sEEnergies

QUANTIFICATION OF SYNERGIES BETWEEN ENERGY EFFICIENCY FIRST PRINCIPLE AND RENEWABLE ENERGY SYSTEMS

D6.2: Modelling platform development for new scenarios based on Energy Efficiency First Principle (EEFP)

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Executive summary

This report presents the modelling platform for developing energy-efficient scenarios for the countries of the European Union and the United Kingdom (EU27+UK), applying the Energy Efficiency First Principle. The platform consists of a data component and an energy-system analysis component – this report describes both components. Energy-efficient scenarios for the energy system of each country include all the energy sectors including transport, industry and buildings. The main aim of the following energy system modelling and energy system analysis is to balance energy efficiency and renewable energy integration, enabled by the modelling platform described in this report.

The energy system scenario results will feed into a Handbook for science-based interaction with policy objectives aimed at achieving the Energy Efficiency First Principle.

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Abbreviations

Term	Description
BEV	Battery electric vehicle
FCEV	Fuel cell electric vehicle
GDP	Gross Domestic Product
HFO	Heavy fuel oil
PHEV	Plug-in hybrid electric vehicle

1 Introduction

In the sEEnergies project, Work Package 6 develops energy-efficient future scenarios for each European Union country and the United Kingdom (EU27+UK herein referred to as EU). This report (delivered as part of Task 6.3: Development of scenarios for the energy systems modelling platform) describes the modelling platform and energy system data used in the next task for establishing various European energy system scenarios (Task 6.4 of the project). The next report Deliverable 6.3: Energy Efficiency Roadmap Europe: A cost-effective and energy-efficient strategy for decarbonizing Europe – describes the final scenarios based on the platform.

The modelling platform makes it possible to iterate scenarios quickly and easily for each country in the EU27+UK, as well as for an aggregated EU system. The platform connects and integrates all the energy system sectors, from electricity to heating, cooling, industry, and transport.

This report contains two main parts that describe:

1. The concept and structural setup of the platform for making energy system scenarios

2. The input data for developing the scenarios, including data from the PRIMES EU energy system model and other sEEnergies Work Packages for energy sectors

In sEEnergies, we refer to two types of future energy scenarios: 1) sector-scenario and 2) system-scenario. The system-scenario in sEEnergies is a core project output and is an energy system configuration in the future year 2050 for both the EU and for individual EU countries. This system configuration combines energy efficiency measures within the energy sectors (determined in different Work Packages). Within each energy sector, sector-scenario variations are developed and with the aid of these sector-scenario variations, a final sector-scenario is determined for applying into the final system-scenario for the EU or for a country. We complete this in Task 6.4 of the project: Establishing various European energy-system scenarios - with results presented in Deliverable 6.3: Energy Efficiency Roadmap Europe: A cost-effective and energy-efficient strategy for decarbonizing Europe.

At a fundamental level, there are two approaches to making future energy scenarios - forecasting and backcasting - and depending on the choice; the structure of the modelling platform differs. Forecasting makes scenarios based on trends and trajectories from the present to the future. Backcasting makes scenarios in the future and indicates the types of changes required now and in the next years to get to the future scenario. The structure of the modelling platform in sEEnergies follows the backcasting principle.

We structure the remainder of this report in two main sections: Section 1 describes the structural setup of the platform based on a backcasting approach, and Section 2 describes the data used as a basis for making future scenarios. The report concludes with a brief description of the next task of establishing various European energy system scenarios (Task 6.4 of the project), using the modelling platform.

2 Part 1: Modelling platform

The modelling platform consists of two main parts: 1) energy data developed and stored in a Microsoft Excel (herein Excel) file, and 2) energy system modelling within EnergyPLAN (Figure 1). Section 3.1 describes EnergyPLAN. All data inputs for EnergyPLAN for each country must be included in the platform. EnergyPLAN does the analysis and if the results are infeasible, we adjust data inputs.

The Excel file and EnergyPLAN are hard-linked using Visual Basic for Applications (VBA) code. This enables quick analysis from the Excel data to EnergyPLAN results for each country and Europe (Figure 1). Due to this hard link, all input data prepared by the other project partners in other Work Packages and the cost database must be transformed into EnergyPLAN inputs ready for system analysis. This transformation is a core function of the modelling platform.

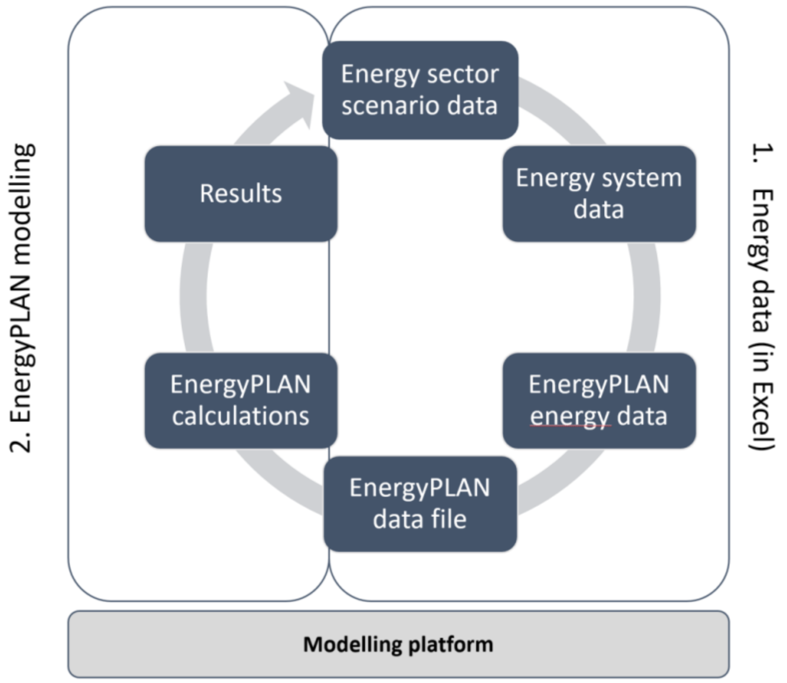

Figure 1. Energy data input, transformation, and EnergyPLAN modelling analysis within the modelling platform

2.1 Modelling platform concept and setup

The modelling platform brings together all the energy sector data in EnergyPLAN for assessment within energy system analyses for each country.

A key consideration during the modelling is how energy-system efficiency measures affect other energy system components. For instance, when energy efficiency measures (i.e., building refurbishment and heat pumps) are integrated into buildings this creates an impact on heat supply, electricity grid reinforcement and so on.

Responsible partners in their Work Package can quantify the total costs for integrating building-refurbishment efficiency measures. However, district heating areas and costs, as well as electric low-voltage grid reinforcement costs (due to the integration of heat pumps and photovoltaic systems), cannot be quantified without the inputs from the building refurbishment heat-saving scenario assumptions. That is because we have spatially distributed district heating systems according to where heat demands exist. For instance, if there are 20% heat savings in buildings, we spatially distribute district heat according to the new heat demand distribution, providing an absolute cost, and we distribute heat pumps between rural and urban locations where district heat is not located. Afterwards, we quantify the (low voltage) electricity-grid reinforcement costs.

Thus, a matrix of heat savings and district heat and heat pump supply costs is required for energy system analysis in each country (Section 3.2.7 describes this further). We use the matrix to develop the final system-scenarios for each country in Work Package 6.

In summary, any data adjustments need to consider the effect they may have on other data inputs. For example, if we should lower the building refurbishment rate, then this will affect costs for building refurbishment, as well as the total amount of district heating and distribution costs, and so on.

In other sectors, the interplay is not as important. For transport and industry, we quantify the effect of energy efficiency measures on the energy system and costs mainly within the scenarios in their respective Work Packages, based on analyses conducted within the tools TransportPLAN and IndustryPLAN. We expect that transport and industry scenarios will remain mostly fixed from their Work Package to the final scenarios. If we need to do minor adjustments to transport or industry scenarios, when including the energy sector scenarios in EnergyPLAN for carrying out the total energy system analysis, then we do this based on a discussion with the project partners in the respective Work Packages. i.e., enquiring about adjusting a transport scenario due to costs. If needed, we may use TransportPLAN and IndustryPLAN again in a new iteration for Work Package 6.

We developed the modelling platform to be able to deal with these adjustments to sector-scenarios and system-scenarios. We integrate the sector-scenarios through two different steps (Figure 2).

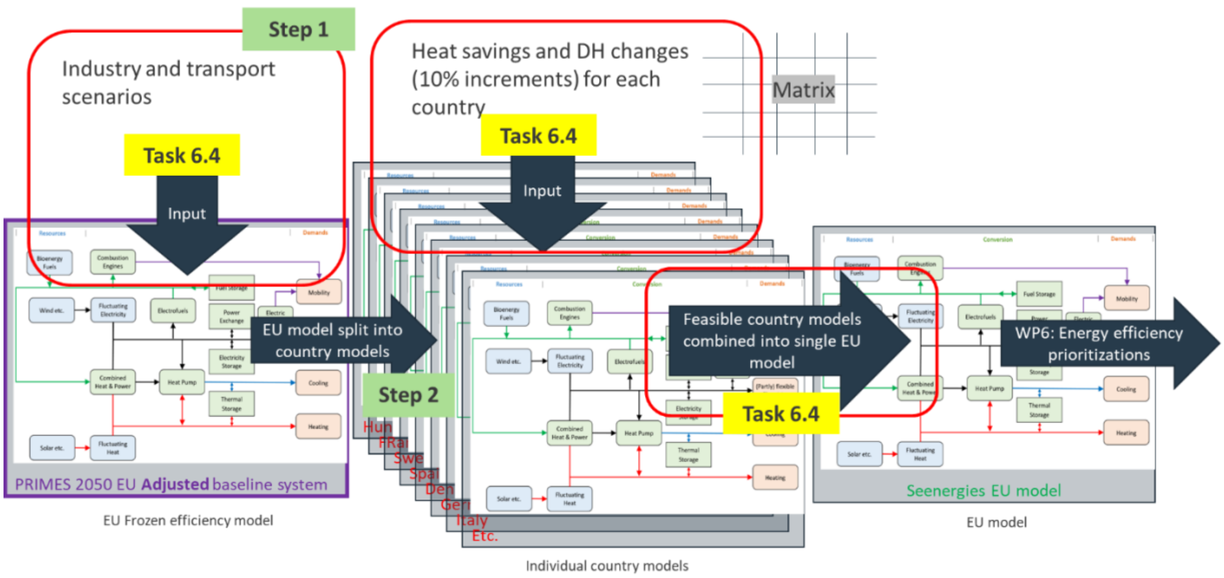

Figure 2. Integration of scenario data into the modelling platform

1. **Step 1 - Integrating transport and industry sector scenarios into the system scenarios in an aggregated EU27+UK**: The first step (green box Step 1) is to integrate **industry and transport sector-scenarios** into an aggregated EU EnergyPLAN model/scenario (purple box) (i.e., sector scenarios are individually made for each country then aggregated into a single European scenario/model).

