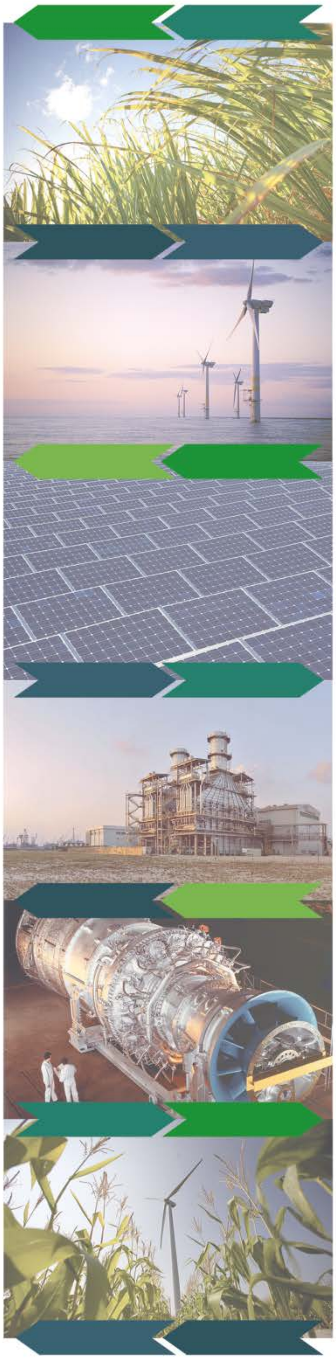
NAVIGATING THE ROADMAP FOR CLEAN, SECURE AND EFFICIENT ENERGY INNOVATION



D.5.1: Draft methodological working paper documenting the methodological approaches and interlinkages for energy demand models, coupled supply side models and interfaces to other WPs

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SET-Nav
Strategic Energy Roadmap

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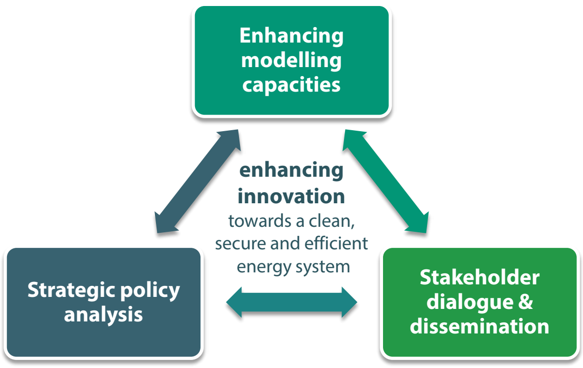
About the project

SET-Nav aims for supporting strategic decision making in Europe's energy sector, enhancing innovation towards a clean, secure and efficient energy system. Our research will enable the European Commission, national governments and regulators to facilitate the development of optimal technology portfolios by market actors. We will comprehensively address critical uncertainties facing technology developers and investors, and derive appropriate policy and market responses. Our findings will support the further development of the SET-Plan and its implementation by continuous stakeholder engagement.

These contributions of the SET-Nav project rest on three pillars: modelling, policy and pathway analysis, and dissemination. The call for proposals sets out a wide range of objectives and analytical challenges that can only be met by developing a broad and technically-advanced modelling portfolio. Advancing this portfolio is our first pillar. The EU's energy, innovation and climate challenges define the direction of a future EU energy system, but the specific technology pathways are policy sensitive and need careful comparative evaluation. This is our second pillar. Ensuring our research is policy-relevant while meeting the needs of diverse actors with their particular perspectives requires continuous engagement with stakeholder community. This is our third pillar.



Who we are?

The project is coordinated by Technische Universität Wien (TU Wien) and being implemented by a multinational consortium of European organisations, with partners from Austria, Germany, Norway, Greece, France, Switzerland, the United Kingdom, France, Hungary, Spain and Belgium.

The project partners come from both the research and the industrial sectors. They represent the wide range of expertise necessary for the implementation of the project: policy research, energy technology, systems modelling, and simulation.

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1 Introduction

This report describes all model adaptations, extensions and linkages for the energy demand models and coupled supply side models applied in SET-Nav. The links and interactions between the various models applied in SET-Nav will be described from the perspective of each model involved in WP5. The aim of all model adaptations and extensions is a comprehensive modelling framework with well-defined linkages that can be used in the case studies and the pathway analysis.

The overall objective of work package 5 is to provide and apply the modelling framework for the demand side of energy systems including buildings, industrial processes and transport. In particular, we deal with specific research and policy questions related to the demand side and flexibility options in form of case studies. This requires corresponding adaptation and extensions of existing models and their interfaces.

The modelling work in the field of energy demand and on-site supply in buildings, industrial processes and transport is covered by the following models: Invert/EE-Lab, Forecast-Industry, ASTRA and the load profile and flexibility interface e-load. While all the models are oriented on the demand side, they also cover decentralised, on-site supply systems, e.g. local space heating boilers. This is necessary to take into consideration the strong link between some energy efficiency options and local, decentralised supply options, in particular in buildings.

2 Coupling of models involved in WP5

In this chapter the links, interfaces and data flows applied and developed within SET-Nav will be described for each case study in WP5 and beyond WP5 for the pathway development in WP9.

2.1 Model coupling and data exchange concept case study 5.2 - Buildings

In this section we describe the model coupling and data exchange concept in the case study 5.2 "Energy demand and supply in buildings and the role for RES market integration".

This case study aims to analyse the link between energy efficiency improvement in buildings, heating system choice, demand side flexibility options and on-site RES deployment. The analysis will reveal the role of these elements in different future energy transition pathways.

The key-question of this case study is:

- How does energy efficiency improvement in buildings, heating system choice, flexibility options (demand response) and on-site RES affect market integration of RES and CHP?

This leads to the following sub-questions:

- Which factors trigger renovation rate and depth and how might building related energy policies and other framework conditions affect energy demand in buildings?
- Which factors trigger heating system choice (including district heating) and the uptake of on-site RES and how might energy policies and other framework conditions affect the energy supply mix of buildings and related generation of on-site RES?

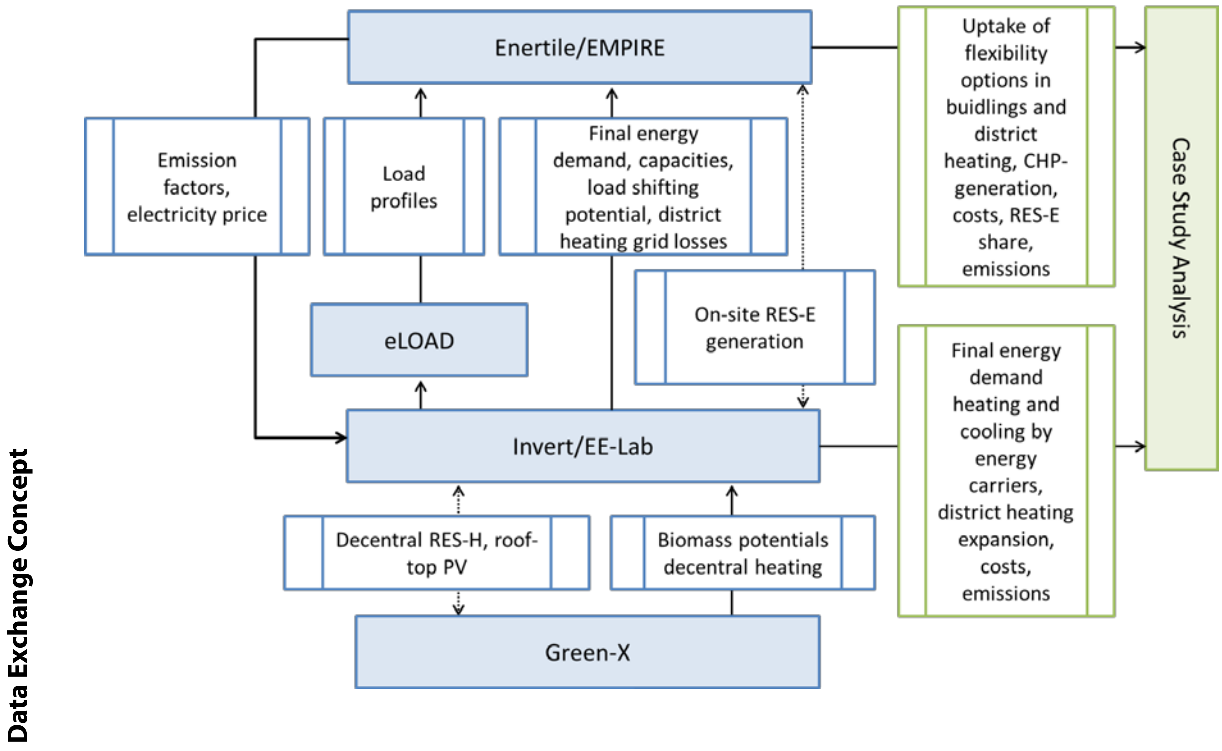
- How will these developments interact with the overall energy system and how can the building sector unlock its potential of flexibility options (P2H, storage etc.)?
- What is the future role of district heating and related CHP potentials in various scenarios taking into account reduced heat demand and related heat densities as well as the economic and policy conditions in the electricity sector?

We start with the development of scenarios for energy demand in buildings and related heating system choice (with corresponding implications on on-site RES deployment) taking into account also the development of district heating grids. Subsequently, the annual demand is converted into load profiles. Flexibility options, related costs and technological restrictions are derived. On this basis, the energy system and supply models optimize the realization of demand flexibility options. Moreover, district heating expansion results from the bottom-up model serve as an input to the electricity models regarding the potential heat supply from CHPs.

Several models are used for the simulations performed within case study 5.2. INVERT/EE-Lab will simulate the development of demand and supply for heating and cooling in the European building sector. eLOAD will be used to transform the output from INVERT/EE-Lab from annual data into hourly load profiles for electrical heating and cooling supply technologies (ACs, heat pumps, direct electric heating). Based on building characteristics also demand response potentials will be derived. Together with potential developments of heat demand for district heating these data will be fed into the supply models Enertile and EMPIRE to study the relationship between the electricity sector and developments in the building sector across the EU in several scenario runs: The model Green-X is will be used to define biomass allocation across sectors to make sure that the potentials for biomass as a source for heating in the building sector is not overestimated. For detailed model description and extensions developed for the main models in WP5 please see model descriptions in chapter 3.

The data exchange concept for case study 5.2 is illustrated in figure 1 below. Solid lines show data exchange for each scenario run. Dotted lines indicate additional optional data exchange for the purpose of model calibration and better understanding, which is not required for each scenario calculation. The latter ones are not explicitly listed in the table of data flows. For details on data formats please see the Appendix of this report.

General assumptions as interest rates and overall input data that is only relevant for one model (e.g. o&m costs of power plants, lifetime of power plants, maximal land use factors for renewable electricity generation) is not managed within the data exchange between models. However it is necessary to keep these assumptions consistent within each case study, and to reach a certain degree of consistency between case studies in the project.



Data Flows

Name/Descriptor	Data Type	from model	into model	advised unit
Energy demand	A	Invert/EE-Lab, eLoad	Enertile, Empire, Analysis	GWh
Capacities	A	Invert/EE-Lab	Enertile, Empire	GW
Electricity generation from CHP, RES-E and roof-top PV	A	Enertile, Empire	Analysis	GWh
Emissions	A	Enertile, Empire, (Invert/EE-Lab)	Analysis	t CO2 equ
Prices	A	Enertile, Empire,	Invert/EE-Lab	Euro2016/MWh
Costs	A	Enertile, Empire, Invert/EE-Lab,	Analysis	Euro2016
Biomass potentials for decentral heat	B	Green-X	Invert/EE-Lab	GWh
Load shifting potential	B	Invert/EE-Lab	Enertile, Empire	GW
District heating grid losses	B	Invert/EE-Lab	Enertile, Empire	%
Retail prices	B	FORECAST-Macro	FORECAST-Industry	Euro/GJ

Figure 1: Data exchange concept from and to the INVERT/EE-Lab model in WP5 for case study 5.2

2.2 Model coupling and data exchange concept case study 5.3 - Industry

In this section, we describe the model coupling and data exchange concept in the case study 5.3 "The contribution of innovative technologies to decarbonise industrial process heat".

The main objective of the simulation of energy in industrial processes is to set-up a modelling framework that allows simulating the transition to a low-carbon energy system for the industrial sector in an integrated manner. Technology solutions like RES, energy efficiency, CCS and the links to the power and gas sectors shall be considered. The analysis will reveal the role of these elements in different future energy transition pathways.

The key-questions of this case study are:

- What is the contribution of RES, energy efficiency and CCS technologies in decarbonising the industrial process heat sector?

This leads to the following sub-questions:

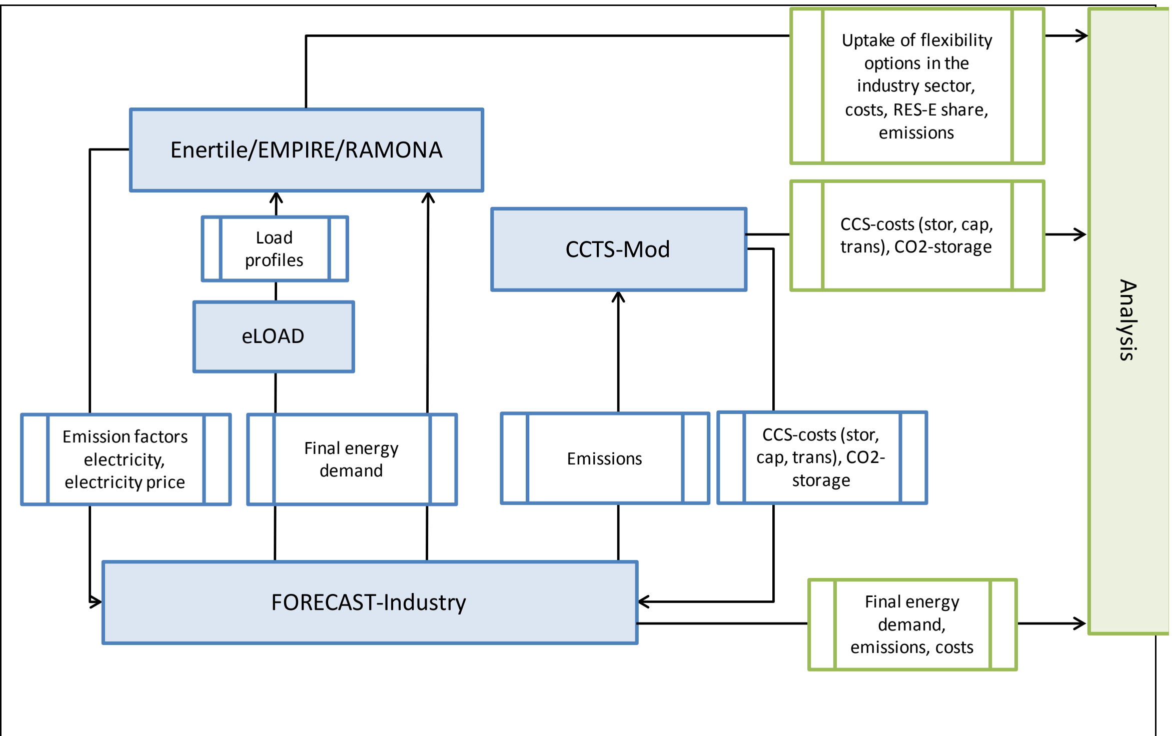
- How is energy demand in industry throughout Europe used for process heating (e.g. which processes and technologies?
- What are the technical options (and restrictions) for RES, energy efficiency and CCS in the various processes and sub-sectors?
- What is the long-term potential and cost of RES, energy efficiency and CCS technologies?
- What is the interaction with the gas and power sectors?
- What is potential of industry to provide flexibility to the power system?

We undertake a scenario analysis using the bottom-up model FORECAST-Industry in connection with Enertile, Empire and Ramona to consider the links to the power and gas sectors. In the case study, the models are used to make a scenario and sensitivity analysis to restrict the availability of individual technologies and vary the speed of technological progress (cost and efficiency) in order to identify robust transition paths. The costs of the individual paths play a major role in the analysis and comparison.

We start with the development of scenarios for energy demand in industry and the related technology choice (e.g. diffusion of energy efficiency measures, usage of CCS, innovative technologies) modelled in FORECAST-Industry, resulting in final energy consumption per energy carrier for all EU member states for the defined supporting years between the base year and 2050 (2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050). Based on the development of final energy consumption from industry - which is an input required by the Enertile/EMPIRE model - the energy system and supply models identify flexibility options and optimize the realization of demand flexibility options and renewable power generation. Enertile provides then the final wholesale prices for electricity per MWh as well as emission factors for electricity generation. Fossil fuel prices are derived from the EU reference scenario 2016. FORECAST-Macro converts these country-specific wholesale prices into retail prices which are used by FORECAST-Industry to rerun the model if necessary. In addition, the annual demand is converted into CO2 emissions by FORECAST-industry which is the basis for simulating CO2-storage and costs in CCTS-Mod. This information is than fed back into FORECAST-Industry to identify industrial costs.

The following figure describes the data flows between the models for the case study "The contribution of innovative technologies to decarbonise industrial process heat (task 5.3)". General assumption as overall input data or technological parameters that are only relevant for one model (e.g. physical production of energy-intensive basic products, lifetime of power plants) is not managed within the data exchange between models but will be harmonized across the case studies. Solid lines in the figure below show data exchange for each scenario run. For details on data formats please see the Appendix of this report.

