Analysis of the European energy system
under the aspects of flexibility and technological progress

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A-CAES	adiabatic compressed air energy storage
BAT	best available technology
BEV	battery electric vehicle
BOS	balance of system
CCGT	combined cycle gas turbine
CCOT	combined cycle oil turbine
CCS	carbon, capture and storage
CHP	combined heat and power
CNG	compressed natural gas
D	deliverable
DR	demand response
DSM	demand-side-management
EAF	electric arc furnace
EEM	energy efficiency measures
EMS	energy management system
ETS	emission trading system
FCEV	fuel cell electric vehicle
FCEV	fuel cell electric vehicles
GasSteam	gas steam turbine
GDP	gross domestic product
GHG	greenhouse gas
HDV	heavy duty vehicle
HEV	hybrid electric vehicle
HOP	heat-only plants
ICE	internal combustion engine
INN	innovations
ITS	intelligent transport systems
IWW	internal waterways transport
LDV	light duty vehicle
LNG	liquefied natural gas
LPG	liquefied petroleum gas
LR	learning rate
MEPS	minimum energy performance standards

NGCC	natural gas combined cycle
NTC	net transfer capacity
nZEB	nearly zero-energy building
OCGT	open cycle gas turbine
OCOT	open cycle oil turbine
OilSteam	oil steam turbine
PCM	phase-changing materials
PEFC	proton exchange membrane fuel cell
PHEV	plug-in hybrid electric vehicles
PR	progress rate
PSP	pumped storage plant
PV	photovoltaic
R&D	research and development
RES	renewable energy sources
SET-Plan	strategic energy technology plan
SFH	single-family-homes
STES	sensible thermal energy storage
TCO	total costs of ownership
TCS	thermal-chemical storage
TES	thermal energy storage
TRL	technology readiness level
WA-DH	weighted average annual district heat
WP	work package

EXECUTIVE SUMMARY

In the next decades the European energy system needs a fundamental change towards a low-carbon energy system to contribute to the mitigation of climate change. Since the United Nations Climate Change Conference in Copenhagen (2009) and Cancun (2010), the objective to maintain the global temperature increase below the level of 2°C is accepted by the international community of states. Therefore, the EU has set the target to reduce the greenhouse gas (GHG) emissions by 80 % to 95 % in 2050 compared to the levels of 1990. To achieve the 2°C target the decarbonisation of all energy sectors is mandatory.

The objective of this report is to analyse the fundamental changes in context of a decarbonised electricity, heat and mobility sector with its cross-sectoral interdependencies between the different demand and supply sectors considering the deployment of renewable energy sources. A decarbonised energy system necessitates high shares of renewable energy sources, which lead to additional challenges in the energy system due to their intermittent nature. Therefore, the need for flexibility in the energy system occurs, which can be provided by a large bundle of technologies as storages, demand-side-management or power-to-x-technologies. In this report an optimal flexibility option portfolio and potentials for system enhancements by inter-sectoral substitution of flexibility measures are identified which can contribute to a successful transformation towards a low-carbon European energy system.

The analysis of system flexibility in different European decarbonisation pathways requires an in-depth techno-economic assessment of various flexible low-carbon technologies with several energy system models. In REFLEX the models are soft-linked with one- and bidirectional data exchanges, and can be distinguished between demand projection models (FORECAST, eLOAD) and fundamental sectoral bottom-up energy system models (ASTRA, ELTRAMOD, TIMES-Heat). Furthermore, the scenario description provides the overall qualitative framework for the modelling activities by setting-up two holistic socio-technical scenarios based on different scenario storylines, which include the definition of the main framework parameters, societal and political environment. Two different main scenarios are distinguished: a reference scenario based on observed energy political trends and most recent projections as well as two policy scenarios representing ambitious decarbonisation pathways with high shares of renewable energy sources for Europe until 2050. A large part of this modelling activity is to determine which technologies will see increased diffusion, and which technologies will be phased out. A key consideration is how the future costs of both incumbent and upcoming technologies will develop in the future. Hence, for this report experience curves are used to estimate future costs of a technology.

The results of this analysis support existing analyses and policy recommendations (e.g. EU Roadmap), such as the improvement of the EU Emissions Trading Scheme (ETS) to enable high CO_2 prices, to provide more long-term clarity and the certainty in price developments and to include more CO_2 emitting sector into the ETS. Additionally, in the context of a highly uncertain environment and large potential investments, public RD&I funding can play an important role in accelerating the market introduction of innovative low-carbon processes (e.g. EC Innovation Fund). Apart from these general recommendations, the detail and the number of coupled models involved in REFLEX enables a comprehensive view on the effort necessary to achieve a transformation of the European energy system. To decarbonise the energy system, the role of the energy demand side becomes crucial, as it is shown in the REFLEX

scenarios. In general, energy demand reductions can be achieved by several options, of which one of them is energy efficiency improvements. Additionally, electricity becomes the most important energy carrier in the model calculation based on the given framework conditions enabling the substitution of fossil fuels. This leads to significant emission reductions in the industry, residential, tertiary and transport sector. Remaining emissions mainly stem from the use of gas as a less emission intensive fossil fuel in all energy demand sectors. Moreover, ambitious policy measures are required to achieve the 2050 target of -60 % GHG emission reduction for the transport sector compared to 1990. The main drivers are efficiency improvements, the diffusion of low-and zero-emission road vehicles and alternative fuels, in particular for aviation and navigation. In addition, modal shift from using individual cars to more efficient modes like public transport, cycling and walking can contribute to decarbonisation. The results regarding the flexibility provision in the electricity market show that the assumed increase in electricity demand can only be served with additional dispatchable power plants. Sector coupling contributes to balance the flexibility needs in the electricity market. To reach ambitious decarbonisation goals, the CO_2 intensive electricity generation must be significantly reduced. Since conventional electricity generation capacity will be needed to some extent, high CO_2 prices result in strong emission reductions. Mainly natural gas power plants will play an important role in reducing emissions (due to the switch from CO_2-intensive energy carriers, such as coal and lignite, to gas). In the model, the need for carbon capture and storage (CCS) technologies occurs from 2040 on, depending on the carbon price policy. In general, CCS should therefore be developed as a further option. If the policy makers, want to deploy these technologies the effort on increasing the competitiveness of CCS technologies as well as on doing research on challenges regarding the storage of CO_2 should be applied from now on. In general, since emissions reductions in other sectors are comparably challenging, the sector coupling by electrification should be enforced. Further, to increase the role of storages, major cost reductions for batteries have to happen and have to be enforced. If cost reductions can be realised, fossil fuel based generation can further be decreased. Significant GHG emission reductions are possible in the district heat generation sector from 60 % to ca. 85 % in 2050 depending on the REFLEX scenarios. Bioenergy (mainly biomass) technologies are increasing their role becoming a key technology in heat supply. Natural gas units are utilised in countries with low bioenergy potentials. Heating only plants, except large solar thermal plants, are losing competition with combined heat and power plants. At the same time, power-to-heat technologies actively respond to electricity price variations and to generated district heat that can be stored.

The results regarding the cumulated CO_2 emissions show that the REFLEX scenarios with high shares of renewable energy sources achieve the ambitious decarbonisation targets formulated by the EU Roadmap. Therefore, when assessing the target achievement and comparing a more central or decentral transformation of the European energy system is not bound to a better or worse performance regarding their ability to decarbonise the energy demand and supply. It is rather a question about an adequate mix of ambitious energy policy targets and measures like it is discussed in the summary above. However, significant additional efforts are necessary, if such scenarios as in REFLEX shall be achieved. Since the interactions between the energy sectors involved are complex, the results of the REFLEX project may help to give an in-depth understanding about optimal pathways to a low-carbon European energy system.

1 The Need for Flexibility in a Low-Carbon and Sector-Coupled Energy System

The transition towards a low-carbon energy system is one of the main challenges the European Union is facing in the coming years and decades. Achieving the targeted emission reductions of 80 % to 95 % in 2050 compared to the levels of 1990 requires a fundamental transformation of the energy sector. Therefore, the EU has established the Strategic-Energy-Technology-Plan (SET-Plan) to accelerate the development and deployment of low-carbon technologies. With the SET-Plan the EU is aiming to create an environment that facilitates the evolution of existing and developing new low-carbon technologies to manage the specific needs for a reliable, cost-efficient and sustainable prospective energy supply. In particular, the deployment of renewable energy sources (RES) and energy efficiency in the heat, transport and electricity sector are promoted. Regarding the SET-Plan several technologies will play a crucial role in the next decades. Especially, the integration of intermittent wind and photovoltaic power challenges the energy system and leads to flexibility requirements. A large bundle of technologies may provide the needed flexibility such as energy storage systems, smart grids, adaptation of flexible power plant technologies, demand side management based on new electricity applications for in different sectors. The latter ones can be complemented by power-to-x-technologies, such as power-to-heat (e.g. heat pumps for district heating), power-to-transport (e.g. electric mobility, fuel cells) and power-to-gas (e.g. H_2 for methanol or ammoniac production).

To analyse the complex links and interdependencies between the different actors in various sectors, the available technologies and the impact of the different interventions on all levels from the individual to the whole energy system different sectoral-based energy system models are combined in work package 4 (WP4) of the REFLEX-project. Performing scenario analyses using interlinked energy system models will provide insights in the role of single technologies as well as on interdependencies between miscellaneous technologies and. These detailed sectoral models provide an in-depth representation of the individual low-carbon technologies as well as flexibility options and finally facilitate the generation of robust and comprehensive results.

1.1 Scope of Deliverable

The deliverable 4.3 (D4.3) “Report on cost optimal energy technology portfolios for system flexibility in the sectors heat, electricity and mobility” provides a detailed techno-economic assessment of low-carbon technologies focusing on flexibility options and applying bottom-up sectoral models and top-down demand projection models of the heat, electricity and transport sector. The report summarizes the findings of WP4, where prospective developments of specific technologies are identified and based on three scenarios, different technology portfolios within the sectors are discussed regarding their contribution to the integration of renewable energy sources. Within this report a distinction is made between energy demand sectors and energy supply sectors. While in the present report on the energy demand side the transport, industry, residential and tertiary sector are included, the energy supply side comprises the electricity and heating sector. Hence, key objectives are to assess the development as well as interdependencies between the different demand and supply sectors considering the deployment of renewable energy sources and the given scenario framework. Further objectives are the identification of an optimal flexibility option portfolio and the identification of potentials for system enhancements by inter-sectoral substitution of flexibility measures. As a result, this deliverable identifies crucial flexibility measures for a successful transformation towards a low-carbon European energy system.

1.2 Structure of Deliverable

In this report, the findings of WP4 are summarized, while its structure is illustrated in Figure 1. In Chapter 2, the approach of the model coupling within the REFLEX project is discussed and the applied models are presented. In Chapter 3 the scenario framework and key assumptions are described. Quantitative framework assumptions are discussed, particularly the availability of demand side flexibility, the renewable energy expansion pathways as well as the implemented technological learning. These key assumptions have an impact on each model outcome. In Chapter 4 model specific input parameter are presented in detail. Furthermore, the focus of this chapter lies in the discussion of the results. Firstly, the energy demand side developments particularly the scenario specific final energy demand projections in the industry, residential, tertiary and transport sectors as well as the hourly demand side management potential are analysed. Secondly, optimal capacity investments and the dispatch of flexible technologies on the energy supply side. Additionally sector specific and overall emission reductions are quantified. Finally, Chapter 5 summarises key technologies and measures enabling the transformation to a low-carbon European energy system and gives policy recommendations.

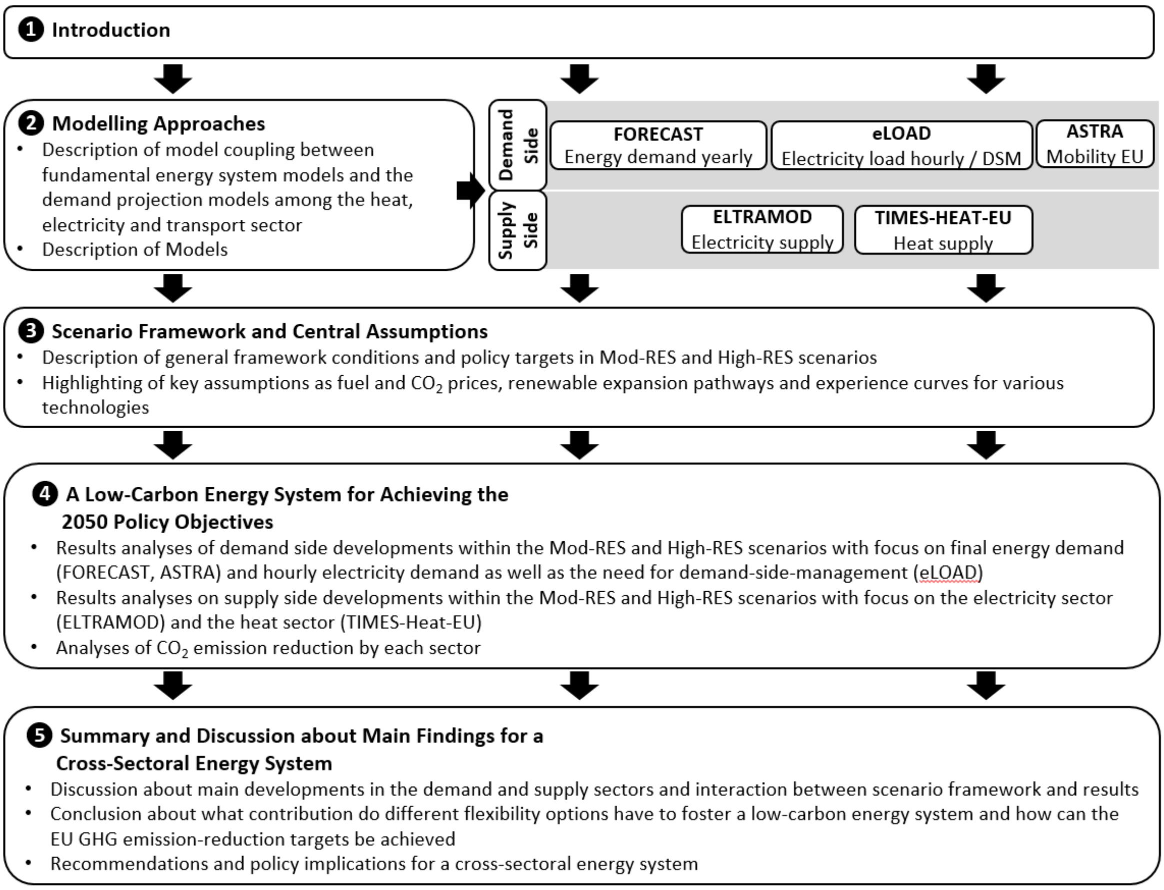

Figure 1: Structure of the report D4.3

Source: own illustration

2 Modelling Approaches

The analysis of system flexibility in different European decarbonisation pathways requires an in-depth techno-economic assessment of various flexible low-carbon technologies with various energy system models. In particular, this is crucial when the role and interdependencies of different flexibility options across the sectors electricity, heat and mobility in a transnational energy system are elaborated (Zöphel et al. 2018). The coupling and enhancement of existing models enables the combination of knowledge for complex analyses like the efficient transformation of the European energy system. In the following Chapter 2.1 an overview of the models included for the model coupling in REFLEX is given. While here the role and linkage of the models is described briefly, further details and enhancements of each model to couple in the present project are discussed in Chapter 2.2.

2.1 Model Coupling

In REFLEX the models are soft-linked with both one- and bidirectional data exchanges. The basis for this linkage builds a scenario framework (see Chapter 3) and a common database with the result that all models are based on identical assumptions. The soft-linked model coupling approach is used since the features and high techno-economical details of the models to couple can be integrated without excessively increasing the computational costs. This way REFLEX takes advantage of the individual strengths of each model while covering all aspects and sectors of the European energy system. In addition, an important disadvantage of the integrated approach can be avoided since relying on extremely complex single models may decrease the understanding and thus, acceptance of model results particularly when communicated to a broader public.

At the same time the soft-linking approach requires a data base harmonization of the different model-specific data sources as well as an iterative process to enable data consistency for all model linkages (Helgesen et al. 2018; Hidalgo González et al. 2015). This is realized by common interfaces for exchanging data and results to facilitate the exchange of information between the models applied. Here a standardisation of input and output data is required, also including definitions of nomenclature, terminology and boundary conditions (for more information see Kunze (2018)).

For the analyses of future needs for system flexibility in Europe the model set up is distinguished between demand projection models (FORECAST, eLOAD) and fundamental sectoral bottom-up energy system models (ASTRA, ELTRAMOD, TIMES-Heat). Figure 2 gives an overview of the model coupling in REFLEX. Providing the specific future demand for electricity and heat, the forecasting models overcome the shortcomings and complement the fundamental models for the electricity and heat sector. This includes the projecting of yearly energy demand with FORECAST for the defined scenarios for each the industry, residential and tertiary energy demand sectors. The yearly electricity and heat demand are broken down to hourly resolved patterns of 8760 hours with eLOAD. Furthermore, eLOAD quantifies the hourly demand response potentials, which are implemented in ELTRAMOD.

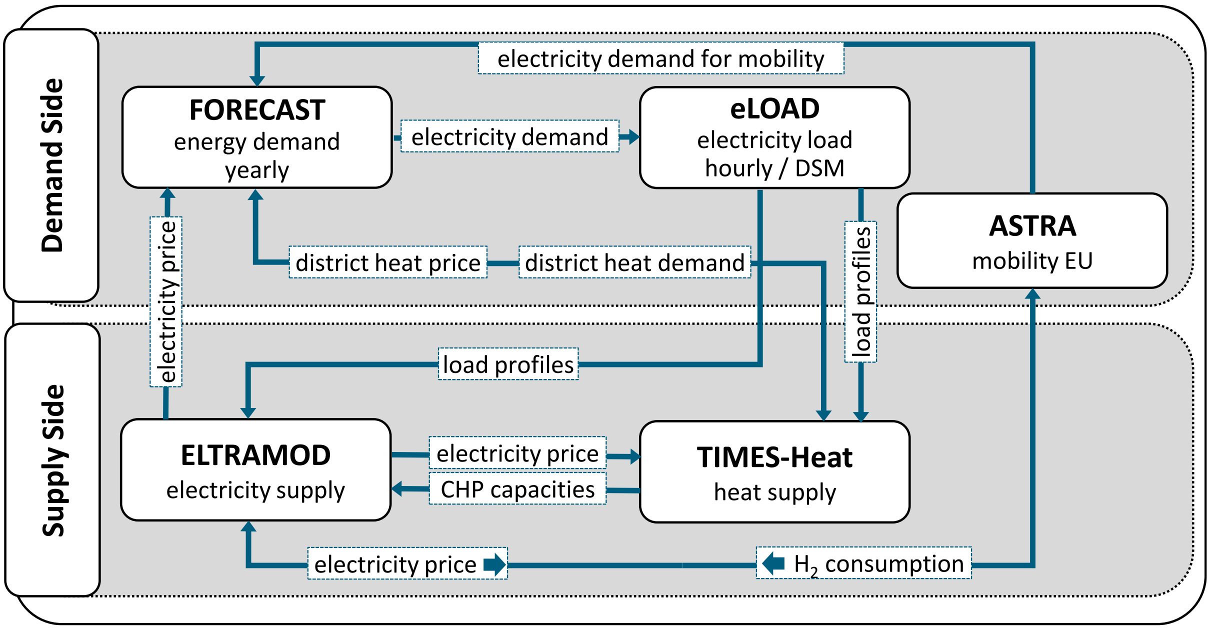

Figure 2: Sectoral-based model coupling of fundamental bottom-up energy system models and demand projection models in REFLEX

Source: own illustration

Analysing the mobility sector, ASTRA is used to simulate the evolution of transport performance in each EU member state for both, passenger and freight transport. It further considers modules assessing the diffusion of fossil and alternative fuel vehicles into the vehicle stock for road modes. As a result the potential contribution of the mobility sector on energy system flexibility and intermittent RES integration as well as emission reduction can be analysed. The scenario specific developments and resulting requirements for different energy carriers calculated by ASTRA are linked to the FORECAST model (electricity demand for mobility) and ELTRAMOD (hydrogen consumption as input for possible power-to-gas applications). With ELTRAMOD the penetration of different flexibility options and their contribution to intermittent RES integration in the electricity sector is analysed. Therefore, cost optimal portfolios of defined key technologies for electricity system flexibility through model endogenous investments and dispatch decisions on generation and storage capacities as well as electricity trade flows are assessed. The heat sector development analysis is performed by TIMES-Heat. By applying hourly demand projections for district heat the model evaluates the cost-minimal mix of heat generating technologies and their dispatch. Similar to ELTRAMOD TIMES-Heat includes key technologies regarding central as well as district heating supply and thermal storages. The marginal costs of the electricity provision in ELTRAMOD can be used as estimation for electricity prices and are coupled as input for TIMES-Heat for the electricity sector coupled heating technologies (e.g. combined-heat-power-plants or power-to-heat applications). The exchange of electricity and heat prices is in general part of the iterative process for the harmonization of model results. These feedback loops are done for each of the above discussed linkages in the model coupling in Figure 2.

2.2 Description of Models

In the following section the applied and coupled models for the analyses within WP4 are briefly described by some general information and by explaining the model structure. Recent model applications and references are listed in the annex (see A Model References).

2.2.1 FORECAST

General Information

The FORECAST model is designed as a tool that can be used to support strategic decisions. Its main objective is to support the scenario design and analysis for the long-term development of energy demand and greenhouse gas emissions for the industry, residential and tertiary sectors on country level. FORECAST considers a broad range of mitigation options to reduce CO_2 emissions, combined with a high level of technological detail. It is based on a bottom-up modelling approach considering the dynamics of technologies and socio-economic drivers. Technology diffusion and stock turnover are explicitly considered to allow insights into transition pathways. The model further aims to integrate different energy efficiency and decarbonisation policy options. The model allows to address research questions related to energy demand including the analysis of scenarios for the future demand of individual energy carriers like electricity or natural gas, calculating energy saving potentials and the impact on greenhouse gas (GHG) emissions as well as abatement cost curves, ex-ante policy impact assessments and the investigation of long-term sustainable energy transition scenarios.

Model Structure

The FORECAST platform comprises three individual modules (see Figure 3), each representing one sector according to the Eurostat (or national) energy balances: industry, services/tertiary and residential. While all sector modules follow a similar bottom-up methodology, they also consider the particularities of each sector like technology structure, heterogeneity of actors and data availability.

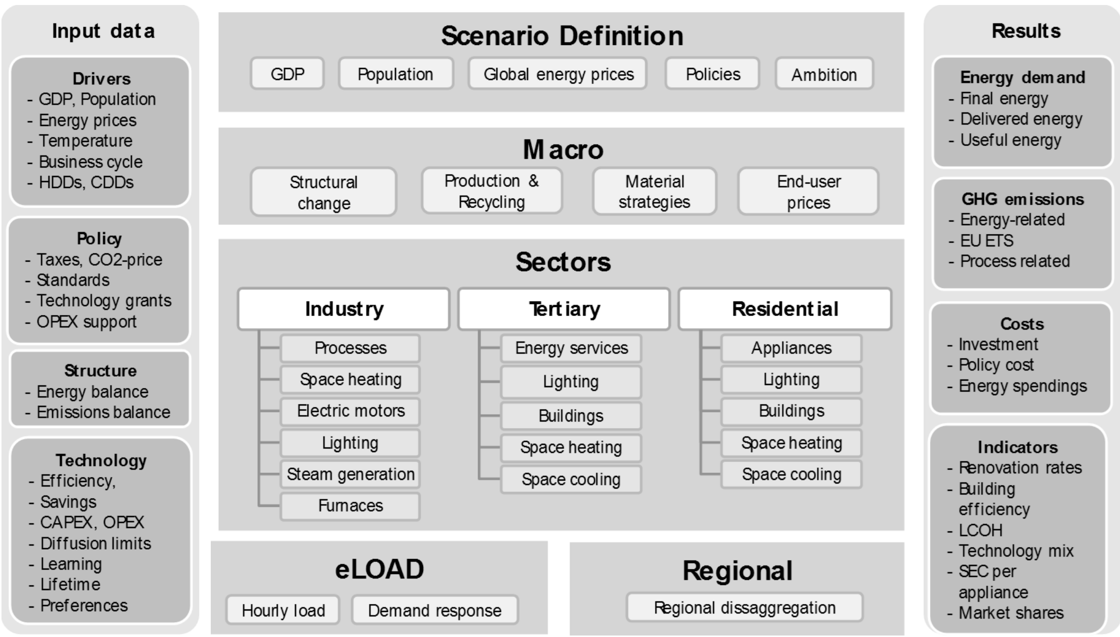

Figure 3: Overview of the FORECAST model structure

Source: FORECAST

The list of selected input data provides an idea of the level of detail of each module. Each sector requires sector specific activity data, like industrial production in the industry sector, the number of employees in the services sector and the number of households in the residential sector. Furthermore, end-consumer energy prices play an important role in each sector as they are distinguished by energy carrier. The third group of input data, the technology characterisation also reflects data availability of the individual sectors. While in the industry and tertiary sector the model works with so-called energy-efficiency measures (EEMs), which represent all kinds of actions that reduce specific energy consumption, in the residential sector the stock of alternative appliances and the market share of different efficiency classes is explicitly modelled. In all cases, energy savings can be calculated and traced back to technological dynamics including cost considerations.