2. **Step 2 – Integrating the heating sector and energy grid scenarios into the system scenarios of individual countries**: The second step (green box Step 2) is to disaggregate the EU model from the first step (which contains transport and industry scenario data for EU27+UK) into individual country models. In each country model, different scenarios for **building** efficiency/heat supply/electricity grid reinforcement can be assessed using the matrix approach. Prior to conducting the second step, the buildings heat demands are based on the PRIMES 2050 Baseline scenario (as described in Section 3 below).

It is important to note that the sector-scenarios to be integrated into the EU and country system-scenarios are determined in the next project task. Numerous sector-scenario variations have been established in the respective Work Packages but only one is used in the system-scenario. We determine this single sector-scenario by taking learnings from the Work Package sector-scenario variations for each sector (presented in Section 3.2.4 and Section 3.2.5 for transport and industry, respectively). Thus, in the subsequent task of establishing various EU energy system scenarios (Task 6.4 of the project), both the feasible country sector- and system-scenarios are determined using the platform (Figure 2).

The core aim of the project is not to determine sector-scenario variations, but rather to determine a system-scenario for each country and the EU that contains sector specific efficiency measures. The transport and industry scenario variations can be considered as extreme scenarios towards technological pathways, i.e., electrification or hydrogenation. The determined sector-scenario will likely be a mixture scenario from the main sector-scenario variations since we do not expect that the energy transition in each sector would strictly follow only one main technological path but would be a mixture of measures.

The final configuration of the system-scenarios is determined via two iterations of analysis. The first is to use the sector-scenario in the system-scenario and the second is to make modifications to the sector efficiency measures in the context of the system and its feasibility. Thus, to determine the final system-scenario for each country and the EU, sector inputs may be adjusted based on the system results and feasibility. This iterative process is indicated in Figure 1.

Once the feasible country system-scenarios are determined (integrating all sectoral efficiency measures and configuring the energy system), the country scenarios are aggregated into a single EU scenario/EnergyPLAN model. The single EU model is compared to the PRIMES low carbon scenario - 1.5TECH, and the PRIMES 2050 Baseline as well the current year model (2015) to compare the energy system scenario outcomes. Although the comparison will be made on the EU level, country-specific results will also be highlighted to provide further details to the comparison.

Energy efficiency prioritisations for the EU and individual countries will be described in Deliverable 6.3: Energy Efficiency Roadmap Europe: A cost-effective and energy-efficient strategy for decarbonizing Europe. Deliverable 6.3 will also include the investment strategies developed in Task 6.5: Quantification of the energy efficiency first principle and development of investment strategies.

In addition to the energy system scenario results, in Task 6.6, additional economic, social, policy and energy market impacts are determined and in Task 6.7, science-based interaction with policy objectives aimed at supporting the Energy Efficiency First Principle is described. The final output from Work Package 6 is Deliverable 6.4, a Handbook for science-based interaction with objectives aimed at achieving the Energy Efficiency First Principle.

3 Part 2: Modelling platform energy data

This section describes the modelling platform energy data required for the energy system-scenarios.

Due to the complexity of the energy system and its many components, it is preferable to do backcasting from a predefined future energy system. Therefore, in sEEnergies the reference scenario is developed based on the PRIMES 2050 Baseline energy system (European Commission, 2018).

In sEEnergies, the aim is to determine energy efficiency scenarios for the different energy sectors and thus any existing energy efficiency measure within the PRIMES 2050 Baseline needs to be removed before adding the sEEnergies scenarios. Once the reference system configuration is set up in the modelling platform, energy efficiency measures in the PRIMES 2050 Baseline are removed for buildings, transport and industry to form a frozen efficiency scenario. This retains the economic and demographic development and energy system configuration, i.e., energy supply technologies etc., but removes the efficiency measures. The result is increasing energy demands for the three sectors - buildings, transport and industry from 2015 to 2050, rather than decreasing as is the case in the PRIMES 2050 Baseline 2050 scenario.

This adjusted frozen efficiency EU model is the basis for making all the scenario iterations in sEEnergies (Figure 3).

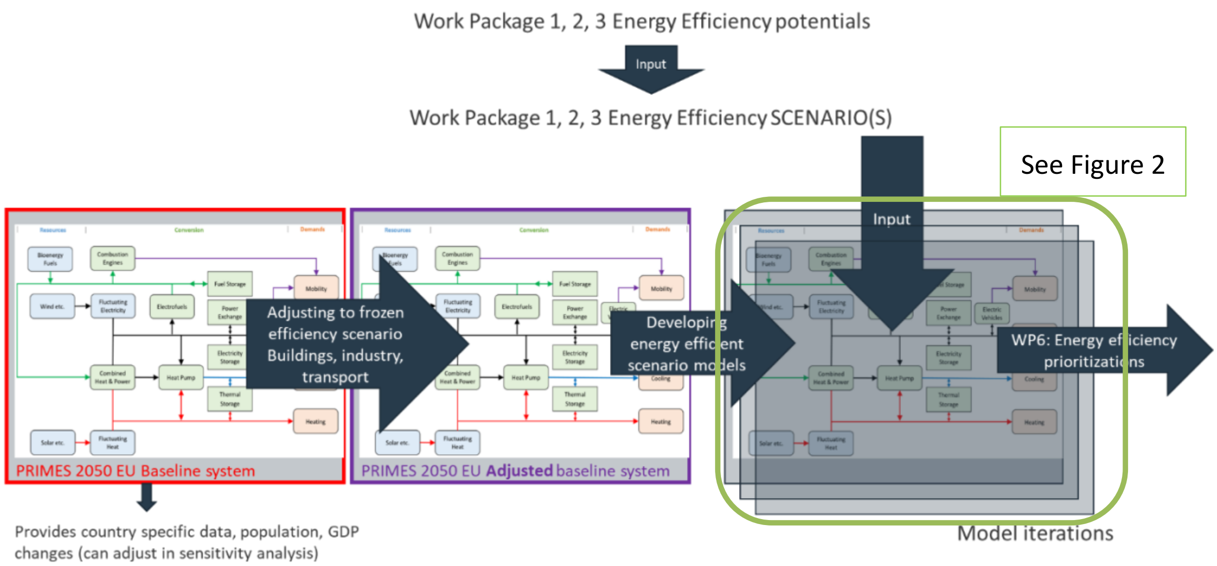

Figure 3. The basic concept behind frozen efficiency and developing model iterations. The energy scenario data is entered into a frozen efficiency European model. Box 1 (red box) is the PRIMES 2050 baseline (reference) scenario. This is adjusted into a frozen efficiency scenario by stripping out the efficiency measures (purple box). See Figure 2 for details about the model development and iteration process.

Before developing the adjusted frozen efficiency scenario, the energy system design of the PRIMES 2050 Baseline is transformed into the EnergyPLAN analyses tool including hour-by-hour energy data for an aggregated EU27+UK (Step 3 in Appendix A: Excel modelling platform development). The energy data is not disaggregated to different countries at this stage although this is done in the platform at a later stage as indicated in Step 2 in Figure 2.

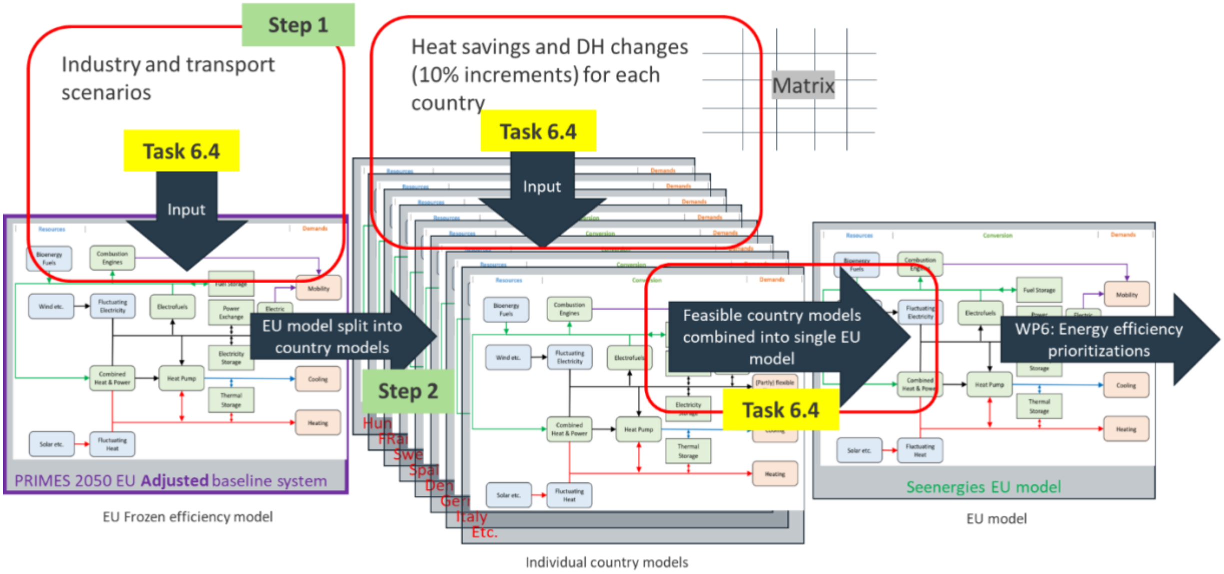

Figure 2

3.1 EnergyPLAN within the modelling platform

As mentioned above, EnergyPLAN is used for the energy system analysis of the scenarios. EnergyPLAN has been used in many research publications on energy system transitions on a local, regional, national, and international level (Østergaard, 2015) and is thereby a well-established and validated tool.