Data Exchange Concept



Data Flows

Name/Descriptor	Data Type	from model	into model	advised unit
Energy demand	A	FORECAST-Industry/eLOAD	Enertile, Empire, Ramona, Analysis	TWh
Electricity generation, RES-E share	A	Enertile, Empire	Analysis	TWh/an, MWh
Emissions	A	Enertile, Empire, FORECAST-Industry	Analysis/CCTS-Mod	t CO2 equ
Prices	A	Enertile, Empire	FORECAST-Industry	Euro2013/MWh
Load shifting potential	B	eLOAD/Enertile	Empire	GW
Costs	A	Enertile, Empire, FORECAST-Industry, CCTS-Mod	Analysis	Euro2013
Retail prices	B	FORECAST-Macro	FORECAST-Industry	Euro/GJ
CO2-storage	B	CCTS-Mod	FORECAST-Industry	Mt CO2

Figure 2 Data exchange concept from and to the FORECAST-Industry model in WP5

2.3 Model coupling and data exchange concept case study 5.4 - Transport

This chapter describes the envisaged model coupling for the case study 5.4 "Ways to a cleaner and smarter transport system". Furthermore, it presents the concept developed for the data exchange between the involved models with the ASTRA model in its centre. The purpose of the transport case study is the analysis of policy measures and strategies to accelerate the challenging transition from a fossil fuel based towards an energy efficient and low-carbon transport sector in Europe. As opposed to other sectors, the final energy consumption of the European transport sector continuously increased over the last decade and accounts for more than 20% of total demand today. Despite having a very innovative transport industry investing a lot in R&D and policies designed to foster the shift towards energy efficient and renewable energy carriers the transport sector is still strongly based on fossil fuels.

The key research question is therefore:

- Which measures have a potential to accelerate the transition of the transport sector from a fossil fuel based towards an energy efficient and low-carbon system and what is the potential of flexibility options as regards the energy sector?

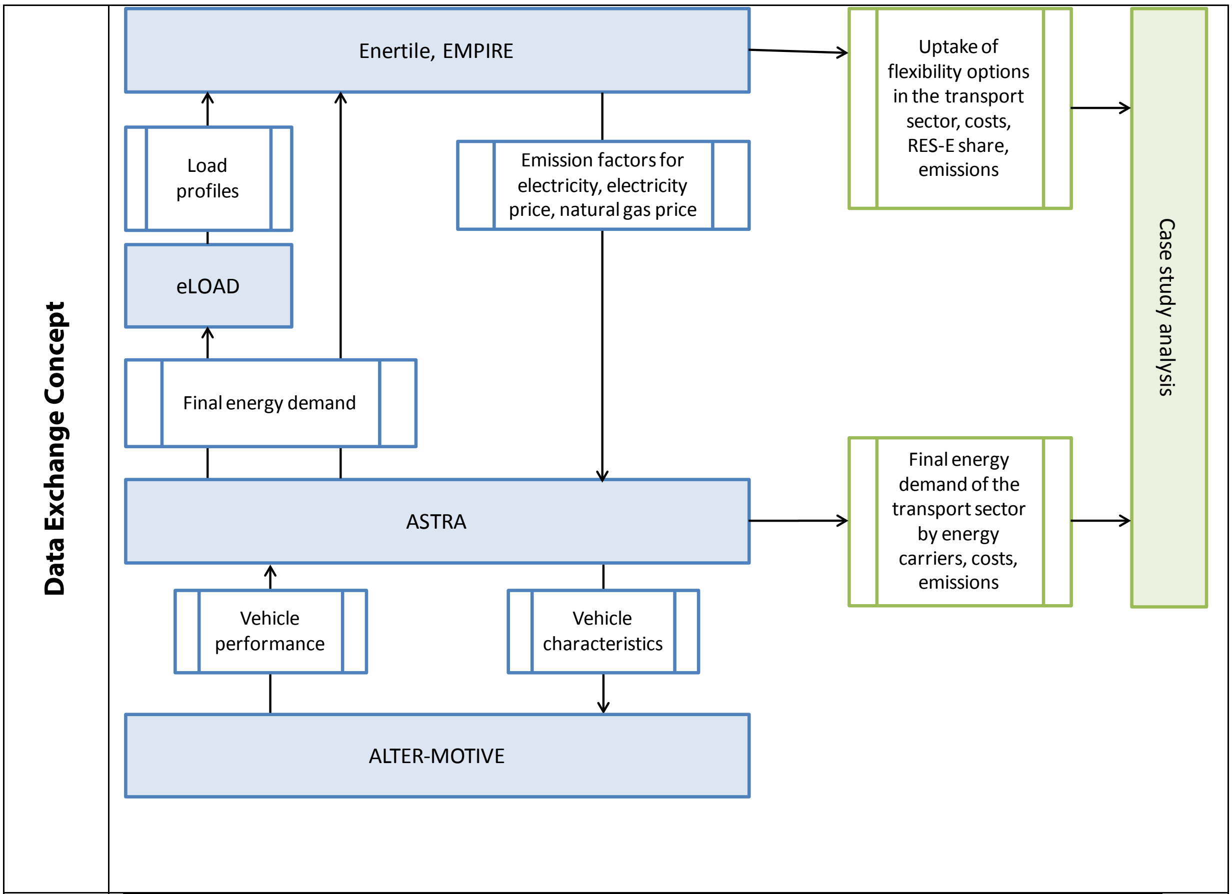
The case study shall find answers on further research questions.

- It shall demonstrate the potential of different fuel and energy options and of energy efficiency in transport.
- Most important, it should provide options to overcome the well-known hen-and-egg problem in the relation between alternative fuel vehicles and the requested filling or charging station infrastructure.

The ASTRA model in this case study is applied for a scenario analysis to assess the impact of transport and energy policy measures on the envisaged transition. For this purpose there are links established with Enertile and EMPIRE in order to provide the bottom-up impulses in terms of fuel/energy price development for each of the major prospective energy carriers relevant for transport. In the modelling analysis, a set of transport and energy policy packages are defined and combined with a techno-economic framework setting the parameters (learning rates, infrastructure deployment, etc.) for energy efficient and alternative fuel technologies for each mode in order to identify cost-efficient pathways towards an energy-efficient transport system largely based on renewable energy carriers.

The data flow between the involved models is highlighted in figure 3. ASTRA starts the modelling sequence using a standard pathway for user prices for all relevant energy carriers and fuels. It then provides resuming vehicle characteristics to the ALTER-MOTIVE model and the resulting final energy consumption per energy carrier for all EU member states for each simulation year between 1995 and 2050 to the eLOAD model. ASTRA calculates final energy consumption in terms of annual loads which are converted via daily load profiles for different vehicle categories and specific users in the eLOAD model. Finally, the development of final energy consumption from transport per hour is an input required by the Enertile and EMPIRE model. The major output from Enertile and EMPIRE are wholesale prices for electricity per MWh. FORECAST Macro converts these country-specific wholesale prices into retail prices which are finally used by ASTRA as a steering parameter for passenger and freight transport performance. Furthermore, energy prices trigger the speed of diffusion of alternative fuel vehicles. Fossil fuel prices are derived from the EU reference scenario 2016.

The ALTER-MOTIVE model provides the evolution of technical characteristics for relevant alternative fuel technologies to ASTRA. This covers the development of average storage capacity of batteries for battery electric (BEV), plug-in electric (PHEV) and fuel cell electric vehicles (FCEV), the average lifetime of batteries and the average weight of batteries for these technologies. For details on data formats please see the Appendix of this report.



Data Flows

Name/Descriptor	Data Type	From model	Into model	Advised unit
Energy demand	A	ASTRA	eLoad, Enertile, Empire, Analysis	GWh
Emissions	A	ASTRA	Analysis	Ton
Emissions	A	ASTRA, Enertile, Empire,	Analysis	Ton
Prices	A	Enertile, Empire,	ASTRA	€2016/MWh
Costs	A	ASTRA, Enertile, Empire,	Analysis	€2016
Vehicle performance	B	ALTER-MOTIVE	ASTRA	Various
Vehicle characteristics	B	ASTRA	ALTER-MOTIVE	n/a
Retail prices	B	FORECAST-Macro	ASTRA	GJ/€

Figure 3: Data exchange concept from and to the ASTRA model in WP5

Flexibility options like power-to-liquid/power-to-gas or like producing hydrogen from renewable energy in times of high supply will be fed into the ASTRA model via user changing prices for the respective energy carrier or fuel.

Based on passenger and freight transport performance and the efficiency and technical composition of road and non-road vehicle fleets, ASTRA calculates annual loads of greenhouse gas and relevant air pollutant emissions for all EU member states per mode. This calculation takes real world emissions and not laboratory drive cycle emissions into account. Therefore, average fuel or energy consumption factors for each vehicle category, fuel technology and emission standard are extracted from the Handbook of Emission Factors (HBEFA 3.2) and converted by a factor representing the difference between drive cycle and real world fuel consumption. ASTRA distinguishes between direct (tank-to-wheel) emissions composed out of hot and cold start emissions and indirect emissions (well-to-tank). By definition, ASTRA provides as output only direct emissions from transport activities. Emissions from electricity generation are provided by Enertile and EMPIRE. FORECAST computes fuel production emissions from other transport fuels.

Further outputs from ASTRA for the analysis of the transport case study are the development of transport costs per mode and the development of the final energy demand from transport by mode.

2.4 Model coupling and data exchange concept beyond WP5

The following chapter will describe the links of the models used in the WP5 case studies for the modelling of the pathways developed in WP9.

2.4.1 Linkages to WP4: Exchange of demand and whole sale energy prices

For the quantifications of pathways defined in WP9 the models used in WP5 will run their simulations based on the global fuel prices simulated in WP4. A tool is set up to transform wholesale market prices into respective retail prices for each sector. This tool also allows for the integration of taxes and other additional charges for each member state. This procedure will guarantee consistent assumptions for each individual sector model within the case studies and within the whole SET-Nav project.

A crucial part of the model coupling process will be the data exchange to the central data platform developed in WP4. The data flow concept and data templates developed within the WP5 case studies also provide the basis for data exchange with the central platform and data inputs for MultiMod.

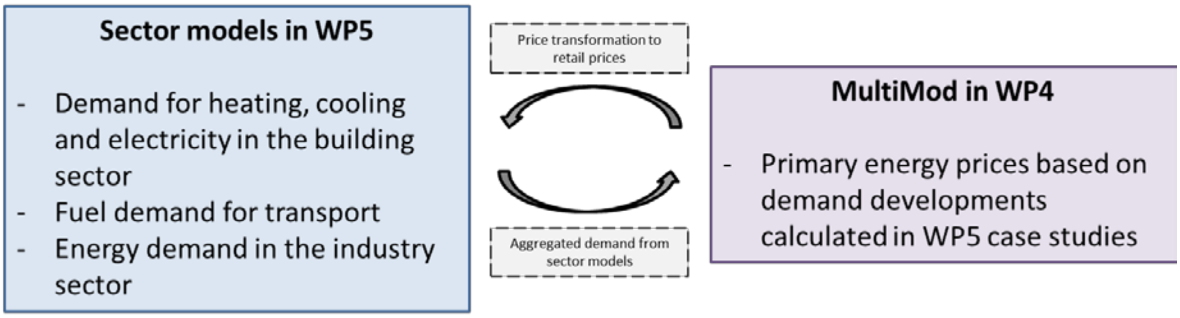


Figure 4: Model links between WP5 case studies and MultiMod in WP4

2.4.2 Linkages to WP6-7: Harmonized assumptions on demand developments, prices and technology costs

For the modelling of transition pathways (WP9) the demand scenarios developed in WP5 will be linked with the supply and infrastructure models applied in WP6 and 7 through the data platform developed in WP4. The data templates and exchange concepts within the case studies in WP5 will also be used for the integration of the generated scenario data into the central platform. While some links have already been established within the case studies, the models outside of WP5 will harmonize their assumptions on demand developments based on the WP5 case study results. On the other hand the demand models used in WP5 will harmonize their price assumptions and technology costs based on the results from other case studies. Both interactions are described below and illustrated in figure 5:

1) Data flows from demand scenarios to supply and infrastructure models: The demand scenarios developed in WP5 will be integrated in the models focusing on infrastructure planning and supply mix development. In particular the development of demand for natural gas and electricity from buildings and industrial sectors are crucial for the models focusing on infrastructure planning. The model link allows to consistently analyze the effects of energy demand developments including changes in demand patterns across Europe (e.g. through the use of heat pumps in buildings, increased cooling needs, electrification of transport sectors). Other important data links between WP5 and the models applied within WP6 and WP7 include the use of biomass in the industrial, building and transport sector for cross sectoral biomass allocation issues and the development of heat demand for district heating for the simulation of electricity supply from CHPs and power to

heat options. However, these links will not be taken into account directly in WP6 and WP7. Rather, they will be prepared for the modelling of overall transition pathways in WP9.

2) Data flows from supply and infrastructure scenarios to demand models (WP6 and WP7 to WP5): The main data flow from supply and infrastructure models to the demand models consists of prices and cost developments. While wholesale fuel prices are derived from WP4 results as described above, model results within WP5, WP6 and WP7 provide scenarios for electricity price developments and infrastructure costs for gas and electricity networks. Those will be integrated into the transformation of wholesale prices to prices for end users in the industrial and building sector. The supply models of WP7 also provide a cross sectoral analysis of biomass use with respect to overall domestic potentials. In high CO_2 mitigation scenarios those potentials might be exploited to a large extend and individual sector demand modelling might overestimate the availability of biomass. In case the supply models indicate a shortage of biomass the demand models will be adjusted and biomass use will be adjusted using cost potential curves or direct limitations of biomass use within the demand models. However, these links will not be taken into account directly in WP5. Rather, they will be prepared for the modelling of overall transition pathways in WP9.

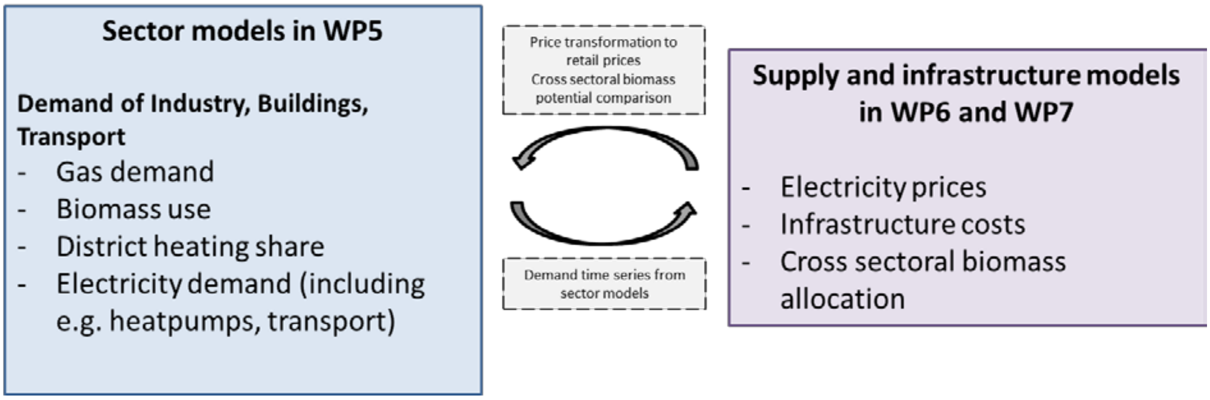


Figure 5: Links between WP5 demand scenarios and supply and infrastructure models

2.4.3 Linkages to WP8 – Macroeconomic models

Each sector model establishes a link with the macro- economic models applied in WP8. The main inputs to the macro- economic models consist of costs and expenditures in the building, transport and industrial sectors. Those expenditures are split up into investment costs (e.g. heating systems, machinery, cars, efficiency measures), running energy costs (for fuels and electricity) and government subsidies in each sector. This link allows for estimating the macro economic effects of transition pathways in line with estimated demand developments within each sector.

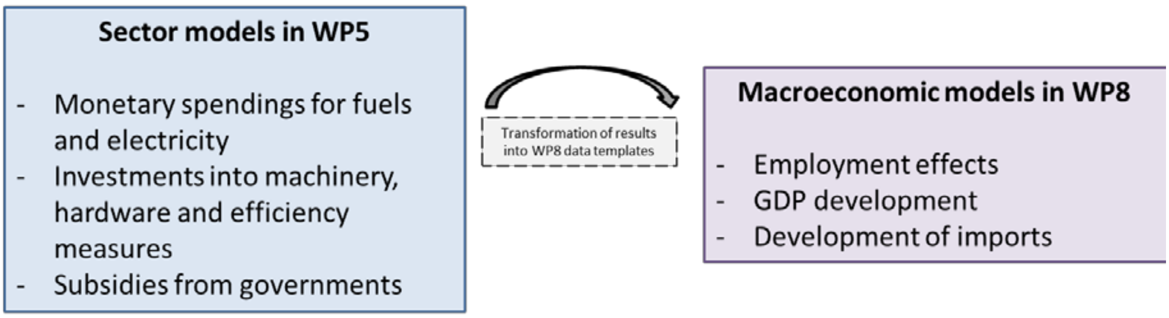


Figure 6: Model links between WP5 demand scenarios and macroeconomic models in WP8

2.4.4 Linkages to WP9: Transition pathway modelling

Within WP9 the technology and policy pathways will be defined. A set of demand scenarios within WP5 will be chosen representing the expected energy demand development in each pathway. The results from the case studies from WP5 will be analysed in the path definition process (Task 9.2). Those results will be available as case study reports. Within Task 9.3 the interaction between all models used from WP5 to WP8 will be coordinated. Assumptions including the most relevant exogenous assumptions for each model will be harmonised and exchanged through the model integration platform developed in WP4. All sector models within WP5 will run simulations for each pathway defined in Task 9.2 with shared assumption along all involved models also beyond the case studies within each work package.

