUROSTAT, presented in [6]. This is described in more detail in the following sub-sections, which deal with the fuels mentioned above individually.

Due to the way EnergyPLAN works and the way the 2015 EUROSTAT data is structured, but also for the correctness of the results, the fuel consumption from agriculture, fisheries, forestry and other sectors not accounted elsewhere is included with the 2015 industry consumption.

5.1.1 Coal

Figure 5.1 shows the gross inland consumption of fuels in the EC scenarios. The upper panel shows the total gross inland consumption in Gtoe, while the lower panel shows the individual fuels’ share of the total gross inland consumption.

Figure 18: Gross inland consumption

		non-energy use (oil)	non-energy use (other)	solids	fossil liquids	natural gas	nuclear	e-liquids	e-gas	renewables	total (Mtoe)
2000		5.6%	0.9%	18.9%	32.7%	22.0%	14.1%	0.0%	0.0%	5.7%	1728
2015		5.1%	0.8%	17.0%	29.3%	21.1%	13.6%	0.0%	0.0%	13.0%	1628
2030		7.3%	1.4%	9.5%	25.0%	19.6%	11.8%	0.0%	0.0%	25.4%	1395
	Baseline	8.9%	1.7%	2.1%	20.2%	19.0%	12.2%	0.0%	0.0%	36.0%	1255
	EE	11.3%	2.1%	0.2%	12.5%	8.8%	14.6%	0.0%	0.0%	50.5%	983
	CIRC	9.5%	1.8%	0.1%	11.5%	8.2%	15.3%	0.0%	0.0%	53.7%	1056
	ELEC	9.7%	1.8%	0.1%	10.9%	9.1%	15.4%	0.0%	0.0%	53.0%	1154
2050	H2	9.1%	1.7%	0.4%	10.4%	8.1%	15.8%	0.0%	0.0%	54.5%	1222
	P2X	7.5%	1.4%	0.3%	8.1%	7.4%	13.7%	3.7%	6.2%	51.7%	1475
	COMBO	9.0%	1.7%	0.4%	8.1%	4.4%	15.9%	1.5%	4.0%	55.0%	1239
	1.5TECH	7.1%	1.2%	0.2%	3.1%	3.7%	16.6%	3.2%	3.5%	61.4%	1285
	1.5LIFE	8.0%	1.4%	0.1%	4.0%	2.5%	17.1%	1.8%	3.8%	61.2%	1099

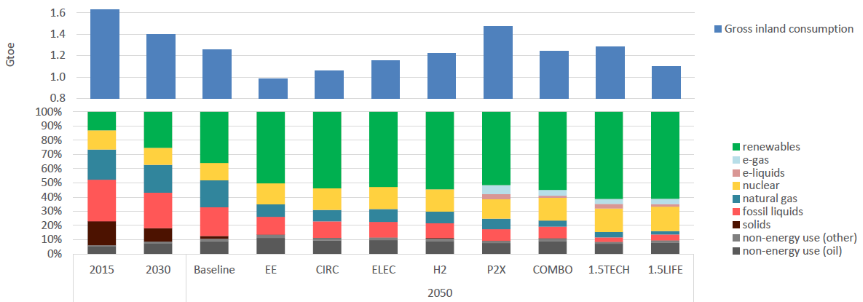


Figure 18: Gross inland consumption in the EC scenarios. (Figure 18 in [2])

The category named "solids" in Figure 18 is assumed to represent mainly coal but also other products as peat or non-renewable waste consumption. With this assumption, the figure shows that while there is significant use of coal in 2015, it represents less than 0.5% in the 2050 scenarios. This is due to coal being phased-out in the electricity and heating sectors, only leaving some consumption in the industrial sector (see e.g. page 41 in [2], which discusses phase out of coal). Therefore, the only remaining coal consumption is assumed to come from the industrial sector and refineries in the replicated scenarios.

The share of coal consumption in Figure 18 is converted to TWh and presented in Table 41, which also shows the industrial coal consumption in 2015, which is based on [6].

Table 39 Coal consumption in the industrial sector. (TWh).

	2015 Reference	2050 Baseline	COMBO	1.5TECH	1.5 LIFE
Coal	357	306	58	30	13

5.1.2 Oil

The oil consumption in the industrial sector in the 2015 Reference scenario is based on [6]. The oil consumption in the 2050 scenarios is identified by subtracting the fossil fuels used in transportation and the oil for individual heating from the gross inland consumption of oil (). The resulting oil consumption in the industrial sector and refineries in the replicated scenarios is presented in Table 42.

Table 40 Oil consumption in the industrial sector. (TWh).

	2015 Reference	2050 Baseline	COMBO	1.5TECH	1.5 LIFE
Oil	878	528	230	159	161

5.1.3 Gas

The gas consumption in the industrial sector in the 2015 Reference scenario is based on [6], while the consumption in the 2050 scenarios is based on Figure 19, Figure 20 and Figure 21, which show the consumption of natural gas, biogas and e-gas, respectively, by sector in the EC scenarios. Additionally, the gas consumption from refineries is added as described in the EC scenarios and found in Table 43. The demands for these gasses are converted to TWh and added together in Table 44.

Figure 28: Consumption of natural gas by sector

		Non-energy	Power	Industry	Residential & services	Transport	Other energy
2015		14	98	86	148	3	10
2030		18	81	65	117	10	0
2050	Baseline	20	80	64	75	16	4
	EE	20	6	38	38	1	4
	CIRC	18	10	33	39	1	3
	ELEC	20	30	39	31	1	3
	H2	20	41	19	32	4	3
	P2X	20	54	23	25	11	-3
	COMBO	20	24	10	11	7	0
	1.5TECH	15	31	4	7	4	1
	1.5LIFE	15	13	4	7	3	1

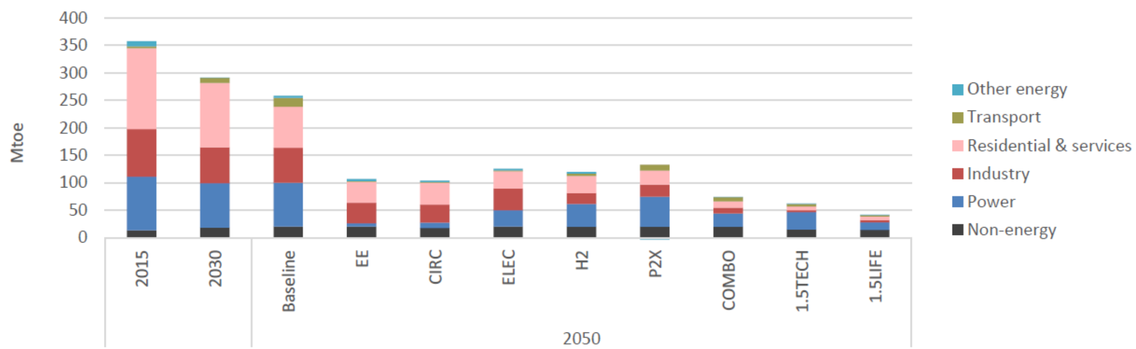


Figure 19: Consumption of natural gas by sector in the EC scenarios. (Figure 28 in [2]).