The tool is a deterministic simulation model, simulating hourly balances for all energy sectors of the energy system including the heating, power, gas, transportation, and industry sectors (Lund et al., 2021). The tool does not include spatial allocation of energy demands and supply in the modelled system, but in sEEnergies, several of the data inputs are based on spatial analyses conducted in the individual work packages. An overview of sectors, technologies and demands in EnergyPLAN can be seen in Figure 4.

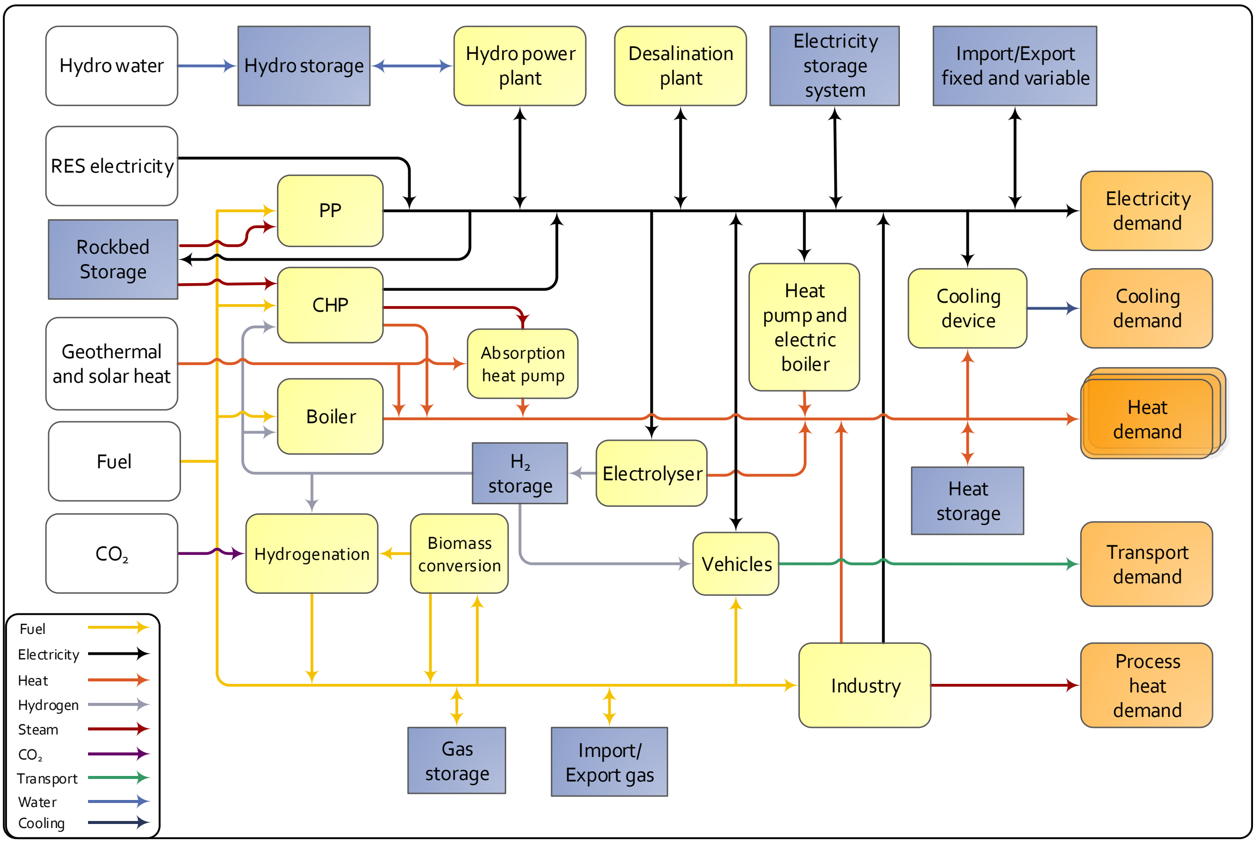

Figure 4. Overview of sectors, technologies and demands in EnergyPLAN

EnergyPLAN is updated regularly to maintain relevance with technological advancements. Updates can be adding new technologies but also adjusting the way algorithms work due to new possibilities made by new technologies for the energy system to operate. The most recent version of EnergyPLAN (16.0) from May 2021 is used. In this version, the algorithms have been updated based on recent technological advancements, for instance, the electrolysers balancing of electricity and thermal storage usage are improved.

The data requirements for EnergyPLAN have a major influence on the structure of the modelling platform, as the data needs to be in a format suitable for EnergyPLAN. Therefore, energy demand and supply data are collected for hour-by-hour time-steps, to accommodate the modelling principle in EnergyPLAN. An overview of the main data input categories needed in EnergyPLAN used to structure the modelling platform, can be seen in Table 1.

Table 1. EnergyPLAN data input categories used to structure the modelling platform

System component	Energy sector	Sub-sector/technologies	Data collected
Demand	Electricity (whole energy system)	Conventional (residential/service buildings, industry) Transport	Total, hour-by-hour
	Heating (whole energy system)	Individual heating	Total, hour-by-hour
		District heating (residential & service buildings, industry)	Total, hour-by-hour
		Individual cooling	Total, hour-by-hour

	Cooling (whole energy system)	District cooling	Total, hour-by-hour
	Industry (fuel)	Aggregated industry	Total
	Transport (fuel)	Conventional and electric vehicles (road, rail, ships and aviation)	Total, hour-by-hour (electric vehicles)
Supply	Combined Heat and electricity	Boilers and CHP	Capacity, efficiency, fuel distribution
	Central power production	Power plants, nuclear, geothermal, hydropower	Capacity, efficiency, fuel distribution
	Variable renewable electricity	Wind (onshore/offshore), PV, river hydro, etc.	Capacity, efficiency
	Heat only	Solar thermal, heat pumps, industrial heat	Capacity, efficiency
	Solid waste incineration	District heating	Waste input, efficiency
Balancing and storage	Electricity grid	Grid stabilisation	Power plant/Combined heat & power stabilisation shares
		Excess electricity	Strategy for excess electricity
	Storage	Electricity, rockbed	Capacity, efficiency
		Thermal storage	Capacity, efficiency
		Liquid fuel storage	Capacity
Costs	General	CO_2 price	Price
		Interest rate	%
	Investments	All technologies	Costs
	Fixed Operation and Maintenance	All technologies	Costs
	Variable Operation and Maintenance	All technologies	Costs
	Fuel prices	All technologies	Costs

3.2 Energy data components

The modelling platform consists of eight main data components, needed to develop the backcasting system scenarios (presented in Table 2). These data components are described in this section. The Microsoft Excel modelling platform includes a data structure consisting of eight separate datasheets (to be populated and used in Task 6.4 of the project). The setup of the Excel includes a mix of calculative methods and data required for establishing the EU country energy system scenarios. The Excel file is not a public deliverable.

Currently, the Excel modelling platform contains temporary energy system data from PRIMES 2050 Baseline, and this is progressively adjusted to form the final energy system scenarios. A detailed stepwise description of the development steps of the platform is provided in Appendix A, where the table shows the process to develop the platform from a blank Excel file.

Table 2. Required components in the modelling platform for making energy efficiency scenarios including methods and data sources

Data component	Method/Data source	Comments
1. Basic energy system configuration for Europe in 2050	PRIMES 2050 baseline	This provides a basic energy system framework from which to make changes based on the Work Package inputs in sEEnergies
2. Frozen efficiency energy system configuration for Europe in 2050	PRIMES 2050 baseline minus energy efficiency in buildings, transport and industry, Work Package 1, 2 and 3	This provides a worst-case scenario from which to place energy efficiency improvements determined in the other Work Packages
3. Energy demand time-series profiles	Numerous, see Table 4	This provides hour-by-hour energy demands
4. Transport energy and cost scenarios for European countries	Work Package 2, TransportPLAN	This data provides country-specific transport energy efficiency and cost scenarios
5. Industry energy and cost scenarios for European countries	Work Package 3, IndustryPLAN	This data provides country-specific industry energy efficiency and cost scenarios
6. Country specific energy system data including transport and industry scenario data	Numerous methods to split European energy data into country-specific data	Country specific data is required before analysing the heat demand and supply mix at the country level
7. Heat demand and supply mix scenarios including costs for each country	Work Package 1, 4 and 5	The matrix of heat demands and supplies allows assessing numerous scenario variations for each country
8. Cost data for energy system components	D6.1 and other Work Packages	Investment and Operation and Maintenance costs for current and future technologies

The data in the modelling platform covers all the fields required for the eight data platform components mentioned in Table 2 and as required for the EnergyPLAN model described in Section 3.1.