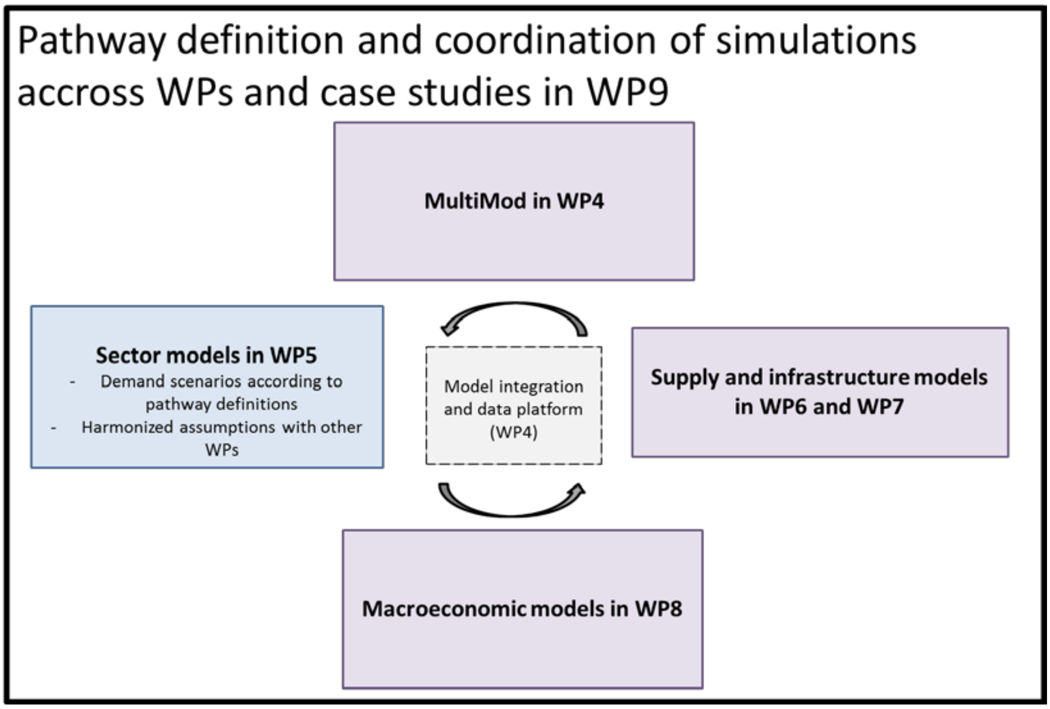


Figure 7: Model integration for pathway modelling in WP9

3 Overview of involved models and model extensions

In this chapter we describe the functionalities, role within SET-Nav, model extension and model links for the main models used for the case studies in WP5.

3.1 INVERT/EE-Lab

3.1.1 Model description (1-2 pages)

Invert/EE-Lab is a dynamic bottom-up building stock simulation tool. Invert/EE-Lab in particular is designed to simulate the impact of policies and other side conditions in different scenarios (policy scenarios, price scenarios, insulation scenarios, different consumer behaviours, etc.) and their respective impact on future trends of energy demand and mix of renewable as well as conventional energy sources on a national and regional level. More information is available on www.invert.at or e.g. in (Kranzl et al., 2013) or (Müller, 2012). The structure and concept is described in Figure 8.

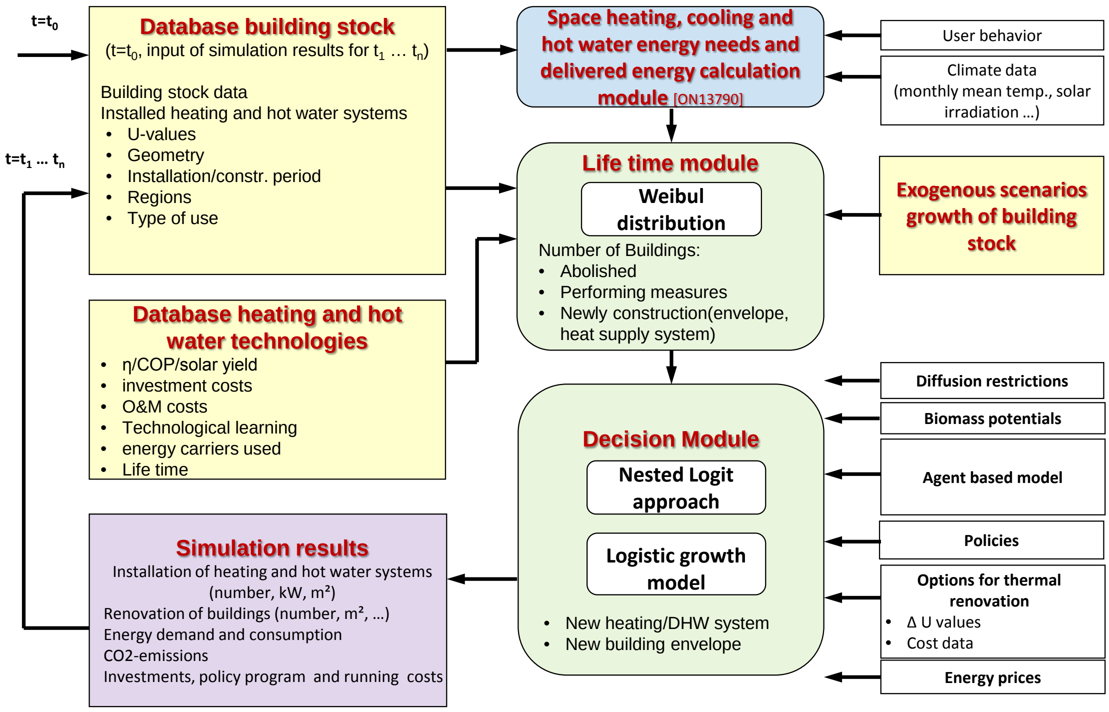


Figure 8: Overview structure of Simulation-Tool Invert/EE-Lab

The basic idea of the model is to describe the building stock, heating, cooling and hot water systems on highly disaggregated level, calculate related energy needs and delivered energy, determine reinvestment cycles and new investment of building components and technologies and simulate the decisions of various agents (i.e. owner types) in case that an investment decision is due for a specific building segment. The core of the tool is a myopical, multinominal logit approach, which optimizes objectives of "agents" under imperfect information conditions and by that represents the decisions maker concerning building related decisions.

Coverage and data structure

The model Invert/EE-Lab up to now has been applied in all countries of **EU-28 (+NO, CH, IS etc)**. A representation of the implemented data of the building stock is given e.g. at www.entranze.eu.

Invert/EE-Lab covers **residential and non-residential buildings**. Industrial buildings are excluded (as far as they are not included in the official statistics of office or other non-residential buildings). The level of detail as e.g. the number of construction periods depend on the data availability and structure of national statistics. We take into account data from Eurostat, national building statistics, national statistics on various economic sectors for non-residential buildings, BPIE data hub, Odyssee. The current base year used in our building stock database is 2012.

As **efficiency technologies** Invert/EE-Lab models the uptake of different levels of renovation measures (country specific) and diffusion of efficient heating and hot water systems.

Outputs from Invert/EE-Lab

Standard outputs from the Invert/EE-Lab on an annual basis are:

- Installation of heating, cooling and hot water systems by energy carrier and technology (number of buildings, number of dwellings supplied)
- Refurbishment measures by level of refurbishment (number of buildings, number of dwellings)
- Total delivered energy by energy carriers and building categories (GWh)
- Total energy need by building categories (GWh)
- Policy programme costs, e.g. support volume for investment subsidies (M€)
- Total investment (M€)

Moreover, due to the bottom-up character of the model, Invert/EE-Lab offers the possibility to derive more detailed and other type of result evaluations as well.

3.1.2 Model extensions

The following model extensions will be carried out in this project:

- Link to load profile and demand flexibility tool and to supply models
- Develop a district heating module

In the following parts, we will describe the model extensions and the key methodological aspects, approaches and new developments.

3.1.2.1 Link to load profile and demand flexibility tool and to supply models

The Invert-EE/Lab model has been extended with a link to the model eLoad. This link allows to derive hourly profiles based on the annual heating and cooling demand calculations from Invert-EE/Lab. The annual energy demand for the aggregated building categories “Single Family houses”, “Multi Family houses”, “Private Service buildings” and “Public Service buildings” has been linked with one of the processes for space heating, space cooling or domestic hot water which are already implemented in e-Load. This link is established for each EU28 member state. For the transformation into hourly load profiles climate data across Europe is used. Note that the same climate data is then also used for the simulation runs in Enertile and Empire to make sure that the demand profiles are also in line with climate effects (e.g. irradiation and wind speed on renewable generation from Wind and PV) in the electricity system and gas models.

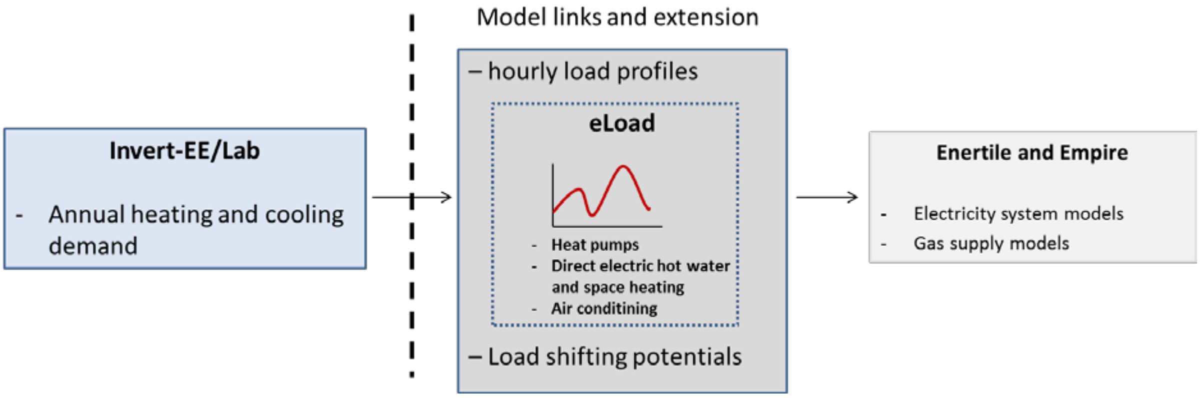


Figure 9: Model extension of Invert/EE-Lab with hourly load profiles and links to Enertile and Empire

This approach allows for a consistent modelling of the impact of developments in the heating and cooling sector on the electricity system. In particular the following effects are covered and can be analysed through this model extension:

- the impact of climate change and diffusion of air conditioning systems on the electricity system

- the effect of thermal efficiency measures in the building stock on energy demand including gas demand and power to heat options

- the impact of increased use of heat pumps on the electricity system with a particular focus on peak loads

Additionally to the load profiles derived through the link between Invert/EE-Lab and e-Load also the demand response potential from electrical heating and cooling devices in the building stock can be derived. Due to computational limits within the electricity system models where each demand response option is implemented similar to storage units the detailed building categories implemented in Invert/EE-Lab are aggregated to 4 building types with similar attributes regarding their hourly load profiles and potential to shift heating and cooling demand throughout a day. We distinguish between 2 types of residential and service sector buildings in each member state. For hot water and space heating we distinguish between buildings with low and with high thermal storage for hot water and/or space heating. For the case of space heating, this includes the thermal mass of the buildings and heat storage units. Note that only heat loads served by electric heating and cooling devices are considered here (heat pumps and direct electric heating). Potential demand shifts for each category are derived from simplified building simulation and literature analysis on demand response in buildings. The distinction of demand response potentials of cooling devices will also be based on simplified building simulation and corresponding literature studies. The main factor for a distinction of cooling building types will be the amount of thermal storage masses options – and optionally also cold-storage – that can be used to shift cooling demand away from peak load hours. A building type with higher thermal storage will be attributed with higher cooling demand shift potentials compared to buildings with low thermal mass or without cold storage, where load shifting potentials might be less than one hour. For the demand response potential to be exploited the appliances will also have to be equipped with controllers that allow for reacting on price or other signals. This limitation of demand potentials will be reflected by assumptions on diffusion rates of smart technologies for each process and building type and each simulation year. Diffusion curves will be applied to estimate the uptake of those technologies until 2050.

The result of these model extensions will be 12 different electrical load profiles (three end uses – hot water, space heating, cooling – and four building types) including their corresponding load shifting potentials for each simulation year and each member state – see Table 1. These parameters will then be integrated in the energy system model Enertile and EMPIRE to analyse the benefits and overall cost saving potentials of demand response options in the building stock across Europe.

Table 1: General approach of demand response parameters in buidlings for data exchange in case study 5.2

process/building type	Residential type 1	Residential type 2	Service type 1	Service type 2
AC	hourly load profile [MW] potential demand shifts [h] diffusion of demand response devices [%]			
Hot water				
Space heating				

3.1.2.2 Develop a district heating module

In order to estimate the potential diffusion of district heating grids Invert/EE-Lab has been extended with a district heating grid expansion module (see also Fritz, 2016). This module results in scenarios for the expansion, extension, re-investment or dismantling of district heating. It is based on spatial high resolved heat density maps (100m x 100m resolution) as well as on heat demand scenarios on MS-level. The district heating expansion module takes into account the costs for grid expansion and extension, depending on heat and building density, the operation and maintenance costs for district heating grids and heat generation costs (exogenously given resp. iterative taken from WP 6). The used algorithm, based on GIS data for EU 28, will be applied to identify the economical district heating potential, considering the efficiency measures in the building stock and the district heating distribution costs in detail. Figure 8 gives an overview about the model link of the existing model Invert-EE/Lab and the district heating expansion module.

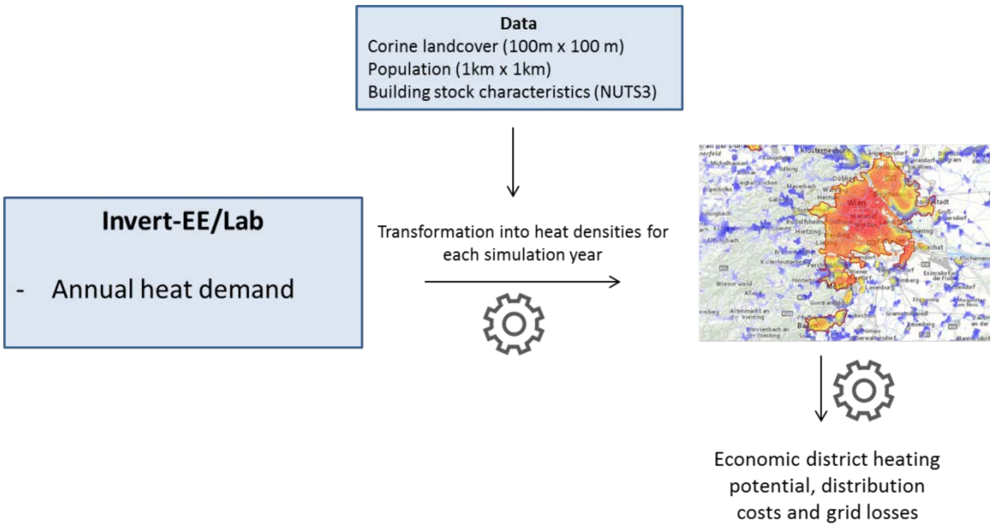


Figure 10: Overview about the district heating expansion module and the interaction with the existing model Invert-EE/Lab

<u>Used data:</u>

The used data for the district heating expansion module are mainly the following:

- Output of the bottom-up building stock simulation model Invert-EE/Lab up to 2050 regarding the development of the buildings heat demand due to efficiency measures and the change rate of heating technologies in the building stock on MS-level
- Population (1km x 1km, Census 2011)
- CORINE Land Cover (100m x 100m, 2012)
- Heating degree days (25km x 25km)
- District heating expansion costs depending on heat and building density ((Persson and Werner, 2011)[1])

<u>Generation of heat density maps:</u>

[1] Persson, Urban, and Sven Werner. "Heat Distribution and the Future Competitiveness of District Heating." *Applied Energy* 88, no. 3 (March 2011): 568–76. doi:10.1016/j.apenergy.2010.09.020.

The spatially resolved heat density maps are based on energy demand scenarios on member state level. This demand is disaggregated on raster cell according the population, the CORINE Land Cover and heating degree days. The update of the heat density maps for the whole simulation horizon considers the development of the buildings' heat demand due to efficiency measures in the building stock.

District heating expansion algorithm:

The district heating expansion module can be divided into three steps:

1. Identification of district heating regions within each MS and identification of the technical potential
2. Determination of the economic district heating potential for these regions
3. Identification of the district heating grid losses

The identification of the technical potential and of district heating regions within each MS is based on the methodology described in Büchele et al., (2015). This approach considers the spatial distribution of heat densities and results in district heating regions. Therefore, a threshold for heat density and thus for each raster cell to be assigned to a district heating region is defined and the relation of each raster cell and the surrounding cells is analysed.