As an outcome of the bottom-up approach model results can be disaggregated with a very high resolution, comprising sectors and sub-sectors, but also end-use technologies and energy carriers. Examples for these fields are shown in the following Figure 4.

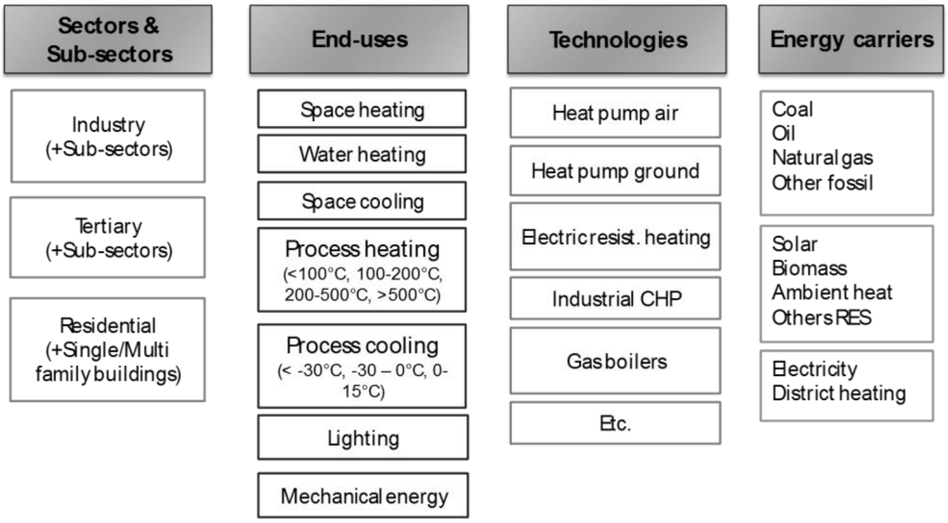

Figure 4: Disaggregation of FORECAST results

Source: FORECAST

A complete list of technologies considered in the model is provided in the following Table 1. The broad scope and high level of technology detail becomes obvious. On the one side, FORECAST includes all major household appliances and on the other side processes in basic materials industries.

The bottom-up approach, which distinguishes individual technologies, allows modelling the diffusion of technologies as the result of individual investment decisions taken over time. For all types of investment decisions, the model follows a simulation approach rather than optimization in order to better capture the real-life behaviour of companies and households.

Whenever possible, the investment decision is modelled as a discrete choice process, where households or companies choose among alternative technologies to satisfy a certain energy service. It is implemented as a logit approach considering the total cost of ownership (TCO) of an investment plus other intangible costs. This approach ensures that even if one technology choice is more cost-effective than the others, it will not gain a 100 % market share. This effect reflects heterogeneity in the market, niche markets and non-rational behaviour of companies and households, which is a central capability to model policies. Still, the resulting technology development (and energy demand) is price sensitive.

Table 1: Technology detail in FORECAST

Industry	**Buildings** (services and residential)	**Appliances** (services and residential)
Energy intensive processes and products – Oxygen and electric steel – Aluminium – Copper – Cement – Paper – Pulp – Flat glass – Ethylene – Ammonia – Methanol – Chlorine etc. **Steam generation** – Boilers (electric, gas, etc.) – Steam and Gas turbines – Fuel cells – Large heat pumps – Internal combustion engines **Electric motor systems** – Pumps – Fans – Compressed air – Machine tools – Process cooling – Other motors **Lighting** **Space heating and cooling**	**Buildings** – Single family – Multi family – Commercial **Space heating** – Electric radiator – Coal boiler – Lignite boiler – Natural gas boiler – Oil boiler – Solar thermal plus others – Biomass boiler – District heating – Heat pump – Combined heat and power (CHP) – Night storage heating	**Residential appliances** – Lighting – Refrigerators and Freezers – Washing machines and Dryers – Dishwashers – TV – IT – Space cooling – Cooking – Circulation pumps – Others **Service sector appliances** – Lighting and street lighting – ICT office and ICT data centres – Ventilation and air-conditioning – Circulation pumps – Elevators – Cooking – Laundry – Refrigeration – Misc. building technologies – Cooling in server rooms

(Source: FORECAST)

The replacement of equipment/buildings/technologies is based on a vintage stock approach allowing to realistically model the replacement of the capital stock considering its age distribution. Some parts of the industrial and the tertiary sector are not using a vintage stock approach, due to the huge heterogeneity of technologies on the one hand and data scarcity on the other. Technology diffusion, however, is modelled based on a similar simulation algorithm taking heterogeneity and non-rational behaviour into account.

Modelling *energy efficiency policies* is a core feature of the FORECAST model. The simulation algorithm and the vintage stock approach are well suited to simulate most types of policies. Minimum energy performance standards (MEPS), e.g. for appliances or buildings, can easily be modelled by restricting the market share of new appliances starting in the year the standards come into force (see Elsland et al. (2013) and Jakob et al. (2013) for examples of ex-ante impact assessments of the EU-Ecodesign Directive). *Energy taxes* for end-consumers can be modelled explicitly on the basis of more than 10 individual energy carriers (electricity, light fuel oil, heavy fuel oil, natural gas, lignite, hard coal, district heating, biomass, etc.). *Information-based policies* are generally the most complicated to model due to their rather "qualitative character". The discrete-choice approach, however, allows to consider such qualitative factors. E.g. labelling of appliances resulting from the EU Labelling Directive can be modelled by adjusting the logit parameters and thus assuming a less heterogeneous market, in which a higher share of consumers will select the appliance with the lowest total cost of ownership. See for example Elsland et al. (2013). *EU emissions trading* can be modelled in the form of a CO_2 price for energy-intensive industries. The detailed technology disaggregation in the industrial sector considering more than 60 individual products allows to consider the scope of the EU emission trading system (ETS) on a very detailed level (examples of products are: clinker, flat glass, container glass, primary and secondary aluminium, oxygen steel, electric steel, coke, sinter, paper, ceramics, ammonia, adipic acid, chlorine). A combined discrete choice and technology vintage model simulates the change in steam generation technologies as a function of technology parameters, demand, prices and policies.

2.2.2 eLOAD

General Information

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 FORECAST model eLOAD assesses the transformation of the load curve due to structural changes on the demand side and the introduction of new appliances (see Figure 5). 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. Apart from that, eLOAD allows to analyse load flexibility, i.e. demand response (DR). Based on a mixed-integer optimisation the model determines cost-optimal load shifting activities of suitable appliances such as electric vehicles or storage heaters.

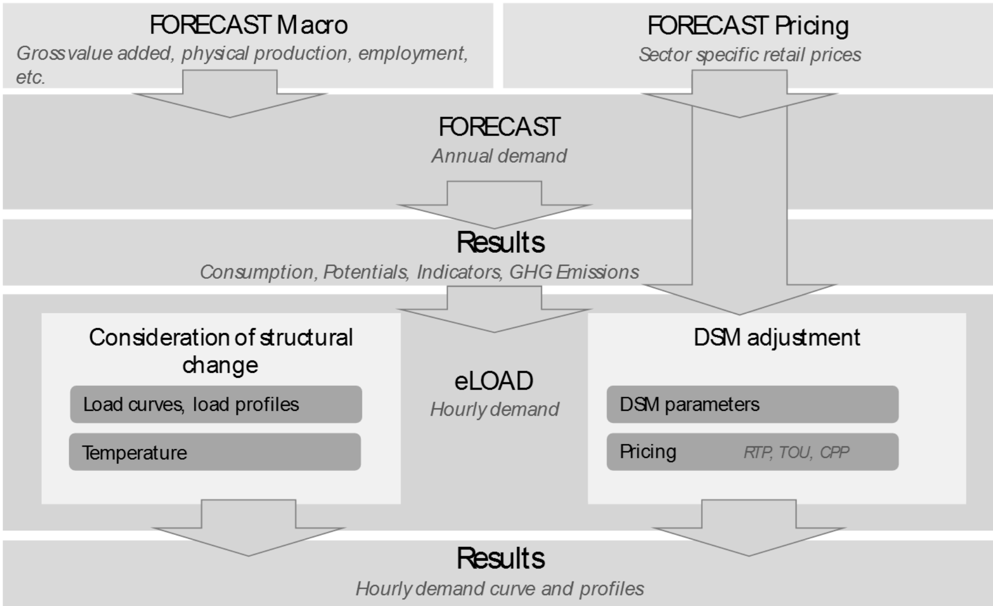

Figure 5: Overview of the FORECAST and eLOAD modeling system

Source: eLOAD and FORECAST

Model Structure

eLOAD aims to estimate the future shape of the national electricity system load curves. It is available for all countries of the EU27 (without Malta) until the year 2050. eLOAD consists of two modules. The first module 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 FORECAST model 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.

The second module of eLOAD addresses the active adjustment of the load curve by means of demand response activities. Based on the load curve of appliances that are suitable for DR and taking into account techno-economic parameters and restrictions of the appliances, a mixed-integer optimization is carried out which determines the least-cost scheduling of the appliances in order to smooth the residual load (as the difference of the system load and the generation of renewable energy sources).

The model is applied to national as well as EU-wide studies. On the EU-level eLOAD is mainly applied in the context of load curve analysis of different multi-national utilities and for the European research project REFLEX. On the national level, eLOAD has been used in the calculations for the “Leitstudie” project of the German Environmental Ministry and for the German Network Development Plan 2030.

2.2.3 ASTRA

General Information

ASTRA is a strategic model based on the systems dynamics modelling approach simulating the transport system development in combination with the economy and the environment until the year 2050. The model is made of different modules that interact among each other with direct linkages and feed-back effects.

Strategic assessment capabilities in ASTRA cover a wide range of transport measures and investments with flexible timing and levels of implementation. A strong feature of ASTRA is the ability to simulate and test integrated policy packages. Geographically, ASTRA covers all EU28 member states plus Norway and Switzerland.

As illustrated in the following Figure 6, ASTRA consists of different modules, each related to one specific aspect such as the economy, transport demand or the vehicle fleet. The main modules cover the following aspects:

- transport, simulating generation, distribution and modal split of passenger and freight movements;
- vehicle fleet, simulating the development through the years of road vehicle fleet composition and technologies;
- population, simulating the evolution of socio-economic population groups;
- economy, which simulates the linkages of the transport sector with the whole economic system and covering the estimation of GDP, input-output matrices employment, consumption and investment;
- foreign trade, both inside EU and to countries / regions from outside EU
- environment, including the calculation of energy consumption, air pollutant emissions, GHG emissions and accidents.

The economy module simulates the fundamental economic variables. Some of these variables (e.g. GDP) are transferred to the transport generation module, which uses the input to generate a distributed transport demand. In the transport module, demand is split by mode of transport. The environment module uses input from the transport module (in terms of vehicle-kilometres-travelled per mode and geographical context) and from the vehicle fleet module (in terms of the technical composition of vehicle fleets), in order to compute fuel consumption, greenhouse gas emissions and air pollutant emissions from transport.

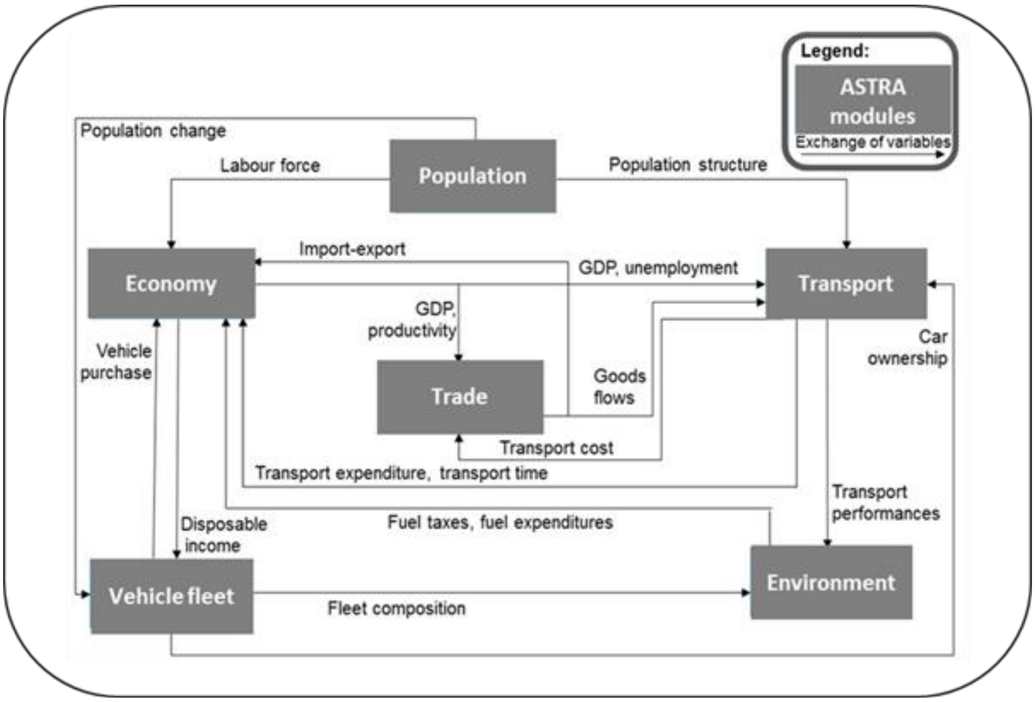

Figure 6: Overview of the linkages between the modules in ASTRA

(Source: ASTRA)

The indicators that ASTRA can produce cover a wide range of impacts; in particular transport system operation, economic, environmental and social indicators. Within REFLEX, ASTRA provides the estimation of final energy consumption for different energy carriers relevant for the transport sector. In order to support this analysis, the model has been enhanced taking into account the requested technical transition of vehicle fleets for all transport modes from fossil fuels towards renewable energy carriers as well as new mobility concepts and behaviour change towards active modes.

The diffusion of alternative drive technologies is simulated separately for different vehicle categories. These categories comprise private and commercial cars, light duty vehicles, heavy duty vehicles in four gross vehicle weight categories, urban buses and coaches. Based on the technical characteristics of available fuel options today and in the future and the heterogeneous requirements of the different users, a set of fuel options is available for each vehicle category. Technologies cover gasoline, diesel, compressed natural gas (CNG), liquefied natural gas (LNG), liquefied petroleum gas (LPG), battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV), fuel cell electric vehicles (FCEV) and trolleys for urban buses and long-distance trucks.

For each road vehicle category, new vehicle purchases are split into fuel types. This split is generated in diffusion models based on an adapted total cost of ownership (TCO) calculation. Total costs comprise fuel costs, annual vehicle and registration taxes, road charges, maintenance costs and discounted average investment costs which are implemented using learning curves for the new technologies. Filling and charging station infrastructure is considered as well in the decision via fuel procurement costs based on the density of the filling or charging station infrastructure for each country and the average range per charge or filling. The probability of the choice of a certain fuel option is finally estimated with a discrete choice approach using logit functions.

Non-road vehicle fleets like inland waterways, maritime ships, air planes and railways are also modelled, however, in less detail due to a lack of detailed statistics, long average lifetimes, and only few renewable fuel options imaginable for the time horizon until 2050. As alternative fuel options, ASTRA considers blended kerosene with biofuels for planes, an increasing share of electrified traction for railways, and biodiesel and LNG for maritime ships and inland waterways.

New mobility concepts are a further development in the transport system that is taken into consideration in ASTRA. The number of car-sharing users grew rapidly in many EU member states within the last ten years and active modes are becoming more popular in several cities. Therefore, specific algorithms have been implemented in ASTRA to simulate the diffusion of car sharing mobility services and their impacts on mobility indicators; furthermore, active passenger transport modes have been explicitly considered in terms of walking and cycling mode in urban areas.

Transport system investments are also modelled in ASTRA. For example, deployment of filling station infrastructure is fed in via exogenous data, but can also develop dynamically in the model based on the scenario e.g. assuming a certain ratio of charging points per battery-electric vehicle. Required investments in transport infrastructure depend endogenously on the transport activity development and are additionally increased in case of policies like an improvement of public transport.

In REFLEX, the ASTRA model is coupled with the models FORECAST, eLOAD and ELTRAMOD to simulate feedback mechanisms between electricity consumption patterns and prices as well as global learning effects for new vehicle technologies.

2.2.4 ELTRAMOD

General Information

ELTRAMOD (Electricity Transhipment Model) is a bottom-up electricity market model (Figure 7). It allows fundamental analysis of the European electricity market. The Net Transfer Capacity (NTC) between regions is considered while the electricity grid within one country is neglected. Each country is treated as one node with country specific hourly time series of electricity and heat demand as well as renewable feed-in. ELTRAMOD is a linear optimisation model which calculates the cost-minimal generation investments and dispatch in additional power plant capacities, storage facilities and power-to-x-technologies (i.e. power-to-heat, power-to-gas). The set of conventional power plants consists of fossil fired, nuclear and hydro plants. Additionally, fossil fuel fired carbon capture and storage (CCS) technologies are included as low-carbon technologies. Further, flexibility options such as adiabatic compressed air energy storages (A-CAES), lithium-ion batteries, redox-flow batteries and power-to-heat (heat pumps) as well as power-to-gas applications (electrolysis) are implemented. Country specific RES capacities, their expansion pathways and generation in hourly resolution are exogenous input for the present analysis. All technologies are represented by different technological characteristics, such as efficiency, emission factors, ramp rates and availability. Technology specific economic parameters are annualized capacity specific overnight investment costs, operation and maintenance costs, fixed costs as well as costs for ramping up and down the generation. Additionally, hourly prices for CO_2 allowances, as well as hourly wholesale fuel prices are implemented in ELTRAMOD. The geographical scope covers the member states of EU28, Norway, Switzerland and the Balkan countries.

For this report ELTRAMOD is used to analyse the penetration of different flexibility options and their contribution to RES integration as well as the interdependencies among various flexibility options in the European electricity system, taking existing regulatory frameworks into account. Furthermore, crucial flexibility measures for achieving the transformation towards a low-carbon electricity system and supporting policy recommendations are identified. The main strengths of ELTRAMOD for the analyses in D4.3 are the high temporal resolution of 8760 hours for all countries and its precise techno-economical representation of a wide range of energy technologies, the endogenously calculated investments in power plants and several flexibility options as well as the flexible model structure, which helps linking ELTRAMOD to other models in this project. This allows for detailed assessment of various research questions concerning the integration of intermittent renewable feed-in, flexibility requirements as well as the resulting trade-offs between relevant investments options in flexible technologies.

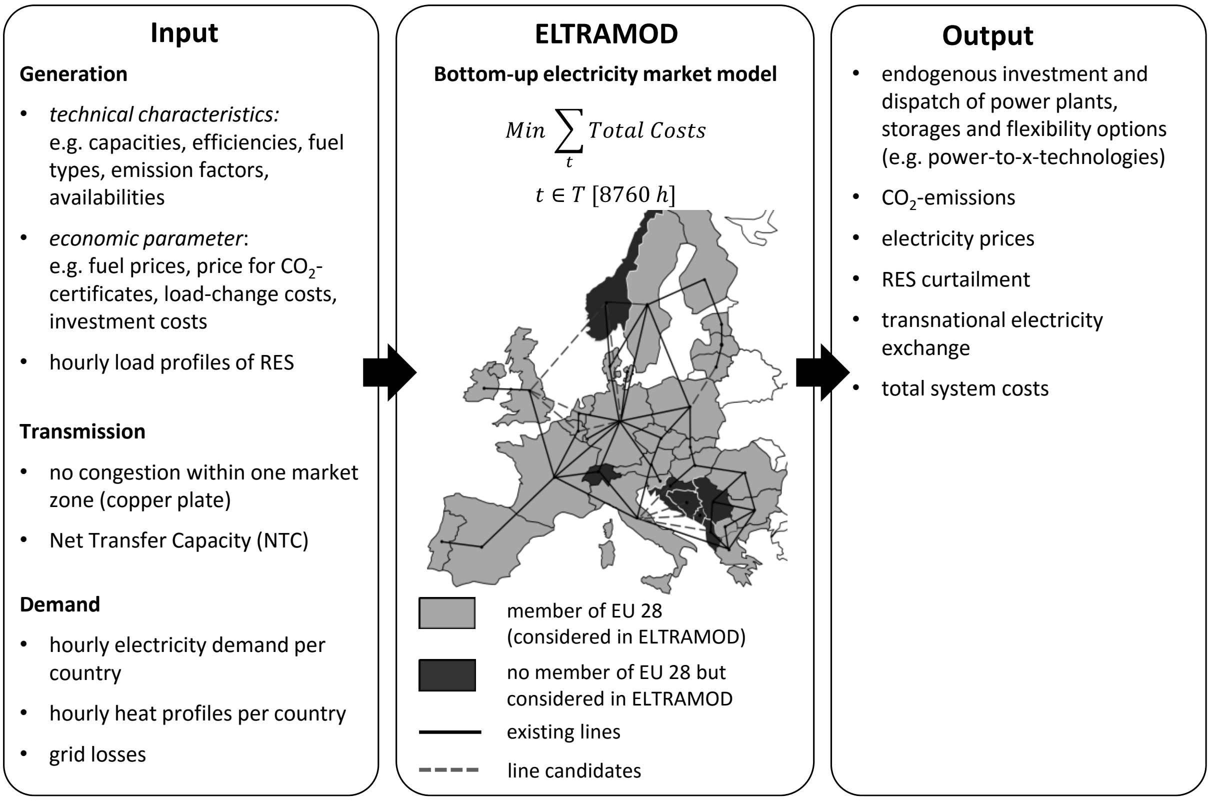

Figure 7: Electricity market model – ELTRAMOD

Source: own illustration

Model Structure

With the aim to satisfy the electricity demand in every time step and region ELTRAMOD calculates the cost-minimal power plant investment and dispatch per country and technology. The *target function* of the linear optimisation problem[1] is the minimisation of the total system costs, which is the sum of the operational costs[2], the load change costs for ramping up and down, annualized investment costs for additional conventional power plants, storages and

[1] The model code is written in GAMS language (General Algebraic Modeling System). A CPLEX solver with a barrier algorithm (interior-point method) is used.
[2] Operational costs are the electricity generation (MWh) multiplied by variable costs, fuel costs and costs for CO_2 emission certificates per technology and time step.

power-to-x-technologies. Due to the size of the optimization problem the model was divided in an investment and a dispatch model. The investment model has a reduced time frame based on represented weeks selected by a hierarchical cluster algorithm. The results of the investment model where fixed and serve as input for the dispatch model with hourly time resolution (8760 h).

The main restriction of ELTRAMOD is the *energy balance*. For each time step and country this constraint in general ensures that the electricity generation per technology has to be equal to the residual load[3]. Additionally, the curtailed intermittent RES, exported and imported electricity as well as load increase due to power-to-x-technologies (i.e. power-to-heat, power-to-gas) are part of the energy balance.

The *investments* in new capacities are restricted for some technologies. Due to geographical limitations, it is assumed that the potential of conventional hydro power plants (pumped storage plants, reservoirs) is exhausted. Further, additional investments in inefficient power plants as plants with gas or oil steam turbines (GasSteam, OilSteam) as well as plants with open cycle gas or oil turbines (OCGT, OCOT) are restricted. Also, the expansion of nuclear, lignite and coal power plants is limited based on national policy targets of each country. Hence, the expansion of nuclear is only possible in those countries, where specific plans for new nuclear power plants exist. Regarding the lignite and coal fired power plants the expansion is only allowed, where countries are not member of the Powering Past Coal Alliance, which declares that a coal phase-out is needed until 2030.[4] As part of the model coupling some fuel specific technologies are implemented with exogenous minimal investment restrictions in ELTRAMOD to include results by TIMES-Heat regarding CHP capacities.

Furthermore, other *technical constraints* limit the generation of conventional power plants to the installed capacity and the technology specific availability. The hourly electricity exchange flows are restricted due to the available NTC. Pump storage plants, adiabatic compressed air energy storages and lithium-ion as well as redox-flow-batteries represent the electricity storages within the model. To display the flexibility of storages accurately, both the charge and discharge process as well as the available storage capacity are modelled. Load increasing power-to-heat-technologies are dependent on the country specific yearly heat demand[5] and normalised hourly heat profiles. As benchmark technology from the heat sector gas boilers can also cover the heat demand. Power-to-gas-applications need to satisfy the yearly hydrogen demand derived from ASTRA based on fuel cell development pathways for the transport sector. Additionally, the yearly hydrogen demand from the industry sector, which results from FORECAST, needs to be covered by further capacity expansion of electrolysers.

Within ELTRAMOD all relevant policies concerning the European electricity market are implemented, such as the feed-in priority of renewable energies is considered in each country with the respective regulatory framework. To ensure priority feed-in, curtailing this amount is not charged. The EU emission trading system (ETS) is modelled implicitly with the help of prices for CO_2 allowances. According to the emission factor these prices influence the generation costs for all fossil power plants.