Figure 29: Consumption of biogas and gas from waste by sector

		Power & heat	Industry	Residential & services	Transport
	2015	13	0	2	0
	2030	24	6	0	0
	Baseline	28	5	0	2
	EE	26	12	8	0
	CIRC	34	20	17	1
	ELEC	37	14	7	0
2050	H2	39	12	6	2
	P2X	39	20	13	7
	COMBO	38	15	9	7
	1.5TECH	48	10	7	6
	1.5LIFE	31	12	7	4

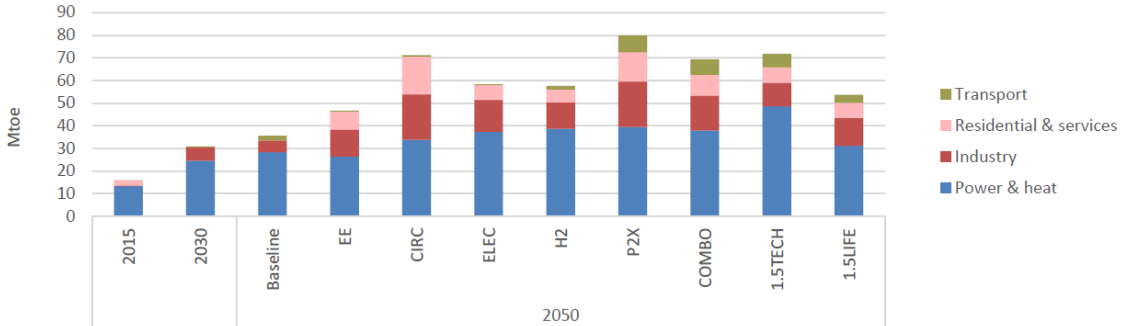


Figure 20: Consumption of biogas and gas from waste by sector in the EC scenarios. (Figure 29 in [2]).

Figure 30: Consumption of e-gas by sector in 2050

	Power	Industry	Residential & services	Transport
P2X	6	30	39	16
COMBO	1	17	20	12
1.5TECH	0	11	22	12
1.5LIFE	0	12	21	8

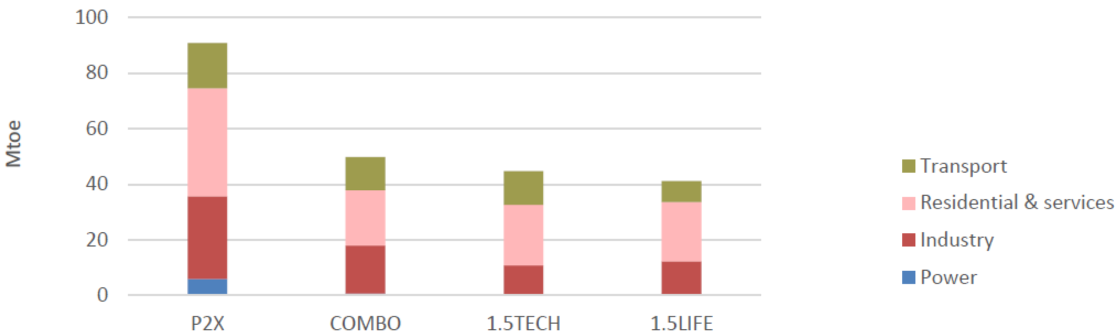


Figure 21: Consumption of e-gas by sector in 2050. (Figure 30 in [2])

Table 41: Differences in final energy consumption in Refineries compared to Baseline 2050 by fuel and scenario (Mtoe)

Figure 151: Differences in final energy consumption in Refineries compared to Baseline in 2050 by fuel and scenario

	ELEC	H2	P2X	EE	CIRC	COMBO	1.5TECH	1.5 LIFE94	1.5LIFE	LIFElowbio
Egas	0.0	0.0	0.3	0.0	0.0	0.1	0.1	0.2	0.1	0.1
Hydrogen	0.0	1.5	1.6	0.0	0.0	1.3	1.6	1.6	1.5	1.4
Electricity	18.9	-0.3	-0.2	-0.4	8.6	0.3	1.1	0.2	-0.1	0.8
Biomass	-0.4	0.3	0.3	0.4	-0.3	0.2	0.2	0.2	0.2	0.0
Reduced Demand	-6.0	13.1	12.5	12.0	4.8	12.1	14.5	15.7	15.9	14.9
Natural Gas (incl. coal gas)	-4.5	-3.7	-4.2	-3.7	-4.7	-5.1	-5.5	-5.6	-5.5	-5.5
Steam	2.5	-0.6	-0.3	2.5	2.4	2.5	1.9	1.7	1.7	1.9
Solids	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fossil Based Liquids	-10.4	-10.2	-10.0	-10.8	-10.7	-11.4	-14.0	-14.0	-13.8	-13.5
Other (solar, geothernal)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 42 Gas consumption in the industrial sector. (TWh).

	2015 Reference	2050 Baseline	COMBO	1.5TECH	1.5 LIFE
Gas	1,152	872	499	297	331

5.1.4 Biomass

The biomass consumption in the 2015 Reference scenario is based on [6], while the consumption in the 2050 scenarios are based on Figure 22 and Table 43, which show the use of bioenergy by sector in the EC scenarios. The resulting biomass consumption in the industrial sector in the replicated scenarios is presented in Table 45.

Figure 83: Use of bioenergy by sectors and by scenario in 2050

	2015	2020	Baseline	ELEC	H2	P2X	EE	CIRC	COMBO	15TECH	15LIFEa	15LIFE	15LIFE-LB
Power	49	62	89	105	106	121	79	93	115	155	120	100	126
Industry	26	33	43	47	47	52	45	52	41	35	35	35	11
Road Transport	16	21	14	25	24	24	24	31	27	18	22	22	12
Air Transport	0	0	2	13	13	5	13	15	12	14	23	23	8
Service & Agriculture	6	7	6	11	10	12	11	14	11	10	10	10	7
Residential	41	44	12	14	15	21	14	23	16	14	13	13	2
Other	1	1	3	4	5	5	5	5	5	5	6	5	4

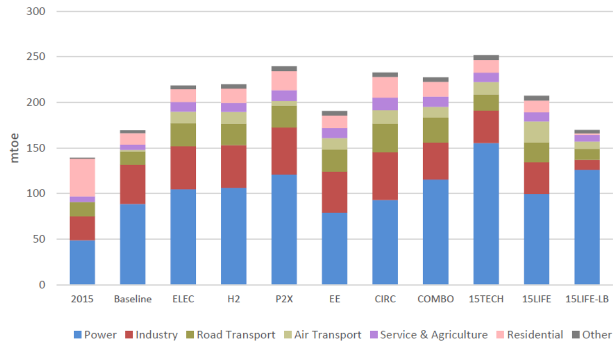


Figure 22: Use of bioenergy by sector and by scenario in the EC scenarios. (Figure 83 in [2]*).*

Table 43 Biomass consumption in the industrial sector. (TWh).