The technical potential serves as basis for the economic assessment of the future role of district heating. Following an initialization of the current share of district heating for each identified region, the future economic potential is determined, considering the costs for expansion/extension, operation and maintenance and heat generation. The yearly potential for district heating is mainly influenced by the development of the buildings heat demand as an output of Invert/EE-Lab and the change rate of heating technologies in the building stock. These assumptions shall ensure the inertia in the building stock and the long-time decision of the building owners for the investments.

Results:

- The effect of efficiency improvement of the building stock on heat demand in existing district heating grids
- The effect of efficiency improvements in the building stock on the distribution costs of district heating grids and related impacts on the competitiveness compared to decentral heating options
- Potentials for expansions of district heating grids and implications on the potential for electricity generation from CHPs in the electricity sector
- Moreover, the results of the model can be used to model district heating grid losses based on heat grid densities, connection rates and assumptions regarding the state of the grid insulation.

These extensions will allow for a better representation and bottom-up foundation of the modelling of district heating and CHP in the energy system and energy supply models used within the SET-Nav project.

3.1.3 Model linkages and role of the model in the overall model framework

Case study 5.2 develops scenarios of energy demand in the building stock, Invert/EE-Lab delivers data to models Enertile and Empire through defined data interfaces. Invert/EE-Lab also delivers annual energy demand data to the model eLOAD where it is transformed into hourly load profiles.

In other case studies, within WP5 and case studies from other WPs the model results from Invert/EE-Lab will not be directly used. In the first stage those case studies will be based on demand scenarios for heating, cooling and electricity within the building sector from the EU reference scenario 2016.

In the overall scenario assessment (WP9) Invert/EE-Lab will be used to deliver heating, cooling and hot water energy demand in the building stock. The links between demand models in WP5 and models involved in other work packages is described in2.4. The results from simulations runs in Invert/EE-Lab will be integrated into the common database following the formats of the data exchange concept of case study 5.2. Templates for additional linkages not covered by the case study (e.g. with macroeconomic models in WP8) will be defined to guarantee a smooth exchange of data also beyond the case studies.

For overall scenario assessment the price assumptions for energy carriers and technologies used for heating and cooling purposes within Invert/EE-Lab will be harmonised with the model results from the involved electricity system and gas market and infrastructure models. The biomass cost potential curved which are used within Invert/EE-Lab will be adjusted to the results on overall biomass use in the supply scenarios from WP7 to make sure that potential scarcity of biomass potentials resulting from biomass use in other sectors is reflected in the demand scenarios within the defined pathways.

3.2 FORECAST-Industry

3.2.1 Model description

The scenario calculations for the industrial sector are conducted using the bottom-up energy demand model FORECAST-Industry. In the following, a brief description of the model is provided. For additional information, we refer to the model website[2] and a number of publications as mentioned below.

Compared to the other sectors, the industrial sector shows the highest degree of heterogeneity with regard to technologies and energy users (i.e. companies). This poses a huge challenge to a bottom-up model, which always needs to focus on large homogenous groups of energy uses / services. At the same time, the number of energy uses should not be too high, as gathering input data is very time and resource intensive.

Thus, the structure of the industrial sector model also reflects this heterogeneity and the data availability in the industrial sector. Selected energy-intensive processes are explicitly considered, while other technologies and energy-using equipment are considered in the form of cross-cutting technologies similarly modeled across all sub-sectors.

The model is a simulation model, which reflects the fact that investment decisions are modeled according to real-life behavior of investors. Thus, in contrast with optimization models often used, FORECAST does not calculate the energy system based on least system cost; even barriers to the adoption of energy efficient technologies are considered. Considering barriers and non-optimization

2 http://www.forecast-model.eu

behavior of investors also allows various policy instruments such as standards, taxes and subsidies to be taken into account.

Following data availability and heterogeneity, different approaches are used in the various modules to simulate technology diffusion. These range from diffusion curves to vintage stock models and discrete choice simulation. Figure 11 shows the simplified structure of FORECAST-Industry.

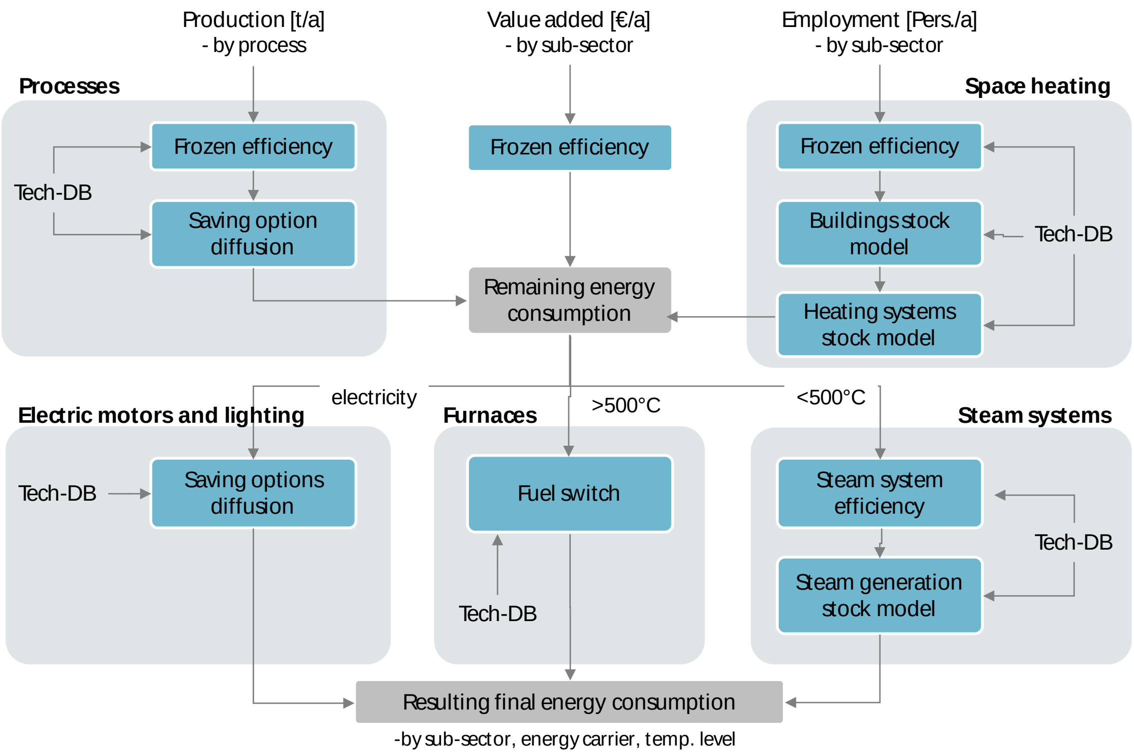


Figure 11: Overview of the model FORECAST-Industry

Source: Fraunhofer ISI

It comprises the following main sub-modules:

Energy-intensive processes: this module presents the core of the bottom-up quantity structure of FORECAST. 64 individual processes/products are considered via their (physical) production output and specific energy consumption (SEC). The diffusion of about 200 individual energy efficiency measures (EEMs) is modelled based on their payback period (Fleiter et al. 2012; Fleiter 2013).

Space heating: space heating accounts for about 9% of final energy demand in German industry. We use a vintage stock model for buildings and space heating technologies. The model distinguishes between offices and production facilities for individual sub-sectors. It considers building refurbishment, demolition and new construction, as well as demolition and new construction of space heating technologies. The investment in space heating technologies such as natural gas boilers or electric heat pumps is determined based on a discrete choice approach (Biere et al. 2014).

Electric motor systems and lighting: these cross-cutting technologies (CCTs) include pumps, ventilation systems, compressed air, machinery equipment, cold appliances, other motor appliances and lighting. The electricity demand of the individual CCTs is estimated based on typical shares by sub-sector. The modelling of the diffusion of EEMs is similar to the approach used for process specific EEMs.

Furnaces: energy demand in furnaces is a result of the bottom-up estimates from the module “processes”. Furnaces are found across most industrial sub-sectors and are very specific to the production process. They typically require heat at a very high temperature level. While EEMs for individual furnaces are modelled in the module "processes", the module on furnaces simulates price-based substitution between energy carriers using a methodology similar to that described by Kesicki und Yanagisawa (2015).

Steam systems: the remaining process heat (<500°C) is used in steam systems throughout most sub-sectors. The module comprises both the distribution of steam and hot water, as well as its generation. As very little information is available about the performance of existing steam distribution systems, based on available literature we assume exogenous efficiency improvements for each scenario. Steam generation is included in the optimisation of central heat and power generation to allow the interdependencies between the two sectors to be captured. This link allows the benefits of electricity from CHP generation and power-to-heat to be examined as a way of using electricity in times of high wind and solar generation.

All modules described above take into account the 14 individual sub-sectors. The FORECAST model is based on a hierarchical structure as shown in figure 12. 64 energy-intensive processes are considered and each is allocated to one sub-sector. CCTs are also considered by sub-sector as the share of electricity demand of the respective sub-sector. The energy demand of CCTs and processes can overlap. For example the electricity demand of the paper machine primarily comes from electric motors which provide mechanical energy. This is accounted for in the "paper" process, as well as in the individual CCTs such as pumps, machine tools and other electric motors. Both present a different perspective on the same demand. EEMs are also considered in processes. They include EEMs related to the process characteristics and those EEMs that are of a horizontal nature, such as replacing electric motors. Energy demand of processes and CCTs changes when EEMs diffuse through the technology stock.

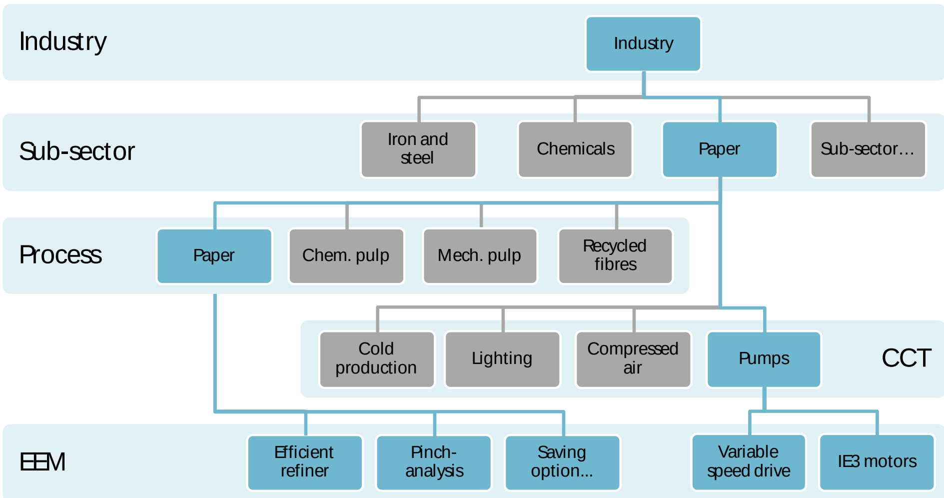


Figure 12: Hierarchical structure of the FORECAST-Industry model for process technologies and cross-cutting technologies (CCTs)

Source: Fraunhofer ISI

3.2.2 Model extensions

While the model FORECAST-Industry has been applied for similar research questions (mostly focussing on energy efficiency), main methodological challenges that require extensions of the existing model/data basis are:

- Price-sensitive modelling of fuel switch in industrial furnaces (and technical restrictions)

- Use of CCS including the modelling of the spatial distribution of CO2-emission

In the following parts, we describe the model extensions and the key methodological aspects, approaches and new developments.

Price-sensitive modelling of fuel switch in industrial furnaces (and technical restrictions)

The first part of the planned model extension consists of a price-sensitive modelling of fuel switch in industrial furnaces.

Inter-fuel substitution is, next to energy efficiency, one of the major options to mitigate climate impact and increase security of supply in industrial energy use. The choice of fuel type is not only a matter of price but of the technology (e.g. type of furnace) it is used in, as well as structural circumstances. Energy demand models that do not address these dependencies may overestimate inter-fuel substitution potentials. In this model extenuation we will include an approach to apply a discrete choice model to industrial high temperature energy demand by integrating technological bottom-up and economic top-down data.

The model will be based on a logit-approach of a random utility methodology considering a variety of different influences (e.g. energy carrier price, CO2-price, price related energy carrier preferences).

Use of CCS including the modelling of the spatial distribution of CO2-emission

Besides the extension of the price-sensitive modelling of fuel switch in a first step a spatial distributed CO2-emission modelling will be included into the FORECAST-Industry. FORECAST-Industry results will be used to generate downstream a spatial resolution of CO2-emissions, which generates differentiated conclusions about the individual units. This approach is implemented as a two-step-process:

(i) the national demand and emissions are calculated based on the existing version of FORECAST-Industry and

(ii) a specific allocation of the total national CO2-emissions to individual installations is estimated by applying specific distribution keys (e.g. production capacity, technological plant characteristics). The individual installations are geo-referenced.

Distribution keys in energy intensive industry could be for example specific energy demand per process, gross value added by subsector, locations, production capacity, and emissions. The data input for this spatial distribution is based on different commercial and public available databases (e.g. Cembureau, Plantfacts, E-PRTR), which represents the numerical framework for the modelling. In terms of methodology, sectoral distribution keys are applied to split CO2-emissions in FORECAST-Industry into further units (e.g. per site, NUTS 1).

In a next step, based on these e.g. site-specific total CO2-emissions, a technical potential of CCS captured CO2-emissions will be identified in FORECAST-Industry for each unit allowing for a further differentiation of CO2-emissions into "potentially captured" and "released" CO2-emissions. This information is then transferred to CCTS-Mod which will play back information on storage location and costs to FORECAST-Industry.

3.2.3 Model linkages

Case study 5.3 aims at developing quantitative pathways to show ways to a low carbon industry sector. For this purpose, the FORECAST-Industry model is linked with the Enertile, the EMPIRE, the RAMONA and the CCTS-Mod models as described in chapter 2.2. In a nutshell, FORECAST-Industry assesses the development of final energy demand from industry which changes energy prices calculated with the help of Enertile, EMPIRE and in the end again final energy consumption simulated by FORECAST-Industry again. So, case study 5.3 is based on a closed feedback loop between the mentioned energy demand and supply simulation models.

Besides case study 5.3 FORECAST-Industry will not be run, but model results will be used by CCTS-Mod case study 6.4. In other case studies FORECAST-Industry will not be directly used and industrial demand scenarios will be based on the PRIMES Reference Scenario.

In the overall scenario assessment WP9 the FORECAST-Industry model will be used to provide final energy demand of the industrial sector. The model linkages for the overall scenario assessment in WP9 resemble the ones illustrated for case study 5.3 (see chapter 2.2).

3.3 CCTSMOD

3.3.1 Model description

CCTSMOD is a scalable, mixed integer, multi-period, welfare optimizing network model for Europe. The CO_2 producing facilities within the model set either have to decide whether to release CO_2 into the atmosphere or store it with CCTS technology. The decision is based on the price of CO_2 certificates and the investment required for the capture unit, the pipeline and the storage facilities, and the variable costs of using CCTS infrastructure (see figure 13). Furthermore, capture, flow and injection quantities based on given costs, storage capacities, and point source emissions are taken into consideration. Illustrates the decision path of CCTSMOD based on the CO_2 disposal chain when using the CCTS technology.

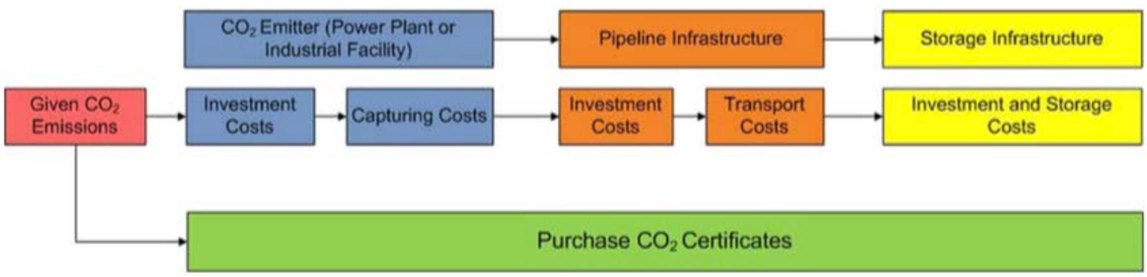


Figure 13: Decision tree in the CO_2 disposal chain of the CCTSMOD.

A single omniscient and rational decision-maker has perfect foresight and makes all investment and operational decisions. Under these simplifying assumptions, the model runs on a single cost minimization. This decision process is adapted in the SET-Nav project as described in 3.3.3.

CCTSMOD includes industry facilities, from the iron and steel production, the cement and clinker production, as well as oil refineries. Furthermore, waste-, natural gas-, lignite-, and coal-fueled power plants that emit more than 100,000 t CO_2 per year are included. Pipeline transportation is considered to be the only economically viable onshore transportation solution that can carry such large quantities and is characterized by high upfront, sunk investment costs. Potential storage capacities are aggregated on a 50 x 50 km grid. Therefore some facilities might consist of several small neighbouring storages.

CCTSMOD can give information about the specific needs for CCTS infrastructure in Europe and how the degree of technology deployment, storage availability and cooperation between different sites influences the installation of CCTS. The main objective of a detailed assessment of Carbon Capture, Transport and Storage is to examine the role of the technology in the electricity and the industrial sector in a future European energy system.