When using the modelling platform to develop the system-scenarios for each country and the EU27+UK, sector-scenario data is entered in a first iteration based on the Work Package sector-scenario variations. The final sector- / system-scenario data can only be determined once we have carried out the EnergyPLAN energy system analysis and results are assessed. This is because the holistic energy system analysis is done by the tool, and it is unknown if the system will be feasible by only adding the sector-scenarios as they are determined from other Work Packages. They need to be analysed all together in the system to identify issues in the system performance, costs, or resource consumption. Thus, a second iteration of system analysis is carried out after adjusting sector inputs.

3.2.1 Basic energy system configuration in 2050

As explained above, the starting point for the energy system configuration needed for the later country-specific scenarios is based on the PRIMES 2050 Baseline. The PRIMES 2050 Baseline data was collected mainly from the "A clean planet for all" report by the European Commission (European

Commission, 2018), where data was extracted to be used in EnergyPLAN, as can be seen in Appendix B.

In the PRIMES 2050 Baseline, macro-economic projections, fossil fuel prices, and current climate and energy policy goals are maintained. The PRIMES scenario does however project that 2030 energy and climate targets are achieved. The PRIMES 2050 baseline also achieves a 35% energy demand reduction in 2050 compared to 2015, and projects that renewable energy production continues to increase. This is achieved mainly through wind power and solar photovoltaic expansion, and for 2050 projects that 73% of electricity is generated from renewable energy.

To ensure the PRIMES 2050 data was collected appropriately, data from a recent year was collected (2015) from Eurostat (European Commission, 2021a). We compared Eurostat data was to the 2015 PRIMES data, which was collected using the same methods as was done for the 2050 Baseline. Because PRIMES 2015 data is based on modelling and not on statistics there may be differences compared to real-world data. However, we did not find large data discrepancies.

The 2015 data is used for two purposes, firstly to check that the EnergyPLAN input data extracted from the PRIMES 2050 data is accurate. If data was not accurate then the methods were improved. Secondly, the 2015 country and EU data were also run within EnergyPLAN to serve as a comparison point for the future 2050 scenarios and to understand the extent of measures suggested in each country. This work meant that a separate Excel file with individual country 2015 system data was developed based on Eurostat.

The energy system results for the PRIMES 2050 Baseline only represents an aggregated EU levels and not disaggregated country results. However, as shown in Figure 2 the energy system design of PRIMES 2050 Baseline is only used to form the basis for an aggregated EU model in EnergyPLAN including hour-by-hour energy data. The energy data is not disaggregated into individual countries in the first step but is disaggregated into countries in the second step, as indicated in Table 2. The approach to disaggregate each energy data point into different countries is presented in Appendix C.

3.2.2 Frozen efficiency energy system configuration in 2050

The PRIMES 2050 Baseline energy system is adjusted so that all energy efficiency measures for heating, transport and industry are removed. This means the energy demands increase in comparison to the PRIMES 2050 Baseline scenario and this creates a frozen efficiency scenario.

These end-use demands affect other energy demands in the energy system. For instance, the increased heat demands increase electricity for heating, and this is similar for transport and industry.

Table 3. Energy demands in PRIMES 2050 baseline, frozen efficiency for buildings, transport and industry for EU27+UK

Unit [TWh]	2050 PRIMES baseline	Frozen efficiency 2050	Comments
Heat demands (incl. residential & service buildings)	2969	3342	No energy efficiency measures advancement from 2015, however, old buildings are replaced, and new buildings are built
Transport fuel demands	4009	4934	Transport demand and activity is expected to continue growing in PRIMES, however, offset by efficiency improvements
Industry energy demands	2943	4054	The baseline includes significant energy efficiency measures e.g., energy savings, electrification, Carbon Capture and Storage/Carbon Capture and Utilisation

3.2.3 Energy demand time-series

The energy system modelling conducted in EnergyPLAN is based on an hourly simulation approach, as described in Section 3.1. EnergyPLAN requires an hourly distribution with 8784 values for demands, resources, and production units operating on an hourly basis.

The PRIMES 2050 Baseline data does not provide time series for energy demands and energy supply. This data is not available. However, this data is required for EnergyPLAN and is included in the sEEnergies system-scenarios to provide a higher resolution of energy system behaviour.

An overview of the hourly time series required for the energy system can be seen in Table 4. The data sources for the data used in sEEnergies and other comments for each hourly profile are presented.

Table 4. Time series included in the energy system

Sector	Sub-sector	Data source	Comments
Electricity	Electricity demand	ENTSO-E ("ENTSO-E Transparency Platform," n.d.)	
	Onshore wind	Open Power System Data (Open Power System Data, 2020)	
	Offshore wind	Open Power System Data (Open Power System Data, 2020)	
	Solar photovoltaic	Open Power System Data (Open Power System Data, 2020)	
	Hydropower	Heat Roadmap Europe 4 (Paardekooper et al., 2018)	
	Nuclear	ENTSO-E ("ENTSO-E Transparency Platform," n.d.)	
Heating	Individual heat demand	Heat Roadmap Europe 4 (Paardekooper et al., 2018)	Based on ("Meteonorm," n.d.) and The Global Renewable Energy Atlas (Andresen, Søndergaard, & Greiner, 2015; Victoria & Andresen, 2019)
	Solar thermal	Heat Roadmap Europe 4 (Paardekooper et al., 2018)	Based on ("Meteonorm," n.d.) and The Global Renewable Energy Atlas (Andresen et al., 2015; Victoria & Andresen, 2019)
	District heating demand	Heat Roadmap Europe 4 (Paardekooper et al., 2018)	Based on ("Meteonorm," n.d.) and The Global Renewable Energy Atlas (Andresen et al., 2015; Victoria & Andresen, 2019)
Cooling	Cooling demand	Heat Roadmap Europe 4 (Paardekooper et al., 2018)	Based on ("Meteonorm," n.d.) and The Global Renewable Energy Atlas (Andresen et al., 2015; Victoria & Andresen, 2019)
Transport	Transport demand	Heat Roadmap Europe 4 (Paardekooper et al., 2018)	Based on Stratego (Connolly, Hansen, & Drysdale, 2015) and MATSim ("MATSim.org," n.d.)
	Transport vehicle to grid	Heat Roadmap Europe 4 (Paardekooper et al., 2018)	Based on Stratego (Connolly et al., 2015) and MATSim ("MATSim.org," n.d.)
Industry	Industry demand	Constant	Demand is assumed to be constant, hence no time series
	Surplus heat	Constant	Supply is assumed to be constant, hence no time series

3.2.4 Transport energy and cost scenarios

Sector-scenario variations for the transport sector from Work Package 2: Comprehensive Energy efficiency potentials in transport and mobility are used to determine a transport sector-scenario for input into the modelling platform into the PRIMES 2050 frozen efficiency system configuration.

Transport scenario data is developed for each country using TransportPLAN and is presented in Deliverable 2.3: Report on energy efficiency potentials in the transport sector and conclusions from the developed scenarios (Abid et al., 2021) - for individual countries and the EU (Figure 5).

Numerous transport scenario variations are developed for each country mainly for technology-specific pathways, i.e., biofuels scenario or hydrogen scenario. The purpose of the technological scenarios is to provide insight into the possibilities of different technologies and actions and this helps to determine the sector-scenario to continue within Work Package 6.

Although one sector-scenario is determined for transport for each country, this single transport sector-scenario should not be considered as final but as a first iteration scenario for use in the system analysis. The most beneficial aspects of the TransportPLAN scenarios will be combined to provide one scenario input to the system-scenario. During the analysis of the system-scenario for each country, some transport elements may be adjusted if required based on the system analysis which leads to the second iteration of sector- and system-scenario development.

As shown in Figure 2 in Section 2, all the determined single country transport sector-scenarios will be aggregated into one EU system-scenario EnergyPLAN model. Individual country EnergyPLAN models will not be developed when integrating the transport scenario. However, the EU model is disaggregated into different countries to start analysing the heating demand and supply data in Step 2.

Results for each transport scenario variation are now available, but the final transport sector-scenario for use in the system analysis will be determined in the next task (Task 6.4: Establishment of various European energy system scenarios using the Energy Efficiency First Principle) when developing the energy-efficient scenarios for the EU and the countries.

	Baseline	Biofuels	Hydrogen (H2)	Electrification and e-fuels	Electrification +	1.5 TECH
Passenger Transport						
Passenger Cars	35% BEV 19% PHEV 4% FCEV 4% Gaseous 18% Gasoline 20% Diesel	35% BEV 40% Biodiesel 25% Bioethanol	35% BEV 65% FCEV	95 % BEV 5% Electrofuels	95 % BEV 5% Electrofuels	80% BEV 15 % FCEV 2% PHEV 1% Diesel 1% Gasoline 1% Gaseous
Buses	5% BEV 36% Hybrid 21% Gaseous 38% Diesel	5% BEV 95% Biodiesel	5% BEV 95% FCEV	100% BEV	100 % BEV	5% BEV 25% Hybrid 5% FCEV 65% Biodiesel
Rail	87 % Electric, 13 % Diesel	87% Electric 13% Biofuels	87% Electric 13% Hydrogen	100% Electric	100% Electric	95% Electric 5% Diesel
Aviation	3% bio-jetfuel 97% kerosene jetfuel	100% Bio-jetfuels	50% Bio-jetfuels 50% Hydrogen	19% Electric 81% Electrofuels	22% Electric 78% Electrofuels	2% Electric 57% Electrofuels 41% Kerosene jetfuel
Shipping	13% Gaseous 87% Diesel and HFO	100% Biofuels	100% Ammonia	50% Electric 35% Electrofuels 15% Ammonia	50% Electric 35% Electrofuels 15% Ammonia	37% Biofuels 13% Ammonia 50% Diesel and HFO
Freight Transport						
Trucks	1% BEV 29% Hybrid 18% Gaseous 51% Diesel	1% BEV 49,5% Biogas 49,5% Biodiesel	1% BEV 99% FCEV	27% BEV 73% Electrofuels	27% BEV 73% ERS-BEV	8% BEV 6& FCEV 20% Hybrid 34% Gaseous 32% Diesel
Vans	26% BEV 1% FCEV 19% PHEV 54% Diesel	26% BEV 38% Biodiesel 36% Biogas	26% BEV 74% FCEV	95% BEV 5% Electrofuels	100% BEV	79% BEV 13% FCEV 3% PHEV 5% Diesel
Rail	87 % Electric, 13 % Diesel	87% Electric 13% Biofuels	87% Electric 13% Hydrogen	100% Electric	100% Electric	90% Electric 10% Diesel
Aviation	100 % Kerosene jetfuel	100% Bio-jetfuels	50% Bio-jetfuels 50% Hydrogen	100% Electrofuels	100% Electrofuels	2% Electric 57% Electrofuels 41% Kerosene jetfuel
Shipping	100 % Diesel and HFO	100% Biofuels	100% Ammonia	100% Electrofuels	100% Electrofuels	37% Biofuels 13% Ammonia 50% Diesel and HFO