	2015 Reference	2050 Baseline	COMBO	1.5TECH	1.5 LIFE
Biomass	278	512	491	422	421

5.1.5 Hydrogen

Figure 23 shows the hydrogen consumption by sector in the EC scenarios in industry whilst Table 44 was used to extract the biomass consumption in refineries. The numbers for the industrial sector are converted to TWh and presented in Table 46.

Figure 32: Consumption of hydrogen by sector in 2050

	Power sector (storage)	Industry	Residential & services	Transport
Baseline	0	0	0	6
EE	7	0	0	8
CIRC	6	0	0	9
ELEC	6	0	0	10
H2	13	48	37	48
P2X	12	5	0	9
COMBO	8	15	7	20
1.5TECH	9	29	7	32
1.5LIFE	8	26	7	28

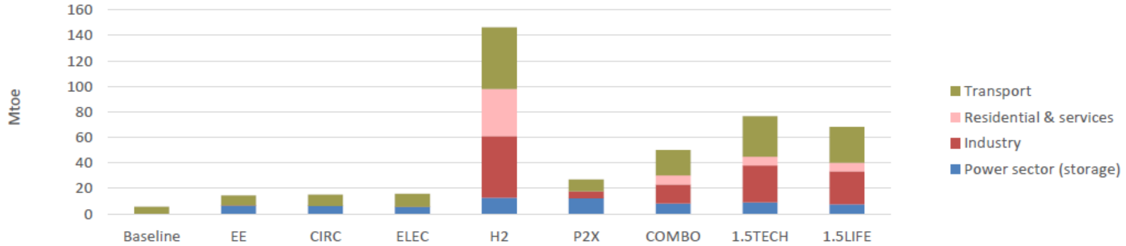


Figure 23: Hydrogen consumption in the EC scenarios. (Figure 32 in [2]*).*

Table 44 Hydrogen consumption in the industrial sector. (TWh).

	2015 Reference	2050 Baseline	COMBO	1.5TECH	1.5 LIFE
Hydrogen	0	0	73	92	91

6 Carbon fuels

This chapter describes how biogas production and CCS (carbon capture and storage) is accounted for in the replication of the EC scenarios in EnergyPLAN.

6.1 Biogas production

Figure 24 shows the total consumption of gas by type in the EC scenarios. In the figure, biogas and waste gas are combined. Since no way of separating the two gases is identified from the EC background report [2], the *biogas and waste gas* category is assumed to be only biogas.

Figure 31: Total gas consumption per gas type

		natural gas	biogas and waste gas	e-gas
	2015	358	16	0
	2030	292	31	0
2050	Baseline	258	36	0
	EE	107	47	0
	CIRC	104.2	71	0
	ELEC	126	58	0
	H2	120	57	0
	P2X	130	80	91
	COMBO	74	69	50
	1.5TECH	63	72	45
	1.5LIFE	42	54	41

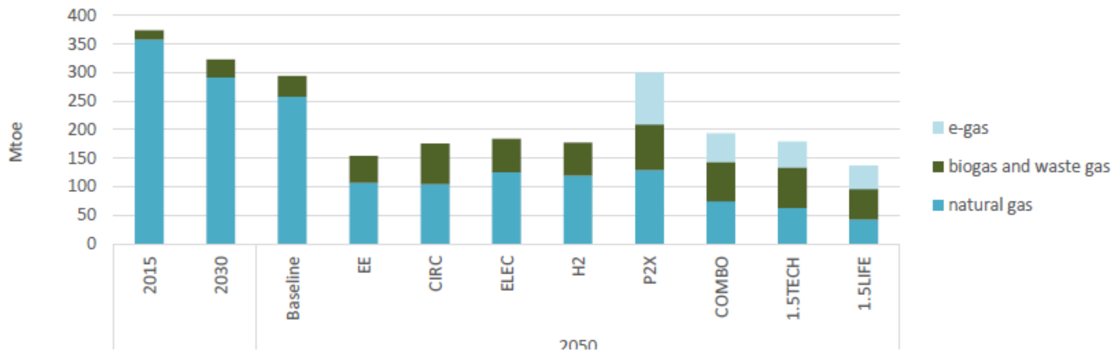


Figure 24: Gas consumption per gas type in the EC scenarios. (Figure 31 in [2])

The biogas production is converted to TWh and presented in Table 47, together with the related electricity consumption shares, which are based on [13].

Table 45 Biogas production in the replicated scenarios (TWh)

	2015 Reference	2050 Baseline	COMBO	1.5TECH	1.5 LIFE
Electricity consumption (% of output)	0.7%	1.6%	3.1%	3.2%	2.4%
Biogas production	186	419	803	837	628

6.2 Electrolysers

Figure 13 presented in Section 3.2.3 shows the electricity storage and new fuel production capacities in the EC scenarios. From the figure, the *Hydrogen* category is assumed to represent the capacity of electrolysers producing the hydrogen. Thus, this capacity in presented in Table 48.

The efficiency for the electrolysers is 64%, as is explained in Section 3.1.8. This represents the efficiency of alkaline electrolysis, one of the mature technologies on the market and with good potential for future energy applications [13]. Ref [2] does not explain what type of electrolysis is used in the scenarios, thus alkaline was considered as the most representative for this purpose.

The EC report does not provide an energy storage capacity for hydrogen storage. Therefore, this capacity is assumed in the same manner as the batteries and pumped hydro; *i.e.* assuming it takes 8 hours to fully charge/discharge the storage, with the electrolyser capacity provided in Figure 3.14. The resulting hydrogen storage capacity is presented in Table 48.

Table 46 Electrolysers and hydrogen storage in the replicated scenarios

	2015 Reference	2050 Baseline	COMBO	1.5TECH	1.5 LIFE
Electrolyser capacity (GW)	0	18	352	511	403
Electrolyser efficiency (%)	0%	64%	64%	64%	64%
Hydrogen storage (TWh)	0.000	0.144	2.528	3.824	2.968

In EnergyPLAN, the hydrogen storage modelled to be available for the transportation sector only, due to the assumption that hydrogen for heating is blended with natural gas.

6.3 Carbon capture

The decarbonised EC scenarios include carbon capture and storage (CCS). Table 49, based on the EC background report [2], shows an overview of CO_2 emitted and captured in the different scenarios.