3.3.2 Model extensions

In comparison to previous versions of CCTSMOD the database was updated. The most recent constructed and decommissioned facilities are taken into account.

3.3.3 Model linkages

The existing CCTSMOD will be linked to the FORECAST-Industry model. FORECAST-Industry will report resulting CO_2 emissions from industrial processes. Therefore the decision on whether to invest in CCTS technology as illustrated above is outsourced from CCTSMOD. Furthermore, the quantity of captured emissions by CCS operations is given and an input for CCTSMOD. These emission values still have to be disaggregated to a nodal level. CCTSMOD provides a high level of technical detail and can be used to distribute the given emissions location-sharp in a cost optimal way on facilities, taking into account economies of scale, storage locations, and the restrictions for pipelines and storages. Calculated costs for CO_2 transport and storage will be fed back to the FORECAST-Industry model to harmonize investment into CCTS technologies and resulting CO_2 balances.

3.4 ASTRA

ASTRA (ASsessment of TRAnsport Strategies) is an integrated assessment model applied since more than 18 years for strategic policy assessment in the transport and energy field. It covers so far all EU27 member states (excluding Croatia) plus Norway and Switzerland. The model is based on the System Dynamics approach and built in Vensim®. A strong feature of ASTRA is the ability to simulate and test integrated policy packages and to provide indicators for the indirect effects of transport on the economic system. The ASTRA model covers the time period from 1995 until 2050. Results in terms of main indicators are available on an annual basis via a user interface. ASTRA consists of six different modules, each related to one specific aspect, such as the economy, the transport demand, the vehicle fleet. The main modules cover the following aspects:

- Population and social structure (demographic structure and income groups)
- Economy (including input-output tables, government, employment and demand side)
- Foreign trade (within Europe and to regions in the rest of the world
- Transport (including demand estimation, modal split, transport cost and infrastructure networks)
- Vehicle fleet (covering detailed stock models for road modes)
- Environment (including air pollutant emissions, CO_2 emissions, fuel and energy consumption, accidents)

A key feature of ASTRA as an integrated assessment model is that the modules are linked together. An overview on the modules and their main linkages is presented in the following diagram.

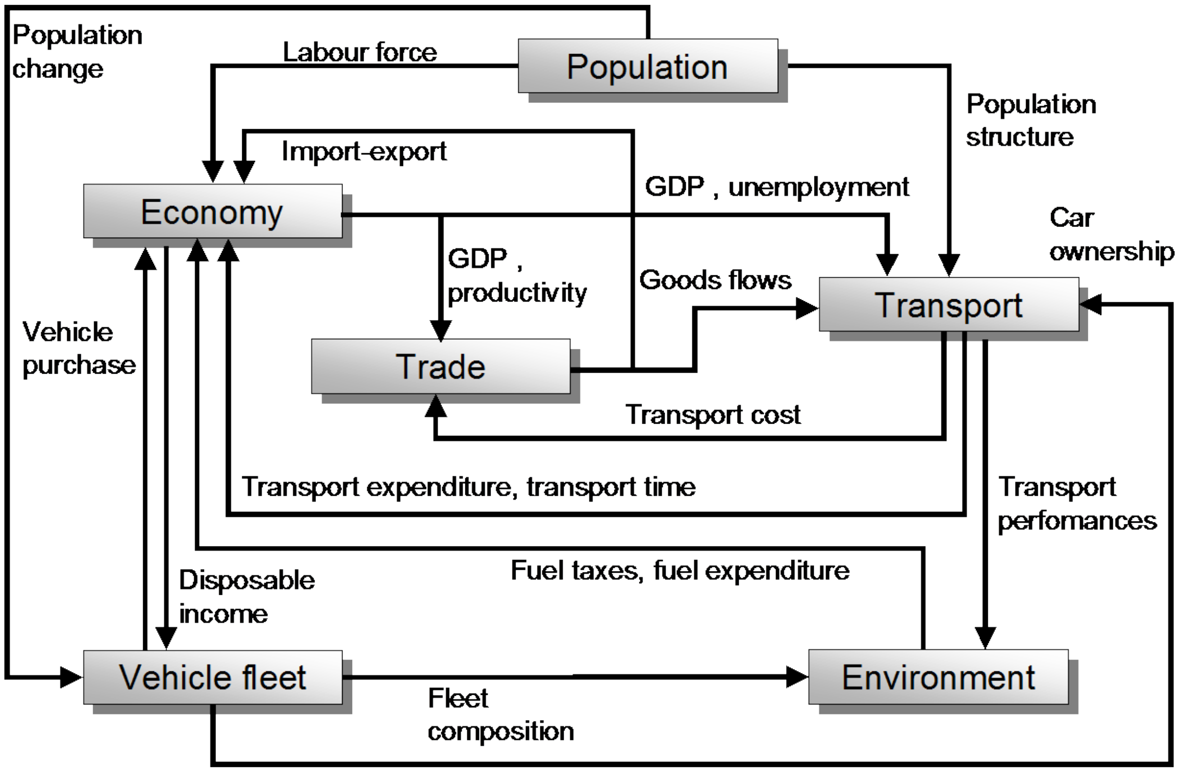


Figure 14: **Overview structure of ASTRA**

Role in SET-Nav

Three ASTRA modules will be mainly tackeled by the proposed SET-Nav approach: economy, transport and vehicle fleet. ASTRA will contribute by integrating the economic bottom-up impulses from other energy sector models as well as from the internally simulated transport sector impulses and by assessing the economic impacts induced by the impulses for each pathway selected. The economic module is relevant for the tasks in WP8 but plays a significant role as well for the transport sector and therefore for WP5. The demand for freight transport is by definition driven by economic activities on domestic territories and by foreign trade between European countries. Therefore, the simulation of economic development under the impulses of selected decarbonisation pathways in SET-Nav is crucial.

The economic module in ASTRA provides the national economic framework, which imbeds the other modules. It cannot be categorised explicitly into one economic category of models for instance a neoclassical model. Instead it incorporates neo-classical elements like production functions. Keynesian elements are considered like the dependency of investments on national income extended by some further influences on investments like exports or government debt. Elements of endogenous growth theory are incorporated like the implementation of endogenous technical progress as one important driver for the long-term economic development. Six major elements constitute the functionality of the economic module. The first is the sectoral interchange model that reflects the economic interactions between 25 economic sectors of the national economies (adapted NACE categorisation). Demand-supply interactions are considered by the second and third element. The second element, the demand side model depicts the four major components of final demand: consumption, investments, exports-imports and the government consumption. The supply side model reflects influences of three production factors: capital stock, labour and natural resources as well as the influence of technological progress that is modelled as total factor productivity. Endogenised total factor productivity depends on investments, freight transport times and labour productivity changes. Fourth element of the ASTRA economic module is constituted by the employment model that is based on value-added as output from input-output table calculations and labour productivity. Employment is differentiated into full-time equivalent employment and total employment to be able to reflect the growing importance of part-time employment. In combination with the population module unemployment could be estimated. Fifth element of the economic module describes government behaviour. As far as possible government revenues and expenditures are differentiated into categories that can be modelled endogenously by ASTRA and one category covering other revenues respectively other expenditures. Categories that are endogenised comprise VAT and fuel tax revenues, direct taxes, import taxes, social contributions and revenues of transport charges on the revenue side as well as unemployment payments, transfers to retired and children, transport investments, interest payments for government debt and government consumption on the expenditure side. Sixth and final of the elements constituting the economic module are the micro-macro bridges. These link micro- and macro-level models, for instance the transport module or the vehicle fleet module to components of the macroeconomics module.

The calculation of changes in final energy consumption for different energy carriers relevant for the transport sector and the impacts on flexibility in the overall energy system today and in the future is the main purpose of applying ASTRA in SET-Nav. The model development foreseen in SET-Nav will be based on the most recent version of ASTRA (ASTRA-EC). Detailed descriptions of the ASTRA model are provided by Fermi et al. (2014), Krail (2009) and Schade (2005). In order to simulate the final energy consumption for transport-related activities, the model needs to simulate first the requested technical transition of vehicle fleets for all transport modes from fossil fuels towards renewable energy carriers. The existing road vehicle fleet modules in ASTRA consist of a classical stock and flow model accounting the vehicle stock per age, emission standard and fuel technology. New registrations are driven by demographic development, by change of income, of fuel and of car prices. The approach for simulating the diffusion of alternative fuel vehicles is based on a calculation of total cost of ownership. On top, the simulation considers the impact of filling/charging station network density in combination with average ranges of vehicles depending on the type of fuel. Depending on the mode, ASTRA will consider the key alternative fuel technologies that are feasible according to the characteristics. More simplified modelling approaches exist for the other road modes (passenger cars, busses, light duty vehicles and heavy duty vehicles). Non-road modes are not represented so far via stock models, such that the technical development for these modes is only reflected via changing CO_2 and air pollutant emission factors over time.

The second major step for assessing the impacts of the transition towards renewable energy carriers for transport is developed by linking the changing costs per vehicle-km driving the transport performance in the passenger and freight transport model. Transport cost changes are supposed to influence in the state-of-the-art four stage transport model applied in ASTRA the distribution of trips and freight volumes but also the modal shift. Especially the shift towards electrified road transport bears some changes in the behaviour of users which needs to be elaborated on in SET-Nav.

Finally, the resulting transport performance in terms of vehicle-km per mode needs to be split into the set of existing fuel technologies with reasonable assumption of average annual mileages. This is then the baseline for the assessment of direct (tank-to-wheel) and indirect (well-to-tank) GHG emissions (in $CO_{2eq.}$), air pollutant emissions (NO_x, CO, VOC and $PM_{2.5}$) per mode and per fuel technology as well as the measurement of final energy consumption per energy carrier.

Besides the assessment of transport and transport technology development for the different pathways, an interface is planned to provide input from other energy-related bottom-up models in SET-Nav to the economic module. Exogenous drivers like changing investment patterns or changing consumption of energy by private households and the industry will then be used to estimate the changes of major macro-economic indicators like GDP and (net) employment on a member state level.

3.4.1 Model extensions

Spatial coverage

Since the last model update of ASTRA in 2013, Croatia acceded the European Union. Previously, the ASTRA model covered all EU27 member states plus Norway and Switzerland. Hence, the first part of the planned model extension consists of adding Croatia as 28th EU member state. This does not require changing the general ASTRA model structure. Therefore, the major work as regards model implementation consists of collecting and adapting the requested data inputs for Croatia in all ASTRA modules. Eurostat and European data sources like EU Transport in Figures will be the major data sources for this model extension.

Vehicle fleet technology

Besides the extension of the spatial coverage two structural changes are envisaged in SET-Nav to allow simulating decarbonisation pathways. The first structural change consists in the update of the Vehicle Fleet module (VFT). So far, the diffusion of alternative fuel vehicles is only implemented for passenger cars in ASTRA but alternative fuels are required in a less carbon intensive future transport sector as well for other road modes. Before estimating the speed of diffusion of alternative fuels a further segmentation of road modes is carried out. Passenger cars will be split into private and commercial cars. Commercial cars cover company car, car rental, taxi and car sharing fleets. The reason for distinguishing these two categories is mainly the different decision process. While the decision process of most commercial customers of passenger cars for a certain fuel option is based on a detailed calculation of total cost of ownership (TCO), the decision of private customers of passenger cars is not only driven by costs. Furthermore, range anxiety, safety issues, public trends and the image of a certain fuel option are driving the decision process as well.

Bus fleets will be differentiated into urban busses and long-distance coaches due to differing driving profiles and requirements. There are more fuel options for urban busses due to the lower daily mileages compared to coaches serving long distances. The same argument holds for heavy duty vehicles (HDV) such that there will be a split according to gross vehicle weight into four truck categories: trucks between 3.5 and 12 tons, between 12 and 26 tons, between 26 and 32 tons and between 32 and 44 tons. The last category covers all semitrailer-trucks and trucks plus trailer combinations. Light commercial or light duty vehicles (LDVs) up to 3.5 tons gross vehicle weight will be modelled separately from HDVs because this vehicle category contains pure freight vehicles driven by freight demand and vehicles mainly used by craftsmen or construction companies.

As opposed to private passenger cars, new registrations of all other categories of road vehicles are supposed to be driven by the development of the respective transport performance. The Freight Transport module in ASTRA calculates annual ton-km and vehicle-km per mode for each country on four distance bands (local up to 50 km, regional up to 200 km, national and international). This split allows for estimating the demand for each LDV and HDV vehicle category. While the demand for new LDVs and trucks up to 26 tons gross vehicle weight is expected to be driven mainly by local and regional freight transport, national and international long distance freight transport is almost exclusively served by semi-trailer trucks and truck and trailer combinations between 32 and 44 tons gross vehicle weight. The approach chosen for ASTRA will then estimate the requested number of vehicles to serve the freight demand for the specific vehicle category by dividing the total annual vehicle-km by the average annual mileage of the specific vehicle category. Average values for annual mileages per vehicle segment are extracted from available mobility and freight surveys from different European countries (e.g. the German KID). The difference between the requested minimum number of vehicles to serve the freight demand and the current stock of vehicles will then be fed into the stock in terms of new registered vehicles. The demand for light duty vehicles will be fed by freight transport performance and by the economic development of the construction sector in the Economic module of ASTRA. The latter shall represent the growing number of craftsmen and construction companies resulting in demand for new LDVs.

A similar approach like the one for trucks exists for urban busses and long-distance coaches which is based on annual passenger-km and vehicle-km by bus on different distance bands computed in the Passenger Transport module of ASTRA.

New registrations per vehicle category are split into fuel options for each road vehicle category. This split will be calculated in separate diffusion models to be implemented for each road vehicle category in ASTRA. According to the technical characteristics of available fuel options today and in the future and the heterogeneous requirements of the different users of road vehicles, a set of fuel options is preselected for each road mode (see following figure). The probability of the choice of a certain fuel option for each mode will be estimated with a discrete choice approach using logit functions. The diffusion models in ASTRA will quantify the total costs per vehicle-km for each preselected fuel option. These costs cover fuel costs (pure fuel costs plus fuel taxes and VAT), annual vehicle and registration taxes, road charges, maintenance costs and discounted average investment costs per vehicle category. Filling and charging station infrastructure will be considered as well in the estimation of the fuel choice for each road vehicle category. Therefore, an approach from Krail (2016) is chosen which incorporates so-called fuel or energy procurement costs based on the density of the filling or charging station infrastructure for each country and the average range per charge or filling.

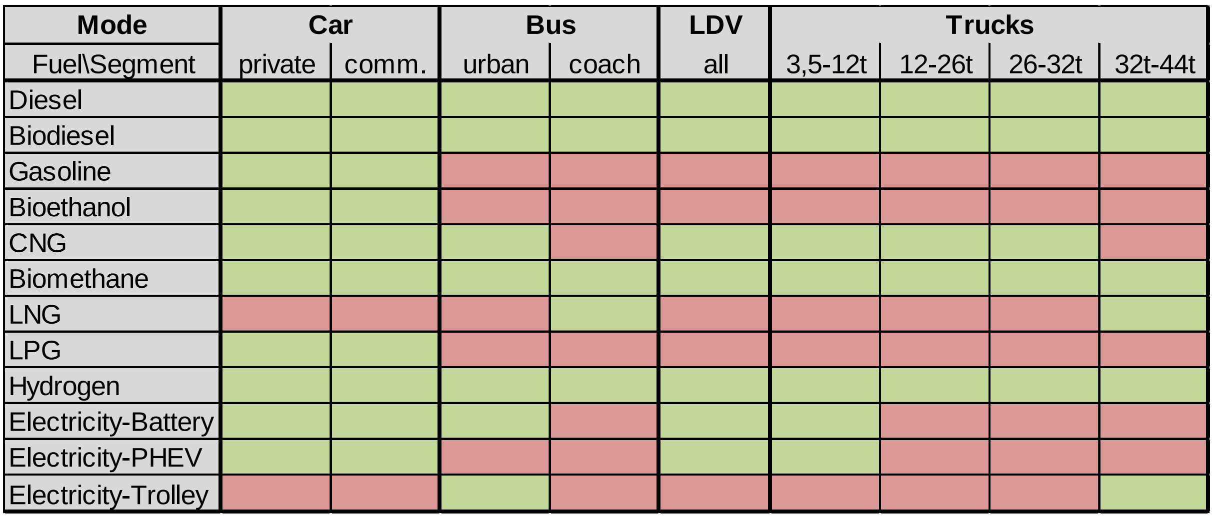


Figure 15: Segmentation of vehicles and differentiation of fuels for road vehicles in ASTRA

Within the new vehicle fleet model there will be a feedback between the ASTRA and the ALTER-MOTIVE model. ALTER-MOTIVE will simulate the technical development of alternative fuel vehicles providing

ASTRA inputs like the development of average range of battery electric, plug-in hybrid electric and fuel cell electric vehicles. ASTRA uses this input to estimate the diffusion of these cars into the vehicle fleets per vehicle category and member state.

Another extension of the road vehicle fleet models in ASTRA is the addition of learning curves. Learning curves will be implemented to simulate the impacts of learning and economies of scale on the manufacturing costs of vehicles for each fuel technology. Learning rates representing the cost decline of a technology per cumulated sales numbers will be fed into the model and will be linked with the endogenously calculated accumulated number of sales. While ASTRA can only model the demand per technology for the European market, the cost decline depends on global sales. Therefore, the global sales per technology will be estimated based on a simplified approach assuming that the European market will be a First Mover market for low-carbon fuel technologies that will be followed with a certain delay in all other major vehicle markets.