Figure 5. Transport scenarios

3.2.5 Industry energy and cost scenarios

Like the process for transport scenarios above, scenario inputs on the industry sector based on Work Package 3: In-depth quantification of Industrial energy efficiency potentials, is built into the modelling platform and integrated into the PRIMES 2050 frozen efficiency system configuration.

A frozen efficiency scenario for the industry sector was established in Deliverable 3.1: Analysis and results of the reference scenarios assessment (Kermeli & Crijns-Graus, 2020a) - and energy efficiency scenarios were established in Deliverable 3.6: Energy Efficiency potentials on top of reference (Kermeli & Crijns-Graus, 2020b). The IndustryPLAN model was developed to assist in developing industry scenarios based on the energy efficiency measures established, and this tool and the scenarios for which it was applied are presented in Deliverable 3.4: IndustryPLAN tool results (Johannsen, Vad Mathiesen, & Ridjan Skov, 2020).

The industry scenario data in IndustryPLAN is available for every EU country for seven industrial sub-sectors. An extensive catalogue of mitigation measures has been established along with frozen efficiency and mitigation scenarios.

Like the transport scenarios, when integrating the industry sector-scenario into the system-scenario, the most beneficial aspects of these scenario variations will be combined to provide one industry sector-scenario for input into the system-scenario. During the analysis of the system-scenario some industry elements may be adjusted if required based on the results of the analysis. For instance, the industry scenarios done so far do not lead to 100% carbon neutrality (although very close) therefore in the system analysis solutions for the industry sector to get to 100% carbon neutrality will be required. This may also cause changes in the industry efficiency measures in the system.

Results for each industry scenario variation are now available, but the final industry scenario for use in the system analysis will be determined in the next task (Task 6.4: Establishment of various European energy system scenarios using the Energy Efficiency First Principle) when developing the energy-efficient scenarios for the EU and the countries.

In Table 5 an overview of developed industry scenarios can be seen.

Table 5. Industry scenarios

Scenario name	Assumptions
Best available technology (no extra recycling)	All best available technologies implemented No extra recycling All available excess heat extracted for district heating
Best available technology (high recycling)	All best available technologies implemented High recycling All available excess heat extracted for district heating
Best available technology + innovative (no extra recycling)	All best available technologies implemented No extra recycling All innovative measures implemented All available excess heat extracted for district heating
Best available technology + innovative technologies (high recycling)	All best available technologies implemented High recycling All innovative measures implemented All available excess heat extracted for district heating
Best available technology + electrification (no extra recycling)	All best available technologies implemented No extra recycling All electrification measures implemented All available excess heat extracted for district heating
Best available technology + electrification (high recycling)	All best available technologies implemented High recycling All electrification measures implemented

	All available excess heat extracted for district heating
Best available technology + hydrogen (no extra recycling)	All best available technologies implemented No extra recycling All hydrogen fuel shift measures implemented All available excess heat extracted for district heating
Best available technology + hydrogen (high recycling)	All best available technologies implemented High recycling All hydrogen fuel shift measures implemented All available excess heat extracted for district heating

3.2.6 Country specific energy system data including transport and industry scenario data

The integration of heat demand reductions (achieved with building refurbishments), district heat supply and heat pumps need to be done at the country level and a feasible heat demand reduction scenario is determined via numerous iterations of heat demand reduction assessments using a matrix approach (as illustrated in Figure 2).

Each country needs to be an independent system and model at this point. Therefore, the aggregated EU model (in Step 1 and including a transport and industry scenario for EU27+UK) is disaggregated by country to established the needed individual country EnergyPLAN models.

The EU data model is disaggregated into separate individual countries, as shown in Figure 2 and Step 6 and 7 in Appendix A. This is done based on numerous data sources and expert assumptions presented in Appendix C. Each country model is a combination of the sector-scenario data for transport and industry combined with time-series data profiles, and the PRIMES 2050 Baseline energy system configuration. Building heat demand remains frozen at this point.

Transport and industry scenarios are also developed at country level however; the choice of the final sector-scenario is not dependent on the sector-scenario effect on the energy system. Whereas for heat demand reductions in buildings the effect on the energy system is important to consider when deciding the final scenario for heat demand reductions. Due to the effect on the heat supply mix which effects the energy system. The main argument for not having a matrix approach for transport and industry scenarios is that when reducing energy demand in these sectors, the effect on the sector-scenario configuration and energy supply mix is not significant. Whereas for the building sector it is. In regards to electric grid reinforcement costs for the addition electric vehicles and charging stations within the transport sector this will affect grid reinforcement costs however, this we can add this as an additional cost but it does not affect the sector-scenario configuration or electric grid mix.

3.2.7 Heat demand and supply mix scenarios including costs

As mentioned above, the building heat-demand reduction and heat supply-mix configurations, as well as the resulting electricity grid reinforcements need to be assessed for each country. The assessment needs to be done for numerous configurations to determine a feasible scenario. For this, a two-step matrix approach is used (see Table 6 and Table 7).

The matrix approach simply means that numerous combinations of the three input parameters can be combined to form numerous scenario variations. The determining factor in the matrix is the building heat demand, which is adjusted down by 10% increments from the frozen efficiency in each country.

The heat demand reductions are combined with different heat supply compositions of district heating and heat pumps. Electricity grid reinforcement for heat pump integration is also determined.

In Step 1 (see Table 6), the following inputs are required as inputs into the matrix:

- **Building refurbishment costs**: Spatially distributed building refurbishment cost curves per country (determining where heat savings are undertaken to which price). Determined in Work Package 1: Energy efficiency and refurbishment strategies in buildings
- **District heating grid investment costs**: Spatially distributed district heating absolute investment costs for each heat-saving increment, per country (considering spatially distributed heat demand reductions). Determined in Work Package 5: Spatial analyses of energy efficiency potentials and development of Geographical Information System visualization platform
- **Reinforcement costs of the low-voltage electricity grid**: Electricity grid refurbishment costs based on spatially distributed heat pump integration for each heat-saving increment, per country. Determined using cost functions from Work Package 4: Assessment of the role and costs of energy grids.

The term "spatially" means that the distribution of building refurbishment and district heating is determined using a Geographical Information Systems (GIS) approach developed by project partners in Task 5.4: Spatial analytics of energy efficiency potentials.

There are two main types of heating applied in the sEEnergies 2050 scenario, being heat pumps (for individual heating) and district heating. All boilers are removed. If there is a certain percentage coverage of total heat demand of 50% district heat, then the remaining 50% of heat demand will be provided by heat pumps; likely in sparsely distributed dwellings such as single-family buildings in suburban areas.

Table 6. Matrix of building heat savings and Heat pump /District heat/ integration into residential and service buildings scenarios for which building refurbishment costs, District heat grid costs and electric grid reinforcement costs are based on. These costs are determined for each cell in the matrix

	Heat demand reduction from frozen efficiency	0%	-10%	-20%	…%	-80%
Heat pump/District Heat percentage coverage of total heat demand						
100% heat pump/0% district heat		Building refurbishment costs, district heat grid costs, electric grid reinforcement costs	Building refurbishment costs, district heat grid costs, electric grid reinforcement costs	….		
90%/10%		Building refurbishment costs, district heat grid costs, electric grid reinforcement costs	….			
…/…		….				
0%/100%						

Step 2 carries out an energy system analysis for each cell to determine the total energy system costs. Step 2 is required since when the district heating shares increase, the district heating heat supply mix needs to be adjusted which affects the energy system scenario. For instance, areas with higher district heat demand can be supplied by larger plants.

Step 2 considers all the energy system components in combination with the data prepared in Step 1. The costs of each cell of Table 6 (identified in step one) are entered into the modelling platform and included in the energy system analysis. The cell in Table 7 with the lowest total energy system cost will be the feasible scenario. Step 2 is the last step in the energy system analysis for system-scenario results. However, if the results show some infeasibility (i.e., resource use is suboptimal) the system-scenario may be adjusted slightly based on expert judgment to correct this.

The starting point for the heat supply mix in the energy system analysis is the PRIMES Baseline 2050 heat supply mix. This data is adjusted based on the heat resource potentials and industrial excess heat potentials in each country determined in Work Package 4: Assessment of the role and costs of energy grids and Work Package 5: Spatial analyses of energy efficiency potentials and development of Geographical Information Systems visualization Platform.