Table 47: Sectoral emission levels and percentage change in total numbers

Table 9: Sectoral emissions levels and percentage change in total emissions

	Baseline	ELEC	H2	P2X	EE	CIRC	COMBO	1.5TECH	1.5LIFE	1.5LIFE-LB
					2030 ($MtCO_2eq$)					
Total GHG excl. LULUCF	3108	3101	3096	3105	3115	3105	3109	3091	3067	3060
Reduction vs 1990	-46%	-46%	-46%	-46%	-46%	-46%	-46%	-46%	-47%	-47%
Total GHG incl. LULUCF	2856	2849	2834	2842	2865	2862	2846	2780	2716	2710
Reduction vs 1990	-48%	-48%	-48%	-48%	-48%	-48%	-48%	-49%	-51%	-51%
					2050 ($MtCO_2eq$)					
Total GHG excl. LULUCF	2214	1054	1050	1051	1004	976	868	343	489	494
Reduction vs 1990	-62%	-82%	-82%	-82%	-83%	-83%	-85%	-94%	-92%	-91%
Total GHG incl. LULUCF	1978	816	806	788	763	684	620	26	25	23
Reduction vs 1990	-64%	-85%	-85%	-86%	-86%	-88%	-89%	-100%	-100%	-100%
ETS GHGs emissions	772	348	362	385	301	275	297	-50	123	137
Reduction vs 2005	-69%	-86%	-86%	-85%	-88%	-89%	-88%	-102%	-95%	-95%
Non-ETS GHG emissions	1442	706	687	665	702	700	571	393	366	358
Reduction vs 2005	-49%	-75%	-76%	-77%	-75%	-75%	-80%	-86%	-87%	-87%
CO2 emissions	1604	717	712	713	666	638	531	5	203	208
Residential	130	49	56	45	60	66	19	12	11	13
Transport	667	328	317	309	325	317	257	86	95	90
Tertiary	78	40	34	30	44	43	23	19	19	19
Industry	484	231	205	217	225	192	176	29	53	39
Power	246	69	99	113	13	20	56	-141	24	47
Non CO2	610	337	337	337	337	337	337	337	286	286
Agriculture	404	277	277	277	277	277	277	277	230	230
Waste	90	32	32	32	32	32	32	32	29	29
Carbon captured	5	65	63	449	65	52	239	606	281	385
From Biomass	0	5	6	114	4	5	95	276	84	122
From Direct Air Capture	0	0	0	264	0	0	83	210	123	186
Carbon used	5	65	63	449	65	52	239	606	281	385
Geological Storage	5	65	63	77	65	52	67	298	80	92
Synthetic fuels	0	0	0	372	0	0	172	227	154	226
Synthetic Materials	0	0	0	0	0	0	0	80	47	67
LULUCF	-236	-238	-244	-263	-241	-292	-248	-317	-464	-472
Sink without carbon price	-236	-238	-244	-263	-241	-292	-248	-247	-329	-340
Enhancement with carbon price	0	0	0	0	0	0	0	-70	-135	-132
					Cumulative CO_2 emissions ($GtCO_2$)					
2018 - 2050	71	60	60	61	59	58	58	49	48	48
2018 - 2070	98	61	61	62	61	58	57	41	39	39
2018 - 2100	136	57	56	57	57	53	49	28	24	23

The category "*Carbon captured*" shows the total captured CO_2, while the sub-categories "*From Biomass*" and "*From Direct Air Capture*" show how much is captured from these sources. The difference between the total CCS and the sum of the two sub-categories is assumed to be from power plants. These values for CCS are converted to $GtCO_2eq$ to fit with EnergyPLAN and presented in Table 50.

Table 48 Carbon capture in the replicated scenarios (GT)

	2015 Reference	2050 Baseline	COMBO	1.5TECH	1.5 LIFE
Total CCS	0	0.005	0.239	0.606	0.281
From gas power plants	0.000	0.005	0.061	0.120	0.074
From Biomass, BECCS	0.000	0.000	0.095	0.276	0.084
Direct air capture	0.000	0.000	0.083	0.210	0.123

7 Comparison of the outputs

The chapters above describe how the various input data has been identified for replicating the EC scenarios in EnergyPLAN, originally modelled in PRIMES. To assess the accuracy of the replication, this chapter compares the EnergyPLAN and the PRIMES outputs across a series of relevant parameters, including:

- Primary energy supply
- Electricity production
- Carbon emissions

7.1 Primary energy supply

Figure 25 shows primary energy supply (PES) of the EC scenarios modelled in PRIMES and EnergyPLAN. In terms of PES, the EnergyPLAN scenarios replicate the PRIMES outputs very accurately, both regarding the total PES as well as the individual fuels used. In the 2015 Reference and the 2050 Baseline, EnergyPLAN has marginally lower PES than PRIMES, 1.5% and 2.4% respectively, while in the remaining scenarios, EnergyPLAN has marginally higher PES than PRIMES. The scenario with the largest difference is the COMBO scenario, where EnergyPLAN has 3.2% higher PES. In 1.5 TECH and 1.5 LIFE, the differences are 1.2% and 2.9% respectively.

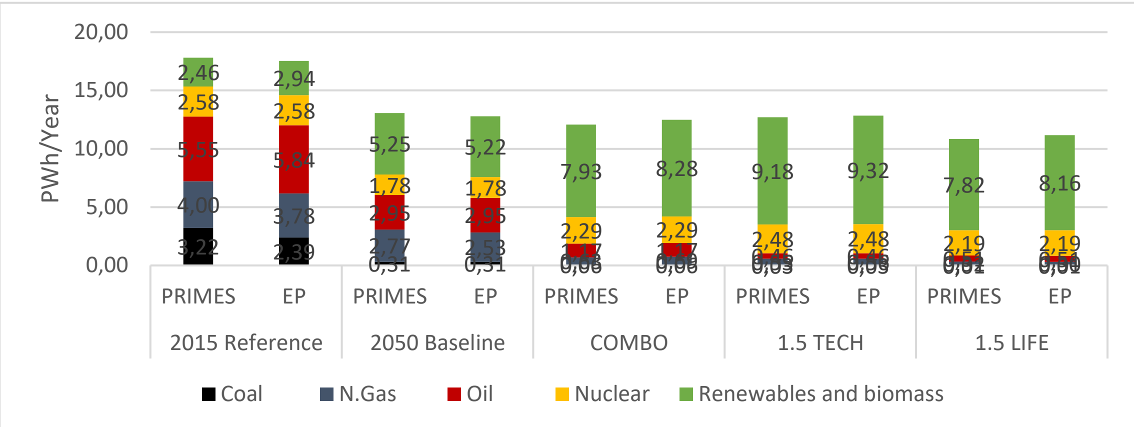


Figure 25: Primary Energy Supply comparison between PRIMES and EnergyPLAN

7.2 Electricity production

7.2.1 Total electricity production

In terms of total electricity production, the EnergyPLAN scenarios vary in accuracy. While COMBO, 1.5 TECH and 1.5 LIFE scenarios show less than 1% difference, the

2015 Reference and the 2050 Baseline show a difference of 7% and 4% respectively, with the original PRIMES scenarios having a higher electricity production than the EnergyPLAN versions. See Figure 26.