Non-road vehicle fleets like inland waterways, maritime ships, air planes and railways will not be modelled as detailed as for road vehicles. One of the reasons for this is that statistics with stock data in the requested level of detail is hard to find. In the case of maritime ships, the additional difficulty consists in the assignment towards EU member states. For all non-road vehicles holds that average lifetimes are between 30 and 50 years and that due to the size of the vehicles and the high energy consumption, only few renewable fuel options are even imaginable. For ships, LNG is the only fuel option foreseeable today. As for planes and for the time horizon until 2050, only kerosene and blended kerosene with biofuels are potential fuel options. And in the case of railways, the direct use of electricity is by far already the most efficient energy option. Therefore, non-road vehicle fleets are treated differently with less detailed approaches. As for railways, the increasing share of electrified traction will be considered. For maritime ships and inland waterways, increasing shares of diesel blended with biodiesel and of LNG are options that can be simulated with ASTRA.

Transport system

The third major model development planned for ASTRA to meet the requirements of SET-Nav is the improvement of the Passenger Transport module. So far, ASTRA does not consider new mobility concepts like carsharing as separate passenger transport mode. Since the numbers of carsharing users grew rapidly in many EU member states within the last ten years, it should be considered as the so-called fifth mode. For this purpose, the passenger modal split needs to be extended by the new mode. This requires a detailed user cost model for carsharing in order to calculate average user prices based on the technical characteristics of the carsharing fleets. As a bridge towards the Vehicle Fleet module, the passenger transport demand for carsharing will be fed back as a driver for new registrations of commercial car fleets.

Carsharing as a new mobility concept can play a significant role on the way towards a decarbonised transport system for several reasons. In general mobility behaviour and mode choice depends on travel costs travel and time. As for private passenger cars, the relevant costs for the decision are according to the transport modelling theory so-called perceived costs. Perceived costs only cover fuel costs and therefore by far not the total cost of ownership. Therefore, high car-ownership levels always lead to high car modal shares. With increasing level of service of carsharing, the probability increases that private car owners will not replace their old car by purchasing a new and chose carsharing. As carsharing services are offered under total costs of ownership, the economic competitiveness between modes increases and a potential shift towards electrified public transport modes grows. A second positive effect of carsharing is the more effective use of cars such that average lifetimes of carsharing cars are only few years which allow for faster diffusion of energy-efficient or alternative fuel cars. On top, the average carsharing fleets are dominated by small cars which lead to a third advantage in terms of energy consumption.

In order to implement carsharing as fifth mode, a comprehensive collection of data on user numbers, carsharing car stocks, average annual mileages and user costs is required in order to calibrate the new passenger transport demand model. Unfortunately, neither Eurostat nor any national statistics offer data on carsharing such that the data needs to be developed analysing European mobility surveys covering carsharing activities.

3.4.2 Model linkages

Case study 5.4 aims at developing quantitative pathways to show ways to a cleaner and smarter transport system. For this purpose, the ASTRA model is linked with the ALTER-MOTIVE, the eLOAD, the Enertile, the EMPIRE and the FORECAST macro model as described in chapter 2.3. In a nutshell, ASTRA assesses the development of final energy demand from transport which changes energy prices calculated with the help of Enertile, EMPIRE and FORECAST macro which then change the diffusion of alternative fuel vehicles, of transport performance and in the end again final energy consumption simulated by ASTRA again. So, case study 5.4 is based on a closed feedback loop between the mentioned energy demand and supply simulation models.

Besides case study 5.4 ASTRA will not be run nor model results will be used by other models in other case studies. In case that this is required in other case studies, transport demand scenarios will be based on the PRIMES Reference Scenario.

In the overall scenario assessment WP9 the ASTRA model will be used to provide final energy demand of the transport sector and to analyse flexibility options between the energy supply and the transport demand sector. The model linkages for the overall scenario assessment in WP9 resemble the ones illustrated for case study 5.4 (see chapter 2.3). On top, ASTRA receives as input for the macro-economic impact assessment the delta between additional and avoided investments in energy technologies, the resulting delta of energy consumption for private households and companies from Invert/EE-Lab and FORECAST and supply models used in SET-Nav.

3.5 E-Load

3.5.1 Model description

The eLOAD (electricity LOad curve ADjustment) model aims to estimate the long-term evolution of electricity system load curves on a national level. Based on appliance specific hourly load profiles and annual demand projections from the demand models eLOAD assesses the transformation of the load curve due to structural changes on the demand side and the introduction of new appliances. Analysing the future shape of the load curve gives insights into the development of peak load, load levels and load ramp rates that are required for investment decisions about new electricity generation capacity and grid infrastructure.

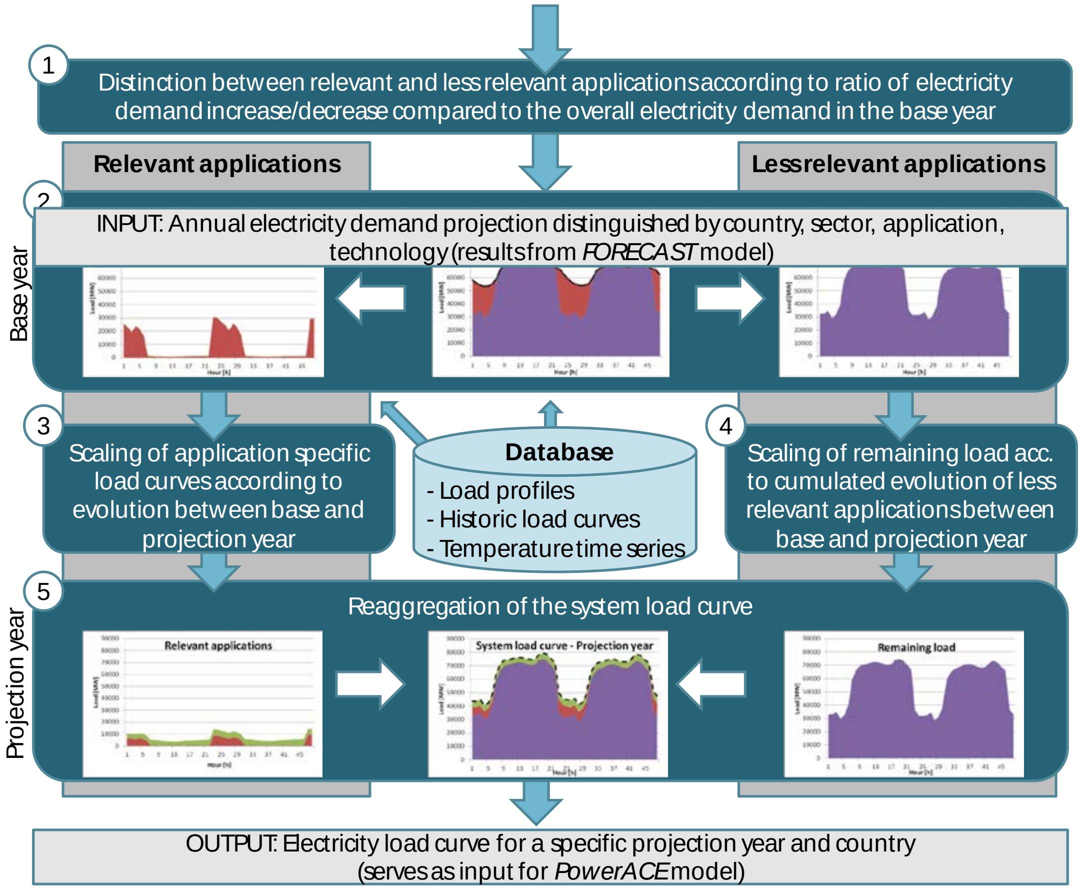


Figure 16: Structure of the eLOAD model for load curve projection

eLOAD aims to estimate the future shape of the national electricity system load curves. It is available for all countries of the EU28 until the year 2050. The model addresses the deformation of the load curve due to structural changes on the demand side and the introduction of new appliances (such as electric vehicles) by applying a partial decomposition approach. The technology specific annual demand projection from the demand models serves for the identification of all "relevant appliances" that feature a significant increase or decrease in electricity consumption over the projection horizon. By using appliance specific load profiles, a load curve can be generated for all relevant appliances for the base year, according to the respective annual demand in the base year. These load curves are deduced from the system load curve of the base year. The resulting remaining load curve and the appliance specific load curves are then scaled for all projection years according to the demand evolution. Reassembling the scaled remaining load and the scaled load curves give the load curve of the projection year.

By using this approach of partial decomposition, characteristic outliers and irregularities can be conserved in the load curve while the general shape of the load curve is adjusted according to the changes on the demand side. Figure 16 shows the structure of the eLOAD model for load curve projection.

3.5.2 Model extensions

In comparison to previous versions of eLOAD the database will be updated. This includes the implementation of a base weather year which is consistent with the other models used within the case studies and across the SET-Nav project. The parameters which define the load curves for water heating, space heating and space cooling will be adjusted for each EU28 member state.

3.5.3 Model linkages

Relevant in all case studies within WP5, eLOAD will transform the annual electricity demand data received from the sector-specific energy demand models into hourly load profiles which are then used as input for the power market models (see case study descriptions). As in the case of INVERT/EE-Lab, FORECAST and ASTRA, eLOAD is part of the closed feedback loop between the energy demand and supply simulation models.

Besides the case studies of WP5 eLOAD will not be run and model results from eLOAD will not be directly used in case studies from other WPs. In the overall scenario assessment (WP9) the eLOAD model will be used to serve as a link between demand and supply and provide hourly load curves. The model linkages for the overall scenario assessment in WP9 resemble the ones illustrated for WP5.

3.6 Enertile

Enertile optimization is an energy system optimization model developed at the Fraunhofer Institute for System and Innovation Research ISI. The model focuses on the power sector, but also covers the interdependencies with other sectors, especially heating/cooling and the transport sector. It is used mostly for long-term scenario studies and is explicitly designed to depict the challenges and opportunities of increasing shares of renewable energies. A major advantage of the model is its high technical and temporal resolution.

Integrated optimization of investments and dispatch

Enertile optimizes the investments into all major infrastructures of the power sector, including conventional power generation, combined-heat-and-power (CHP), renewable power technologies, cross-border transmission grids, flexibility options, such demand-side-management (DSM) and power-to-heat storage technologies. The model chooses the optimal portfolio of technologies while determining the utilization of these in all hours of each analysed year.

High spatial coverage

The model currently depicts and optimizes Europe, North Africa and the Middle East. Each country is usually represented by one node, although in some cases it is useful to aggregate smaller countries and split larger ones into several regions. Covering such a large region instead of single countries becomes increasingly necessary with high shares of renewable energy, as exchanging electricity between different weather regions is a central flexibility option.

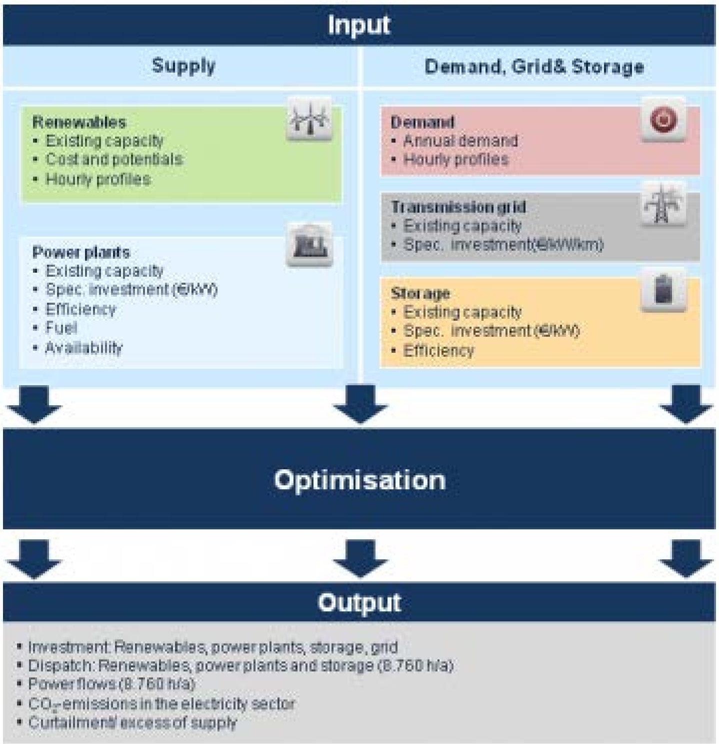


Figure 17: Simplified structure of the model.

High temporal resolution

The model features a full hourly resolution: In each analysed year 8,760 hours are covered. Since real weather data is applied, the interdependencies between weather regions and renewable technologies are implicitly included.

Detailed picture of renewable energy potential and generation profiles

The potential sites for renewable energy are calculated on the basis of several hundred thousand regional data points for wind and solar technologies with consideration of distance regulations and protected areas. The hourly generation profile is based on detailed regional weather data.

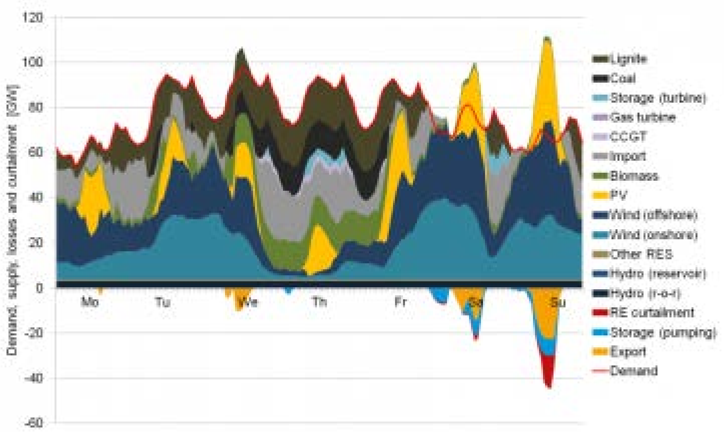


Figure 18 Example of the hourly matching of supply and demand.

The involvement of Enertile in different work packages is shown in Table 2. The role in work package 6 is highlighted and focuses on the expansion and operation of the electricity system.

Table 2: Involvement of Enertile in SET-Nav

Work Package	Case Study	Role of Enertile
WP5	Energy demand and supply in buildings and the role for RES market integration	Analysis of power to heat and combined heat and power options and its impact on the electricity system, quantification of benefits from demand response options in buildings
	The contribution of innovative technologies to decarbonise industrial process heat	Analysis of power to heat and combined heat and power options for industrial process heat focussing on the impact on the electricity system, quantification of benefits from demand response options in industry
	Ways to a cleaner and smarter transport sector	Provide bottom-up impulses for electricity price developments, analysis of the impact of additional electricity demand in the transport sector for the electricity system
WP6/WP7	Decentralised vs. centralised development of the electricity sector - Impact on the transmission grid	
WP7	Diffusion rate of renewable electricity generation	

3.6.1 Model extensions

Enertile has a strong focus on the electricity sector, based on its nature as an optimization model for the electricity sector in Europe and neighbouring regions. The integration of rising shares of renewable electricity in the electricity sector is a crucial task for the next decades. On one hand this can be addressed by additional flexibility within the electricity sector, on the other hand, a stronger linkage to other sectors could help to integrate renewable electricity. Within the SET-Nav project, Enertile was expanded by different modules to integrate demands and flexibilities from the heating and the transport sector.

3.6.1.1 Flexibility module

In the developed flexibility module different flexibilities from different sectors can be covered. Flexibility options are characterised by an annual demand and a load profile as well as a maximum capacity that can be capped (load shedding) or shifted (load shifting). In the optimisation of the electricity sector these flexibilities can be used within one country as well as other countries taking into account transport capacities.

Flexibilities can be covered in higher technical detail for special applications. One important bottleneck in modelling flexibility is data availability on the technical level and computational capacities in the optimisation. For the building sector and the transport sector two technology specific modules where developed and tested for the case of Germany. These options were selected for their high total potential and relatively low costs.

3.6.1.2 Flexibility in the heating sector – Test Case Germany

Within the heating sector heat pumps, as well as combined heat and power plants and electric heater in heat grids can be covered as flexibility options.

Decentralised heat pumps

For decentralised heat pumps and for heat grids an hourly heat demand profile is used as a basis. The flexibility is provided by the use of a heat storage representing storage capacity of the building as well as a hot water storage integrated in the heating system. The hourly operation of the heat pump is integrated in the overall optimisation problem and takes into account changing efficiencies of the heat pump during the year, heat losses of the heat storages as well as impacts on the electricity system as the possible use of excess renewable electricity generation or costs of electricity generation during high electricity demand and low production of renewable electricity.

Bottlenecks for the use of the developed module are mainly calculation time and to some part also data availability.

Heat grids

For heat grids flexibility options can be even higher than for decentralised heat pumps, as often heat generation in district heating is covered by more than one energy carrier. Depending on heating technologies used in a heat grid, flexibility can be provided by a switch between different heating technologies (combined heat and power production, heating based on fuels, heating based on electricity) as well as the use of heat storages.

In the developed module, two types of heat grids are distinguished. District heating grids provide mainly heat for hot water and heating purposes in buildings and have a typical seasonal pattern in their heat demand. Industrial heat grids cover mainly demand for process heat on a higher temperature level (100 to 500 °C) with a less significant seasonal demand pattern.