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[3] The residual load is defined as the difference between the electricity demand and the feed-in of RES, which include wind onshore and offshore, photovoltaic roof top and ground mounted.

[4] Up to now Germany is no member of the Powering Past Coal Alliance, but due to the national policy targets, it is neither planned to expand lignite nor coal fired power plants.

[5] Power-to-heat technologies cover the heat demand, which is not satisfied by CHP heat generation in TIMES-Heat.

2.2.5 TIMES-HEAT-EU

General Information

TIMES-HEAT-EU has been developed to assess the transition pathways towards more sustainable district heat (DH) supply and to analyze the role of DH systems in enhancing energy system flexibility. It is built with the use of TIMES generator (Loulou, 2008) and belongs to the class of integrated capacity expansion and dispatch planning models. It is dedicated to modelling the centralized heat supply by heat-only plants (HOPs) as well as combined heat and power plants (CHPs). District heat demand is split into three categories depending for which end-use sector it is supplied i.e.: households, tertiary and industry (see 4.1.1).

Model Structure

The model uses a bottom–up approach in which CHPs and HOPs were aggregated into main types according to the fuel used and type of installed turbine (see Figure 8). The model considers main types of thermal energy storage (TES) in a short-term and seasonal perspective. The use of TES makes it possible to decouple power generation from heat generation as the operation of CHPs is influenced by the electricity price signals. Power-to-heat technologies such as large electric heaters and heat pumps can use electricity that would be otherwise curtailed. The geographical coverage of the model considers the member states of the EU28. The time horizon covers the time period from 2015 to 2050 with 5 years' time steps. Each modelling year is further divided into 224 time slices derived by aggregating the data every three hours in seven days for four seasons (8 x 7 x 4). The model has been calibrated for the 2015 based mainly on the EUROSTAT data.

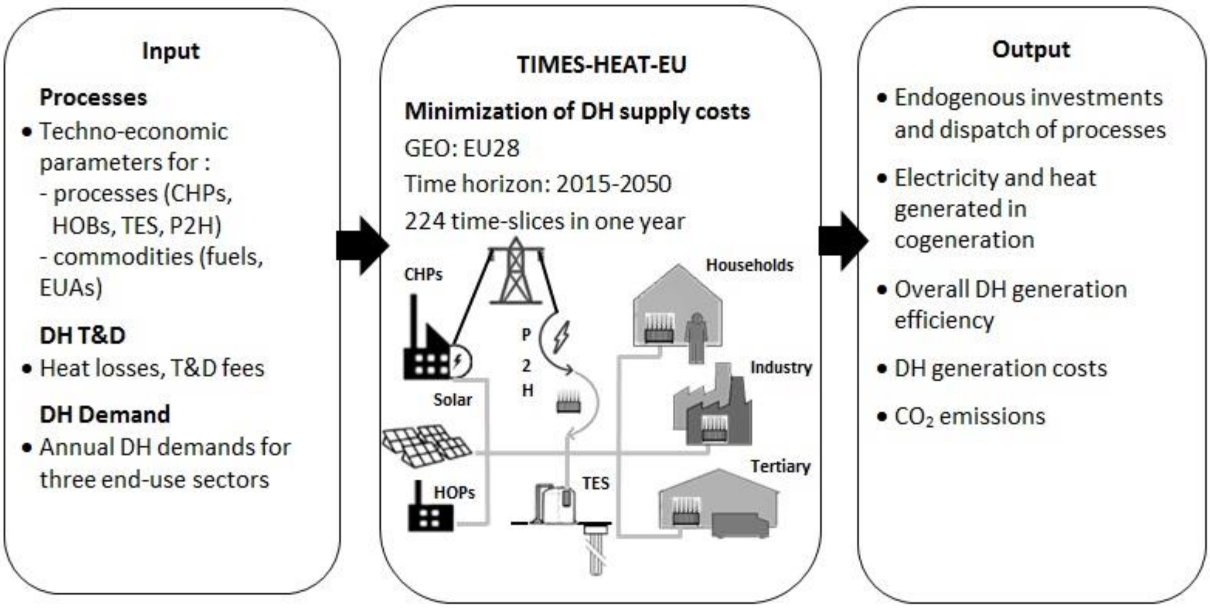

Figure 8: District heat supply model – TIMES-HEAT-EU

Source: TIMES-HEAT-EU

TIMES-HEAT-EU solves the linear programming problem of DH supply costs minimization. The optimization is constrained by a set of equation and inequalities. The main equations include: (i) commodity balance equations e.g. for district heat and electricity, (ii) CHP annual overall efficiency requirements in compliance with the EU legislation, (iii) required share of electricity generated in highly efficient cogeneration, (iv) ramping constraints for the operation of units.

TIMES-HEAT-EU operates on three hours long time slices. To model the technical ability of variating the output of the individual technology, the constraint that limits changes of electricity generation between two consecutive time slices in relation to existing capacity, is introduced to the model. The main output is the cost-minimal mix of heat generating technologies and their dispatch as well as the DH prices. For a given country the DH price is calculated as the weighted average (by heat production level) of DH generation costs of individual CHPs and HOBs including costs of purchasing CO_2 allowances under consideration of the ETS. The results of TIMES-HEAT-EU underline and support the formulation of policy recommendations to foster the economic feasibility of more flexible and RES-oriented cogeneration.

3 Scenario Framework and Central Assumptions

The scenario description provides the overall qualitative framework for the modelling activities by setting-up two holistic socio-technical scenarios based on different scenario storylines, which include the definition of the main framework parameters, societal and political environment.[6] Two different main scenarios are distinguished: a reference scenario based on observed energy political trends and most recent projections as well as two policy scenarios representing ambitious decarbonisation pathways for Europe until 2050. Overall differences occur between the scenarios, both at European and country level. The main definitions of framework conditions and policy targets for the REFLEX scenarios are illustrated in Figure 9 (see also Herbst et al. 2016a).

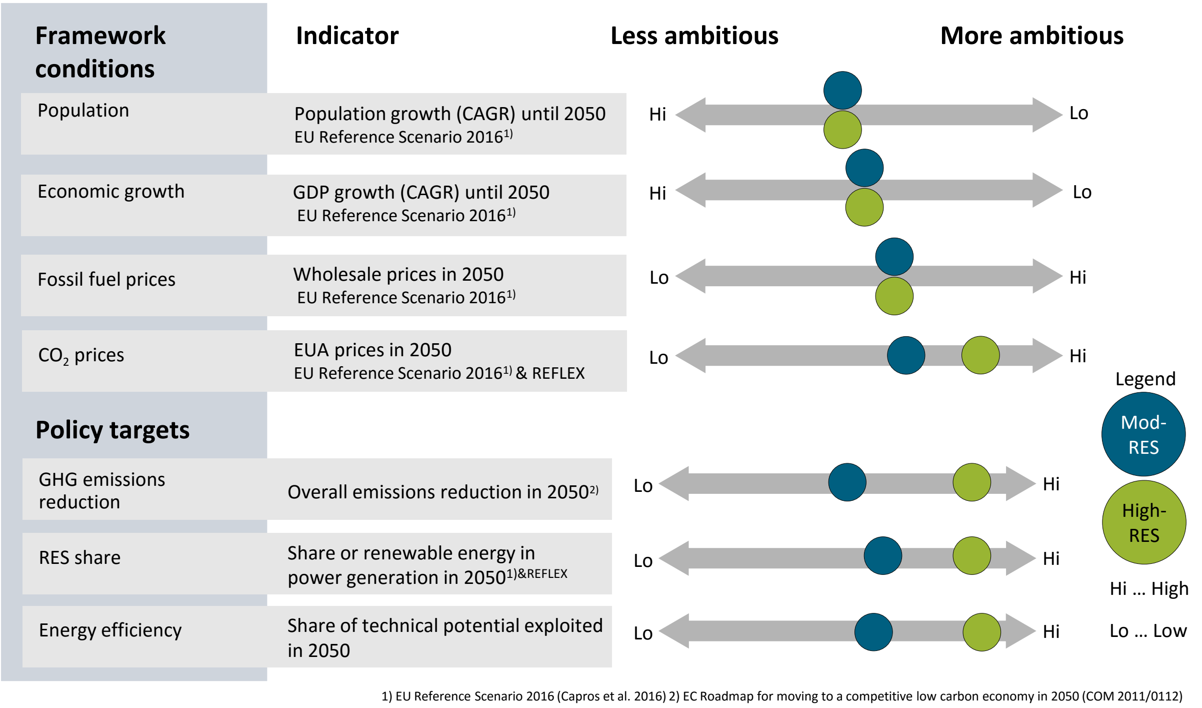

Figure 9: Framework conditions and policy targets of the Mod-RES and High-RES scenario

Source: REFLEX

The framework conditions of the *reference* or *moderate renewable scenario* (**Mod-RES**) are based on the EU Reference Scenario 2016 (Capros et al. 2016). It is defined to reflect the development of electricity demand taking into account past dynamics but also the future developments regarding current economic development and energy policies.[7] Present policy targets and actions which have been already decided or implemented will be reflected in Mod-RES. This is not necessarily the most likely or the most probable future development, but rather serves as a projection to which the policy scenarios with ambitious decarbonisation pathways are compared to (Figure 9).

The framework conditions of the *policy* or *high renewable scenarios* (**High-RES**) are similar to those of Mod-RES in terms of population and economic growth, while energy prices and CO_2

[6] This section is based on the deliverables D1.1 and D1.2, which provide more information about the scenario framework, see Herbst et al. (2016a and 2016b).
[7] The potential cut-off date is the end of 2015/2016.

prices are assumed to be higher (Figure 9). This reflects more ambitious climate policies in these scenarios. One major target of the scenarios is to limit global temperature increase to 2°C, by more drastically reducing greenhouse gas emissions and achieving the EU 2020 energy saving targets in the short term. Higher contribution from learning curves and need for flexibility options due to a large share of intermitting renewable energy are assumed. To display different possible developments of a future energy system two cases of the High-RES scenario are developed: the decentralized and the centralized scenario. The major difference concerns the amount of decentralized technologies on the generation and supply side in the sectors electricity, heat and transport. The High-RES decentralized scenario is dominated by trends to decentralized solar power, while the High-RES centralized scenario is characterised by centralized wind power.

The main drivers of the scenario framework are fossil fuel and CO_2 prices, the available demand-side flexibility, the RES expansion pathways as well as the learning curves of specific technologies. While the energy demand sector models apply a scenario specific emission reduction target, this is implicitly done for the energy supply models by different CO_2 price development paths. In the following subsections the main drivers are explained more in detail.

3.1 Quantitative Framework Assumptions

The macroeconomic framework data (gross domestic product, gross value added, population) for the model-based analysis is taken from the European Reference Scenario 2016 (Capros et al. 2016) and stays the same across the scenarios. The reason for this assumption is the better comparability of changes in policy parameters and assumptions between the scenarios. The same holds true for the assumptions on international wholesale fossil fuel price development (coal, gas, oil) illustrated in Figure 10, which are also based on the European Reference Scenario 2016 and held constant between the scenarios.

The macroeconomic framework data presented in Table 2 indicates that industry is expected to continue growing until 2050. However, energy-intensive industries like the iron and steel industry and the non-ferrous metals industry grow below industrial average (<1% p.a.) in the scenarios. An exception is the chemical industry, which is growing at a slightly above average rate (probably caused by growth in the less energy intensive pharmaceutical industry compared to the energy-intensive basic chemicals) and the non-metallic minerals sector (including cement production). Stronger growth is to be expected in non-energy-intensive sectors like engineering (incl. vehicle construction) and the food industry, which reflects structural change in industry towards less-energy-intensive branches. Energy carrier prices are increasing up to 2050. Between scenarios only electricity prices differ, assuming a stronger increase for the policy cases compared to the reference case due to the higher share of renewables expected/necessary in the energy system.

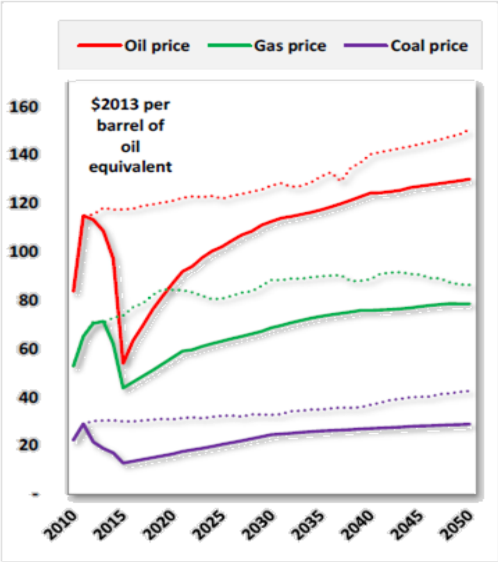

Figure 10: EU28 fossil fuel prices European Reference Scenario 2016 (2010-2050)[8]

Source: Capros et al. 2016

Table 2: Macroeconomic framework assumptions

EU 28	**Compound Annual Growth Rate (CAGR) 2015-2050**
Population (in million)	0.1 %
Gross domestic product (GDP) (in trillion EUR 2013)	1.5 %
Gross value added (GVA) industry (in trillion EUR 2013)**:**	1.0 %
Iron and steel	0.3 %
Non-ferrous metals	0.5 %
Chemicals	1.1 %
Non-metallic minerals	0.9 %
Paper	0.8 %
Food, drink, tobacco	1.1 %
Engineering	1.3 %
Textiles	-1.2 %
Other	0.9 %

Source: Capros et al. 2016

[8] The dotted lines represent the fossil fuel price assumptions of the EU Reference Scenario 2013 (Capros et al. 2013).

3.2 Availability of Demand-Side Flexibility

There is great uncertainty to which extent and at what point in time load management will be deployed throughout the EU countries.[9] Since the deployment of load management is linked to the market diffusion of smart control systems for scheduling of flexible appliances, diffusion scenarios for smart load control were developed in analogy to the higher-level scenario definition.

3.2.1 Mod-RES and High-RES Centralized Scenario

In the Mod-RES and High-RES centralized scenarios it is assumed that no further incentives to participate in demand-side-management (DSM) measures are taken. The share of flexible technologies (referred to as “smart share”) is thus mainly dependent on the willingness of companies and households to participate in DSM.

Within the REFLEX project, the smart share for the flexible appliances in the tertiary sector is therefore deduced from the survey that was conducted as part of the project (Reiter et al. 2017, see Table 3). It is further assumed that industrial companies behave in a similar manner than large companies of the tertiary sector.

To assess the current and future participation in DSM measures, the following two questions have been developed for the survey[10]:

Q1: "Does your company participate in load management measures?"

(i) Yes
(ii) No, load management has been tested but not implemented
(iii) No, currently no experience or interest in load management

Q2: "Would you allow an external company to access your energy applications to exploit the load management potential in your company?"

(i) No, absolutely not
(ii) Little imaginable
(iii) Possible
(iv) Yes, probably
(v) Definite

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[9] Dallinger (2012) has calculated that the potential revenues for the owner of an electric vehicle - through its use of a load management system and the use of price spreads on the spot market - are in the order of about 100 to 200 EUR per year. If one compares this revenue with the potential investment of approx. 2000 to 5000 EUR (according to industry information) for an intelligent charging station, it becomes clear that such an investment hardly pays off for a private car owner. On the other hand, it is conceivable that energy suppliers or distribution and transmission system operators may have an interest in raising the flexibility potential of the demand side through corresponding incentive payments. Similarly, it is also possible for the legislator to initiate financing programmes, if it becomes apparent that the introduction of load flexibility (particularly in comparison with other flexibility options) is associated with economic benefit.

[10] See Reiter et al. (2017) for the detailed survey.

If question Q1 is answered with "yes", it can be assumed that the willingness to participate in DSM measures exists. The share of currently participating companies is relatively low in all of the considered countries (see Table 3). The response rate was predefined with the survey company and includes 300 full data sets per country. Therefore, the number of respondents is limited. However, the participants were randomly selected from the group of companies fulfilling the predefined parameters such as branch, company size and language area and therefore, representing a good overview of the market potential.

Table 3: Findings from the survey in the tertiary sector

	Participate in DSM Q1: (i)	**Would allow external access for purpose of DSM** *Q2: (iii)-(v)*	**Would not allow external access for purpose of DSM** *Q2: all but (i)*
UK	6 %	9 %	26 %
Poland	3 %	30 %	69 %
Italy	4 %	19 %	58 %
Switzerland	7 %	40 %	72 %

Source: REFLEX

In the midterm future, i.e. in 2030, it is assumed that all companies will participate in DSM that are willing today to allow an external company to exploit their DSM potential. These are the companies that answered question Q2 with "possible", "yes, probably" or "definite". When now other incentives or regulations are taken, we assume that in the long-term future, i.e. 2050, all companies will participate DSM that are today not absolutely against an external company exploiting their DSM potential. With the three data points resulting from the survey, a logistic S-curve could be defined that reflects the smart share in the different countries for all future years (see Figure 11).

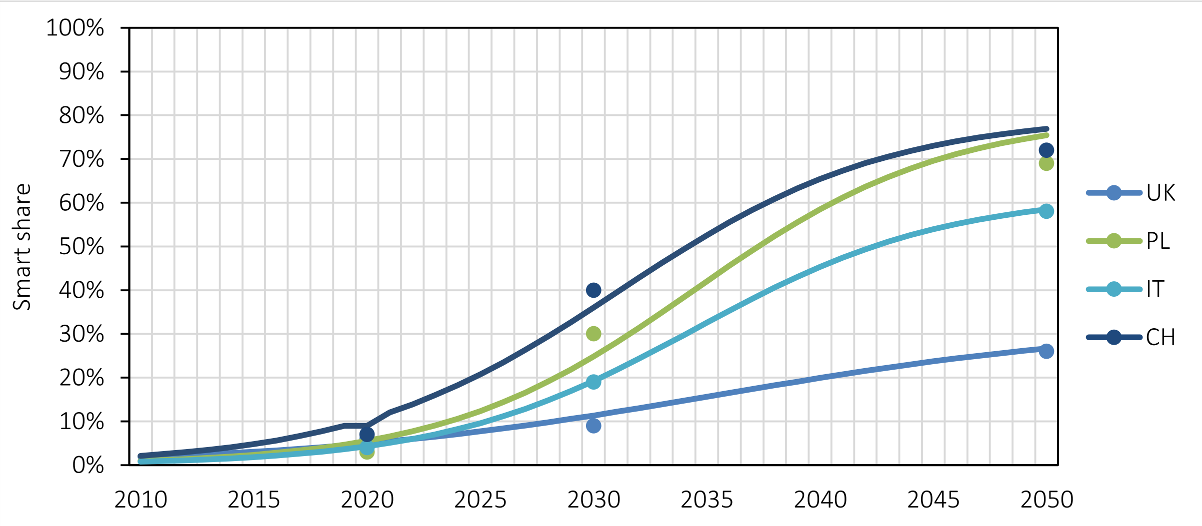

Figure 11: Smart share in the tertiary and industry sector

Source: REFLEX

For the residential sector, it is assumed that all newly installed appliances for which smart control has no effect on performance or consumer comfort, such as heat pumps, will be DSM ready from 2025 onwards. For consistency, the smart share of electric vehicles and air-conditioning was taken from the Set-NAV project.

Table 4: Smart share in the residential sector and for private electric vehicles

	2020	2030	2040	2050
Heat pumps	6 %	25 %	58 %	75 %
Electric vehicles	3 %	9 %	22 %	31 %
Air-conditioning	3 %	9 %	22 %	31 %

Source: Set-NAV and REFLEX

As empirical data is only available for four countries, country-analogies are used to derive the potential DSM development for all EU28 countries, Norway and Switzerland (see Table 5).

Table 5: Country groups for assignment of smart share

Country group	Assigned countries
“high acceptance”	BE, DK, EE, FI, NL, SE, NO, **CH**
“high potential acceptance”	AT, FR, DE, LV, LU, **PL**, SI
“medium acceptance”	CY, CZ, ES, GR, HU, **IT**, PT, SK, RO, BG, HR
“lower acceptance”	IE, **UK**

Source: Set-NAV and REFLEX

3.2.2 High-RES Decentralized Scenario

In the High-RES decentralized scenario it is assumed that DSM measures are encouraged to facilitate renewable integration on a local level. Therefore, ambitious smart shares for all three sectors are assumed. New flexibility options, namely *decentralized batteries* and *hydrogen electrolysers*, are considered to be 100 % DSM ready from the time of their installation. It should also be noted that in the High-RES decentralized scenario, it is assumed that hydrogen is produced on site at the industrial plants and therefore, the electricity consumption is on the demand side (in contrast to the High-RES centralized scenario, where hydrogen is produced on centralized plants and the demand side consumes hydrogen directly instead of electricity). The smart shares for the tertiary, industry and residential sector as well as for batteries and electrolysers are presented in the following Table 6.

Table 6: Smart shares in the High-RES decentralized scenario

	2020	2030	2040	2050
Tertiary, industry sector	6 %	50 %	92 %	99 %
Residential sector	3 %	50 %	92 %	99 %
Hydrogen electrolysis	100 %	100 %	100 %	100 %
Batteries	100 %	100 %	100 %	100 %

Source: REFLEX

3.3 Renewable Energy Expansion Pathways

For the centralized and decentralized scenarios, the theoretical share of RES at total electricity generation needs to be defined for each European country. In addition, these shares need to be allocated technology specific shares. The RES technologies included in the REFLEX project can be categorised in controllable and intermittent RES. Controllable RES include run-of-river, biomass and other RES as geothermal plants. Intermittent RES consist of wind onshore, wind offshore as well as photovoltaic (PV) roof top and ground mounted plants. The electricity generation of controllable RES is based on the EU Reference Scenario 2016 (Capros et al. 2016) and is kept constant for all three scenarios. The share of electricity generation from intermittent RES differs between all three scenarios. Since the PRIMES Data does not distinguish between wind onshore and offshore as well as PV roof top and ground mounted plants in a first step assumptions are made for the scenario consistent intermittent RES expansion paths, as presented in Table 7.

Table 7: Assumptions on different RES shares in the scenarios

	Mod-RES	High-RES Centralized	High-RES Decentralized
Share of RES in Europe	55 %1)	82 %2)	82 %2)
Share of wind generation on total RES generation in 2050	56 %1)	62 %2)	52 %
Solar rooftop ratio of total solar generation in 2050	≥ 30 %	≥ 20 %	≥ 40 %
Wind offshore ratio of total wind generation in 2050	15 %1)	30 %	15 %

1) Based on PRIMES Reference Scenario Data; 2) Based on PRIMES High Renewable Scenario Data (Capros et al. 2016)

Source: REFLEX, based on Capros et al. 2016

The total RES share for Europe is based on the EU Reference Scenario for the Mod-RES scenario and on the PRIMES High Renewable scenario for the two High-RES scenarios. The input data also differs regarding the share of wind generation with 56 % in the Mod-RES scenario and 62 % in the High-RES centralized scenario. In the decentral High-RES scenario this share is decreased by 10 % and the solar share is vice versa increased by 10 % compared to the central scenario. Furthermore, Table 7 shows the assumptions concerning the allocation of the wind and PV generation to the more detailed technology representation applied in the REFLEX project. Again, to be consistent with the scenario frameworks the High-RES decentralized scenario is determined by a higher share of solar roof top plants on total solar generation as well as a lower wind offshore ratio on total wind generation. In addition, the RES share per country is limited to 95 % in each scenario. The overall RES share in power generation by country does not differ between the centralized and decentralized scenario.

The second step includes the simulation of hourly intermittent RES feed-in curves. Instead of upscaling existing capacities a weather data based optimal renewable allocation planning approach is applied. The capacity expansion for wind and solar plants is calibrated for the year 2015 and afterwards based on the EU Reference Scenario and on the high renewable path discussed above. The hourly times series of the generation of wind onshore and offshore as well as solar ground mounted and roof top are based on 20 x 20 km weather data of the Anemos data base. The capacity expansion is further restricted by geospatial information about land use, protected areas and surface roughness. By using weather data generation, potentials of the different intermittent RES technologies within Europe can be derived. The pattern of the optimal allocation planning for these plants is therefore based on these potentials, while technology costs only influence the costs of the different expansion paths.