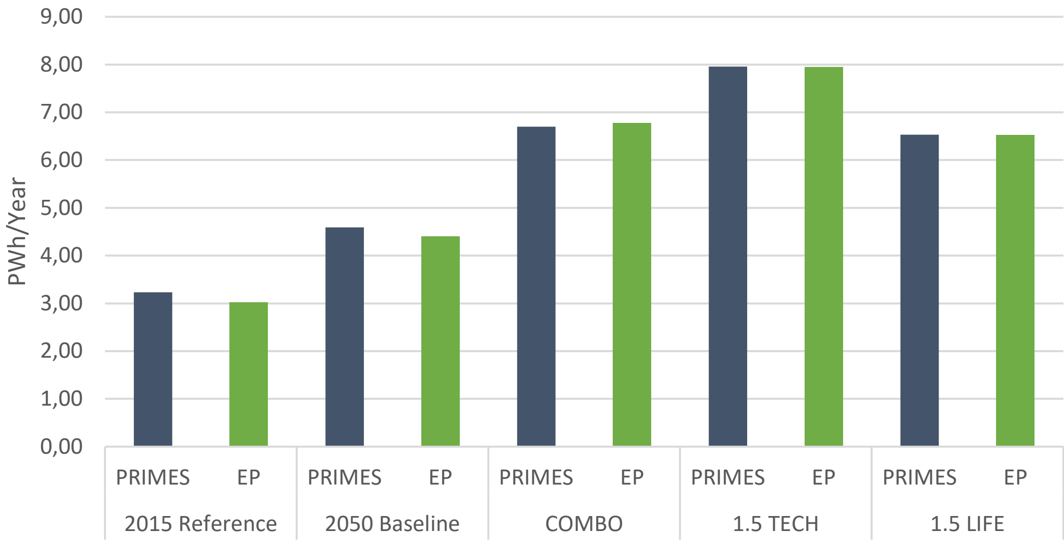


Figure 26: Total electricity production comparison between PRIMES and EnergyPLAN.

Although the accuracy of the 2015 Reference and the 2050 Baseline scenarios is not as high as in the other scenarios, these two scenarios are documented in higher detail than the remaining ones in the EC background report [2]. Therefore, the electricity production mix can be compared in more detail for these two scenarios. This helps to explain the differences. Figure 27 shows that the electricity production from *Wind*, *Solar*, *Hydro*, and *Nuclear* is identical in both models for both scenarios. However, there are differences in the production from thermal plants using *Fossil fuels* and *Biomass & Waste*. In the 2015 Reference, EnergyPLAN uses marginally less coal, natural gas and biomass, but more oil, compared to PRIMES, while in the 2050 Baseline scenario, EnergyPLAN uses slightly less of all four fuels. The reason for this small mismatch can be due to differences in the model applied. EnergyPLAN operates in hourly simulation, resulting in different fuel consumptions, while PRIMES operate with a higher spatial detail level meaning it can account for bottlenecks. Finally, assumptions regarding grid losses, fixed operation of power plants and other small differences that are difficult to account for in the process of replication can result in uncertainties. However, the assumptions used in this document allow for a close representation for all scenarios.

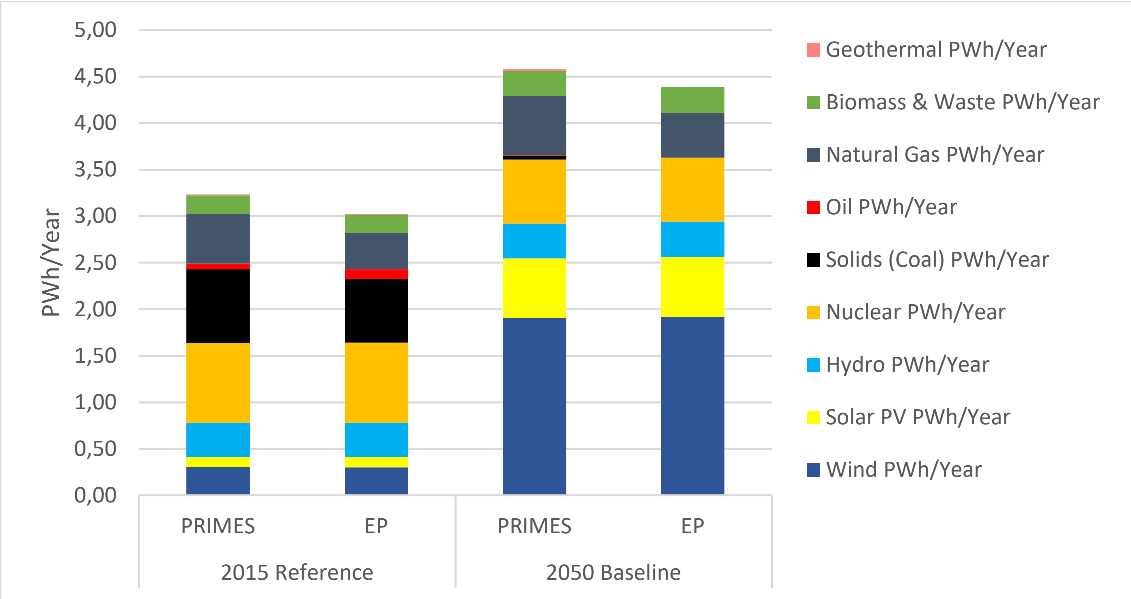


Figure 27: Electricity production by source, comparison between PRIMES and EnergyPLAN.

7.2.2 Critical Excess Electricity Production

One of the major differences between PRIMES and EnergyPLAN is the temporal resolutions. PRIMES has a resolution of five-year time slices, while EnergyPLAN has an hourly resolution. The hourly resolution renders the possibility of capturing details in the hourly dynamics of the energy system, which the five-year time slice model does not. One of these details is the critical excess electricity production (CEEP). THE CEEP is the total amount of electricity the energy system cannot make use of that may be exported, if export is in place, or otherwise curtailed. While there is no mentioning of CEEP or curtailment in the EC background report [2], the EnergyPLAN scenarios show that there are in fact several hours where there is an overproduction of electricity or CEEP. Figure 28 shows that CEEP occurs in all 2050 scenarios, ranging from 1% of the total electricity production in the 2050 Baseline to almost 10% in the 1.5 LIFE scenario. The absence of CEEP in the EC background report may also relate to some of the assumption behind the models, where EnergyPLAN is operated as a closed system without any imports and exports, while PRIMES considers that the excess electricity may just be exported.

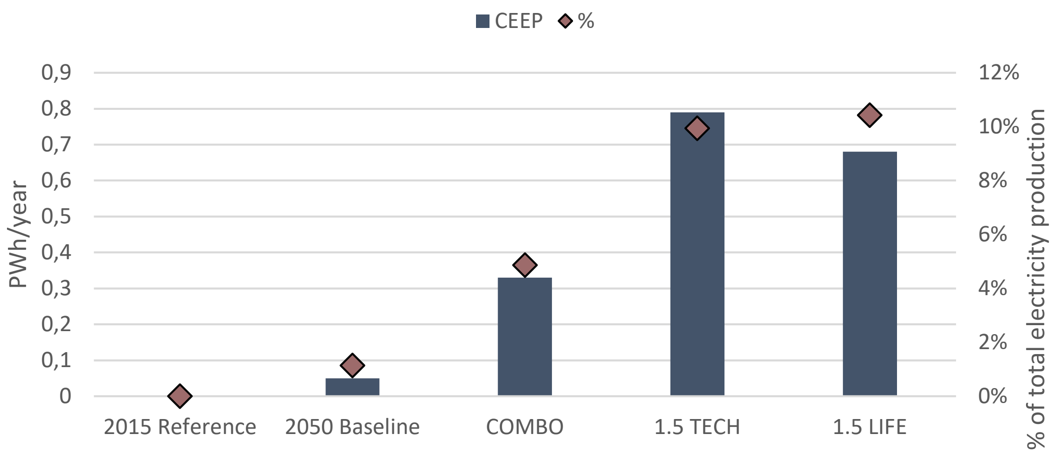


Figure 28: CEEP in the scenarios modelled in EnergyPLAN.