Within the developed flexibility module for heat grids the operation as well as the installation of heating technologies - including power to heat facilities - and heat storages can be integrated in the optimisation problem. Depending on the level of detail and the number of regions that are covered, the calculation time for the optimisation problem can increase strongly. Therefore, an important bottleneck for the use of the developed module is calculation time. In case of heat grids data availability on heat grids, heat demand profiles and heating technologies in different countries is a crucial limitation.

3.6.1.3 Flexibility in the transport sector – Test Case Germany

Rising shares of electricity demand from the transport sector influence electricity demand and flexibility needs in the electricity sector. The additional electricity demand from the transport sector can be flexible taking into account the actual conditions in the electricity sector, assuming intelligent loading infrastructure and sufficient incentives to provide flexibility.

The load profile of the additional demand as well as the potential flexibility from the transport sector strongly depends on driving profiles and time slots for charge. For Germany, different driving profiles are available at Fraunhofer ISI and where combined to a driving profile that is used in the flexibility module for the transport sector. The profiles define at which time can be charged and at which times certain charging states are necessary; For example, many cars have to be charged in the morning to allow the commute to work. When they arrive in the evening, charging does not necessarily have to start immediately but can be postponed, if the owners are willing to participate in smart charging.

The applicability of the developed technology specific modules for the pathways as well as for the case studies itself depends on data availabilities and calculation resources and can only be determined during the case study iterations. In an overall view it is important to cover flexibility options at a similar level of detail for the whole region.

3.6.2 Model linkages

In work package 5 Enertile will be linked to the demand side models Invert/EE-Lab, Forecast and ASTRA. In other work packages Enertile will also be linked to the renewable policy model Green-X and the electricity grid model TEPES.

3.7 Empire

3.7.1 Model description

EMPIRE is a capacity expansion model for the European power system, formulated as a multi-horizon stochastic program. The objective is to minimize system cost of the European power system, including investment cost and expected operational costs, while satisfying the demand for electricity. This formulation is commonly used in energy system models to represent strategic and operational decision-making in a perfectly competitive market. The main function of EMPIRE is to assess cost-efficient decarbonization pathways for the European power sector, with a particular focus on the interplay between low carbon technologies with different characteristics such as solar PV, wind energy, carbon-capture and storage and nuclear power.

Spatial and temporal resolution

Most of the European countries represented in the ENTSO-E are included in EMPIRE, and each country is represented by a separate node in the transmission system model. Figure 19 (left) shows the geographical coverage and spatial detail used. Strategic decisions (e.g. investments) are considered in five-year time intervals, starting from 2020, until the model time horizon of 2050 (expansion this horizon is straightforward). For each strategic period, annual system operation is optimized, at an hourly resolution, using eight representative days split across four seasons. See Figure 19 (right) for a stylized illustration of the level temporal detail used in EMPIRE. In addition to the representative days EMPIRE includes six periods with a duration of five hours each where the system is put under high stress (high load periods). The main purpose of including high load periods is to account for those situations during a year where capacity may be scarce, which is important to consider for investments back-up technologies, usually identified by low-to-medium capital costs and high operational costs.

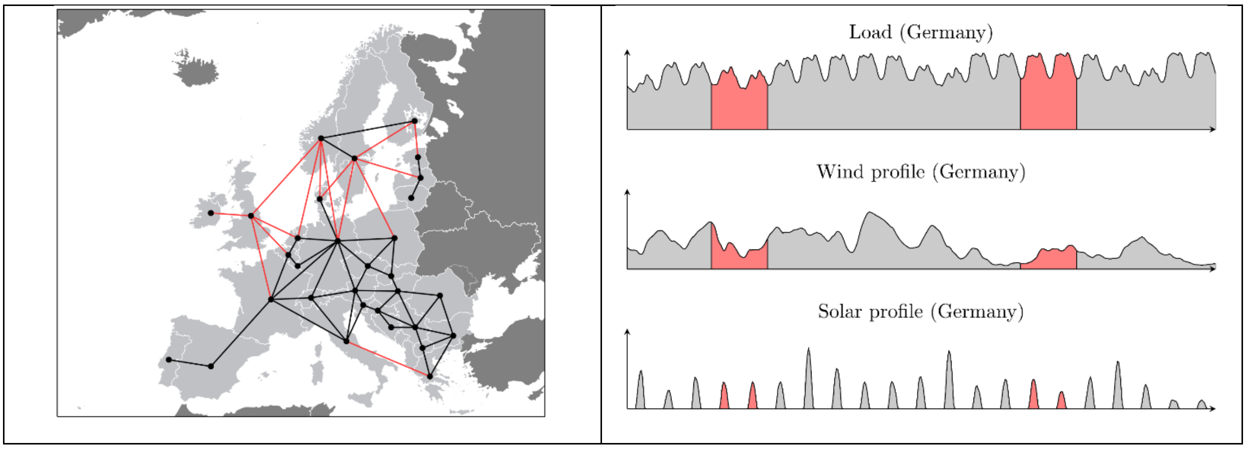


Figure 19: Left: EMPIRE geographical coverage. Black lines in this map indicate overhead lines while red lines indicate submarine cables. Right: Stylized illustration of the representative days modelling used in EMPIRE.

Technical modelling of generation, transmission and storage

EMPIRE incudes a total of 23 generation technologies with various characteristics. These technologies can broadly be grouped into three categories which have a particular technical implementation. These are: thermal power plants (nuclear, fossil generation, CCS, biomass), intermittent power generation (wind, solar, run-of-the-river hydro) and energy constrained generation (reservoir hydro). All technologies are modelled with a maximum capacity on their power generation output. The thermal generation in addition have fuel costs and technical constraints (e.g. ramping limits). The intermittent power generation are modelled using predefined production profiles, and energy constrained generation have a limit on total output over a time interval (to represent available energy stored in reservoirs). Within each category, the different technologies are distinguished through their technical specifications and costs.

The transmission infrastructure is modelled by cross-border interconnectors and national grids are not explicitly included. As a result, each country is modelled as a copper plate and internal grid bottlenecks are not considered. The flows in the network are computed using a transportation model, which means that loop-flows are not handled.

In addition to the generation and storage, EMPIRE model electricity storage. These are implemented with a charging unit (pump), discharging unit (generator) and an energy reservoir, all with their respective capacities. In the operation, the energy balance of the reservoir is respected, and losses are incurred in the charging/discharging process. In terms of investments in new storage there are two types of possibilities in EMPIRE, investment in energy storage units where the power and energy capacity ratio is given (typical for electro chemical batteries), and independent investments in power and energy capacity (possible for pump hydro storage).

Multi-horizon stochastic programming formulation

One of the key strengths of EMPIRE is the use of multi-horizon stochastic programming to design a system which is optimal over a wide range of annual operational conditions. By operational conditions we mean load profiles, wind and solar production profiles, and hydro reservoir inflow. It is difficult to predict the future outcomes of such parameters at the time strategic decisions are made, and therefore, taking several possible outcomes into consideration will make the strategic decisions more robust to alternative futures, and reduce the risk of sub-optimal performance.

At each strategic decision period several annual operations are optimized (parametrized using different operational conditions). As an underlying assumption we do not consider dependence between operational decisions in one year, and strategic and operational decisions in future years. As a result, the operational modelling in each strategic time-period is in a sense terminated, and thus represent a separate horizon in the full model (thereof the name multi-horizon). Figure 20 shows the structure of the multi-horizon stochastic programming formulation in EMPIRE. In this figure the following symbols are used:

- $\boldsymbol{x_i}$ - Strategic decisions (investments) in strategic period *i* (2020, 2025, 2035,…). *I* is the end of horizon, typically, 2050.
- $\boldsymbol{y_{i\omega}}$ - Collection of all operational decisions (dispatch, flows, etc.) in strategic period *i stochastic* scenario ω. The stochastic scenario represents different operating conditions (as previously discussed). *O* is used to denote the number of stochastic scenarios (usually around 10 scenarios are used).

All the strategic and operational decisions are co-optimized in a single optimization problem.

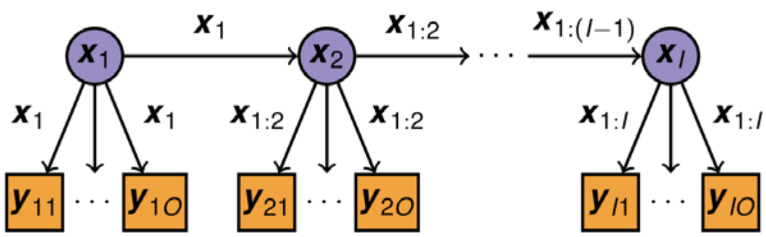


Figure 20: Multi-horizon stochastic programing structure in EMPIRE

3.7.2 Model extensions

3.7.2.1 Modelling of demand flexibility

We are implementing two types of demand side flexibility in EMPIRE, load shedding and load shifting. This involves

1. Technical implementation of the logic of the demand side flexibility measures
2. Parameterization of different forms of the demand side flexibility measures, which mostly involves data collection.
3. Implementation of investment logic for demand side flexibility measures.

Both load shedding and load shifting will be implemented as generic modules in EMPIRE. For load shedding this will be done by allowing an amount of the system load to not be served at certain cost. Different classes of load shedding will then be included, distinguished by the amount of load not served and cost. This will reflect the availability of load shedding in different demand sectors like residential, commercial, industry and transport. Load shifting will be implemented by setting an amount of load that can be moved within a limited time-frame. As with the load shedding measure, several classes will be included for load shifting to represent different sectors where this can be used.

A significant part of the work to include demand side flexibility measures in EMPIRE is to find good data on potentials and costs for the various classes used. Wherever available we will used data from the demand-side models in WP 5.

With demand side flexibility modelling in place EMPIRE can provide results such as:

1. Deployment of various types of the demand side flexibility measures
2. Cost-savings related to increased demand side flexibility
3. Utilization of different types of demand side flexibility

3.7.2.2 Representing interaction between the power sector and demand for heat

Currently, EMPIRE only considers the power sector, and all other linkages to other parts of the energy system are handled exogenously. With more combined heat-and-power (CHP) plants being deployed throughout Europe it is important to capture the link between the power sector and centralized heat production. A key target is therefore to implement a logic to endogenously handle investment and operation of CHP plants in EMPIRE. This will entail modelling of heat demand, the operational characteristics of CHP plants. In particular we aim to represent how CHP plants running in different modes (electrical/heat driven production) can provide, or require, flexibility to/from the power system.

3.7.3 Model linkages

In WP5 EMPIRE will be linked to Invert/EE-Lab, Forecast-Industry and ASTRA. These models will provide data on electricity demand in the building, industry and transport sectors, which will first be passed to the eLoad model to construct electricity load profiles that can subsequently be used in EMPIRE. From the Invert/EE-Lab model also data on flexibility potential will be passed to EMPIRE.

In other work packages EMPIRE is linked to the models TEPES (WP7), Nexus (WP7), CCTSMOD (WP6) and Green-X (WP7). EMPIRE will also be integrated with natural gas infrastructure model Ramona in WP7.

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5 Appendix

5.1 Data flow documentation case study 5.2 “Buildings”

5.1.1 Energy demand

This data flow contains final energy demand for space heating, cooling and hot water in buildings on Member State level. Hourly data is provided for electricity (for different corresponding heating, hot water and cooling technologies) in 3-4 building types. Final energy demand for all other energy carriers is provided as annual values.

We will discuss to which extent a further distinction between district heating types is possible taking into account the processing restrictions in Enertile and EMPIRE.

Catagory	Structure	Keys
Dataset key	from model	Invert/EE-Lab, E-Load
Dataset key	into model	Enertile, Empire, Analysis
Dataset key	Unique ScenarioID	xxxx
Dataset key	Sector	Building sector
Data keys	Perspective	Demand
Data keys	Supertype	residential, non-residential privat, non-residential public
Data keys	Type	Space heating, hot water, cooling, auxiliary
Data keys	Technology	heat pumps, electric direct heaters, wood log, wood chips, wood pellets,
Data keys	Subtechnology/Specification	building types
Data keys	Fuel	district heating, electricity, gas, oil, coal, biomass, solar thermal, ambient heat
Data keys	Parameter	final energy demand
Time Key	Year	2020, 2030, 2040, 2050
Time Key	Hour	0,1,2,…,8759 in UTC+1 or empty
Time Key	Country	MS-level
Data	Region	-
Data	Value	
Data	Unit	GWh

5.1.2 Capacities

Capacities of heating and cooling generation in buildings based on electricity.

Be aware: Capacities for space heating and hot water preparation must not be added, since a share of the system are combined boilers.

Catagory	Structure	Keys
Dataset key	from model	Invert/EE-Lab
Dataset key	into model	Enertile, Empire
Dataset key	Unique ScenarioID	xxxx
Dataset key	Sector	Building sector
Data keys	Perspective	Demand
Data keys	Supertype	-
Data keys	Type	Space heating, hot water, cooling, auxiliary
Data keys	Technology	heat pumps, electric direct heaters, wood log, wood chips, wood pellets,
Data keys	Subtechnology/Specification	building types
Data keys	Fuel	district heating, electricity, gas, oil, coal, biomass, solar thermal, ambient heat
Data keys	Parameter	installed capacities
Time Key	Year	2020, 2030, 2040, 2050
Time Key	Hour	-
Time Key	Country	MS-level
Data	Region	-
Data	Value	
Data	Unit	GW

5.1.3 Electricity generation

Relevant for the analysis of this case study is electricity generation from CHP and RES-E.

On-Site PV generation is covered in various models with different approaches; this data exchange will only occur for better understanding and for calibration purposes between the models Green-X, Invert/EE-Lab, Enertile and Empire. (Therefore, it is not explicitly listed below.)

We will discuss at a later stage whether a feedback from Enertile and Empire to Invert/EE-Lab regarding primary energy factors and renewable electricity and renewable district heating is possible This might make sense in order to properly take into account RES use obligations in the building sector.

Catagory	Structure	Keys
Dataset key	from model	Enertile, Empire
Dataset key	into model	Analysis
Dataset key	Unique ScenarioID	xxxx
Dataset key	Sector	Electricity, Heat
Data keys	Perspective	Power Generation
Data keys	Supertype	Generation
Data keys	Type	Renewables, Conventional, Demand, Storage Trading
Data keys	Technology	Wind, PV, Gas, Coal, Lignite, Demand, Pump storage, Export, Import,…
Data keys	Subtechnology/Specification	onshore, offshore, rooftop, open-field, GT, CCGT, CHP, ST, pump, genera-tion, Heat pump, el. Vehicle, DE_0, DE_1, FR_0…
Data keys	Fuel	
Data keys	Parameter	generated power, generated heat
Time Key	Year	2020, 2030, 2040, 2050
Time Key	Hour	empty for annual data, or 0,1,2,…,8759 in UTC+1
Time Key	Country	MS-level
Data	Region	-
Data	Value	
Data	Unit	GWh

5.1.4 Emissions

This dataflow contains all emissions (CO_2 equivalents) of power generation and heat supply.

Catagory	Structure	Keys
Dataset key	from model	Enertile, Empire, (Invert/EE-Lab)
Dataset key	into model	Analysis
Dataset key	Unique ScenarioID	xxxx
Dataset key	Sector	Electricity, Building sector
Data keys	Perspective	Power generation, demand
Data keys	Supertype	Emissions
Data keys	Type	CO2
Data keys	Technology	Renewables, Conventional, Storage, Trading, heat pumps, electric direct heaters, district heating, fuel oil boiler, gas boiler, coal boiler, biomass boiler, air conditioning, auxiliary energy demand
Data keys	Subtechnology/Specification	GT, CCGT, CHP, ST
Data keys	Fuel	Gas, Coal, Lignite, …
Data keys	Parameter	CO2-emissions, CO2-emission factor
Time Key	Year	2020, 2030, 2040, 2050
Time Key	Hour	-
Time Key	Country	MS-level
Data	Region	-
Data	Value	
Data	Unit	t CO2 equ

5.1.5 Prices

This data flow delivers feedback on wholesale electricity and gas prices from Enertile and Empire to Invert/EE-Lab (via Forecast Macro, see sheet retail prices).

Catagory	Structure	Keys
Dataset key	from model	Enertile, Empire
Dataset key	into model	Invert/EE-Lab (via Forecast Macro)
Dataset key	Unique ScenarioID	xxxx
Dataset key	Sector	Electricity, Gas
Data keys	Perspective	Power Generation, Gas market
Data keys	Supertype	price
Data keys	Type	
Data keys	Technology	
Data keys	Subtechnology/Specification	
Data keys	Fuel	electricity, natural gas
Data keys	Parameter	wholesale price
Time Key	Year	2020, 2030, 2040, 2050
Time Key	Hour	
Time Key	Country	MS-level
Data	Region	-
Data	Value	
Data	Unit	Euro2016/MWh

5.1.6 Costs

This data flow contains all annual cost (Investments, fuel costs, O&M where relevant[3]) of electricity generation and / or heat generation and considered efficiency measures (only renovation, not including: efficient new buildings) in the building sector

Catagory	Structure	Keys
Dataset key	from model	Enertile, Empire, Invert/EE-Lab,
Dataset key	into model	Analysis
Dataset key	Unique ScenarioID	xxxx
Dataset key	Sector	Building sector
Data keys	Perspective	Demand
Data keys	Supertype	residential, non-residential privat, non-residential public
Data keys	Type	Space heating, hot water, cooling, auxiliary
Data keys	Technology	heat pumps, electric direct heaters, wood log, wood chips, wood pellets,
Data keys	Subtechnology/Specification	
Data keys	Fuel	district heating, electricity, gas, oil, coal, biomass, solar thermal, ambient heat
Data keys	Parameter	investments, energy expenditures, subsidies
Time Key	Year	2020, 2030, 2040, 2050
Time Key	Hour	
Time Key	Country	MS-level
Data	Region	-
Data	Value	
Data	Unit	Euro2016

[3] O&M costs of heating systems are not explicitely covered since we estimate that the difference of O&M costs between the scenarios will not be significant.