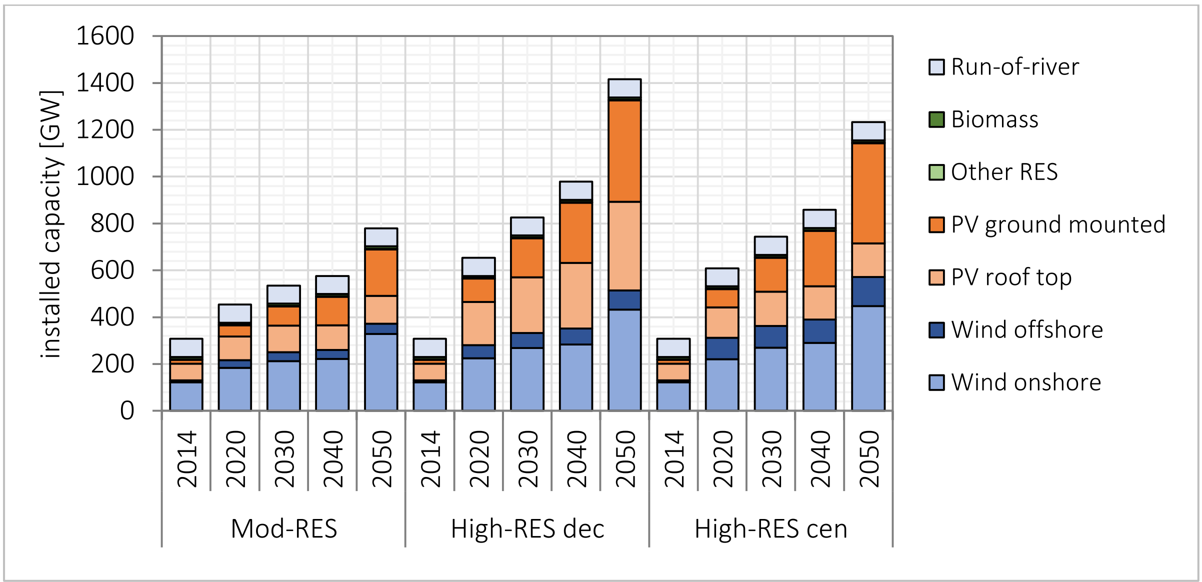

Figure 12: Capacity expansion paths in the REFLEX scenarios

Source: own illustration based on REFLEX data

Figure 12 presents the resulting capacity expansion paths in the scenarios. Starting from the same installed capacities for all scenarios in the year 2014 the Mod-RES scenario shows about 800 GW of RES capacities in the year 2050. More than 370 GW of the installed capacity are wind power plants. The High-RES scenarios have higher installed capacities to cover the assumed shares of over 80 % on the electricity generation. Since solar based electricity generation is characterised by a lower availability compared to wind the higher PV shares in the decentral scenario require more overall capacities (1400 GW) compared to the central scenario (1200 GW).

Analysing the resulting generation for the year 2050 in the Mod-RES scenario the intermittent RES capacities generate around 1470 TWh with more than the half generated by wind power plants (see Figure 13). While there are 2680 TWh produced in the High-RES scenarios in 2050 there is a clear difference between the amounts of electricity generated by PV ground mounted and wind offshore in the central and decentral scenario respectively.

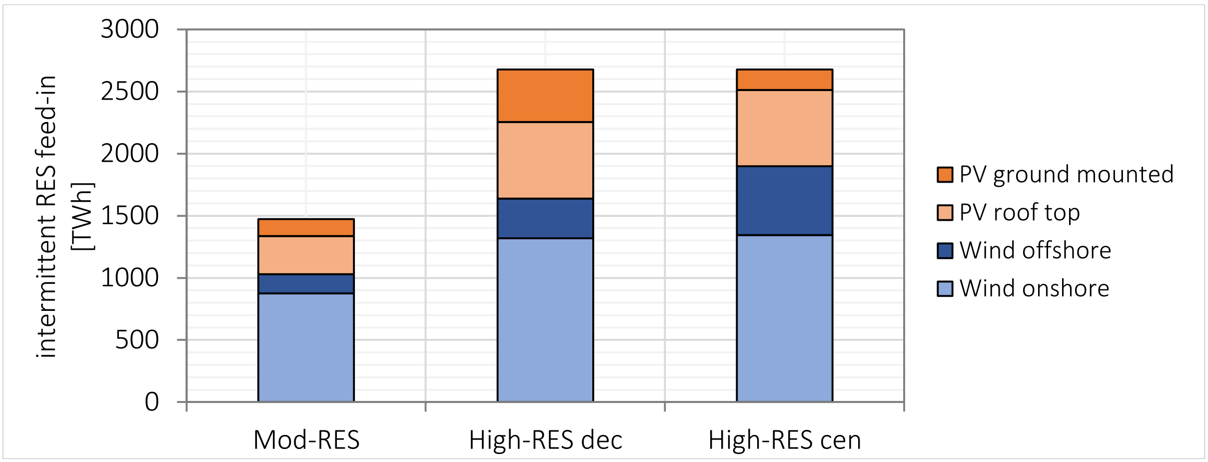

Figure 13: Intermittent RES generation in the REFLEX scenarios

Source: own illustration based on REFLEX data

3.4 Technological Learning Progress and Costs Assumptions

Technological Learning

In WP4 a set of energy models, representing all sectors of the energy system, are coupled to analyse which technologies that offer energy flexibility can play a role in the future energy system. A large part of this modelling activity is to determine which technologies will see increased diffusion, and which technologies will be phased out. A key consideration is how the future costs of both incumbent and upcoming technologies will develop in the future. Technology costs can decrease through a variety of mechanisms, mainly learning-by-doing, learning-by-researching (R&D), product upscaling (larger products) and production upscaling (larger production facilities). Experience curves are one of few methods that use empirical data to derive a mathematical function that relates cost decreases of a technology to cumulated production experience. Using experience curves, future costs of a technology can be estimated, given some exogenously derived development of cumulative production. Since the modelling activities within WP4 (task 4.2 and 4.3) require accurate cost estimations of different technologies in the future energy system, WP3 focused on gathering empirical data to develop future cost estimations using experience curves.[11]

Experience curves are based on the concept in economics that the production costs of a technology (or other parameters relating to the economic performance) improve significantly as producers gain experience with production of this technology. The experience curve was developed by the Boston Consulting Group (BCG 1968), as an evolution of previously known learning effects in manufacturing (Junginger et al. 2010). BCG presented the experience curve to describe the reduction of total product costs as a function of cumulative production of this product.

$$C(cum) = C_1 \cdot cum^b \qquad (3.1)$$

Where $C(cum)$ is the cost C of the product at cumulative production cum, C_1 is the cost of the first unit produced, and b is the experience parameter. Two terms have been connected to the experience parameter b: the progress ratio (PR) and the learning rate (LR).

$$PR = 2b \qquad (3.2)$$

$$LR = 1 - 2b \qquad (3.3)$$

At a learning rate of 20 % (PR of 80 %), the cost of a product decreases with 20 % for every doubling of cumulative production cum. The experience curves are the basis for the implementation of technological learning and cost reductions with cumulative deployment in a number of the energy models included in D4.3 of the REFLEX project. However, experience curves can only be used to project production costs of technologies, but these do not necessarily reflect market prices, which also depend on demand, subsidies, competition with other technologies, and other exogenous factors.

[11] This section is based on the REFLEX Policy Brief „Technological Learning in Energy Modelling: Experience Curves" by Louwen et al. (2018a and 2018b).

The Table 8 below gives an overview of determined learning rates and learning rate errors for specific technologies. These data have been assessed on behalf of WP3. More details can be found in deliverable 3.2 "Comprehensive Report on Experience Curves" (Louwen et al. 2018a).

Table 8: Overview of learning rates and learning rate errors for selected technologies

Technology	Learning rate	Error	Cumulative data unit	Functional unit
Solar PV: modules	21.4%	0.8%	MW installed	Wp
Solar PV: BOS	12.9%	1.7%	MW installed	Wp
Solar PV: systems	18.6%	1.0%	MW installed	Wp
Power-to-H_2 (alk. electrolysis)	17.7%	5.3%	GW installed	kW
Heat pumps	10.0%		Units sold	kW
Gas + CCS	2.2%		MW installed	kW
NGCC + CCS	2.2%		MW installed	kW
Coal + CCS	2.1%		MW installed	kW
Industrial CCS	11%-12%		n.a.	n.a.
Residential lithium-ion storage	12.5%	3.0%	GWh sold	kWh
Utility lithium-ion storage	15.2%	3.7%	GWh sold	kWh
Utility redox-flow storage	14.3%	6.1%	GWh sold	kWh
BEV battery packs	15.2%	2.9%	GWh sold	kWh
FCEV fuel cell stacks	18.0%	1.7%	GWh sold	kWh
HEV battery packs	10.8%	0.6%	GWh sold	kWh
Wind offshore system	10.3%	3.3%	GW installed	MW
Wind onshore system	5.9%	1.3%	GW installed	MW
PEFC micro-CHP	19.3%	1.6%	Units sold	kW

Source: REFLEX based on Louwen et al. 2018 a and 2018b

For all technologies the experience curves show production or price decline. No technology has been identified with increasing costs (not over several cumulative doublings of deployment). In some cases, especially onshore and offshore wind, prices have remained stable or even increased in a number of years. This can (almost always) be attributed to market effects and does not imply that actual production cost did not decline. The highest rates observed are for PV modules, which also show the lowest error term and thus can be extrapolated with fairly high confidence. On the other hand, the error in e.g. the experience curve slope for utility redox-flow storage is significant, and extrapolation over 2-3 cumulative doublings would already result in a large range of possible costs. These aspects will need to be taken into account when evaluating the model results.

Cost Assumptions

The Table 8 represents the original technologies selected at the start of the REFLEX project. Since the scenarios analysed in REFLEX determine the penetration levels of e.g. renewable electricity generation technologies beforehand (see Chapter 3.3), future costs do not affect the investment decisions in these technologies and thus experience curves for wind and photovoltaic power plants will not be implemented, but only used ex-post to analyse the cost developments of these technologies. While for technologies without technological learning progress an overview is given in Table 26 in Annex B, Table 9 below represents investment cost assumptions for technologies, which are implemented in the sectoral based energy system models with technological learning progress. For technologies as power-to-x, CCS, batteries or CHP technological progress is considered from 2014 to 2050. Due to the scarcity of data no differences exist for batteries and power-to-x between the Mod-RES and High-RES scenarios.

Table 9: Costs assumptions of selected technologies, that are implemented in considered sectoral based energy system models

Technologies with learning progress and implemented in models	**Investment costs in EUR/kW$_{el}$**			
	Mod-RES		**High-RES**	
	2014	**2050**	**2014**	**2050**
Power-to-H_2 (alk. electrolysis)	1,370	784	1,370	784
Power-to-heat (heat pumps)	401	243	401	243
Gas + CCS	1,225	1,079	1,231	1,072
NGCC + CCS	1,207	991	1,231	1,004
Coal + CCS	3,186	2,677	3,265	2,657
Lignite + CCS	3,868	3,324	3,904	3,300
Utility lithium-ion storage (1 MWh/MW)	868	199	868	199
Utility lithium-ion storage (4 MWh/MW)	3,028	694	3,028	694
Utility lithium-ion storage (10 MWh/MW)	7,348	1,684	7,348	1,684
Utility redox-flow storage (10 MWh/MW)	4,222	752	4,222	752

*data rounded to the thousanth place

Source: REFLEX data based Schröder et al. (2013) and Louwen et al. (2018a and 2018b)

4 A Low-Carbon Energy System for Achieving the 2050 Policy Objectives

This chapter provides in-depth analyses on the comprehensive modelling results regarding the development of the annual final energy demand and consumption as well as on the techno-economic assessments of low-carbon technologies. Additionally, the interferences with focus on flexibility options of different European energy sectors are evaluated. Therefore, fundamental bottom-up models of the demand side sectors (FORECAST, eLOAD), the transport (ASTRA), electricity (ELTRAMOD) and heat (TIMES-HEAT-EU) sector are applied. The general assumptions of each model and the given scenario framework presented in Chapter 3 have a strong impact on the demand side model results in Chapter 4.1 (FORECAST, eLOAD, ASTRA), which consequently influence the results of the supply side models in Chapter 4.2 (ELTRAMOD, TIMES-HEAT-EU). In Chapter 4.1.1 the developments on the annual final energy demand in the industry, residential, tertiary and transport sector are analysed. The hourly demand side model results and the demand side flexibility are estimated in Chapter 4.1.2. The supply side developments in the electricity and heat sector regarding the capacity and generation technology mix are analysed in Chapter 4.2. For each sector CO_2 emissions have been estimated and analysed in Chapter 4.3.

4.1 Demand Side Developments

In the following section, the results of the demand models ASTRA (annual), FORECAST (annual) and eLOAD (hourly) in the project are discussed. The following analyses are based on the overall scenario definition in section 3 and detailed sector-specific assumptions as discussed below. The chapter is divided into two sections: first, the analysis and discussion of the annual model results; second, the analysis and discussion of the hourly model results and demand-side flexibility. The sectors analysed in the following are: the industry, residential, tertiary and transport sector.

4.1.1 Annual Final Energy Demand

To give an overview, the overall energy demand developments in the REFLEX scenarios are presented at first. Figure 14 shows the total energy demand for the EU 28 (final energy demand plus energy content of feedstock use in the chemical industry, see 4.1.1.1) by sector and scenario from 2014 to 2050 in TWh. In the Mod-RES scenario total energy demand is already decreasing by 8% between 2014 and 2050, due to energy efficiency progress and fuel switch driven by electricity and CO2-prices. In the more ambitious High-RES scenario the reductions in energy demand are more drastic from 12151 TWh in 2014 to 8882 TWh in the centralized scenario (-27%) and 8944 TWh in the decentralized scenario (-26%) in 2050. The sectoral distribution of energy demand over time stays nearly the same as in 2014 in the High-RES policy scenario in 2050: transport (30%), industry (29%) + feedstock (6%), residential (29%, slight increase), tertiary (12%, slight decrease). For a more detailed energy demand and emission analysis on sector level, see the subsections below.

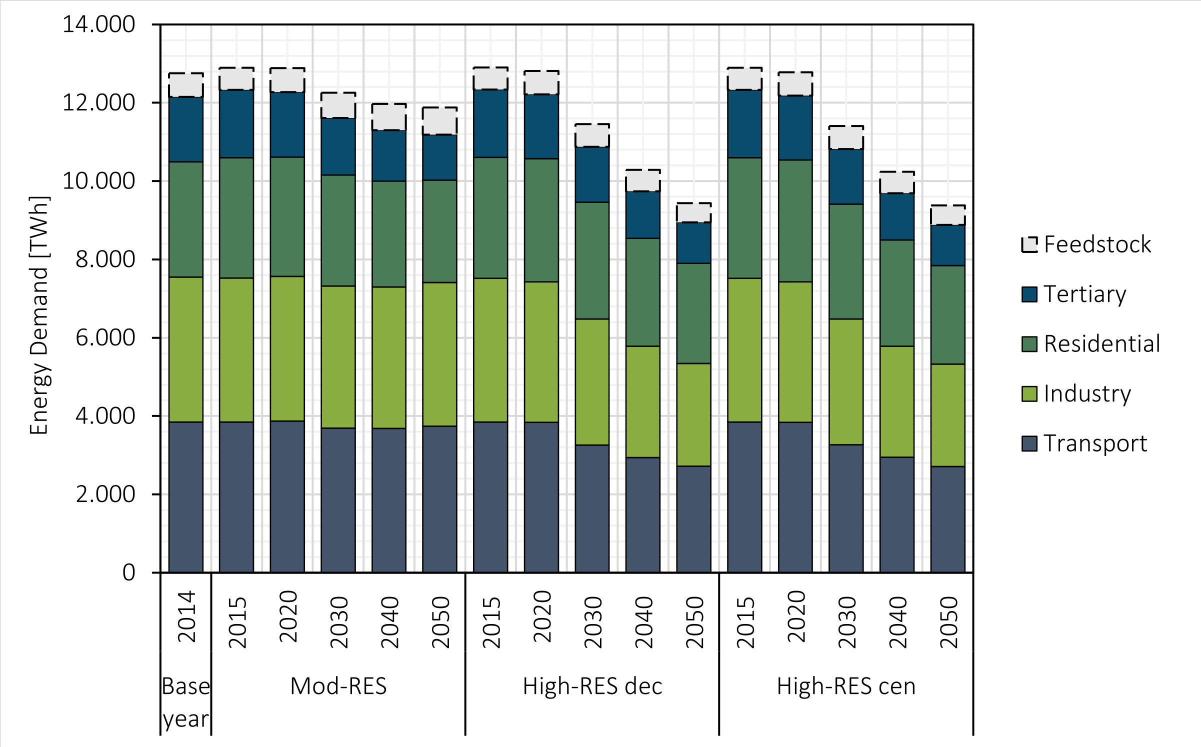

Figure 14: EU28 Total direct emissions from transport, industry, residential and tertiary (2015-2050)

Source: FORECAST, ASTRA

4.1.1.1 Industry Sector

The industrial sector accounts for around 25 % of the EU28 final energy demand. It mainly uses fossil fuels such as gas, coal and oil, but also electricity. Energy-intensive industries and processes/products like e.g. steel (iron and steel), cement (non-metallic minerals), and ammonia (chemicals) being mainly accountable for demand and CO_2-emissions. Some sectors already use a high proportion of electricity and biomass, but industry needs to make significant further efforts to reduce the use of fossil fuels in the coming decades. A particular challenge is the reduction of process emissions, as these emissions can only be reduced by radical changes in the production process, product mix or the use of CO_2 capture and storage. In terms of end-use, most industrial greenhouse gas emissions result from high-temperature process heat, either in the form of steam or hot water, or from direct firing of different types of furnaces. The high temperatures and the specific technological requirements limit the use of renewable energies to biomass or secondary energy sources. The above-mentioned process-related emissions account for around 2 % of all direct emissions and are very difficult or even impossible to avoid in the processes currently used (Herbst et al. 2018a, 2018b, 2018c).

Scenario assumptions

In the following, three scenarios will be analysed for the industry sector including refineries (which are normally assigned to the transformation sector in the Eurostat energy balance, see Eurostat (2018)). In the Mod-RES scenario energy efficiency progress in industry is expected to take place according to the current policy framework and historical trends. The same holds true for recycling and material strategy improvements. Fuel switch in the Mod-RES scenario is taking place to some extent but is mainly driven by energy and CO_2 price developments (see Table 10). In the High-RES scenarios any remaining energy efficiency potentials in industry are almost completely exploited implying that effective policies are in place to overcome barriers to improved energy efficiency (e.g. EMS, audits, minimum standards). In addition, high financial support for RES is assumed to support fuel switching to biomass[12], power-to-heat and power-to-gas (see Table 10). Radical changes in industrial process technologies also drive fuel switch to hydrogen in the iron and steel and the chemical industry. Further, radical process changes take place in the cement and glass industry, assuming the market entry of low carbon cement sorts and electric smelting furnaces. In addition, a stronger switch to secondary production takes place in the steel, aluminium, glass and paper industry as well as increasing efforts for material efficiency improvements (e.g. trends to higher value added via product accompanying services or higher quality products) and substitution (e.g. wood in the construction sector, magnesium and aluminium in vehicle construction) are assumed.

Furthermore, a CO_2 price increase to 150 EUR/tCO_2 in 2050 is assumed. Companies in the High-RES scenario can anticipate increasing prices ten years in advance, implying a stringent and well-communicated commitment to the EU ETS or even a CO_2 floor price path.

In the High-RES scenario, two different versions are calculated:

- A **High-RES centralized** case reflecting a world in which heat supply is managed more on a centralized level (e.g. city level) and large-scale thermal storages and heat pumps are available.

- A **High-RES decentralized** case reflecting a world in which heat supply is managed more on an individual level (e.g. plant, building).

Consequently, in the High-RES centralized scenario, the financial support of district heating is higher compared to the decentralized case, where the support of biomass and electricity is correspondingly higher. In addition, in the High-RES decentralized scenario, hydrogen is produced on-site for industrial purposes and consequently leading to a high on-site industrial electricity demand for hydrogen electrolysis. In the central case, hydrogen electrolysis for all end-users takes place on central level at the energy suppliers, implying that in this case the companies do not purchase electricity but hydrogen directly from the utilities. In the industry sector, both High-RES scenarios are driven by the emission reduction targets and can thus be seen as normative scenarios.

[12] See Annex C for information about the calculation of the potential.

Table 10: Scenario characterisation for the industry sector by mitigation option

Clusters of mitigation options	Mod-RES	High-RES
Incremental efficiency improvement	Energy efficiency progress according to current policy framework and historical trends.	Faster diffusion of **incremental process improvements** (BAT & INNOV ≥TRL 5).*
Fundamental processes improvement	-	**Radical process changes** (INNOV ≥TRL 5)
Fuel switching to RES, decarbonised electricity and hydrogen	Fuel switching driven by energy prices and assumed CO_2 price increase.	**High financial support** for RES technologies (biomass, power-to-heat, power-to-gas). Additional financial support for the use of district heating in the centralized scenario. **Radical changes** in industrial process technologies drive fuel switch (e.g. **switch to hydrogen**).
Recycling and re-use	Slow increase in recycling rates based on historical trends.	Stronger **switch to secondary production**
Material efficiency and substitution	Based on historic trends.	**Increase in material efficiency and substitution**.

* BAT – best available technology, INNOV – innovation, TRL – technology readiness level

Source: FORECAST

Scenario results regarding the industry sector

The presented results show the impacts of the above mentioned mitigation options, such as incremental and BAT energy efficiency improvements, fundamental process improvements, fuel switching, recycling and re-use, as well as material efficiency and substitution on EU28 CO_2 emissions and energy demand. In both ambitious policy scenarios significant direct emission reductions of 73 % compared to 2015 can be achieved (see Figure 15). This corresponds to an 83 % direct emissions reduction compared to 1990.

In the iron and steel industry 90 % of direct emissions are reduced in 2050 in the High-RES scenarios compared to 2015. This major reduction was achieved by replacing oxygen steel as far as possible with electric steel and substituting the remaining blast furnace route with electrolysis based direct reduction and hydrogen-based steel production routes (H_2 plasma steel, DR H_2+EAF). Direct emission reductions in the non-metallic minerals sector achieve -55 % in 2050 compared to 2015. Portland cement production is substituted in the High-RES scenarios by different innovative cement sorts using new binders and reducing the specific energy- and process-related cement emissions by between -30 % and -70 %. Further potentials in the non-metallic minerals sector have been tapped using electric melting processes in the glass industry as well as incremental process improvements (e.g. oxyfuel combustion incl. waste heat recovery) and fuel switching.

Remaining emissions in 2050 in the High-RES scenarios stem mainly from the use of natural gas (~30 % of total direct emissions in 2050) and chemical reactions within the production process (process emissions: ~40 % of total direct emissions in 2050). The main contributor of industrial CO_2 emissions in 2050 in the High-RES scenarios is the non-metallic minerals sector (42 % in 2050) including emissions from smaller point sources (e.g. bricks, lime, ceramics) and the remaining process emissions in the cement and glass industry. The chemical industry is responsible for 16 % of the remaining direct emissions in 2050 mainly caused by the use of natural gas and process emissions.

The European Roadmap for moving to a competitive low carbon economy in 2050 has identified a target of -83 to -87 % emission reductions for the industry sector in 2050 (European Commission 2011a). This target is in line with the emission reduction shown in the High-RES scenarios. However, to achieve a higher level of emission reduction than shown in the REFLEX High-RES scenarios (-83 % compared to 1990) the use of synthetic methane instead of natural gas in 2050 is conceivable. But the costs of such an option are uncertain and likely to be very high. This is the reason why this option is not further pursued in the REFLEX project.

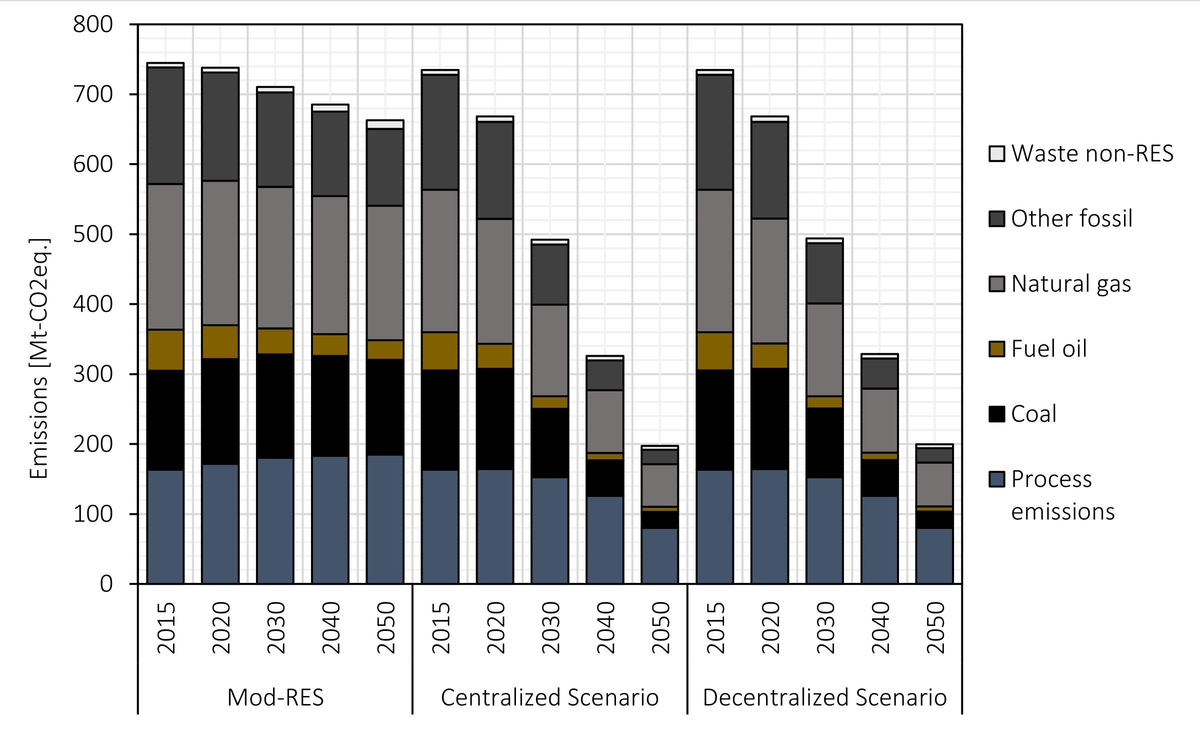

Figure 15: EU28 industrial direct emissions by energy carrier (2015-2050)

Source: FORECAST

In the Mod-RES scenario industrial final energy demand (including refineries) is only slightly decreasing by -1% from 3704 TWh in 2014 to 3668 TWh in 2050 (see Figure 16). In the High-RES scenarios, final energy demand is decreasing by ~-29 % to 2615 TWh in the centralized and 2626 TWh in the decentralized case in 2050. Main energy carriers used in 2050 in the High-RES scenarios are electricity (1422 TWh High-RES central, 1469 TWh High-RES decentral), biomass (231 TWh High-RES central, 242 TWh High-RES decentral), ambient heat (231 TWh High-RES central, 272 TWh High-RES decentral) and natural gas

(299 TWh High-RES central, 308 TWh High-RES decentral). Whereby electricity is with a share of 54-56 % in final energy demand by far the most important energy carrier in industry in 2050. Due to higher financial support of district heating in the High-RES centralized scenario, the share of district heating in final energy demand is higher (7 % compared to 3 % in High-RES decentralized scenario) while in the decentralized case the share of electricity and biomass is correspondingly higher.