7.3 Carbon emissions

Figure 29 is a comparison between the CO_2 emissions from the EC scenarios modelled in PRIMES and EnergyPLAN. The figure includes emissions from the power, industry, transportation, tertiary and residential sectors as well as carbon capture, while it omits emissions from non-CO_2 Agriculture, Non-CO_2 Other and LULUCF (Figure 91 in [2]).

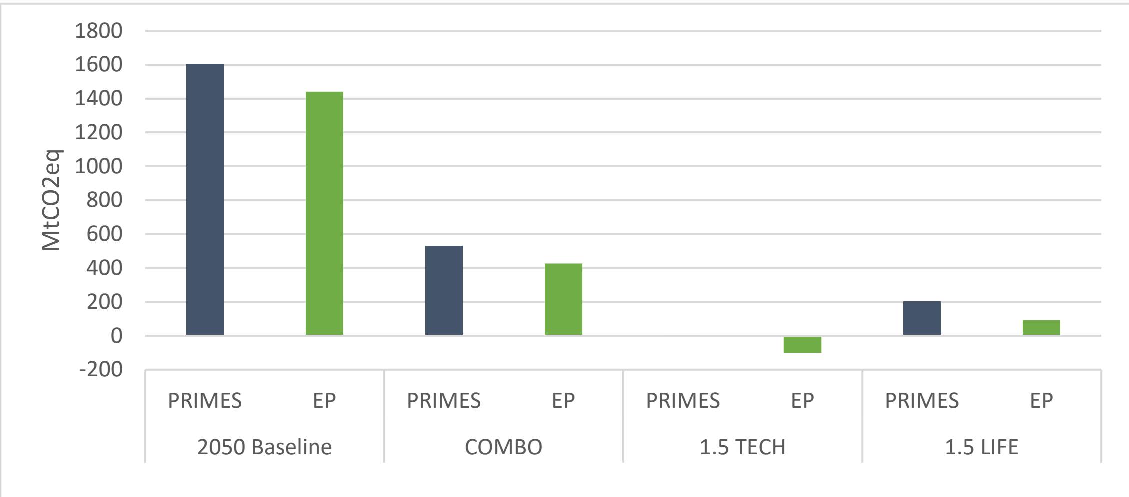


Figure 29: Net CO_2 emissions comparison between PRIMES and EnergyPLAN.

The CO_2 emissions vary between the two models with EnergyPLAN having less emissions in all scenarios. Although the aim is to replicate the EC scenarios as accurately as possible in EnergyPLAN, some discrepancies are expected, when it comes to CO_2 emissions. For example, the way in which the carbon capture and utilization (CCU) technologies are modelled varies between the models, leading to different levels of carbon capture, with EnergyPLAN having more carbon capture than PRIMES in all scenarios. Also, some discrepancy must be anticipated due to the hourly modelling in EnergyPLAN versus the five-year time slices in PRIMES. Furthermore, since the fuel production pathways are not documented in detail in the EC background report [2], assumptions have to be made in EnergyPLAN, which are not necessarily accurate.

8 Cost assumptions

This chapter describes and documents the cost data used for replicating the EC scenarios in EnergyPLAN. Furthermore, it compares the total costs of the EC scenarios, as found by PRIMES and EnergyPLAN. Finally, the chapter describes some of the challenges and limitations of replicating the costs of the EC scenarios in EnergyPLAN.

8.1.1 Technology cost data

The EC scenarios apply costs described in the Technology Pathways report [5]. This report contains technology data and costs for most relevant technologies, but not all. However, in several cases, the data is ill-fitted to be used in EnergyPLAN, due to the specific setup of the model. For most technologies, the report [5] includes an array of cost levels, ranging from Low, Medium, High, and Very High. For some technologies, the report [5] also includes geographically determined efficiencies of technologies, *e.g.* domestic heat pumps in Southern countries, Middle south countries, Middle northern countries, and Northern countries. However, the EC background report [2] does not explain which of these technologies are used in PRIMES, nor how they are used. Because of this limitation, such costs must be estimated, based on the authors' best available knowledge.

As a rule of thumb, the technology costs applied in the replication of the EC scenarios are based on the Technology Cost Database developed in the Sustainable Energy Planning Research Group at Aalborg University [20]. The database is based mainly on cost data from the Danish Energy Agency's technology data catalogues, which are available from [21], and a few other acknowledged sources. All costs have been validated against their counterparts in [5], to ensure that they are reasonably similar and not significantly different. The interest rate used is 10%, which is the same as is used in PRIMES, as stated in footnote 458 on page 207 in [2].

8.1.2 Comparing the costs of PRIMES and EnergyPLAN

This section compares the costs of the EC scenarios found by PRIMES and EnergyPLAN. Since the setup of the two models differs in terms of how they account for the various costs of the energy system, and since the technology data is not exactly the same, some discrepancy between the total energy system costs of the two models is expected. The following sections elaborate on some of the discrepancies and describes a few challenges and limitations of replicating the costs presented in the EC report [2].

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Figure 30 presents the cost profiles of the EC scenarios modelled in PRIMES and EnergyPLAN. Overall, the two models provide relatively similar total costs, although EnergyPLAN has higher costs in all scenarios. The largest difference is found in the 1.5 LIFE scenario, where EnergyPLAN has 11% higher costs than PRIMES. For the 2050 Baseline, the COMBO and the 1.5 TECH scenarios, the differences are 3%, 8% and 2% respectively.