The integration of photovoltaics on building rooftops also affects the electricity grid reinforcement costs. The cost function provided to determine the grid reinforcement costs allows for entering different levels of photovoltaic coverage. Thus, in step 2, along with all remaining energy system components, the photovoltaic integration level will be added to the cost function to assess additional changes to the electricity grid reinforcement costs. The photovoltaic level will be kept constant for each cell in Step 2. The photovoltaic integration level will be based on the EU PRIMES 2050 Baseline photovoltaic level disaggregated into individual country levels. The photovoltaic level may later need to be adjusted based on the system analysis results.

The lowest energy system cost in the matrix cells in Step 2 will be selected as the feasible sEEnergies system-scenario.

Table 7. Matrix after heat supply resources and PV are added. The total energy system cost is quantified in each cell of the matrix

	Heat demand reduction from frozen efficiency	0%	-10%	-20%	...%	-80%
Heat pump/District Heat percentage coverage of total heat demand						
100% heat pump/0% district heat		Total energy system costs (including all energy system components)	Total energy system costs (including all energy system components)	….		
90%/10%		Total energy system costs (including all energy system components)	….			
.../...		….				
0%/100%						

This matrix approach has previously been used in Heat Roadmap Europe 4 (Paardekooper et al., 2018), which investigated the 14 largest heat consuming countries in Europe. The approach here advances in three main ways. Firstly, in Heat Roadmap Europe 4, the heat savings in the matrix started from a baseline scenario that already contained heat savings. In sEEnergies, the heat saving increments start from the frozen efficiency which is zero heat savings in 2050.

The second advancement is that the district heating grid costs are calculated for each heat demand level on a spatially distributed basis. Calculations are spatially explicit since heat savings occur in different buildings of different ages and the location of lower heat demands means the distribution and cost of district heat also change. To calculate the district heat demands, the heat demand needs to be spatially determined using Geographical Information Systems in Work Package 5: Spatial analyses of energy efficiency potentials and development of Geographical Information Systems visualization platform. This is done by two main advancements. Firstly, a new population forecast model and secondly, building types and construction ages can be used for the estimation of future heat demand distributions. The new population model can be based on the new regional Nomenclature of territorial units for statistics (NUTS3) population forecast published by Eurostat in April this year, adjusted to national PRIMES data (European Commission, 2021b). The new population grid can also be the basis for the identification of new-built areas, within which new buildings are to be placed. The new heat demand model distributes heat demands and saving potentials by building type and construction age and aims for mapping heat demands, saving potentials and investment costs for building refurbishments on the hectare level. The model can rely on the Global Human Settlement (GHS) built-up time-series data provided by the Hotmaps project (Hotmaps, 2021).

Thirdly, the low-voltage electricity grid reinforcement costs are a new addition. The results of Work Package 4 provides more details on grid costs and an improved understanding of the impact from heat pumps and photovoltaic in residential buildings. A detailed model developed by the project partners in Work Package 4: Assessment of the role and costs of energy grids – is utilised to assess grid reinforcement costs using a cost function.

3.2.8 Cost data

Cost data as described in the report Energy system cost database (Deliverable 6.1) (Maya-Drysdale, 2021) is included in the modelling platform. There are seven cost datasets and these provide all the costs required for the energy system analysis in EnergyPLAN. They include costs for the current year and a range of future years 2030, 2040 and 2050, depending on the energy system component, for:

1. Energy conversion and storage technologies
2. Heat conservation
3. Industrial efficiency
4. Energy grids
5. Transport infrastructure
6. Extracted and synthesised fuels/energy
7. Environmental cost (CO_2 price)

3.3 Sensitivity analyses and COVID-19 impact

The modelling platform is set up to investigate the long-term impacts from COVID-19 and other sensitive parameters. In this subchapter, the impacts will be described qualitatively, since the sEEnergies scenario is an ambitious backcasting scenario to 2050. I.e., it is a scenario based on a feasible way to go forward (in terms of socio-economic costs and resource consumption) and we plan towards this. It is not a forecasting scenario that would be impacted by COVID-19. Thus, COVID-19 is by the nature of the modelling approach, considered in the sEEnergies scenario. The long-term effects of COVID-19 are largely unknown; hence this section should be considered as predictions and estimations based on what we consider to be likely effects.

Sensitivity analyses will be conducted as part of the modelling in this Work Package (Work Package 6). For instance, for the industry sector, this is expected to be in form of analyses investigating the impacts of increased self-sufficiency within the EU, and scenarios with improved material efficiency. This is partly inspired by the increased emphasis on supply-chain stability and security of supply because of the COVID-19 pandemic, and a response to the long-lasting trend of globalisation.

The effects of COVID-19 on the energy system have been significant in the short term, causing a decrease of CO_2 emissions in 2020 by 7% compared to 2019 (Le Quéré et al., 2021). While the decrease in CO_2 emissions due to COVID-19 is a positive for the climate and the environment, investments in renewable energy technologies were also reduced during this period because of lower economic capacity and supply chain disruptions (International Institute for Applied Systems Analyses, 2020). In the end, the actual climate effect of the immediate global response and COVID-19 related restrictions is negligible, and long-term effects likely rely more on the recovery strategies deployed going forward.

Long-term lasting effects may occur in form of structural changes within specific energy sectors. The transportation sector was particularly affected, with significantly reduced international air traffic, and reduced commuting due to work from home conditions. Long-term effects remain uncertain, as particularly the aviation and service sector push for a rebound, but domestic holidays may also see a resurgence. Remote working has increased, and as companies have experienced how productivity can remain intact, cultural, and structural changes may persist with companies offering permanent or partial work from home conditions. This could reduce the importance of living in cities in general and reduce peak transport demands (and thereby the need for road expansions).

The industrial sector has experienced changes to production patterns, supply chain disruptions, and in some countries, the complete lockdown of industries. There are however no signs of changing consumer demands – if any, demands for electronic products have increased. COVID-19 has emphasized the relevance of domestic production and shorter supply chains for critical products. This may in the future result in political attention to bringing back production facilities to Europe.

For buildings, a slight increase in domestic energy demand occurred; this is however to some extent offset by lower demand in office buildings. This may be a lasting change, as people continue working from home, and possibly accelerated if increased work from home conditions also result in a general increase in houses. The increased time spent at home is also reflected in house renovation, where it seems the reduction in other activities e.g., travel has resulted in more time for renovation and home improvements – these improvements may however not be energy-related.

The effects of COVID-19 underlines the extent of measures and actions that need to be undertaken to tackle climate change (Le Quéré et al., 2021). However, the effects from COVID-19 cannot on their own be expected to have long-term lasting effects on energy demands and CO_2 emissions (Forster et al., 2020). Instead, rebound effects and structural changes need to be monitored, as they are more likely to affect long-term energy scenarios.

3.4 Non-energy impacts

Non-energy impacts are quantified in sEEnergies, where possible. Some non-energy impacts are qualitatively assessed. There are four approaches to assess these non-energy impacts in sEEnergies:

Number 1 is sector-specific, and numbers 2-4 will be reported in the present Work Package (Work Package 6). The impacts will be assessed in the present Work Package for the individual countries and on the EU level.

1. **Sector-specific (disconnected from energy system)** – numerous impacts are quantified for economic costs and resource consumption for different energy sectors, e.g., the industry sector (as reported in the report Economic and social impact assessment of Energy Efficiency measures in the Industrial sector: Deliverable 3.7). But this is without input from the system perspective.
2. **Sector-specific including impacts on energy system** – In Work Package 6 more information is added to the sector-specific results. For example, in the industry sector, the hydrogen scenario at the sector level has numerous sector-level impacts, in Work Package 6 more information is added about these impacts after applying the hydrogen changes at the system level.
3. **Sector-specific + sector-specific + sector-specific** – Some impacts are additive and they can simply be added to provide a cumulative impact from sector additions, such as economic investments or avoided deaths, thus in Work Package 6 the sector impacts can be summed.
4. **Energy system** – This is where the sector-specific impacts are ignored, and a combined system impact analysis is carried out and the entire country or the EU and its energy system impact is assessed. This approach includes the synergies between sectors.

It is not certain which impact categories will be included in Work Package 6, since this will be decided in Task 6.6: Additional economic, social, policy and energy market impacts - for Deliverable 6.3: Energy Efficiency Roadmap Europe: A cost-effective and energy-efficient strategy for decarbonizing Europe. However, they will likely include the following, with the approach expected to be applied.

- **Impacts on renewable energy targets** - assessing the ease of achievement of renewable energy supply targets due to energy efficiency – Approach 2 and 4, sector analysis within the system and total system analysis.
- **Employment effects** – Approach 3 and 4, cumulative sector impacts and system impacts
- **Potential impact on energy prices** – Approach 4, system-level analysis determines the full scale of all changes in energy efficiency
- **Impact on public budgets** – increasing jobs and taxes, Approach 4, system impacts
- **Energy security** – Assessing the impact on import dependency of a country and larger supplier diversity, Approach 4, system impacts

Other impacts may include air pollution, health and wellbeing, i.e., avoided deaths, impact on jobs, disposable income and Gross Domestic Product.

4 Next steps: Establishment of various European energy system scenarios (Task 6.4)

This report has presented the modelling platform for developing energy-efficient scenarios for the EU including the United Kingdom. In the next task - Task 6.4: Establishment of various European energy system scenarios using the Energy Efficiency First Principle - the placeholder energy data in the modelling platform will be replaced with the sector- and system-scenario data and the final scenarios will be developed following the modelling process described in this deliverable (Figure 2 and Figure 3).

The final scenario results will be described in the report - Energy Efficiency Roadmap Europe (Deliverable 6.3). This roadmap will describe a cost-effective and energy-efficient strategy for decarbonizing the EU and the United Kingdom. This energy efficiency roadmap, built on the analyses of the scenarios developed in Work Package 6, will provide several guidelines on how different countries in Europe can take steps towards energy-efficient decarbonisation. This will feed into the last Deliverable 6.4 to produce a Handbook for science-based interaction with policy objectives aiming at achieving the Energy Efficiency First Principle.