5.1.7 Biomass potentials

This data flow contains biomass potentials available for (decentral) heat supply. Since Invert/EE-Lab does not cover all parts of the energy system, it needs to receive biomass potentials which are in line with overall transition pathways.

Catagory	Structure	Keys
Dataset key	from model	Green-X
Dataset key	into model	Invert/EE-Lab
Dataset key	Unique ScenarioID	xxxx
Dataset key	Sector	Building sector
Data keys	Perspective	Overall energy system
Data keys	Supertype	Ressource potential
Data keys	Type	decentral heating
Data keys	Technology	biomass
Data keys	Subtechnology/Specification	solid fuels
Data keys	Fuel	biomass
Data keys	Parameter	Potential
Time Key	Year	2020, 2030, 2040, 2050
Time Key	Hour	
Time Key	Country	MS-level
Data	Region	-
Data	Value	
Data	Unit	GWh

5.1.8 Load Shifting Potential

For 3-4 buildings types and different electricity driven heating, hot water and cooling technologies, load shifting potentials are indicated on an hourly basis (or at least distinguishing different periods/seasons).

Uptake of flexibility options is modelled in Enertile. Merit order of storage in buildings is not explicitly covered in this data exchange. Rather it is implicitly considered in the data delivery from Invert/EE-Lab to Enertile and Empire. The restrictions regarding controllable heat pumps and other technologies are taken into account by Invert/EE-Lab.

We will discuss at a later stage to which extent load shifting in district heating grids will also be delivered from Invert/EE-Lab to Enertile and Empire.

Catagory	Structure	Keys
Dataset key	from model	Invert/EE-Lab
Dataset key	into model	Enertile, Empire
Dataset key	Unique ScenarioID	xxxx
Dataset key	Sector	Building sector
Data keys	Perspective	Demand
Data keys	Supertype	Load shifting potential
Data keys	Type	space heating, hot water, cooling
Data keys	Technology	heat pumps, electric direct heaters, auxiliary
Data keys	Subtechnology/Specification	Building type X
Data keys	Fuel	Electricity
Data keys	Parameter	Load shifting potential
Time Key	Year	2020, 2030, 2040, 2050
Time Key	Hour	0,1,2,…,8759 in UTC+1
Time Key	Country	MS-level
Data	Region	-
Data	Value	
Data	Unit	GW

5.1.9 District heating grid losses

On MS-level (and maybe for some selected MSs distinguished into different district heating types or regions) district heating grid losses are provided.

Catagory	Structure	Keys
Dataset key	from model	Invert/EE-Lab
Dataset key	into model	Enertile, Empire
Dataset key	Unique ScenarioID	xxxx
Dataset key	Sector	Building sector
Data keys	Perspective	Demand
Data keys	Supertype	district heating
Data keys	Type	space heating, hot water, cooling
Data keys	Technology	
Data keys	Subtechnology/Specification	
Data keys	Fuel	district heating
Data keys	Parameter	grid loss
Time Key	Year	2020, 2030, 2040, 2050
Time Key	Hour	-
Time Key	Country	MS-level
Data	Region	-
Data	Value	
Data	Unit	%

5.2 Detailed documentation of data flows in case study 5.3 "Industry"

In a first step the techno-economic bottom-up model FORECAST-Industry will deliver annual energy demand for electricity and gas taking into account efficiency improvement, the shift between end-uses, new on-site technologies like e.g. CCS or other innovative processes to the market models ENERTILE and RAMONA. This link will be operationalized by the load profile and demand flexibility interface from case study 5.1. ENERTILE will then use the provided data to model endogenously the load shifting based on the key load profile scenarios and elasticity. Even though there will be a data flow in form of electricity prices and natural gas prices from ENERTILE and RAMONA to FORECAST-Industry, no iterative calculations will take place.

In addition FORECAST-Industry will deliver annual emissions for selected ETS-sectors (e.g. steel, cement, refineries (optional) to the carbon capture, transport, and storage infrastructure model CCTS-Mod for Europe from the DIW (link to case study 6.4), which then calculates the respective investment, transport and storage costs of the system. The capture and storage costs, storage locations, capture rates and market diffusion rates (costs) will be fed back to/harmonized with the industry model to develop a consistent emissions balance.

Data exchange flows will be defined in detail in the following section including a short description of the data as well as proposed data keys for the standardized data structure.

5.2.1 A - Standardized data

This first category of datasets ("Standardized data") contains data that is relevant for the pathway analysis and the energy balance or emission balance of the system. In the end this data should be part of a predefined data structure, which will be the same for all case studies.

Category	Structure	Level	Keys
Dataset key	Model	general[1]	FORE CAST, Enertile, RAMONA, CCTS-Mod
	Unique ScenarioID	general[1]	xxxx
	Output	specific for each data flow	
Data keys	Perspective	specific for each data flow	
	Supertype	specific for each data flow	
	Type	specific for each data flow	
	Subtype	specific for each data flow	
	Param/Fuel	specific for each data flow	
	subparam	specific for each data flow	
Time Key	Year	general	2050
	Hour	specific for each data flow	0,1,2,…,8759 in UTC+1 or empty
Geographical key	Country	general	
Data	Value		
	Unit	Specific for each data flow	

5.2.1.1 Final energy demand electricity

This dataflow contains all annual final energy demand data for electricity for a given country. This data has to follow two important rules. Firstly, energy that is put into the system (electricity demand by process) is always positive. It can be subdivided into the different branches of the industry sector and even further broken down to specific processes or technologies.

Category	Structure	Keys
Dataset key	from model	FORECAST-Industry
	into model	eLOAD, Enertile, Analysis
	Unique ScenarioID	xxxx
	Output/ Secondary Fuel	Electricity
Data keys	Perspective	Industry
	Supertype	Consumption
	Type	Consumption
	Subtype	Electricity
	Param/Fuel	Physical production
	subparam	EAF, BOF, Cement, Paper, Heat pumps, etc.
Time Key	Year	2050
	Hour	empty
Geographical key	Country	AT, DE, etc. (EU28)
	Region	-
Data	Value	
	Unit	TWh

5.2.1.2 Final energy demand natural gas

This dataflow contains all annual final energy demand data for natural gas for a given country. This data has to follow two important rules. Firstly, energy that is put into the system (electricity demand by process) is always positive. It can be subdivided into the different branches of the industry sector and even further broken down to specific processes or technologies.

Category	Structure	Keys
Dataset key	from model	FORECAST-Industry
	into model	RAMONA, Analysis
	Unique ScenarioID	xxxx
	Output/ Secondary Fuel	Natural gas
Data keys	Perspective	Industry
	Supertype	Consumption
	Type	Consumption
	Subtype	Natural gas
	Param/Fuel	Physical production
	subparam	EAF, BOF, Cement, Paper, Heat pumps, etc.
Time Key	Year	2050
	Hour	empty

Geographical key	Country	AT, DE, etc. (EU28)
	Region	-
Data	Value	
	Unit	TWh

5.2.1.3 Investments

This dataflow contains all investments into new or more efficient technologies (e.g. in the steel or cement sector).

Category	**Structure**	**Keys**
Dataset key	from model	FORECAST-Industry
	into model	Analysis
	Unique ScenarioID	xxxx
	Output/ Secondary Fuel	Electricity, Natural gas
Data keys	Perspective	Electricity Sector, Natural gas Sector
	Supertype	Investment
	Type	Investment
	Subtype	Electricity, Natural gas
	Param/Fuel	Iron and steel, FDT, etc.
	subparam	EAF, BOF, Cement, Paper, etc.
Time Key	Year	2050
	Hour	empty
Geographical key	Country	AT, DE, etc. (EU28)
	Region	-
Data	Value	
	Unit	Euro2013

5.2.1.4 Costs

This dataflow contains all annual cost (Annuity of investments, O&M, fuel cost) of industrial final energy demand.

Category	**Structure**	**Keys**
Dataset key	From model	FORECAST-Industry
	into model	Analysis
	Unique ScenarioID	xxxx
	Output/ Secondary Fuel	Electricity, Natural gas
Data keys	Perspective	Electricity Sector, Natural gas Secto
	Supertype	Cost
	Type	Capital Cost, OandM Cost, CO2-Cost, Fuel Cost
	Subtype	Electricity, Natural gas
	Param/Fuel	Iron and steel, FDT, etc.
	subparam	EAF, BOF, Cement, Paper, etc.

Time Key	Year	2050
	Hour	empty
Geographical key	Country	AT, DE, etc. (EU28)
	Region	-
Data	Value	
	Unit	Euro2013

5.2.1.5 Emissions

This dataflow contains all emissions (CO_2 equivalents) of industrial final energy demand. This includes direct energy-related emissions from conversion of fuels, direct process related emissions (e.g. CO_2 from clinker calcinations or NO_2 from adipic acid production) and indirect emissions from electricity consumption based on emission factors derived from the power sector modeling in Enertile.

Category	Structure	Keys
Dataset key	From model	FORECAST-Industra
	into model	Analysis/DIW Case study 6.4
	Unique ScenarioID	xxxx
	Output/ Secondary Fuel	Emissions
Data keys	Perspective	Electricity Sector, Natural gas Sector, Industry
	Supertype	Emissions
	Type	CO2
	Subtype	Conventional
	Param/Fuel	Gas, Coal, Oil, …
	subparam	Steel, Cement, etc.
Time Key	Year	2050
	Hour	empty
Geographical key	Country	AT, DE, etc. (EU28)
	Region	-
Data	Value	
	Unit	t CO2 eq

5.2.2 B - Special data

This second category of datasets deals with specialized data that needs to be exchanged between models but is not necessarily needed in the aggregate pathway analysis within this project.

5.2.2.1 B01 Emission factors

Emission factors derived from the power sector modeling in Enertile.

Example:

Category	Structure	Keys
Dataset key	from model	ENERTILE
	into model	FORECAST-Industry
	Unique ScenarioID	xxxx
Time Key	Year	Yearly up to2050
	Hour	empty
Geographical key	Country	AT, DE, ...
	Region	

Example

Category	2012	…	2050
Light fuel oil	kg/TWh	kg/TWh	kg/TWh
Natural gas	kg/TWh	kg/TWh	kg/TWh
Electricity	kg/TWh	kg/TWh	kg/TWh
….	kg/TWh	kg/TWh	kg/TWh

5.3 Detailed documentation of data flows in the case study "Transport"

This chapter aims defines the data that is needed in the case studies. The documentation includes a short description of the data as well as proposed data keys for the standardized data structure.

5.3.1 A - Standardized data

This first category of datasets ("Standardized data") contains data that is relevant for the pathway analysis and the energy balance or emission balance of the system. In the end this data should be part of a predefined data structure, which will be the same for all case studies.

Category	Structure	Level	Keys
Dataset key	Model	general[1]	TEPES, Enertile
	Unique ScenarioID	general[1]	xxxx
	Output	specific for each data flow	
Data keys	Perspective	specific for each data flow	
	Supertype	specific for each data flow	
	Type	specific for each data flow	
	Subtype	specific for each data flow	
	Param/Fuel	specific for each data flow	
	subparam	specific for each data flow	
Time Key	Year	general	2050
	Hour	specific for each data flow	0,1,2,…,8759 in UTC+1 or empty
Geographical key	Country	general	as defined in Region-Shapefile
	Sub-Region	general for case study	as defined in Region-Shapefile
Data	Value		
	Unit	specific for each data flow	

5.3.1.1 A01 - Energy demand

This dataflow contains all annual energy demand for a given region. It is subdivided by the different energy carriers that are applicable in the transport sector.

Category	Structure	Keys
Dataset key	from model	ASTRA
	into model	eLoad, Enertile, Empire
	Unique ScenarioID	Xxxx
	Sector	Transport
Data keys	Perspective	Demand
	Supertype	Public passenger transport, private passenger transport, freight transport
	Type	Bus, Train, Car, Truck, Ship, Airplane
	Technology	Electric vehicle, vehicle with combustion engine, gas vehicle

	Subtechnology	
	Fuel	Gasoline, Diesel, CNG, LPG, LNG, Electricity Hydrogen, Biofuels
	Parameter	Final energy demand
Time Key	Year	Yearly until 2050
	Hour	Empty
Geographical key	Country	EU28
	Region	-
Data	Value	
	Unit	GWh

5.3.1.2 A02 - Emissions

This dataflow contains all data regarding the emissions that stem from the transport sector.

Category	Structure	Keys
Dataset key	from model	ASTRA, Enertile, Empire
	into model	Analysis
	Unique ScenarioID	Xxxx
	Sector	Transport
Data keys	Perspective	Demand
	Supertype	Emissions
	Type	CO2, CO, NOx, SO2, VOC, PM
	Technology	Bus, Train, Car, Truck, Ship, Airplane
	Subtechnology	
	Fuel	
	Parameter	Emissions
Time Key	Year	Yearly until 2050
	Hour	Empty
Geographical key	Country	EU28
	Region	-
Data	Value	
	Unit	T

5.3.1.3 A03 - Prices

This data flow delivers feedback on wholesale electricity and gas prices from Enertile and Empire to ASTRA (via Forecast Macro, see sheet retail prices).

Category	Structure	Keys
Dataset key	from model	Enertile, Empire
	into model	ASTRA (via Forecast Macro)

	Unique ScenarioID	Xxxx
	Sector	Electricity, Gas
Data keys	Perspective	Power Generation, gas market
	Supertype	Price
	Type	Wholesale
	Technology	
	Subtechnology	
	Fuel	Electricity, natural gas
	Parameter	Wholesale electricity price, wholesale gas price
Time Key	Year	Yearly until 2050
	Hour	Empty
Geographical key	Country	EU28
	Region	-
Data	Value	
	Unit	€2016/MWh

5.3.1.4 Costs

This data flow contains relevant annual data on the cost of transport.

Category	**Structure**	**Keys**
Dataset key	from model	ASTRA
	into model	Analysis (& Macro Models)
	Unique ScenarioID	Xxxx
	Sector	Transport
Data keys	Perspective	Costs
	Supertype	Housholds, Industry, Policy
	Type	
	Technology	
	Subtechnology	
	Fuel	
	Parameter	Expenditures for transport, tax revencues, subsidies
Time Key	Year	Yearly until 2050
	Hour	Empty
Geographical key	Country	EU28
	Region	-
Data	Value	
	Unit	€2016

5.3.2 B - Special data

This second category of datasets deals with specialized data that needs to be exchanged between models but is not necessarily needed in the aggregate pathway analysis within this project. These data should only be documented but not forced into a defined structure.

5.3.2.1 B01 - Vehicle performance

Data describing the batteries for the different vehicle categories

Example:

Category	Structure	Keys
Dataset key	from model	ALTER-MOTIVE
	into model	ASTRA
	Unique ScenarioID	xxxx
Time Key	Year	Yearly up to2050
	Hour	empty
Geographical key	Country	NUTS0
	Region	

Category	Power-train	Specific energy [Wh/kg]	Specific power [W/kg]	Lifetime [years]	Cost [€/kWh]	Weight [kg]	Capacity [kWh]
Passenger Cars	Plug-in-Hybrid						
	Battery Electric						
	Fuel Cell Electric						
Trucks	Plug-in-Hybrid						
	Battery Electric						
	Fuel Cell Electric						
Trains	Electric						
	Fuel Cell						

5.3.2.2 B02 - Vehicle characteristics

The different vehicle categories and powertrain technologies that are considered within the model are specified. Special focus lies on those vehicles that utilize a battery.

Category	Structure	Keys
Dataset key	from model	ASTRA
	into model	ALTER-MOTIVE
	Unique ScenarioID	Identical for all scenarios
Time Key	Year	No yearly changes
	Hour	empty
Geographical key	Country	NUTS0
	Region	

Mileage [km/year]

			Application			
Category	**Powertrain**	**Size [kW]**	**Commuting**	**CarSharing**	**Leisure**	**…**
Passenger Cars	Plug-in-Hybrid	50				
		80				
		200				
	Battery Electric	50				
		80				
		200				
	Fuel Cell Electric	50				
		80				
		200				
Trucks	Plug-in-Hybrid	Tbd				
	Battery Electric	Tbd				
	Fuel Cell Electric	Tbd				
Trains	Electric	Tbd				
	Fuel Cell	Tbd				

5.3.2.3 B03 - Retail prices

Retail prices for the different fuels are provided by the model Forecast macro with and without tax for the different world regions.

Category	Structure	Keys
Dataset key	from model	Forecast Macro
	into model	ASTRA
	Unique ScenarioID	Xxxx
	Output/ Secondary Fuel	n/a
Data keys	Param/Fuel	Electricity, Natural Gas, Oil,…

	subparam	n/a
Time Key	Year	2050
	Hour	empty
Geographical key	Country	NUTS0
	Region	n/a
Data	Value	
	Unit	GJ/€