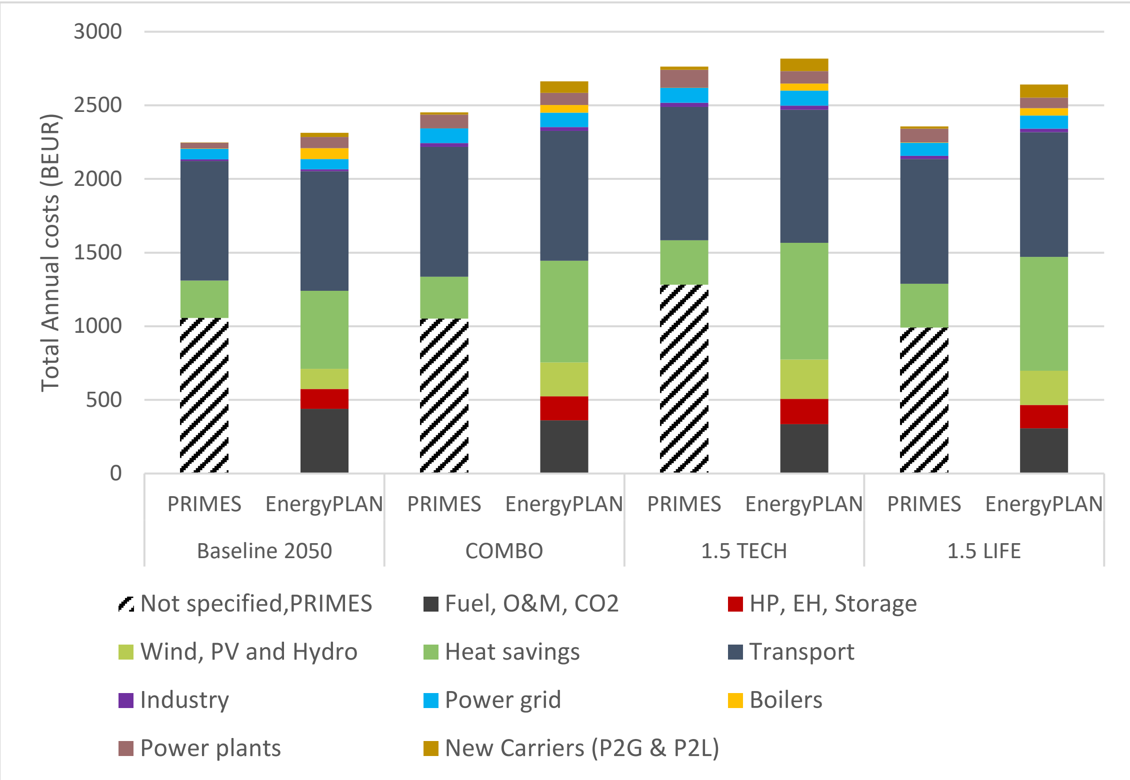

Figure 30: Comparison of EC scenario cost profiles modelled in PRIMES and EnergyPLAN

When looking at the individual cost categories, there are several differences. These are described in the following section.

8.1.3 Challenges in assigning costs to technologies

Due to structural and operational tool differences between PRIMES and EnergyPLAN, and due to the way the cost data are conveyed in the EC background report [2], some challenges arise when replicating the costs of the EC scenarios in EnergyPLAN. These are described below.

The "Not specified" fraction by PRIMES

The costs of the EC scenarios are presented two places in the EC background report [2]. Figure 31 shows the total energy system costs, while Table 51 shows the annual investment costs of the scenarios (although it seems there are some obvious investments missing from this overview, including *e.g.* investments in wind, PV, and hydro).

Figure 97: Total energy system costs, 2005-2070

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070
BL	1282	1468	1553	1814	1990	2105	2149	2185	2219	2247	2288	2277	2313	2368
ELEC	1282	1468	1553	1813	1990	2107	2140	2237	2301	2359	2425	2437	2500	2610
H2	1282	1468	1553	1813	1992	2105	2186	2315	2381	2446	2552	2572	2622	2677
P2X	1282	1468	1553	1813	1991	2105	2160	2303	2406	2483	2575	2594	2648	2704
EE	1282	1468	1553	1815	1990	2111	2120	2216	2255	2297	2356	2380	2432	2522
CIRC	1282	1468	1553	1813	1990	2107	2124	2187	2214	2225	2267	2276	2330	2399
COMBO	1282	1468	1553	1814	1992	2109	2153	2291	2381	2453	2499	2517	2547	2590
1.5 TECH	1282	1468	1553	1815	1993	2112	2190	2435	2588	2763	2713	2675	2648	2648
1.5 LIFE	1282	1468	1553	1814	1992	2111	2164	2321	2381	2358	2354	2315	2295	2266

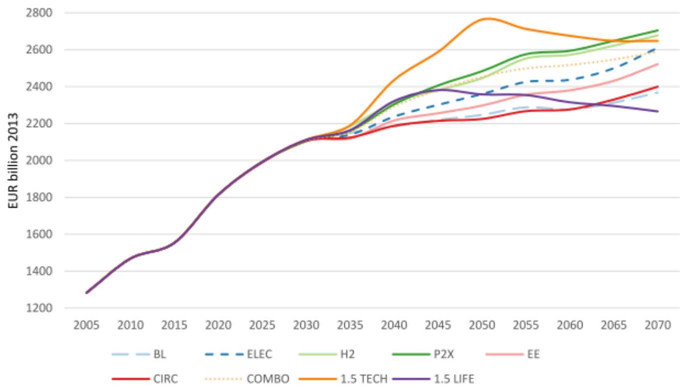

Figure 31: Total energy system costs of the EC scenarios modelled in PRIMES. (Figure 97 in [2]*)*

Table 49: Annual investment costs of the EC scenarios in BEUR, modelled in PRIMES (Table 11 in [2]*)*

	Baseline 2021-2030	**Baseline**	**EE**	**CIRC**	**ELEC**	**H2**	**P2X**	**COMBO**	**1.5 TECH**	**1.5 LIFE**
Supply	**115**	**113**	**133**	**154**	**190**	**184**	**233**	**210**	**246**	**201**
Power grid	59.2	71.3	80.7	91.0	110.3	91.1	95.3	99.4	102.8	90.3
Power plants	53.9	40.2	50.5	60.3	76.8	86.6	107.9	93.6	120.3	93.9
Boilers	1.7	1.3	1.1	1.8	1.9	1.0	0.6	0.7	0.8	0.6
New carriers	0.1	0.3	0.9	0.9	1.0	5.5	28.9	16.2	21.9	16.5
Demand exc. trans.	**281**	**264**	**335**	**285**	**285**	**270**	**271**	**312**	**330**	**318**
Industry	18.1	11.1	35.6	13.2	13.6	13.2	13.8	26.3	28.1	22.3
Residential	198.9	199.4	235.1	211.6	214.4	198.9	198.1	218.3	225.9	227.7
Tertiary	64.3	53.7	63.8	60.3	57.0	58.0	59.5	67.1	76.0	67.8
Transport	**685**	**813**	**857**	**837**	**881**	**907**	**843**	**881**	**904**	**847**
TOTAL	***1081***	***1190***	***1325***	***1276***	***1356***	***1361***	***1347***	***1402***	***1480***	***1366***
(TOTAL exc. trans.)	(396)	(377)	(468)	(439)	(475)	(454)	(504)	(522)	(576)	(519)

Source: PRIMES.

Since no further information is provided, the difference between investment costs and total energy system costs is illustrated by the "*Not specified*" fraction in Figure 30 (black and white stripes). This fraction is assumed to include fuel costs, fixed and variable O&M costs, CO2 costs as well as investment costs of individual heating technologies, Wind, PV and Solar.

The "*not specified*" fraction in the PRIMES scenarios should therefore be compared to the sum of the "*Fuel, O&M, CO2*", the "*HP, EH, Storage*" and the "*Wind, PV and Hydro*", *i.e.* the black, red and light-green fractions of the EnergyPLAN scenarios in Figure 30. This comparison shows that, although relatively consistent, the *"Not specified"* fraction is significantly higher than the EnergyPLAN counterparts in all scenarios.