The decrease in final energy demand is less pronounced than the change of direct CO_2 emissions due to an increasing demand for secondary energy carriers like electricity and hydrogen in the ambitious policy scenarios that counteract the effects of incremental process improvements and material efficiency on final energy demand. An important field for fuel switching are industrial furnaces. Furnaces often work at high temperatures above 1000°C, e.g., in the cement, glass and steel production. Fuel switching is possible, but the use of energy carriers experiences technical restrictions and RES are sometimes difficult to integrate. In the High-RES scenarios, a strong shift towards electricity and hydrogen takes places for example in the iron and steel industry (DR electrolysis, H_2 plasma, DR H_2+EAF) and the glass industry (electric melting). In general, electricity, ambient heat, biomass substitute a large part of industry's demand for natural gas in High-RES scenarios (see Figure 16).

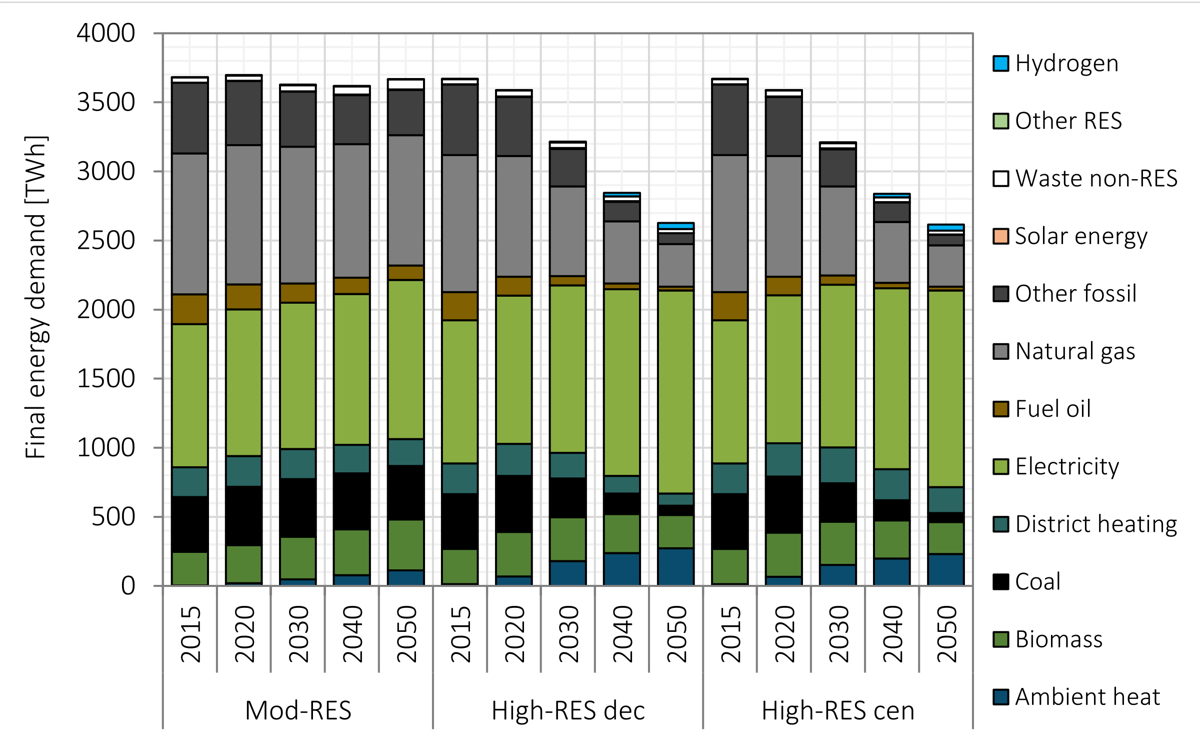

Figure 16: EU28 industrial final energy demand by energy carrier (2015-2050)

Source: FORECAST

Another important aspect of the High-RES scenarios are the assumed radical process improvements in the chemical industry. Due to these improvements the production of ammonia, methanol and consequently ethylene is no longer based on fossil sources (e.g. natural gas, naphta) leading to a significant drop in demand for refinery products.[13]

[13] International trade is assumed to remain constant between scenarios.

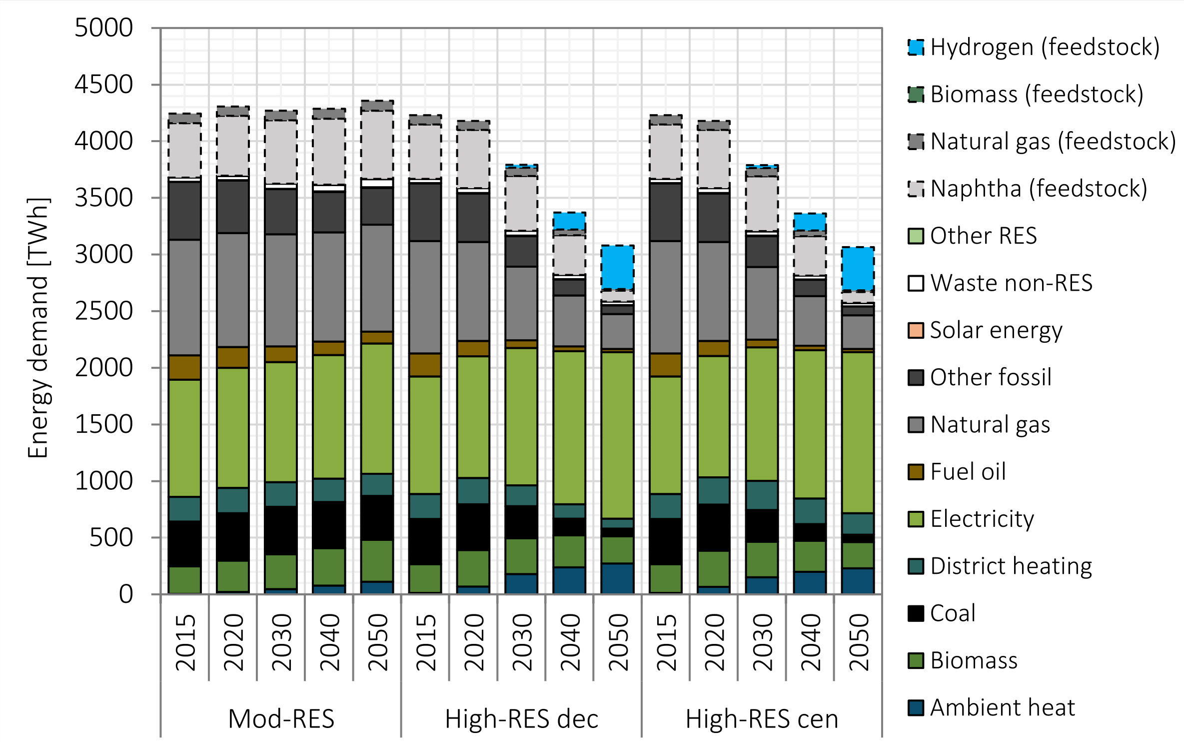

Figure 17: EU28 industrial final energy demand by energy carrier including feedstock demand (2015-2050)[14]

Source: FORECAST

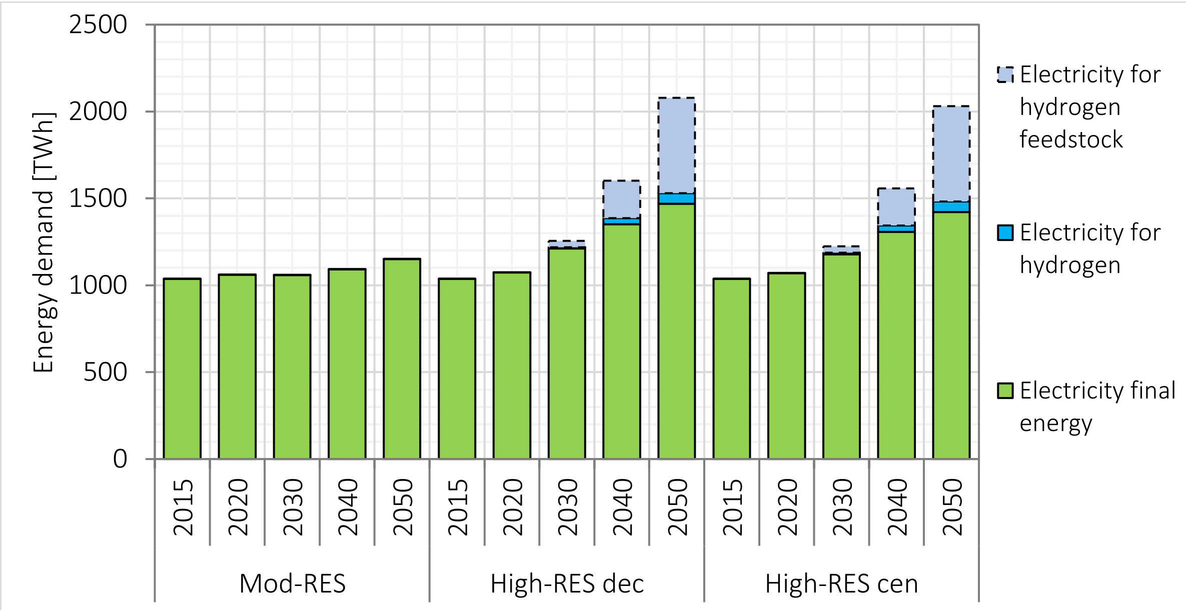

Figure 18: EU28 industrial final electricity including demand for feedstock (2015-2050)[14]

Source: FORECAST

H_2 feedstock use is assumed to take place at a large scale leading to additional 384 TWh of hydrogen demand to the industrial final demand (see Figure 17 and Figure 18). The emission

[14] Dotted bars relate to feedstock demand. Hydrogen is split up into feedstock and energetic use. Electricity consumption does not include demand for hydrogen electrolysis.

reductions due to feedstock switches in the chemical industry are not considered in the above shown analysis of direct CO_2 emissions (Figure 15) and would lead to further emission reductions depending on the electricity generation mix. If hydrogen is produced exclusively via electrolysis using electricity from RES, than these products would be CO_2 neutral.

The processes currently used to produce energy-intensive basic material products have been optimised over many decades consequently the remaining energy efficiency potentials due to applying the BAT are limited. In addition, fuel switching from fossil fuels like natural gas to RES is limited due to the high temperature levels required in industrial furnaces and the competition for biomass with other sectors. Although incremental improvements of energy efficiency and fuel switching are important pillars of industrial decarbonisation pathways, these two options alone will not suffice to achieve a low-carbon industry sector by 2050.

Deep emission cuts require substantial changes in the iron and steel, cement and chemicals industries, but also support for RES and energy efficiency in other sectors and companies. Biomass is the most important RES in industry, particularly in the medium term. However, biomass resource potentials and their sustainability are limited. In the long-term, RES-based electricity (power-to-heat) can play a more important role, particularly if electricity generation has very low emission levels. However, electricity is not yet competitive with biomass even in the most ambitious transition policy scenario, meaning that replacing biomass by electricity require policies that are more specific.

The scenarios envisage radical changes to industrial production systems like innovative processes and large-scale power-to-heat for steam generation mainly in the time horizon after 2030. Before 2030, energy efficiency improvements combined with fuel switching to biomass and progress towards a circular economy are the main mitigation options that drive CO_2 emissions downward. However, in order to have new process technologies and innovations ready by 2030, substantial research, development and innovation activities need to take place in the coming decade. Pilot and demonstration plants need to be built to prepare for market introduction. It might easily take ten years for new processes in the materials industry to progress from lab-scale to market. Certification processes such as those needed for new cement types can prolong the time taken even more.

Consequently, the current policies need to be adjusted in order to effectively support R&D activities directed at the decarbonisation of industrial production (see Chapter 5). In general, it is necessary to set incentives towards a low-carbon industry as early as possible to accelerate the market entry of efficient and innovative processes as increases of CO_2 price probably take place after 2040 and consequently affect only a small share of investment decisions taken.

4.1.1.2 Residential Sector

The residential sector accounts for more than 25 % of EU final energy demand in 2015, of which over 80 % is consumed for residential heating (Eurostat 2018). The remaining energy end uses include mainly electrical appliances and ventilation in households. Thus, the dominant energy carriers in the residential sector are on the one hand electricity and on the other hand gas and fuel oil. The share of electricity demand for appliances is 66 % in 2015, while electric boilers for domestic hot water and electric space heating have an equal share (Eurostat 2018). Within the residential sector, the future adoption of heating technologies plays a crucial role for the future achievement of European climate targets. This includes substantial further efforts to increase the energy efficiency of buildings and reduce the use of fossil fuels. Additionally, the adoption of more efficient appliances can lead to a further reduction of electricity demand. The source for direct GHG emissions from the residential sector is space heating and hot water demand, accounting for 12 % of the direct demand-side emissions. In the following, transition pathways for residential buildings and appliances will be analysed in different scenarios.

Scenario assumptions

The socio-economic drivers like population, space per dwelling, number of households and disposable income remain the same between all scenarios (Capros et al 2016). The scenario-specific assumptions include behavioural aspects like adoption of new technologies and overcoming of barriers and policy measures like financial incentives and regulations. An overview is given in Table 11. In the Mod-RES scenario, the main regulations and stay in force and are implemented as far as announced (state 2018). This includes the national implementations of the Directive on Energy Performance of Buildings (EPBD) (Directive 2010/31/EU) defining building standards and the Ecodesign Directive (Directive 2009/125/EC) defining efficiency classes for appliances and electrical products. It should be stated, that the specified requirements are already high, even though the compliance is not 100 %. The refurbishment rate of residential buildings stays constant, and the average lifetime of heating systems is 30 years, resulting in slow technological adoption as old oil and gas boilers stay in the system for a long time.

In the High-RES scenario, the remaining energy efficiency potentials are almost completely exploited implying that effective policies are in place to overcome barriers to improved energy efficiency (e.g. building minimum standards). This results in a high adoption of efficient appliances and a deep refurbishment depth, complying to the minimum standards. However, even though the refurbishment rate increases up to 70 % compared to the base year, it is by far not sufficient for the retrofit of all buildings. This reflects the still existent barriers to building refurbishment for the owners, even though it is economically to do so. Regarding the heating technologies, financial support for investments of heat pumps and district heating is implemented, leading to a high RES share. Furthermore, the installation of new oil boilers will be prohibited in the EU28 from 2030, and regulations as well as incentives are in force for shortening the average lifetime to 20 years. The Ecodesign Directive (2009) is tightened, introducing new efficiency classes. The High-RES scenario is distinguished by central and decentral, implying a different expansion of heating networks. In the central scenario, heating system networks are installed or reinforced so that more buildings connect to it, which allows a more central decarbonisation of buildings. In the decentral scenario, the share of biomass and heat pumps is correspondingly higher.

Table 11: Scenario characterisation for residential buildings by mitigation option

Clusters of mitigation options	Mod-RES	High-RES
Energy efficiency of residential buildings Building standards for new and renovated buildings, compliance	Current national implementation of regulations (nearly zero-energy buildings from 2021), high compliance	Higher building standards for renovation, very high compliance, financial incentives
Renovation rate	Remains at the current status	Increases by 70 % (up to 2 %) until 2050
Heating supply Technology choice, lifetime	Implemented national incentives and subsidies stay in force, no additional fuel tax average lifetime 30 years	Financial incentives for heat pump investments, financial revenue for heat pump flexibility, expansion of district heating networks, ban of oil boilers from 2030, additional tax on gas and oil average lifetime 20 years
Energy efficiency progress of appliances	Ecodesign directive (2009) in today's implementation and further announced reinforcement	Ecodesign directive (2009) in today's implementation and further announced reinforcement, plus new efficiency classes and more products from 2025

Source: FORECAST

Scenario results regarding the residential sector

The results presented in following analyse the impacts of the several mitigation options, like the improvement of energy efficiency of buildings and appliances as well as increasing renovation rates and the technology choice of heating supply on the residential final energy demand and CO_2 emissions. Overall, the results show that these options can lead to a reduction of the final energy demand (~ -20 % in 2050 compared to 2015) and to a significant reduction of CO_2 emissions (~ -90 % compared to 2015) in the High-RES scenario. This reflects an overall emission reduction of 91% compared to 1990.

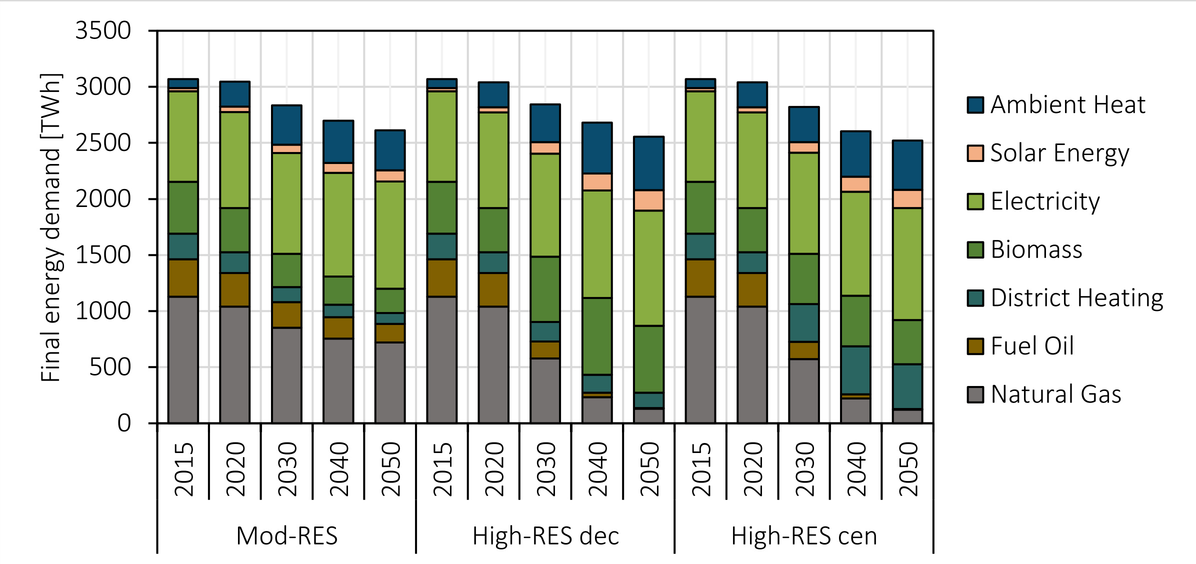

Figure 19: EU28 residential final energy demand by energy carrier (2015-2050)

Source: FORECAST

In the Mod-RES scenario, the impacts of refurbishment and efficiency measures can be shown by the final energy demand reduction of all energy carriers, as shown in Figure 19. In the High-RES scenario, the additional efficiency gains are moderate, as the measures in the Mod-RES scenario are ambitious already. However, the incentives and installation subsidies for RES heating supply as well as the shorter lifetime of heating systems have a great impact. The energy carrier composition is in strong contrast between the scenarios. In the centralized scenario, district heating networks are reinforced and more buildings can be connected to it. Thus, the district heating demand increases by 30 % although the specific energy demand is reduced until 2050 because of refurbishment and new construction of highly efficient buildings. In the decentralized scenario the heating technology choices concentrate more on decentralized solutions like heat pumps wherever possible, and biomass (increasing by 7 %).

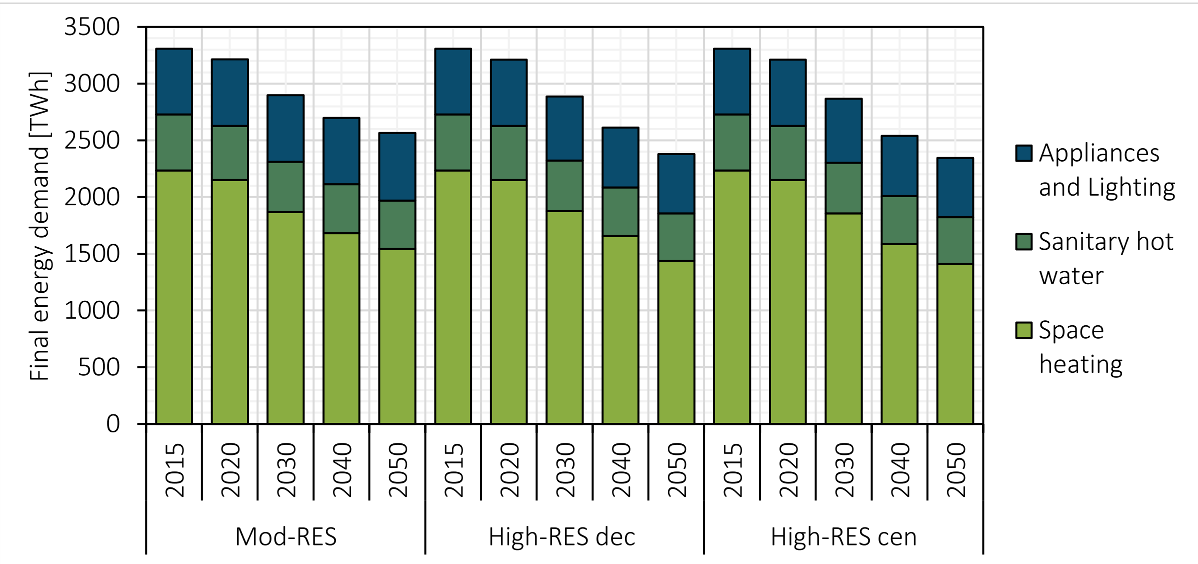

Figure 20: EU28 residential final energy demand by energy service (2015-2050)

Source: FORECAST

Comparing the reduction of the final energy demand by energy service (Figure 20) shows that the highest further reduction lies within the appliances (-10 % compared to 2015) in the High-RES scenario comparing to the Mod-RES scenario (constant compared to 2015), while sanitary hot water reduction (-15 % compared to 2015) remains constant in all scenarios. Space heating demand, which is the highest share of final energy demand, reduces by 37 % compared to 2015 in the High-RES scenario, while in the Mod-Res by 31% compared to 2015.

In terms of direct CO_2 emissions, space heating demand again is the main contributor, accounting for 83 % of the overall sector emission from residential buildings. It should be noted, that for this analysis, emissions from electricity and district heating consumption are accounted for in the power sector. Therefore, the sources for direct CO_2 emissions in the residential sector are only the natural gas and fuel oil consumption for heating purposes, see Figure 21. In the Mod-RES scenario, having gas and oil boilers in the system until 2050 and especially gas boilers still being installed in the modelling time horizon, the emission reduction is partly based on efficiency progress of residential buildings and heating systems, and partly because of the increasing share of heating pumps and other RES like biomass and solar thermal in contrast to the base year. The overall emission reduction is 40 % compared to 2015 and 45 % compared to 1990. For further reductions and target achievement until 2050, measures additional to the already very ambitious building standards need to be implemented. Not only the renovation depth, but also the renovation rate is a lever for reducing the emissions from the residential sector. Cutting the emissions down to under 10 % compared to 1990, necessitates a combination of investment subsidies for RES heating sources, a fuel tax on gas and oil and a ban of newly installed oil boilers.