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6 Appendix

A. Excel modelling platform development

The process of building the platform was through a number of steps (Table 8).

Table 8. Excel modelling platform development steps

Step	Step description	Comments about step
1	Make independent data structure based on EnergyPLAN inputs for PRIMES baseline 2050 scenarios, PRIMES baseline frozen efficiency scenario, PRIMES 1.5TECH, sEEnergies Scenario	The data structure is for EUROPE, country-level data structures are made in Step 5. The sEEnergies scenario will be an aggregation (with minor adjustments) of the country EnergyPLAN scenarios in Step 11
2	Extract PRIMES baseline 2050 energy data and convert it into EnergyPLAN inputs	PRIMES data is extracted from reports
3	Fill in the data structure for EnergyPLAN with PRIMES baseline 2050 data and energy time-series data for Europe.	It completes EnergyPLAN model for PRIMES baseline for Europe
4	Copy PRIMES baseline 2050 data into the frozen efficiency EnergyPLAN data structure and replace energy demands for transport, industry and heating in buildings with frozen efficiency demands	It completes EnergyPLAN model for frozen efficiency for Europe
5	Integrate transport and industry scenario results for the aggregated EU27+UK energy system in the form of EnergyPLAN inputs into Excel	It completes EnergyPLAN model for transport and industry scenarios for each country in Europe
6	Make independent data structure for EnergyPLAN inputs for each country	Each country has its own EnergyPLAN inputs
7	Split the PRIMES frozen efficiency 2050 data including transport and industry data into country-specific data fields	The aggregated European data is disaggregated into country-level data following different approaches for each data point
8	Fill in the data structure for EnergyPLAN with PRIMES frozen efficiency 2050 country data including the transport and industry data	It completes EnergyPLAN model for frozen efficiency and transport and industry scenarios for each country in Europe
9	Integrate the matrix data structure into the EnergyPLAN data structure for each country	Prepares the EnergyPLAN data for each country for matrix scenarios
10	Add heating demand, supply and electricity grid cost data to each matrix cell	Enters scenario data for each cell for heating demand, supply and electricity grid costs
11	Run scenarios for each country for each cell in the matrix to test platform performance	Runs different matrix scenario inputs and develops results for the scenarios
12	Check scenario results for feasibility	Assess the feasibility of the results for each country
13	Adjust energy data until feasible scenarios determined	Finalise scenarios for each country by manually adjusting energy data; this requires numerous runs of EnergyPLAN.

B. PRIMES documentation

Documentation for establishing PRIMES scenarios based on the "Clean planet for all"-report by the European commission (European Commission, 2018)

PRIMES Scenario Documentation	Units	2015 Reference	2050 Baseline	1.5TECH	NOTES **a) = Notes regarding 2015 Reference** **b) = Notes regarding PRIMES Scenarios**
Electricity					
Electricity Demands					
Fixed electricity demand	PWh/year	1.5696	2.1154	1.6872	ab) Includes electricity demand for the Household and Tertiary sector, excluding electricity for heating and flexible electricity demand. Calculated in "PRIMES PES and Electricity" tab. Calculated based on figures in PRIMES report, identifying all final electricity demands from figure 10 and 20.

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Flexible electricity demand (1 day)	PWh/year	0.0000	0.2350	0.2301	a) Assumed it is 0 in 2015 b) Used the share of flexible electricity demand from TIMES scenarios. Hence, COMBO has 10%, 1.5 TECH has 12% and 1.5 LIFE has 13% Calculated in "PRIMES PES and Electricity" tab.
Transmission and distribution losses for both domestic and industry.	PWh/year	0.0000	0.0000	0.0000	a) PRIMES does not mention it specifically, but it shows up in the EU energy balances. b) Adjusted to a similar level as the losses in 2015 (about 6,4% of total electricity generation)
Max-effect for flexible electricity demand (1 day)	GW	0.0000	24.9600	21.9700	EnergyPLAN is used to provide this figure by using the electricity demand distribution for the EU28.
Electricity Own Consumption (Also added to additional electricity demand)	PWh/year	0.0000	0.0000	0.0000	Not assumed

Variable Renewable Electricity production	**Units**	**2015 Reference**	**2050 Baseline**	**1.5TECH**	**NOTES** **a) = Notes regarding 2015 Reference** **b) = Notes regarding PRIMES Scenarios**
Wind					
Capacity	GW	130.416	440.867	758.727	ab) Fig 24
Annual production	PWh/year				
Offshore Wind					
Capacity	GW	11	142.859	451.383	ab) Fig 24
Annual production	PWh/year				
Photo Voltaic					
Capacity	GW	94.678	441.49	1029.767	ab) Fig 24
Annual production	PWh/year				

Dammed hydro					
Capacity	GW	152.4	154	163	a) Adjusted to EUROSTAT b) PRIMES mentions that hydro capacities increase modestly compared to 2015, but does not present any increase figure. See note for Condensing power plant capacity – biomass. Capacity in 2016 is 154 GW
Efficiency	%	0.95	0.95	0.95	Standard efficiency of the capacity established by expert judgment. Not provided by PRIMES
Annual production	PWh/year	0.371	0.376	0.396	a) Fig 8 b) obtained through an iteration process in relation with the 2015 values for production and capacity
Water supply	PWh/year	0.39	0.40	0.42	Obtained through an iteration process to achieve the desired annual production.
Geothermal					
Capacity	GW	0.822			a) Adjusted to EUROSTAT

Thermal power production	**Units**	**2015 Reference**	**2050 Baseline**	**1.5TECH**	**NOTES** **a) = Notes regarding 2015 Reference** **b) = Notes regarding PRIMES Scenarios**
Nuclear power					
Nuclear capacity	GW	121.957	86.822	121.346	a) Adjusted to EUROSTAT b) Figure 24
Nuclear Efficiency	%	0.334	0.386	0.386	ab) The PRIMES Technology Pathways report states an efficiency of 38% for the years 2020 to 2050. However, with this efficiency, power production and PES do not add up in the 2050 Baseline scenario (which is the only 2050 scenario, where we know the power production split between technologies). Therefore, efficiency is adjusted to 0,386 to make both PES and power production fit with PRIMES.

Nuclear Correction Factor	%	0.97	1.09	1.082	The PRIMES Technology Pathways report states that Nuclear plants have a Capacity factor of 85% from 2020 to 2050. Our distribution, however, has 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.
Condensing power plants					
Condensing power plant capacity – biomass, renewable waste, biogas, and other bioenergy and renewable waste	GW	43.7	55.6	82	a) Used Fig 24 and subtracted the hydro capacity from the total Other RES capacity. b) The other RES in Fig 24 includes biomass and hydro. Apparently, the highest capacity for biomass capacity is achieved in P2X scenario: 83 GW. So hydro capacity is adjusted using a biomass capacity of 80-82 TW. Page 78. Ref 2050 is a bit off. Should be minimum 60 here and minimum 153 dammed hydro. However, this sums up to more than 209,6, which is the value for other RES in fig 24.
Condensing power plant capacity	GW	436.399	255.3	184	a) adjusted to EUROSTAT b) This value is an aggregation of 'Fossil Fuels' + 'Fossil Fuels CCS' + 'BECCS' of Fig. 24 in main report
Condensing power plant electric efficiency	%	0.385	0.55	0.43	ab) Adjusted the efficiencies on the PP based on the PRIMES tech catalogue and type of fuel used.
Minimum Power Plant operation	GW		0.825	49.35	b) The minimum PP is 75% of the capacity of PP with carbon capture (Fig. 24). We assume that most of them need to work constantly, otherwise you cannot use/explain the investments in carbon capture.
Cogeneration power production					

CHP	PWh/year				

Electricity storage	**Units**	**2015 Reference**	**2050 Baseline**	**1.5TECH**	**NOTES** **a) = Notes regarding 2015 Reference** **b) = Notes regarding PRIMES Scenarios**
Pumped hydro	TWh	0.379712	0.471952	0.4108	ab) Assuming a capacity of 8 hours to fully charge (figure 27 * 8)
Pumped hydro capacity	GW	47.464	58.994	51.35	ab) Fig 27
Pumped hydro efficiency	%	0.8	0.8	0.8	a) Assumption based on DEA Technology Data for energy storage, Pumped hydro
Batteries	TWh	0	1.112984	0.549464	b) Grid scale; stationary; Assuming a capacity of 8 hours to fully charge. Modelled as Electricity Storage 2, Storage Capacity
Batteries	GW	0	139.123	68.683	b) Figure 27. Modelled as Electricity storage 2 in EP, Charge and Discharge
Battery efficiency	%	0.975	0.98	0.98	ab) assumption based on DEA Technology Data for energy storage, Lithium Ion Batteries. They Assume 0,985 for charge and 0,975 for discharge. We assume 0,98 for both.