The reason for this could be that PRIMES assumes higher costs for some of the categories, than those used in EnergyPLAN. Since the technology costs used for both models are similar, technology cost differences cannot be the reason. The fuel costs could, however, be the source of some discrepancy. The EnergyPLAN scenarios apply the projected fossil fuel costs from the *Sustainable Development scenario* from the International Energy Agency's World Energy Outlook 2017 [22]. This is considered a medium price level, since it is higher than *e.g.* the historically low prices of 2016, and lower than *e.g.* the projected costs of the *Current Policies* scenario in [22]. Furthermore, the EnergyPLAN scenarios apply a medium price level for wood pellets, based on [23]. The costs of these fuel assumptions are presented in Table 52. The EC background report [2] does not state, which fuel costs are applied in the modelling of the scenarios in PRIMES. To test whether the fuel costs are the source of this discrepancy, a sensitivity analysis has been performed using the High cost level. However, this does not significantly change the picture since there is relatively low fuel consumption in the 2050 scenarios.

This indicates that the *"Not specified"* fraction includes some other costs, not mentioned here. However, no further data is available besides the official EC reports.

Table 50: Fuel cost levels (€/GJ). For fossil fuels, the Low price level is the historical price level of 2016, while the Medium and the High price levels are projected by the International Energy Agency's World Energy Outlook 2017 [22]. *The wood pellet price levels are from* [23]. *The Medium level is applied when modelling the EC scenarios in EnergyPLAN.*

Price level	Crude Oil	Natural Gas	Coal	Wood Pellets
Low (41 $/barrel)	7.6	5.7	2.4	7.7
Medium (64 $/barrel)	12.1	9.3	2.4	9.6
High (136 $/barrel)	25.8	12.3	3.6	11

Cost of heat savings

The costs of heat savings differ significantly between PRIMES and EnergyPLAN, illustrated by the green fractions of the bars in Figure 30. In all scenarios, EnergyPLAN has about three times higher heat savings costs than PRIMES. This is because the two models apply different assumptions regarding heat savings costs. Heat savings are an output from PRIMES, and the related costs are calculated based on renovation costs presented in the Technology Pathways report [5]. However, to be able to create new scenarios with other levels of heat savings in the next phase of the RE-INVEST project, the heat savings costs used in EnergyPLAN are based on cost data developed in the Heat Roadmap Europe 4 project [24].

Cost of the transportation sector, power grids and industry

In the replication of the EC scenarios in EnergyPLAN, the individual costs for the different modes of transport are not included in the study. Instead, the cost of the entire transportation sector, which is listed in [2], is added as an *additional cost* in EnergyPLAN. This has no implications on the outputs of the replicated models. The transport sector is modelled and studied in more detail in the next phases of the RE-INVEST project.

The costs of the power grids and the industrial sector are also not modelled in detail in EnergyPLAN, so their investment costs, which are listed in [2], are also added as *additional cost* in EnergyPLAN.

9 References

[1] European Commission. A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. 2018.

[2] European Commission. IN-DEPTH ANALYSIS IN SUPPORT OF THE COMMISSION COMMUNICATION COM(2018) 773 - A Clean Planet for all A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. 2018.

[3] E3MLab. PRIMES MODEL VERSION 2018 Detailed model description. 2018.

[4] Paardekooper S, Lund RS, Mathiesen BV, Chang M, Petersen UR, Grundahl L, et al. Heat Roadmap Europe 4: Quantifying the Impact of Low-Carbon Heating and Cooling Roadmaps. 2018.

[5] De Vita A, Kielichowska I, Mandatowa P, Capros P, Dimopoulou E, Evangelopoulou S, et al. Technology pathways in decarbonisation scenarios. 2018.

[6] EUROSTAT. Energy balances - Eurostat 2019.

[7] European Commission. IN-DEPTH ANALYSIS IN SUPPORT OF THE COMMISSION COMMUNICATION COM (2018) 773 A Clean Planet for all A European long-term strategic vision for a prosperous , modern , competitive and Table of Contents 2018.

[8] IEA-ETSAP. Optimization Modeling Documentation 2016.

[9] Nijs W, Gonzáles IH, Paardekooper S. EnergyPLAN comparison Deliverable 6.3: Methodology report for comparing the. 2018.

[10] Hannula I. Hydrogen enhancement potential of synthetic biofuels manufacture in the European context: A techno-economic assessment. Energy 2016;104:199–212. https://doi.org/10.1016/j.energy.2016.03.119.

[11] Schmidt P, Weindorf W, Roth A, Batteiger V, Riegel F. Power-to-liquids. Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel. Munich: 2016.

[12] Baliban RC, Elia JA, Weekman V, Floudas CA. Process synthesis of hybrid coal, biomass, and natural gas to liquids via Fischer-Tropsch synthesis, ZSM-5 catalytic conversion, methanol synthesis, methanol-to-gasoline, and methanol-to-olefins/distillate technologies. Comput Chem Eng 2012;47:29–56. https://doi.org/10.1016/j.compchemeng.2012.06.032.

[13] Danish Energy Agency, Energinet. Technology Data-Renewable fuels. 2017.

[14] Andresen GB, Søndergaard AA, Greiner M. Validation of Danish wind time series from a new global renewable energy atlas for energy system analysis. Energy 2015;93:1074–88. https://doi.org/10.1016/j.energy.2015.09.071.

[15] Danish Energy Agency, Energinet. Technology Data-Energy storage. 2019.

[16] Lund H, Thellufsen JZ. EnergyPLAN Advanced Energy Systems Analysis Computer Model Documentation Version 15. 2019.

[17] Danish Energy Agency, Energinet. Technology Data-Energy Plants for Electricity and District heating generation First. 2019.

[18] Carpos P, De Vita A, Tasios N, Siskos P, Kannavou M, Preopoulos A, et al. EU Reference Scenario 2016 - Energy, transport and GHG emissions - Trends to 2050. 2016. https://doi.org/10.2833/9127.

[19] Mathiesen BV, Lund H, Hansen K, Ridjan I, Djørup S, Nielsen S, et al. IDA's Energy Vision 2050 - Technical data and methods. 2015. https://doi.org/10.1016/j.energy.2012.11.030.

[20] EnergyPLAN modelling Team. EnergyPLAN Cost Database 4.0 2018. http://www.energyplan.eu/costdatabase/ (accessed August 15, 2019).

[21] The Danish Energy Agency. Technology Data 2019.

[22] IEA. World Energy Outlook 2017. Int Energy Agency Paris, Fr 2017:1–15. https://doi.org/10.1016/0301-4215(73)90024-4.

[23] Bang C, Vitina A, Sterling Gregg J, Lindboe HH. Analysis of biomass prices. 2013.

[24] Paardekooper S. Cost-curves for heating and cooling demand reduction in the built environment and industry Deliverable 4.2 and 4.3: Report on cost-curves for built environment and industrial energy efficiency options. n.d.