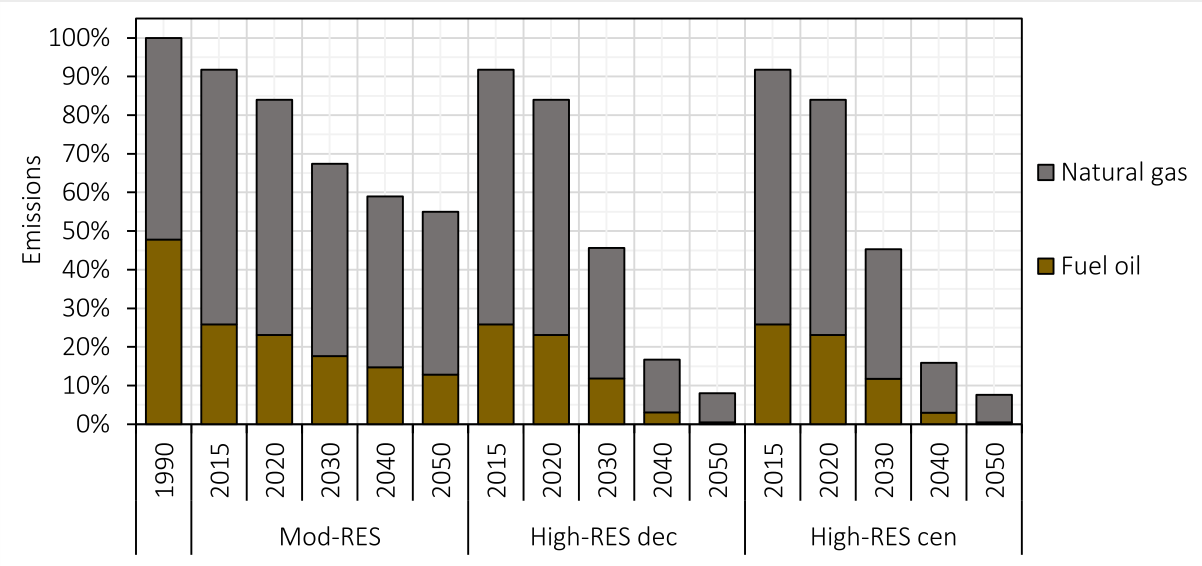

Figure 21: EU28 residential emission reduction in percent compared to 1990

Source: FORECAST

Space heating is the main contributor to both residential final energy demand and CO_2 emissions. Therefore, building efficiency progress and increase of RES for heating demand should be enforced. In the scenario analysis, it could be shown that the refurbishment rate and depth of buildings leads to a reduction of useful energy demand by 18 % in Mod-RES scenario and by 27 % in the High-RES scenario, as shown in Figure 22. These numbers include the refurbishment of old buildings (erected before 2009) and new buildings (erected after 2009), the demolition of and construction of buildings. It should be noted, that the number of buildings increases in the EU28 until 2050 by 20 %. As stated before, the building minimum standards in the EU are already very high and include nearly zero-energy buildings (nZEBs) for new residential buildings from 2020. The effect of a higher compliance to these standards as well as a higher renovation rate and depth are mainly in the reduction of the useful energy demand of old buildings in the High-RES scenario. Further reduction could be reached by further increase in both renovation rate and depth. However, reaching this would include measures for overcoming barriers for building owners and cost reduction of materials. Nevertheless, a high refurbishment rate and depth as included here, are necessary for the deployment of low-exergy RES sources like solar thermal and heat pumps.

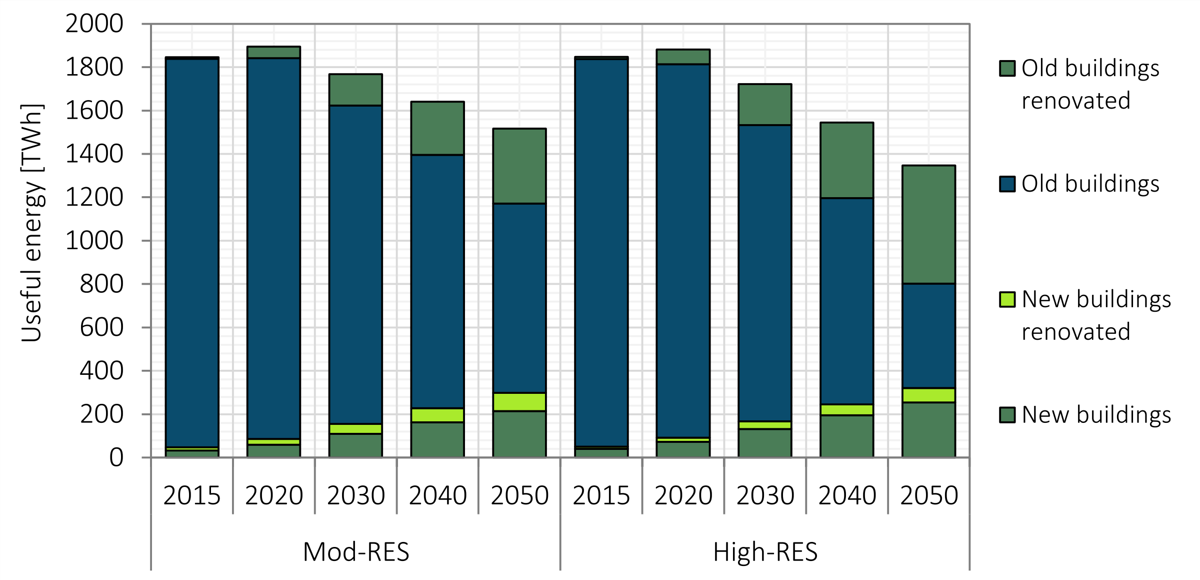

Figure 22: EU28 residential useful energy demand by old and new buildings and refurbishment (2015-2050)

Source: FORECAST

In summary, EU-wide regulations for efficiency progress and RES deployment in the residential sector already in force are a great lever for efficiency gains regarding appliances and building standards. Therefore, a great amount of potential efficiency gains can be exploited in the reference scenario Mod-RES. These efficiency gains imply ongoing compliance, and national measures to implement European regulatory, especially for building standards, as renovation rates are low and renovation depths are not often according to regulatory requirements. The transformation of the residential sector necessitates the activation and cooperation between many actors like tenants, building owners, communal planning and local manufacturers. The policies and regulations need to be designed to reach all actors and stakeholders in this highly divers sector. Further reduction in the High-RES scenario means huge effort, combination and strong interaction of European directives, national legislative, subsidies, removal of barriers for owners and users, as also found by other studies (Hartner 2018). The final energy demand is not much further reduced in the High-RES scenario, as renovation depth and standards for new buildings are already high in the Mod-RES scenario. Measures for an increase of the refurbishment rate of old buildings only tap off from 2025 and then not sufficient until 2050 (+70 %) which, as it was shown, is not enough for the refurbishment of the building stock. However, refurbishment is needed in most cases for deployment of low-exergy sources like heat pumps or district heating demand should be low for newer technologies like 4th generation DH systems with lower temperatures for inclusion of RES. Generally, more RES need to be applied, which also means a package of measures as mentioned above, like replacement of heating systems after 20 years, no installation of oil boilers, investment subsidies and fuel tax for oil and gas for private consumers. Overall, fossil fuel demand reduces by 90 % and RES demand increases by 74 % from 2015 until 2050 in the High-RES scenario. With all these mentioned measures and combined effort, the target of carbon emission reduction of 88-91% can be achieved in the residential sector.

4.1.1.3 Tertiary Sector

The tertiary sector uses electricity, gas and heating oil as the dominant energy carriers. This share in final energy demand is mainly due to electricity demand for appliances and processes and heating and cooling demand from tertiary sector buildings. Within this sector, therefore, improvements of the buildings infrastructure to reduce heating demand are particularly relevant for the future achievement of European climate targets. Some sub-sectors already use a high share of electricity and biomass but tertiary sector still needs to make substantial further efforts to reduce the use of fossil fuels especially for heating purposes. Reducing emissions from heating appears to be a long-term goal, as these types of emissions can only be reduced by building refurbishments and new construction. In terms of end-uses, most tertiary direct GHG emissions are from space heating and hot water. Such sector-related emissions account for about 34 % of all direct emissions. In the following, a potential transition pathway towards a low-carbon tertiary sector focusing on different aspects of space heating is assessed.

Scenario assumptions

In the High-RES scenario remaining energy efficiency potentials in tertiary sector are further exploited implying that specific policies need to be in place to overcome remaining barriers to improve energy efficiency. In addition, financial support for RES is assumed to support fuel switching to biomass, district heating and power-to-heat. Furthermore, as mentioned before a CO_2 price increase to 150 EUR/tCO_2 in 2050 is assumed. Companies in the High-RES scenario can anticipate such additional costs and will switch towards renewable solutions in due time.

In all scenarios, the socio-economic drivers like employment, floor area per employee or GDP remains constant. The scenario-specific assumptions include behavioural aspects like adoption of new technologies and overcoming of barriers and policy measures like financial incentives and regulations. An overview is given in Table 12. In the Mod-RES scenario, the main regulations regarding building codes and efficiency standards are implemented as far as announced (state 2018). This includes again the national implementations of the EU directives defining building standards and the Ecodesign Directive defining efficiency classes for appliances and electrical products ((Directive 2010/31/EU and Directive 2009/125/EC). As for the tertiary sector, the specified requirements are already high in terms of stringent building codes, however the compliance rate varies and is difficult to estimate. Especially in the tertiary sector, where building functions can often refer to multiple building code classes, the appropriate selection and application of respective standards remains challenging. In the tertiary sub-sector model, the refurbishment rate is an output of the model simulations and therefore increases, depending on economic and technological assumptions (e.g., lifetime of heating systems).

In the High-RES scenario, the remaining energy efficiency potentials are evaluated according to their additional potential to increase efficiency. This results in a higher adoption of efficient appliances and a slightly deeper refurbishment depth, complying to the minimum standards. Regarding the heating technologies, additional support for district heating is implemented in the case of the centralized scenario, given the assumption of more centralized supply of RES. The Ecodesign Directive is tightened, introducing new efficiency classes.

Table 12: Scenario characterisation for the tertiary sector by mitigation option

Clusters of mitigation options	Mod-RES	High-RES
Energy efficiency of residential buildings Building standards for new and renovated buildings, compliance	Current national implementation of regulations (nearly zero-energy buildings from 2021), high compliance	Higher building standards for renovation, higher compliance
Heating supply Technology choice, lifetime	Implemented national incentives and subsidies stay in force, no additional fuel tax average lifetime 20-30 years	Expansion of district heating networks, additional tax on gas and oil average lifetime 20 years
Energy efficiency progress of appliances	Ecodesign directive (2009) and further announced reinforcement	Ecodesign directive (2009) and further announced reinforcement, plus new efficiency classes and more products from 2025

Source: FORECAST

Scenario results regarding the tertiary sector

The results presented in following analyse the impacts of the different mitigation options. Overall, these options lead to a reduction of the final energy demand (~-40 % in 2050 compared to 2015) and to a significant reduction of direct CO_2 emissions (~-88 % compared to 2015) in the High-RES scenario.

As introduced, in the Mod-RES scenario, the impacts of refurbishment and efficiency measures reach already high levels of -30 % (see Figure 23). In the High-RES scenario, the additional efficiency gains are limited, as the existing building codes and regulations are already stringent. However, the further measures for RES heating supply as well as the shorter lifetime of heating systems have an impact and reduce final energy demand by an additional 7-9 % compared to the Mod-RES scenario. It has to be noted that electricity demand from appliances and processes will dominate final energy demand in the future. The current share of 49 % of electricity in terms of final energy demand in 2015 will increase to 65 % in 2050, although on lower levels. Electricity demand is expected to decline by 10 % until 2050, compared to 2015. The energy carrier mix varies between the scenarios, although in all scenarios, renewable heating plays a major role. It has to be noted, that due to technical limitations, fossil sources will partially remain (e.g. in protected buildings where heat pumps or biomass-based systems are not available).

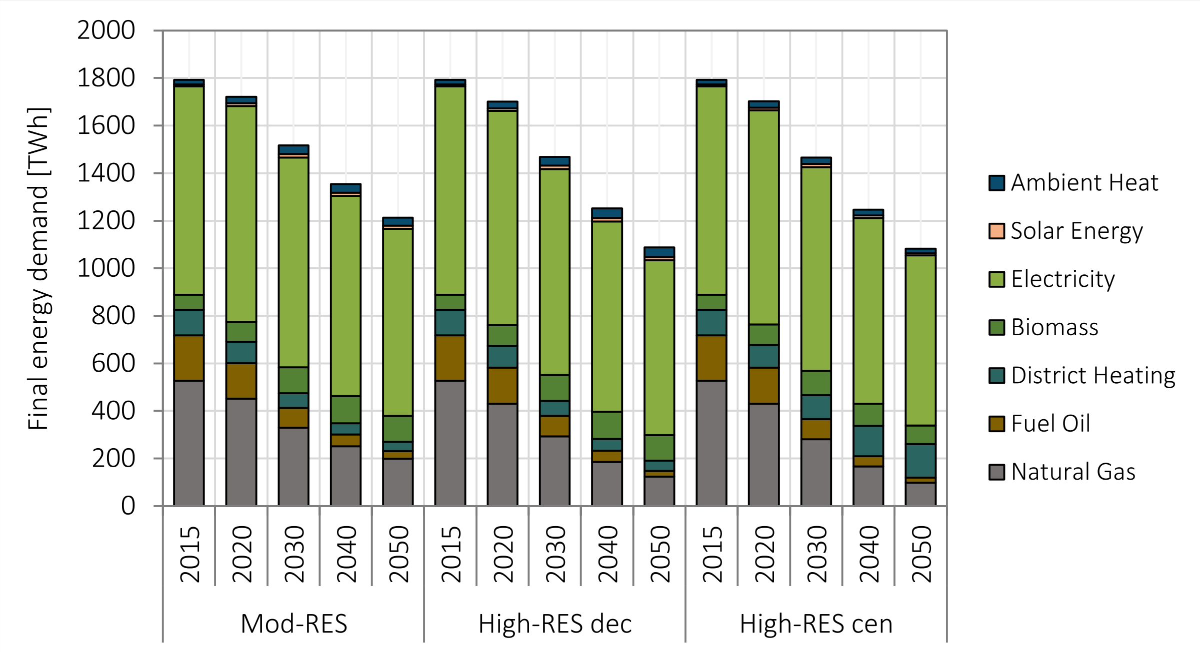

Figure 23: EU28 tertiary sector final energy demand by energy carrier (2015-2050)

Source: FORECAST

In terms of final energy demand by energy service (Figure 24), electricity demand from appliances and processes can be reduced by additional 5-10 % in the High-RES scenarios compared to the Mod-RES scenario. Space heating demand, is expected to be reduced by more than 65% until 2050 in the High-RES scenario, offering as well 5-10 % of additional savings. Ventilation and cooling are expected to grow in the Mod-RES scenario, whereas cooling demand can be stabilized in the High-RES scenarios.

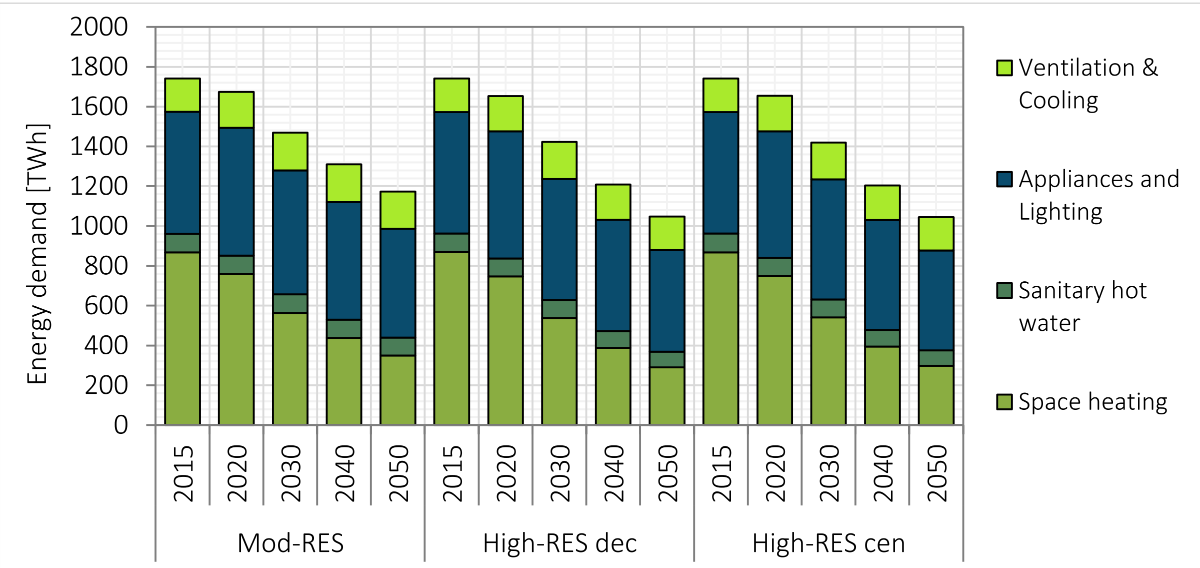

Figure 24: EU28 tertiary final energy demand by energy service (2015-2050)

Source: FORECAST

In terms of direct CO_2 emissions, space heating demand is the main contributor, accounting for 90 % of the overall sector emission from tertiary buildings. As stated for the residential sector, emissions from electricity and district heating demand are accounted for in the power sector. Therefore, the sources for direct CO_2 emissions in the tertiary sector are dominated by natural gas and fuel oil consumption for heating purposes, see Figure 25 with negligible amounts of coal used. In the Mod-RES scenario, having gas and oil boilers in the system until 2050 and especially gas boilers still being installed, the emission reduction is partly based on efficiency progress of tertiary buildings and heating systems. In the High-RES scenarios, gas-based systems remain part of the solution but with reduced emissions partly because of the increasing share of the use of biogas which is currently not fully accounted for in the model. For further reductions and target achievement until 2050, additional measures to the already very ambitious building standards need to be implemented. Not only the renovation depth, but also the exchange for renewable heating systems is a lever for reducing the emissions from the tertiary sector.

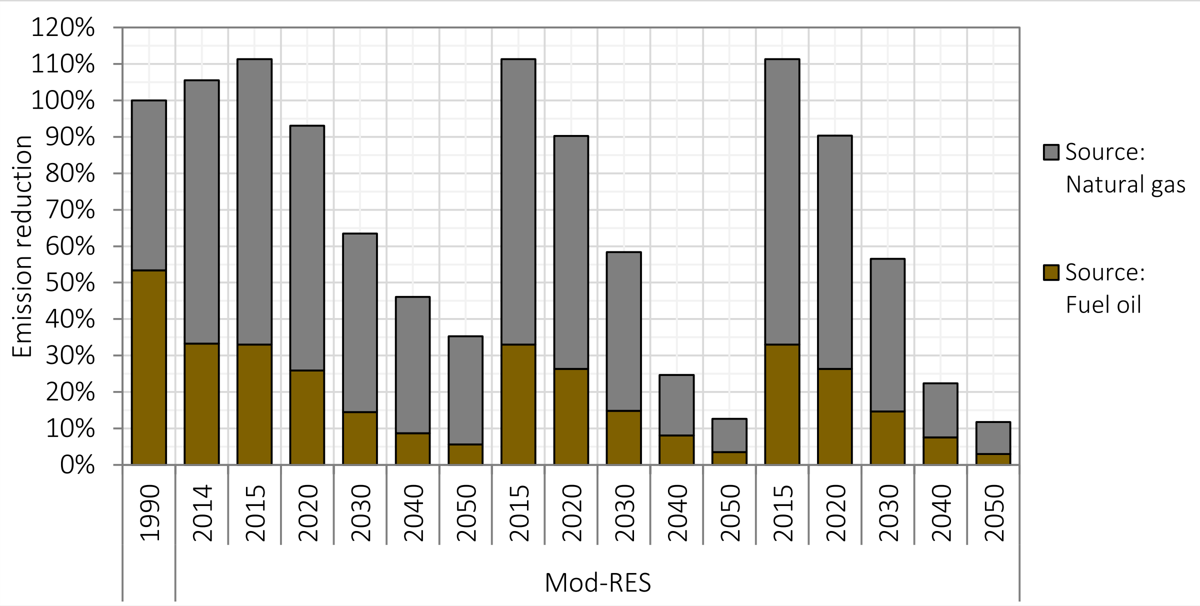

Figure 25: EU28 tertiary direct emission reduction in percent compared to 1990

Source: FORECAST

4.1.1.4 Transport Sector

The European Roadmap for moving to a competitive low carbon economy in 2050 aims at domestic emission reductions of -80 % across all sectors. For the transport sector, a possible range of emission reduction potential of about -54 % to -67 % in 2050 depending on the rate of technological innovation and different fossil fuel prices is identified (European Commission 2011a), which leads to a communicated emission reduction target of -60 % (European Commission 2011b). This GHG reduction target is set as target guideline for both High-RES scenarios.

The transport sector accounts for around 30 % of the European greenhouse gas emissions in 2015. As reported by the European Environment Agency (European Commission 2017), emissions mainly stem from road transport (73 %) and from aviation (13 %). Road transport emissions are mainly caused by passenger cars (61 %), by heavy duty trucks (HDV) and buses (26 %) and by light duty vehicles (LDV) (12 %). The transport sector is responsible for about 33 % of final energy consumption in EU28 countries (European Commission 2017).

Nevertheless, transport activities are responsible for less than 3 % (about 60 TWh in 2015) of the total electricity demand in the EU28.

The European Strategy for low-emission mobility (European Commission 2016) sets clear guiding principles for the transition towards a low-carbon transport sector. The three main strategic elements are:

1) Increasing the efficiency of the transport system by making the most of digital technologies, smart pricing and further encouraging the shift to lower emission transport modes, in particular ships, rail and public transport,

2) Speeding up the deployment of low-emission alternative energy for transport, such as advanced biofuels, electricity, hydrogen and renewable synthetic fuels and removing obstacles to the electrification of transport,

3) Moving towards zero-emission vehicles: accelerating the transition towards low- and zero-emission vehicles[15] comprising PHEV, BEV and FCEV electric vehicles while making further improvements to the internal combustion engine (ICE).

This strategy is taken as major basis to set up the policy framework for the High-RES scenarios.

Scenario assumptions for Mod-RES

The Mod-RES scenario assumes all policy targets and actions that are already implemented or decided at European and national level by the end of 2017. These include among others:

- The Renewable Energy Directive 2009/28/EC on the required share of renewable energy in the final energy demand of the transport sector;
- CO_2 emission standards for new cars and light duty vehicles in line with the EU regulations (Regulation (EU) No 333/2014; Regulation (EU) No 253/2014);
- Filling and charging station deployment for alternative fuels with an implementation degree that the member states defined in their National Policy Frameworks as response to Directive 2014/94/EC on the Deployment of Alternative Fuels Infrastructure (AFID);
- Policies related to emissions in aviation (Single European Sky II, ICAO Chapters 3) and maritime energy efficiency (IMO Energy Efficiency Design Index (EEDI));
- Guidelines on the Trans-European Transport Network (TEN-T) which aims also at increasing the competitiveness of railways and inland waterways. The scenario assumes that the Core Network representing the most important connections is completed by 2030, and the Comprehensive Network covering all European regions by 2050.

Thus, some aspects of all three European strategies for the transition towards a low-carbon transport sector are already considered to a certain extent in the Mod-RES scenario.

[15] EU legislation currently refers to low-emission vehicles as vehicles having tailpipe emissions below 50g/km. This would include some plug-in hybrids, full electric cars and fuel cell (i.e. hydrogen-powered) vehicles. The latter two examples also represent zero-emission vehicles.

Scenario assumptions for High-RES scenarios

For the more ambitious High-RES policy scenarios, some measures from Mod-RES are further intensified and complemented by additional regulations in order to achieve a stronger shift to more efficient modes, to low- and zero-emission vehicles and to alternative fuels.

General drivers for both High-RES scenarios are related in particular to road infrastructure pricing with the internalization of external cost for emissions, the diffusion of Collaborative Intelligent Transport Systems (ITS) applications, urban policies to promote sustainable mobility and measures promoting efficiency improvements and multimodality. In addition, improved fuel efficiency is fostered by more ambitious vehicle efficiency standards, acting in the low- and zero-emission vehicles area and not only being applied for new cars and vans, but extended to buses and trucks. Furthermore, the penetration of cleaner vehicles is enforced by expanded recharging and refueling infrastructure and by advanced research and innovation in electro-mobility and fuel-cell technology. Increased fuel tax for conventional fuels and reduced fuel tax for electricity, hydrogen, and biofuels, further contribute to the utilization of low-emission energy.

Two implemented measures have a major impact on the consumed energy carriers: in both scenarios, phase-outs of internal combustion engine vehicles are implemented for new urban buses with completion in 2035 and for new cars and light duty vehicles in 2040, in line with the current plans and strategies of several European countries.[16] For freight road transport, a technology choice is required that will be explained in the following: Battery electric vehicles are not an option for intermediate and long-distance trucks due to the limited capacity and the weight of batteries. As more suitable alternatives for this use case, the two technologies fuel cell electric trucks and hybrid trolley trucks are under development and are currently tested in pilot studies. Both technologies seem to be quite promising decarbonisation options for trucks. However, the introduction of both technologies would be too expensive due to the investments in two completely different infrastructure systems. It is not yet clear which technology will prevail. Table 13 compares pro and con arguments for both technologies.