Heating	**Units**	**2015 Reference**	**2050 Baseline**	**1.5TECH**	**NOTES** **a) = Notes regarding 2015 Reference** **b) = Notes regarding PRIMES Scenarios**
Total heat demand (Residential + Tertiary), PWh	PWh/year	2.88	2.21	1.67	From El+heat demands xlsx
Central district heating					
District heating share	%				

District heating demand	PWh/year	0.3652	0.2872	0.2047	a) Fig 44 b) Accounted as fuel consumption in buildings (Fig 44). When added to EP, industry DH fuel consumption is added too together with geothermal (for geothermal see Individual heating; Other RES)
Heat losses	%	0.14	0.14	0.14	a) EU28 energy balances b) Same as 2015
CHP Back Pressure Mode Operation					
CHP Electric Capacity	GW	38	30	25	Adjusted to match to 40% of DH mix, since no other information is available about CHPs
CHP Electric efficiency	%	0.35	0.4	0.4	
CHP Thermal Efficiency	%	0.4	0.45	0.45	used the EP numbers
Waste incineration					
Waste input	PWh/year	0.33	0.34	0.23	Assumed based on the data extracted in Fig. 83 and 84
Heat production efficiency	%	0.2	0.05	0.05	Rather low efficiency as few WTE plants produce both heat and power.
Electricity production efficiency	%	0.3	0.34	0.5	ab) From Technology Pathways report: MBW incinerator CHP
Compression heat pumps					
Electric capacity	GW	0	0	0	HP share in DH is not mentioned
COP	%	0	0	0	
Boilers					
Thermal capacity	GJ/s	79	90	55	adjusted to be 120% of max capacity EnergyPLAN
Boiler efficiency	%	0.84	0.95	0.94	Technology pathways report, weighted average between natural gas and biomass boilers
Fixed boiler share	%	0	0	0	EP number

Industry fuel consumption	Units	2015 Reference	2050 Baseline	1.5 TECH	NOTES a) = Notes regarding 2015 Reference b) = Notes regarding PRIMES Scenarios

Coal in industry	PWh/year	0.356	0.306	0.030	a) EU energy balances b) Obtained from total PRIMES PES since only industry is using it (see e.g. p 41, which discusses the coal phase-out)
Oil in industry	PWh/year	0.878	0.528	0.159	a) EU energy balances b) obtained by substracting the fossil oil of transport and heating from the total PRIMES fossil liquid PES.
Gas in industry	PWh/year	1.152	0.872	0.297	a) EU energy balances (Natural gas and biogases + b) PRIMES fig 28 - 30 Natural gas + biogas/gas from waste + synthetic methane
Biomass in industry	PWh/year	0.278	0.512	0.422	a) EU energy balances b) Fig 83
Hydrogen in industry	PWh/year		0.000	0.092	b) Used the number in Fig 32.
Electricity in industry (add to additional electricity demand)	PWh/year	1.142	1.195	1.392	a) EU energy balances – includes industry with own consumption. This number is not presented in the report but extracted from EU Energy Balances excel file. b) From p. 155: "The scenario with the highest electricity demand in industry is 1.5TECH (…) [with] 1344 TWh …" Then using figure 69 we deducted the electricity consumption in the remaining scenarios. Calculated in PRIMES PES and Electricity tab. Additionally, this also includes the Refineries and coke ovens, with the data gathered from section 7.6.6 main report
Solar thermal	PWh/year	0.0002	0	0.0026	Ignored, very small
District heating demand industry	PWh/year	0.300			Aggregated all industry and own consumption heat demands, added the same losses as for DH and considered them as being produced by fuels in boilers. Since our fuel calibration lacks on coal, added this value under 'Various coal'

Transport fuel consumption	Units	2015 Reference	2050 Baseline	1.5 TECH	NOTES **a) = Notes regarding 2015 Reference** **b) = Notes regarding PRIMES Scenarios**
Conventional fuels					a b) Fig 52. There is some level of electrification in airplanes in hybrid versions by 2050. This figure should be already accounted for in electricity – dump charge
JP (Jet fuel) - fossil	PWh/year	0.6199	0.735	0.278	a b) Natural gas + e-gas + biogas (Fig 57)
JP (Jet fuel) - biofuel	PWh/year		0.0209	0.1593	
JP (Jet fuel) - electrofuel	PWh/year		0	0.2303	
Grid gas	PWh/year	0.021	0.2035	0.2605	a b) This number is obtained by reducing Fig 57 with the fuel used as JP and should represent the demand for heavy duty road transport and navigation.
Liquid - fossil	PWh/year	3.3087	1.6782	0.0209	ab) Figure 57
Liquid - biofuel	PWh/year	0.1907	0.1617	0.1687	
Liquid - electrofuel	PWh/year		0	0.243	

Hydrogen - electrofuel	PWh/year	0	0.0663	0.3687	
Electricity (PWh/year)					a) Figure 57 b) Data from El+heat demands.xlsx
Electricity - dump charge	PWh/year	0.0558	0.1352	0.174	
Electricity – smart charge	PWh/year	0	0.2301	0.4296	
Max. share of cars during peak demand	%	0	0.2	0.2	Used the reference scenario Gpkm and put the number in EP. also used the share of vehicles in the report to determine the capacity
Capacity of grid to battery connection	GW	0	1800	3330	
Share of parked cars grid connected	%	0	0.7	0.7	
Efficiency (grid to battery)	%	0	0.9	0.9	Extracted from TransportPLAN
Battery storage capacity	TWh	0	3	3	Extracted from TransportPLAN

Capacity of battery to grid connection	GW	0	90	166	Extracted from TransportPLAN
Efficiency (battery to grid)	%		0.9	0.9	a b) Fig 52. There is some level of electrification in airplanes in hybrid versions by 2050. This figure should be already accounted for in electricity – dump charge

C. Disaggregation method

In the table below the used method for disaggregating (splitting) aggregated scenarios to individual country scenarios is indicated.

						Splitting for 2015 (x) and 2050 (o)				
			2015 Reference	2050 Baseline	PRIMES-1.5TECH	As of today/according to forecast	Proportional to the corresponding country load (2015)	Proportional to the corresponding country peak load (2015)	Proportional to the corresponding country heat demand (2015)	Renewables according to CF times average load (2015)
Energy demands	Electricity demand	Fixed electricity demand (TWh/year)	1,569.58	2,115.39	1,687.22		xo			
		Additional electricity demand (industry) (TWh/year)	1,142.00	1,195.15	1,391.70		xo			
		Flexible electricity demand (1 day) (TWh/year)	0.00	235.04	230.08		xo			
		Max-effect for flexible electricity demand (1 day) (MW)	0.00	24,960.00	21,970.00			xo		

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	Central heating demand	District heating demand (TWh/year)	365.20	287.20	204.70	xo				
		Heat losses (%)	0.14	0.14	0.14	xo				
	Individual heating fuel consumption (TWh)	Coal boilers	140.72	0.00	0.00	x			o	
		Oil boilers	562.88	7.00	5.80	x			o	
		Gas boilers	1,686.35	831.50	379.20	x			o	
		Hydrogen boilers	0.00	0.00	74.40	x			o	
		Biomass boilers	523.40	161.70	122.10	x			o	
		Solar thermal	16.30	55.80	38.40	x			o	
	Individual heating heat demand (TWh)	Heat pumps	9.69	704.80	569.40	xo				
		Electric heating	248.93	72.00	59.00	xo				
	Industry fuel consumption (TWh)	Coal	369.30	306.50	29.89	xo				
		Oil	1,064.50	527.99	158.60	xo				
		Gas	1,202.30	872.30	297.00	xo				
		Biomass	302.30	511.80	422.25	xo				
		Hydrogen	0.00	0.00	91.90	xo	o			
	Transport demands (TWh)	JP (Jet fuel) - fossil	619.90	735.00	278.00	xo				
		JP (Jet fuel) - biofuel	0.00	20.90	159.30	xo				
		JP (Jet fuel) - electrofuel	0.00	0.00	230.30	xo				
		Liquid - fossil	3,308.70	1,678.20	20.90		xo			
		Liquid - biofuel	190.70	161.70	168.70		xo			

		Liquid - electrofuel	0.00	0.00	243.00		**xo**			
		Grid gas	21.00	203.50	260.50		**xo**			
		Hydrogen - electrofuel	0.00	66.30	368.70		**xo**			
		Electricity - dump charge (non-EV)	55.80	135.20	174.00		**xo**			
		Electricity – smart charge (EV)	0.00	230.10	429.60		**xo**			
Energy supply	Renewables capacity (MW)	Wind (onshore)	130,416.00	440,867.00	758,727.00	**x**				**o**
		Wind (offshore)	11,000.00	142,859.00	451,383.00	**x**				**o**
		PV	94,678.00	441,490.00	1,029,767.00	**x**				**o**
		Hydro - capacity	152,400.00	154,000.00	163,000.00	**xo**				
		Hydro - annual production (TWh)	371.00	376.00	396.00	**xo**				
	Thermal power production (MW)	Condensing power plant capacity	480,099.00	484,900.00	266,000.00	**x**				
		CHP (MW)	38,000.00	30,000.00	25,000.00	**xo**				
		Nuclear (MW)	121,957.00	86,822.00	121,346.00	**xo**				
	Waste Incineration	Waste input (TWh/year)	330.74	340.64	226.06	**xo**	**o**			
	DH capacity	Fuel boilers (MW)	79,000.00	90,000.00	55,000.00			**xo**		
		*Compression heat pumps (MWe)	0.00	0.00	0.00			**xo**		

		*Geothermal from absorption heat pumps (TWh/year)	16.30	55.80	38.40		**xo**			
		*Solar Thermal (TWh/year)	0.00	0.00	0.00		**xo**			
		*Industrial Excess Heat (TWh/year)	0.00	0.00	0.00		**xo**			
	Biogases	Biogas output (TWh)	186.10	418.70	837.40	**xo**				
	Fuel production	Liquid (TWh)	0.00	0.00	570.00		**xo**			
		Gaseous (TWh)	0.00	0.00	523.00		**xo**			
Storage	Electricity storage	Pumped hydro (TWh)	0.05	0.06	0.05	**xo**				
		Pumped hydro (MW)	47,464.00	58,994.00	51,350.00	**xo**				
		Grid batteries (TWh)	0.00	0.14	0.07		**xo**			
		Grid batteries (MW)	0.00	139,123.00	68,683.00			**xo**		