In the REFLEX project, a special focus is set on investigating the influence and potential of flexibility mechanisms that seem to be required in an efficient energy system with a large share of volatile renewable energy. Power-to-gas for hydrogen production via electrolysis can provide a certain flexibility potential to the energy system. Therefore, fuel cells are chosen as main alternative technology for long-distance trucks in both High-RES scenarios and it is assumed that hydrogen is produced in Europe. A further advantage of this solution is that more use cases are possible: Hydrogen-based fuel cell vehicles can also be applied for passenger cars, buses and intermediate trucks. This increases technological learning and enables spillover effects to other vehicle types.

Most assumptions are identical for both High-RES transport scenarios, but they differ for some aspects due to the scenario dependent deployment of the energy system. While renewable power generation mainly takes place in large wind parks in the centralized High-RES scenario, renewable power generation is more regionally distributed using for example rooftop PV and distributed onshore wind plants in the decentralized case.

[16] As an example: Norway, Ireland, The Netherlands, Slovenia, France and United Kingdom, as reported by Transport & Environment on the basis of published announcement and national press.

Table 13: Comparison of pros and cons of the two possible technologies for trucks

FCEV-Trucks based on P2G-Hydrogen	Hybrid-Trolley-Trucks
(+) Provides high flexibility for the energy system	(-) No flexibility for the energy system
(-) Doubling of energy demand compared to Hybrid-Trolley due to transformation losses	(++) High degree of efficiency
(+) More use cases: FCEV can also be applied for passenger cars, buses and intermediate trucks	
(+) Higher acceptance by truck manufacturers	
(-) Market penetration might start later due to more challenges related to the technology, the hydrogen production and its distribution to refuelling stations.	(-) Hybrid-technology would be based on fossil fuel to bridge the distance to and from the electrified highways at least until 2030, afterwards only a certain share might use battery technology as extension.

Source: ASTRA

Three assumed factors are expected to lead to a faster diffusion of electric vehicles in the decentralized High-RES compared to the centralized scenario:

- The number of households with rooftop PV strongly increases over time in the decentralized scenario. Studies indicate that households living in Single-Family-Homes (SFH) with rooftop PV have a higher probability to purchase a BEV or PHEV vehicle. This purchasing behaviour might be triggered by financial incentives due to own generation of the electricity for charging the batteries and by higher technical affinity or familiarity.
- Battery prices decline faster due to additional learning curve effects based on spill overs from stationary battery storages leading to lower selling prices of BEVs and PHEVs.[17]
- As people are more familiar with DSM and digitalized monitoring and control, a higher acceptance of multi-modal transport is assumed including more use of car sharing as well as more walking and cycling. This behaviour change increases the number of vehicles in car sharing fleets that tend to have a higher share of electric vehicles. Besides, ownership rates of private cars are reduced, which increases the use of public transport.

Further factors that differ between the two High-RES scenarios can influence the diffusion of FCEV trucks. These factors comprise the production and distribution of hydrogen and conditions with an impact on financial incentives and perceived reliability. While electrolysis to hydrogen and its compression will be operated directly at the filling station in the decentralized

[17] Simulations have finally shown that this effect is neglectable in High-RES decentral as battery capacities that are produced for vehicles worldwide are in a far larger size than for stationary storage. This relation is in line with numbers found in a recent study on experience curve effects for electrical energy storage (see Schmidt et al. 2017).

scenario, hydrogen is produced in larger plants and transported to the filling stations by combining trailers and pipelines in the centralized scenario. In the centralized system, joint and clear decisions for infrastructure deployment and announcements for a favourable and stable hydrogen price leads to higher perceived reliability and thus to slightly faster diffusion. In contrast, a decentralized energy system with more diverse actors and more need for coordination activities could lead to a slower penetration that varies more widely between countries.

The following Table 14 provides an overview on key policies, measures and assumptions for the two High-RES scenarios that are considered to be additional to the interventions assumed for the Mod-RES scenario.

Table 14: Summary of key assumptions and differentiating factors for both High-RES transport scenarios

<table>
<tr><th colspan="3">Strategies*</th><th colspan="2">High-RES</th></tr>
<tr><th>1)</th><th>2)</th><th>3)</th><th>Decentralized</th><th>Centralized</th></tr>
<tr><td>x</td><td></td><td>x</td><td colspan="2">Road infrastructure pricing based on emissions, diffusion of Collaborative Intelligent Transport Systems applications, urban policies to promote sustainable mobility, measures promoting efficiency improvements and multimodality</td></tr>
<tr><td></td><td>x</td><td></td><td colspan="2">Increased fuel tax for conventional fuels, reduced fuel tax for electricity, hydrogen, and biofuels</td></tr>
<tr><td></td><td>x</td><td>x</td><td colspan="2">Filling and charging station deployment is further expanded, fast charging increases acceptance of BEV and enables driving longer distances</td></tr>
<tr><td></td><td></td><td>x</td><td colspan="2">More ambitious CO_2 standards for new cars and light duty vehicles and extension of standards to buses and trucks</td></tr>
<tr><td>x</td><td></td><td>x</td><td>Higher acceptance of multi-modal transport increases the use of car sharing and leads to more walking and cycling. Car sharing fleets have a higher share of electric vehicles.</td><td></td></tr>
<tr><td></td><td></td><td>x</td><td>Strongly increasing number of households with rooftop PV accelerates the diffusion of electric vehicles due to economic advantages by own electricity production and higher technical affinity.</td><td></td></tr>
<tr><td></td><td></td><td>x</td><td>Spill overs from stationary battery storages could accelerate the reduction of battery prices</td><td></td></tr>
<tr><td></td><td>x</td><td>x</td><td colspan="2">FCEV as zero-emission technology choice for intermediate and long-distance trucks, advanced research and innovation for fuel cell technology and decision on deployment of hydrogen refuelling infrastructure in all EU28 countries</td></tr>
<tr><td></td><td>x</td><td></td><td>Hydrogen production directly at the filling stations</td><td>Hydrogen production in larger plants with distribution by trailers and pipelines</td></tr>
<tr><td></td><td>x</td><td>x</td><td></td><td>Higher perceived reliability concerning hydrogen infrastructure deployment and stability of hydrogen prices compared to decentralized world due to less actors and need for coordination combined with clear decisions and communication.</td></tr>
<tr><td></td><td></td><td>x</td><td colspan="2">Phase-out of pure ICEvehicles for new urban buses with completion in 2035 and for new cars and light duty vehicles in 2040</td></tr>
</table>

* Impact of the assumptions related to the three main European strategies as explained in the text above:
1) Increasing the efficiency of the transport system
2) Speeding up the deployment of low-emission alternative energy
3) Moving towards zero-emission vehicles

Source: ASTRA

Scenario results regarding the transport sector

In the following, results of the simulations with the ASTRA model are described. As shown in the following Figure 26, annual final electricity demand from the transport sector is expected to reach 200 TWh by 2050 in the Mod-RES scenario, while it grows up respectively to 647 TWh and 600 TWh by 2050 in the High-RES decentralized and centralized scenarios. It means that electricity demand will be ten times higher compared to the level of 2015. This impact is mainly a result of the electrification of passenger road transport with the diffusion of electric and hybrid electric vehicles. It is worth noticing that these vehicles will represent nearly carbon-neutral technologies, following the increasing share of renewables in the EU28 energy and the related fall in GHG emissions from electricity production.

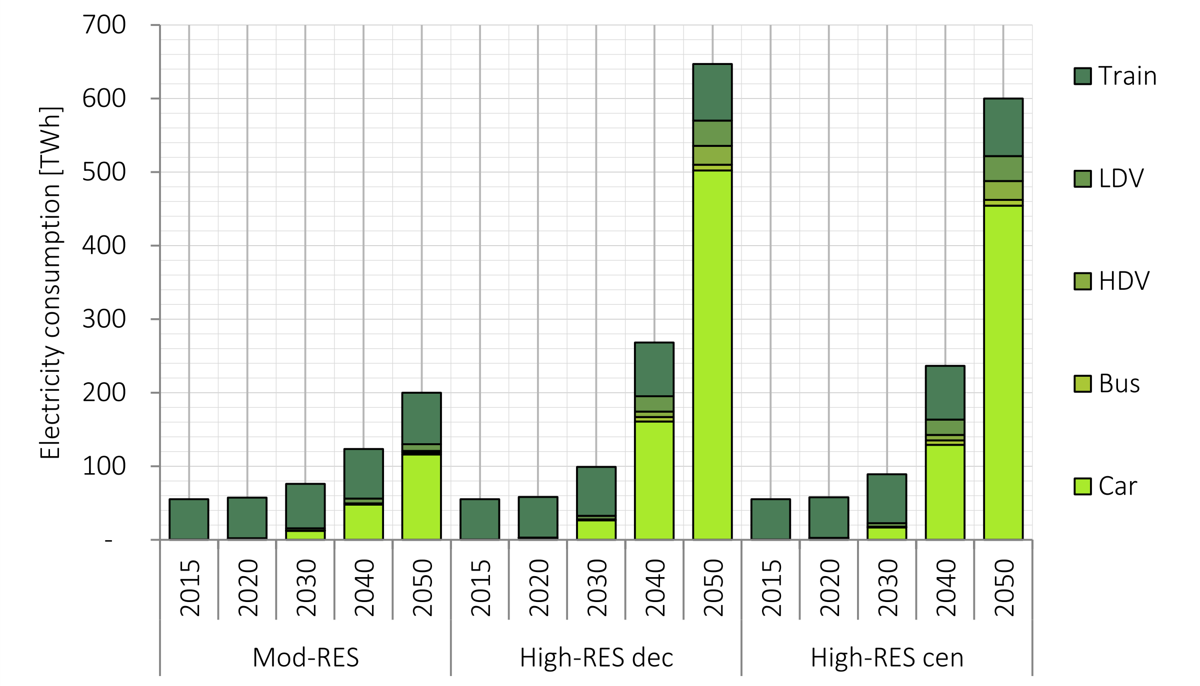

Figure 26: Development of final electricity demand of the transport sector for EU28 by scenario

Source: ASTRA

Furthermore, final hydrogen demand of the transport sector is estimated to range between 380 TWh and 418 TWh by 2050 in the centralized and the decentralized High-RES scenarios respectively (see Figure 27). This development is driven by the uptake of fuel cell trucks in road freight transport, which will request about 80 % of the hydrogen consumption of the transport sector.

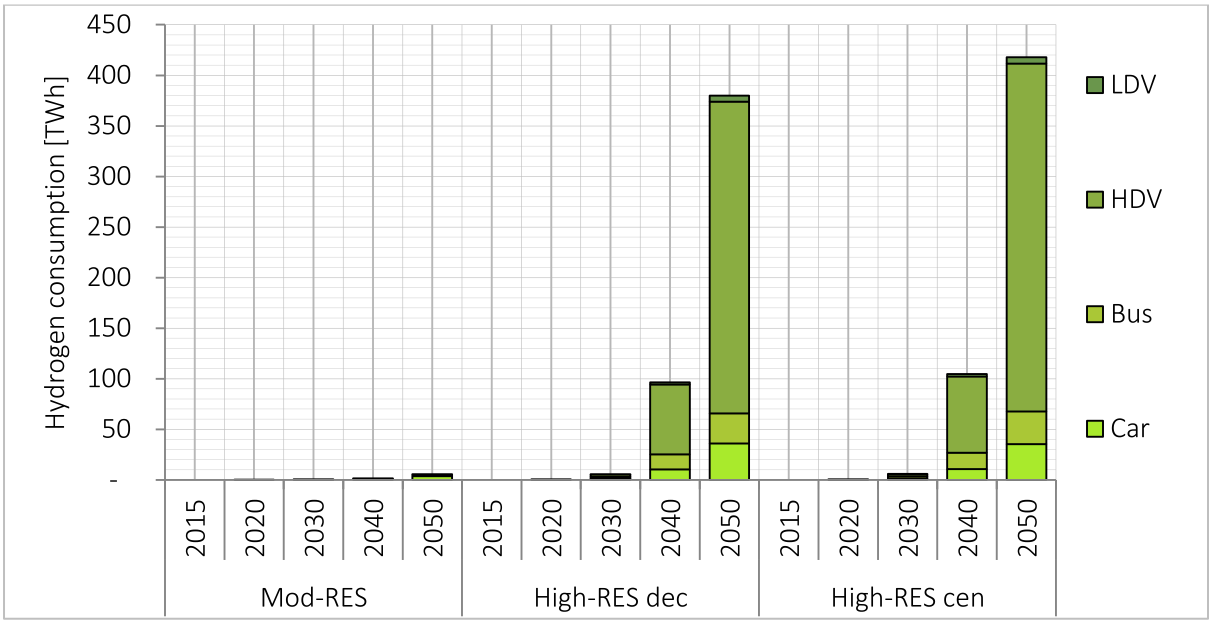

Figure 27: Development of final hydrogen demand of the transport sector for EU28 by scenario

Source: ASTRA

The demand for biofuels in the transport sector is also estimated to grow significantly, almost triplicating from 2015 to 2050 in the High-RES scenarios with about 488 TWh requested at 2050. Compared to the electrification of the vehicle fleet, biofuels make a smaller but still important contribution to decrease future transport GHG emissions. For example, bio-kerosene used in air transport is estimated to reach almost 221 TWh by 2050, helping to reduce the high carbon footprint of the aviation sector.

Focusing on tank-to-wheel CO_2 emissions (see Figure 28), the results of the High-RES scenarios indicate that the largest CO_2 reduction at 2050 with respect to 2015 is obtained in the road sector achieving approximately, -90 % for LDV, -80 % for car and bus, and -65 % for HDV, with small differences between the centralized and decentralized cases. The rail sector contributes only marginally to tank-to-wheel CO_2 emissions, although a reduction of about -80 % is observed with respect to 2015. While the CO_2 emitted by internal waterways transport (IWW) is slightly increasing, the CO_2 emissions related to air passenger transport are reduced by about -30 % with respect to 2015, contributing to the achievement of the target at 2050. The latter one can be considered as a quite positive policy achievement, particularly in the light of the constant increase in overall transport demand (see section below). In particular, looking at the results of transport indicators, it can be highlighted that rather than the modal shift from road to rail and maritime, it is the development in fuel efficiency and zero-emission technologies (electric and fuel cell engines) that result to be the key drivers for decarbonising the transport sector.

As a final result, both High-RES scenarios confirm the achievement of the CO_2 emission target reduction at 2050 for the transport sector[18], with a decrease of -60 % with respect to 1990 level and about 3,954 TWh / year.

[18] Excluding deep sea maritime transport

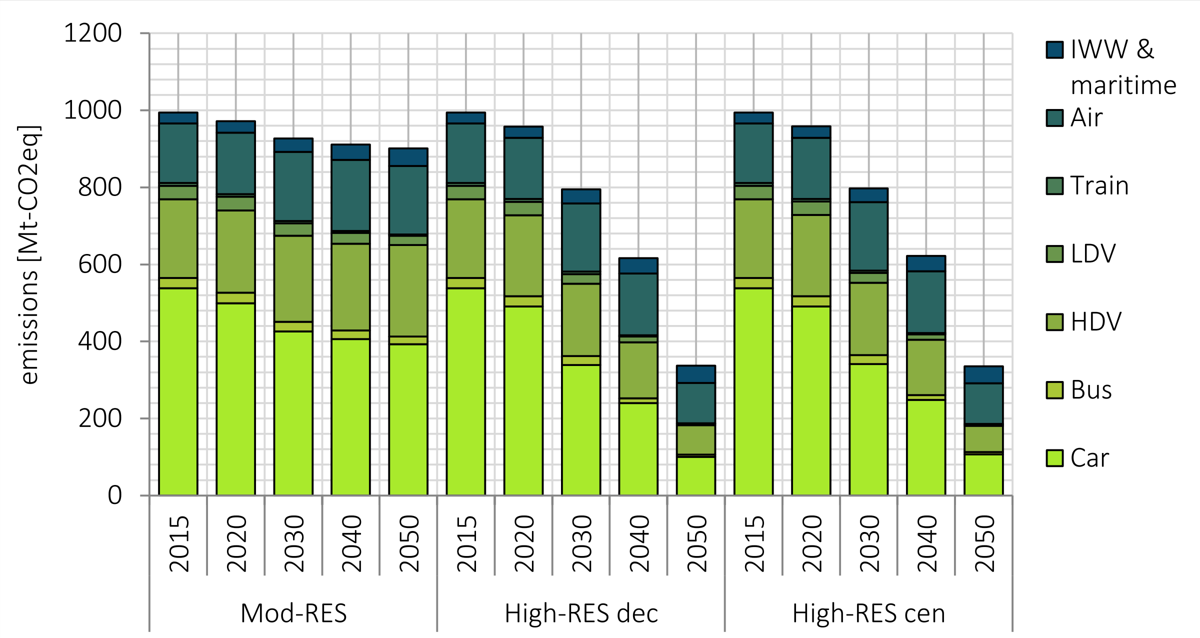

Figure 28: Development of tank-to-wheel CO_2 emissions from the transport sector for EU28 by scenario

Source: ASTRA

The above presented results in terms of energy demand and CO_2 emissions are the combined outcomes of the evolution of vehicle fleet composition in terms of technologies and the trends on the transport demand.

As already anticipated, the fleet technology composition (and related policies) can widely contribute to meet the reduction target (2050 vs. 1990 CO_2 emissions). As described in Figure 29 below, the ASTRA model predicts a substantial technological change in the car passenger vehicle fleet, moving from conventional powertrains (gasoline and diesel) to low-emission technologies. The model estimates that by 2050 battery electric, plug-in hybrids and fuel cells, from their current negligible share in the base year 2015, will have a share of over 80 % of the total passenger car stock of the EU28 in the High-RES scenarios, compared to 27 % in the Mod-RES scenario.

Importantly, the large diffusion of low-emission technologies in the period 2035-50 in the High-RES scenarios is due to the ban of conventional engine cars (gasoline, diesel, LPG and CNG) as of 2040 that implies that new sales involve only low- and zero-emission vehicles having effects on purchase decisions starting already in the preceding years. Due to this phase-out assumption, the substitution of oil based powertrains with alternative fuels is more rapid in the High-RES scenarios. As this strong intervention forces all car users to change to electric vehicles, PHEV to BEV share is assumed to increase in the years around the completion of the phase-out. Some differences also exist between the High-RES scenarios, especially in terms of a larger share of battery electric vehicles in the decentralized scenario compared to the centralized High-RES. This is due to the assumption that in a decentralized world the number of BEV grows faster thanks to an increasing number of households generating electricity and hence, have the possibility to charge at home. Moreover, in a decentralized world, consumers are assumed to be more familiar with devices enabling DSM, with positive implications for the acceptance of charge control and for the technology diffusion assuming that consumers benefit from lower electricity prices when allowing for charge control.

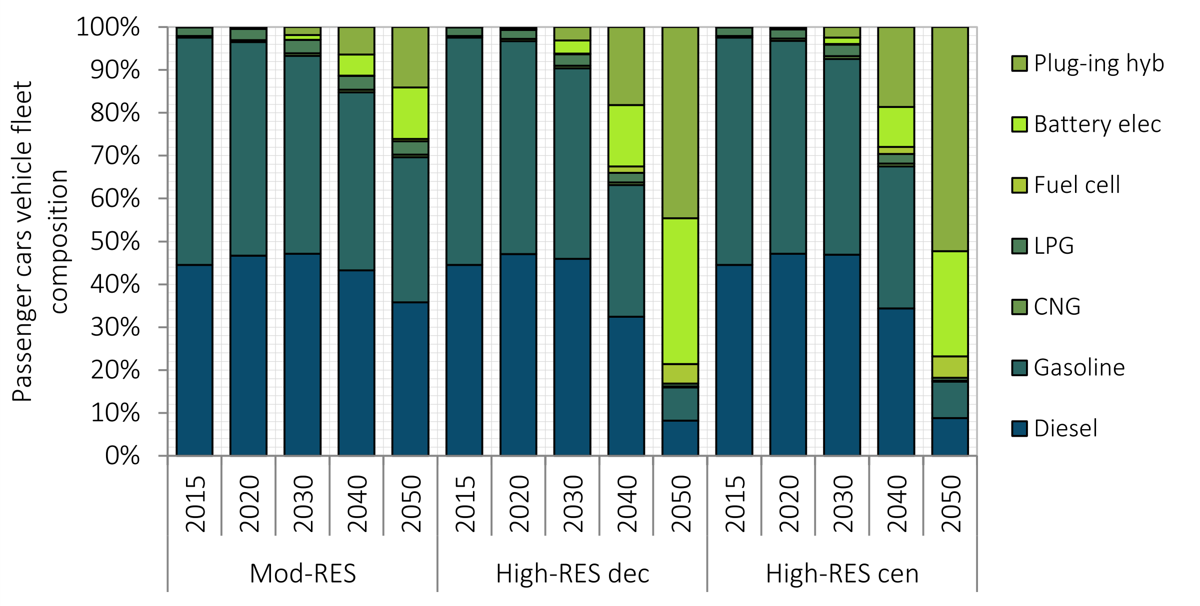

Figure 29: Development of the car fleet composition from the transport sector for EU28 by scenario

Source: ASTRA

In road freight transport, the energy transition process towards low-emission technologies is more delayed than in the passenger segment (see Figure 30). The ASTRA model predicts that diesel will remain the dominant fuel still for the next two decades. Indeed, no significant change is expected in the HDV fleet composition in the Mod-RES scenario, suggesting that road freight transport will not experience any technology evolution unless more ambitious environmental and energy policies are put in place, i.e. with the diffusion of electric powertrains that occurs after 2030 in the High-RES scenario.

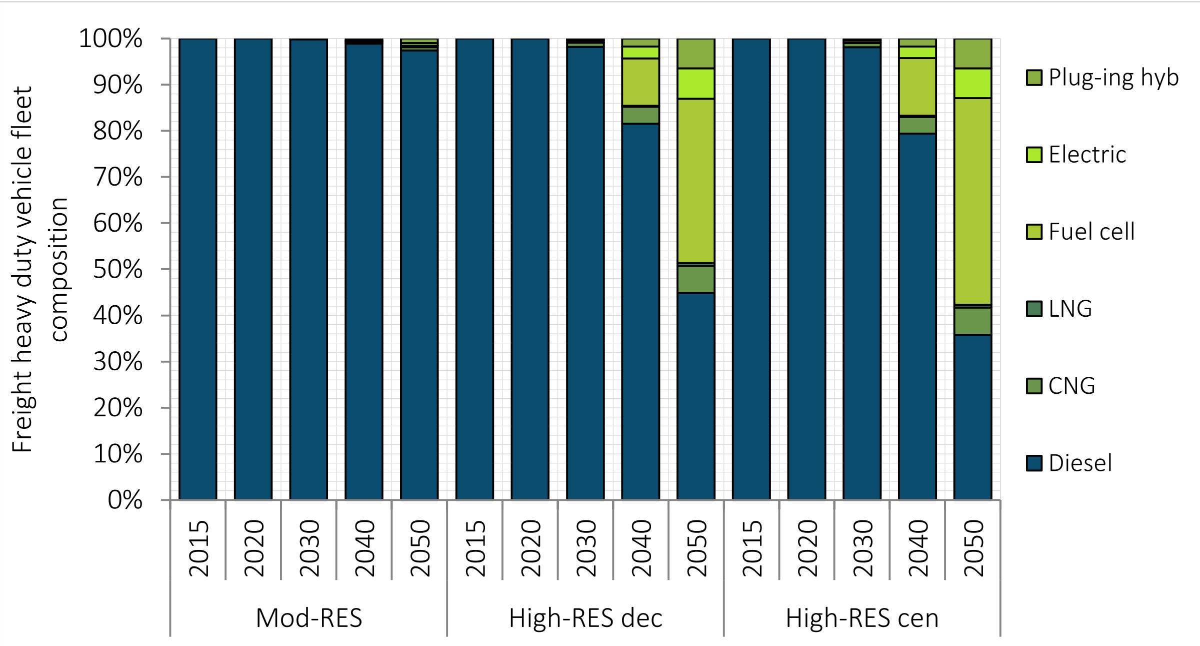

Figure 30: Development of the truck fleet composition from the transport sector for EU28 by scenario

Source: ASTRA

These results indicate that, in the mid-term, low-emission technologies do not seem to be an option for long-distance trucks, due to their higher costs, limited range and technical issues (e.g. fuelling infrastructure, powertrain weight and dimension leading to negative impacts on load factors). The change happens after 2030 with the penetration of alternative technologies, notably hydrogen powered trucks, supported by investments in infrastructure and R&D, tax incentives and tighter fuel efficiency standard that contribute to make alternative fuels more cost competitive and attractive compared to diesel vehicles. The ASTRA model results show that in the High-RES scenarios low-emission vehicles are estimated to reach a share of 48 % to 58 % in 2050, where about 13 % are electric and plug-in hybrid trucks that belong to the lower weight category of trucks while the remaining part is fuel cell trucks. Besides, the production of fuel cell electric trucks leads via experience curve effects also to a certain diffusion of fuel cell technology for cars, light duty vehicles and buses.

Transport and mobility demand are other key variables for the analysis of the impacts on the energy system. They represent the level of transport activity and so the energy required and consumed by the transport sector. As mentioned above, transport demand is expected to increase over time until the time horizon of 2050, mainly caused by economic and population growth expected in the future decades. Passenger transport demand is expected to increase by 34 % and freight transport by 60 % until 2050 with respect to 2015 level.

Nevertheless, road transport will experience a reduced growth rate in the High-RES scenarios with respect to Mod-RES scenario, thanks to policies discouraging the use of private vehicles for passengers (availability of shared mobility, better public transport, and partially also higher travel cost due to higher energy taxes) and improved alternatives for freight (enhancement of railways, logistic policies, etc.).

This impact is especially visible in Figure 31 when looking at the modal split: for passenger total transport demand, at 2050 the modal share for cars[19] is estimated to decrease with respect to 2015 by 2.4 % in Mod-RES and about 4.7 % and 5.6 % respectively in High-RES decentralized and centralized scenario, mostly in favour of rail and air transport. Air transport is also estimated to gain some 3 % modal share by 2050, although energy taxes on aviation fuels like kerosene may limit part of the long-term expansion of air traffic.

[19] Including also the use of car sharing

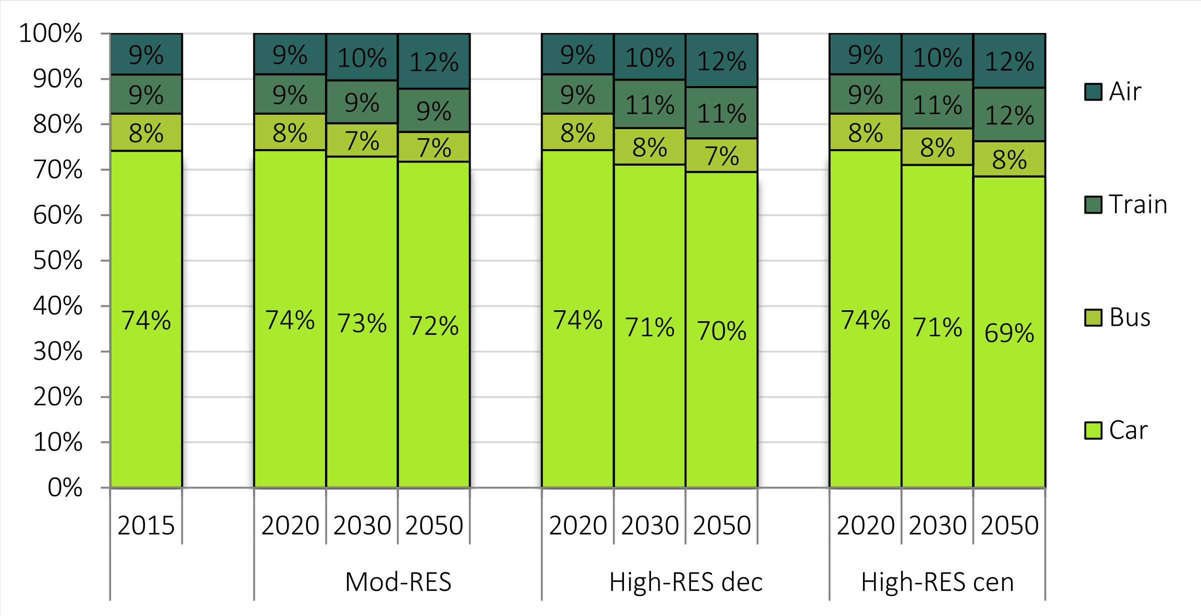

Figure 31: EU28 countries - Passenger modal split of total transport demand

Source: ASTRA

Further interesting results can be observed when looking at short-distance transport demand (i.e. below 50 km). As shown in the following Figure 32, the modal shift from private cars to more sustainable modes is in fact more pronounced. Looking more in details at the results of the High-RES policy scenarios, the private car share is estimated to decrease by 7.6 % and 4.8 % in the decentralized and centralized scenario respectively, although part of the demand is shifted to car sharing service (increasing to 4.7 % and 2.1 % in terms of mode share at 2050). An increased share at 2050 is observed for High-RES scenarios also in terms of active modes (bike, e-bike and pedestrian) used for about 15 % of demand. The use of buses is also encouraged and slightly increased in these scenarios by about 1 % with respect to 2015. These results suggest that the combination of policy measures such as rail infrastructure investments, improved public transport services, coupled with relevant technological developments (shared transport, ITS, demand management, etc.), can make a significant contribution in reducing car use locally. Overall, the results from REFLEX suggest that, while for long-distance transport private cars are likely to remain the main option (although with a reduced role), different and more sustainable modes are expected to gain share in short-distance transportation. These include not only public transport services (bus, train, etc.) but also innovative mobility solutions (shared mobility and e-bikes) and active modes (walking and cycling).

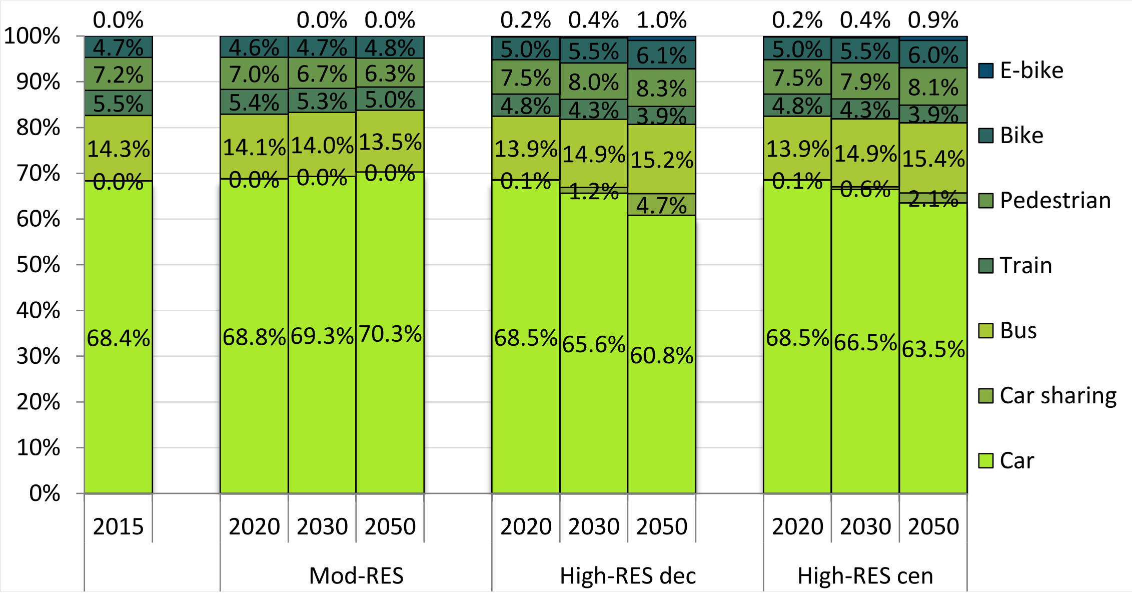

Figure 32: EU28 countries - passenger modal split of local transport demand

Source: ASTRA

With reference to freight transport demand (see Figure 33), the differences observed between the 2015 and the 2050 in terms of modal shares are in the range of 3 %, involving mainly a shift from road to sea transport. These results suggest that, irrespective of the policy scenario considered, road transport will keep playing a central role in the freight sector. Indeed, policy measures on fuel efficiency, emission standard and refuelling infrastructure (electric and hydrogen) will eventually make road freight transport relatively clean but also economically convenient, supporting the use of trucks instead of other modes. In this context, the more low-emission technologies (hydrogen, electric) penetrate in the HDV vehicle fleet, the more the dominance of road transport in comparison to the other modes is supported, as reflected in the rebound effect of truck share in the modal split in 2050 with respect to 2030.

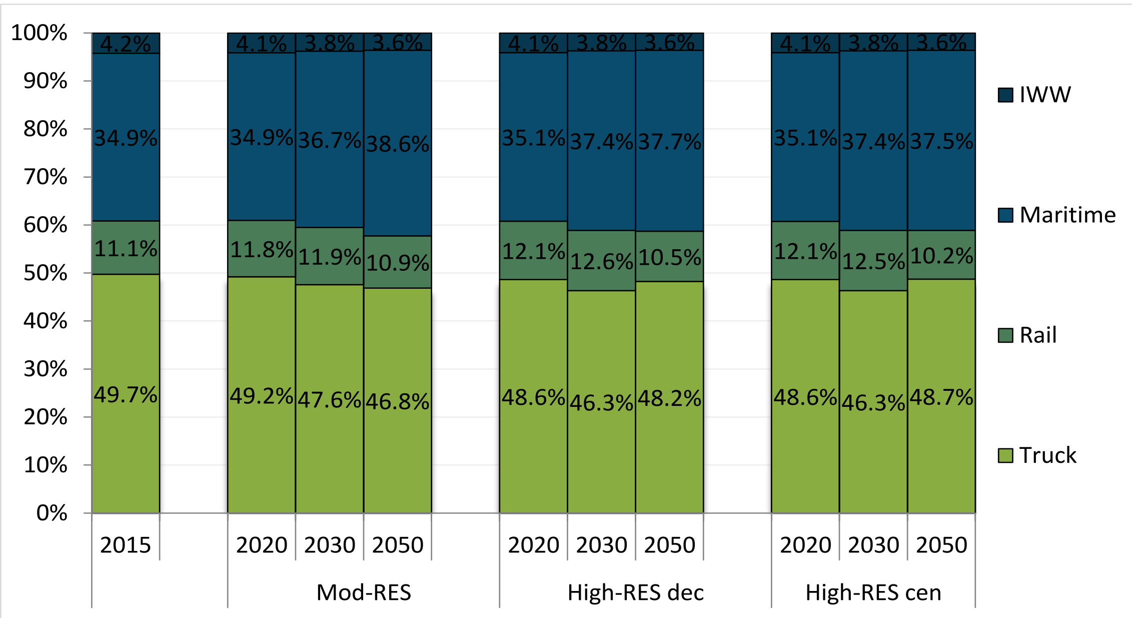

Figure 33: EU28 countries - freight modal split of transport demand

Source: ASTRA

Conclusions and recommendations for the transport sector

The results of the REFLEX scenarios show how the EU GHG reduction target of 60 % for transport in 2050 can be achieved in this normative scenario, if a set of ambitious policy measures on energy and mobility is put in place. In fact, the continuous growth of passenger and freight transport demands require strong and timely responses at the policy level.

Firstly, the transition to a sustainable EU transport sector depends on the diffusion of key innovative, low-carbon technologies and fuels, acting on the composition of passenger and freight vehicle fleets. On the one hand, battery electric and plug-in hybrid vehicles are expected to contribute to a widespread electrification of passenger transport, as they will soon become competitive with conventional oil-based cars thanks to economies of scale in global battery production. On the other hand, fuel cell hydrogen-based electric vehicles could lead the technology transition for long-haul trucks. However, accelerating the speed of transition towards low- and zero-emission vehicles also requires a strong commitment to phasing-out internal combustion engines (in particular gasoline, diesel and LPG) by 2040 latest. In addition, R&D and subsidies for fuel cell technology seem still required to achieve competitive prices, if the FCEV technology is intended to prevail for trucks. While prices for battery electric vehicles decline, range anxiety is currently one of the biggest barriers to the purchase of electric vehicles. Therefore, sufficient charging infrastructure - including stations for fast charging - are key to ensure that users of BEV can complete all their trips (see also conclusions by Funke et al. 2019). Furthermore, incentives for homeowners with rooftop PV to buy battery electric vehicles can contribute to the technology diffusion.

Having in mind the GHG emissions reduction target of 60 % by 2050, the modelling simulations indicate that the fleet technology composition and related policies alone can contribute to reduce by 26 % the CO_2 emissions with respect to 1990 level. Another key driver of transport decarbonisation is fuel efficiency, which has a direct impact on energy demand and fuel consumption of transport activities. By adding efficiency improvements to the above mentioned fleet technology composition effect, a 44 % reduction can be achieved at 2050. Therefore, the introduction of tighter fuel efficiency standards for new vehicles represents a fundamental instrument to reduce overall GHG transport emission. Additional technology change towards the use of alternative fuels in other carbon-intensive modes (e.g. bio-kerosene in the aviation sector, bio-methane for ships) leads to further CO_2 reduction, almost closing the gap to the required GHG target in 2050. Therefore, research and investments related to alternative fuels are required to define an adequate strategy of using sustainable biofuels and synthetic fuels based on power-to-fuel production. It is important moreover that such technology and energy focused measures are supported by a combination of complementary strategies, including improvements in the rail and public transport systems, as well as policies in favour of sustainable transport modes. Examples are urban planning measures and infrastructure provisions in favour of active modes, improvement of public transport to increase coverage and reduce waiting time, and the development of ICT-based integrated multimodal mobility system. In fact, it is fundamental to sustain modal shift especially for short-distance passenger transport, as urban areas show the most pressing congestion challenges but also the highest potential for behavioural change and technology transition.

The diffusion of BEV/PHEV and FCEV vehicles leads to a substantial increase of electricity and hydrogen demand from the transport sector. At the same time, both technologies also provide a certain flexibility potential via charge control and load shifting. Hourly demand patterns and effects of demand side management will be described comprehensively in the next chapter across all demand side sectors.

4.1.2 Hourly Demand and Demand-Side-Management

On the demand side, efficiency improvements that reduce electricity demand of end-uses, as well as the dissemination of new electricity consumers that shift selected sectors (e.g. heating and transport) towards the use of carbon neutral electricity, affect not only the total amount of electricity that is consumed, but also change the shape of the system load curve.

The difference between the system load and electricity generation from RES, which is referred to as the residual load, must be satisfied by conventional generation capacities and other flexibility options. If electricity generation from RES exceeds the actual system load, the residual load drops below zero, meaning that RES need to be curtailed in the absence of alternative flexibility options. Thus, increasing shares of RES and a transforming system load curve could drive the need for conventional generation capacities, while the utilisation, and hence profitability, of new and existing capacities could deteriorate. In this section, the load changes are explained and the load curves are analysed in a systematic way.

4.1.2.1 The Mod-RES Scenario – Overview of Available DSM Options

In the Mod-RES scenario, the system load of the EU28, Norway, Switzerland[20] increases particularly in the evening hours due to electric vehicle charging (in the Mod-RES scenario, electric vehicles are assumed to be charged after the last trip, which is mostly in the evening) and in midday hours due to ventilation and air-conditioning. Efficiency gains particularly in lighting diminish the increasing demand to some extent (see exemplarily Figure 34).

[20] The calculations for the hourly demand as well as for the DSM application are done for these countries. Due to the lack of available data the load profiles for the remaining Balkan countries are not smoothed by DSM.

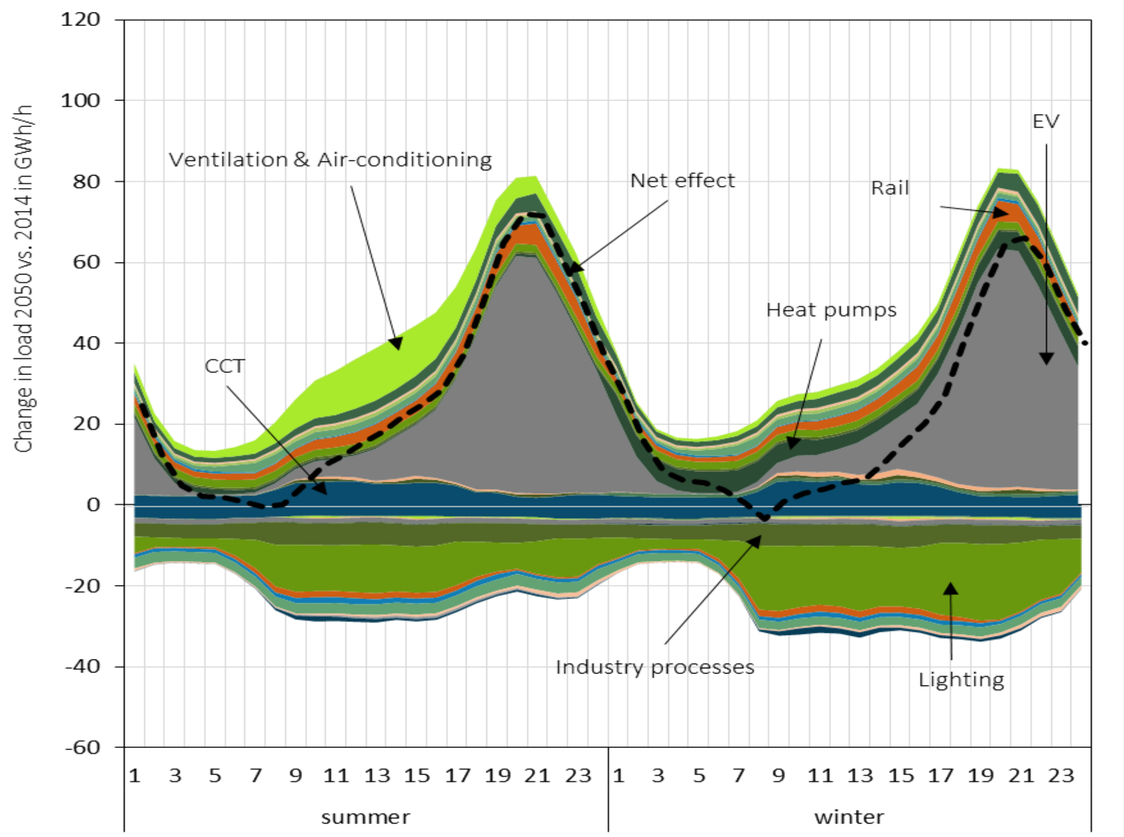

Figure 34: Load curve projection – average load change 2050 vs. 2014 by process in summer (left) and winter (right)

Source: eLOAD

An example of the structural changes in the system load is depicted in Figure 35, which shows the average system load curve for typical days in Germany. In Germany, the electricity demand decreases by 8 % between 2014 and 2050, while the peak load increases by 4 %.

As a net effect of the above described developments, the peak load increases in total by 21 % until 2050 in the EU28+2. Since the average hourly electricity demand increases by merely 12 % in the Mod-RES scenario, the fluctuations in the system load curve are increasing. The standard deviation, as a common metric for fluctuation, is increasing on average by 25 % between 2014 and 2050.

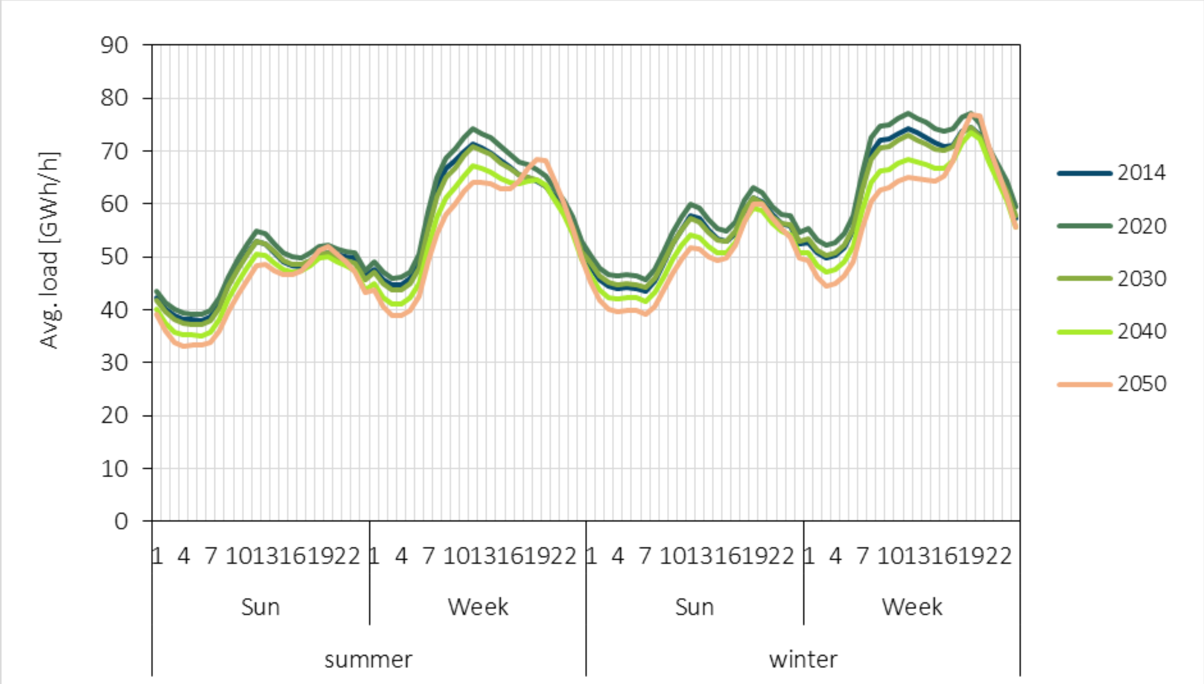

Figure 35: Development of the German average load in summer and winter on Sundays and weekdays for the years 2014 to 2050

Source: eLOAD

The load fluctuation increases for all European countries until 2050, but individually different in degrees: Particularly the system loads of countries with high efficiency gains in processes with an even electricity consumption, such as industry processes like steel production or increasing volatile loads, such as air-conditioning and electric vehicles, gain fluctuation. In the Mod-RES scenario, this is the case for Luxemburg, Norway, and Slovakia with decreasing consumption in steel and aluminium production, as well as Denmark and the Netherlands with an over proportional increase in electricity consumption for vehicle charging (see Figure 36).

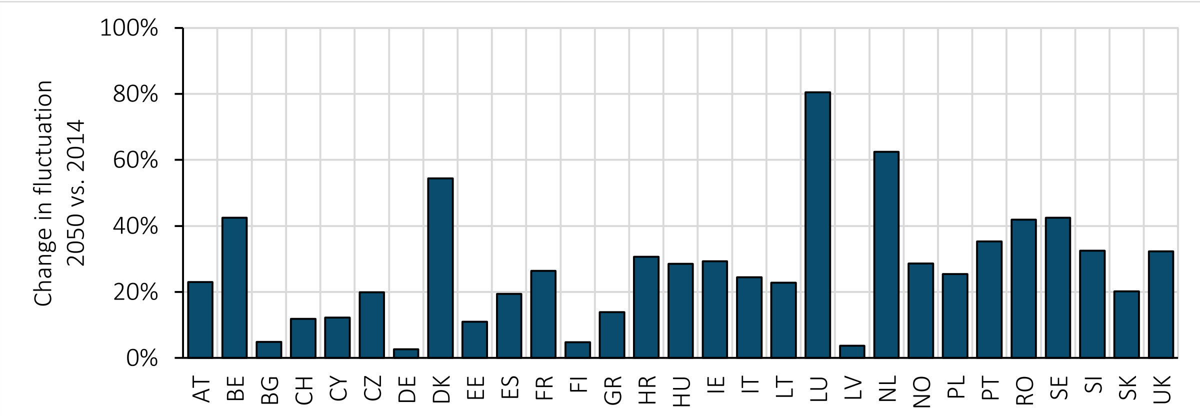

Figure 36: Change in load fluctuation between 2014 and 2050 for the EU28 + NO + CH

Source: eLOAD

As mentioned earlier, the additional electricity demand that occurs particularly in the evening hours can – in most cases – not be served by RES and requires additional conventional generation capacities or other flexible technologies. However, in 2050 there is an excess of

RES, in total 133 TWh[21], occurring mostly in midday hours with high solar generation. Through the adjustment of consumer load (DSM) the renewable electricity generation can be balanced and less RES needs to be curtailed.

Since in the REFLEX Mod-RES scenario excess RES is available mostly in summer and the transition period and, to a lesser extent, on weekend days, the time availability of flexible processes is relevant. Table 15 and Table 16 list the availabilities of temperature and day-type dependent DSM processes. Note that the availability is an endogenous model result based on installed capacities and storage sizes.

Table 15: Availability of mainly temperature dependent DSM processes

Air-conditioning	0%	0%	0%	2%	4%	46%	100%	42%	5%	0%	0%	0%
Heat pumps	84%	86%	100%	87%	59%	25%	8%	15%	49%	87%	84%	85%
Refrigeration	100%	87%	92%	85%	87%	83%	85%	88%	89%	93%	94%	97%
Ventilation	100%	87%	84%	75%	79%	65%	65%	70%	76%	82%	95%	98%
	Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**

Source: eLOAD

Table 16: Availability of mainly day-type dependent DSM processes

Cement grinding	43%	55%	100%
Electric arc furnace	21%	20%	100%
Mechanical pulp	26%	83%	100%
e-Mobility	15%	14%	100%
	Sat.	**Sun.**	**Week.**

Source: eLOAD

The resulting availabilities identify particularly air-conditioning as suitable for DSM in the Mod-RES scenario. However, the process allows only a load shift of maximum one hour, without loss of user comfort and therefore the shifted amounts of electricity are comparable small (see Table 17). Besides the length of the load-shifting interval, the installed capacity of smart appliance is relevant for the actual deployment of the flexibility. Table 17 shows the different processes' share in the deployed load shifting. The table shows that in the short-term future (i.e. 2020), refrigeration is the most important DSM option. In the long-term future, refrigeration as well as industry processes decrease in importance regarding DSM, due to efficiency gains and thus a reduced DSM potential, while electric mobility, as a new technology, gains in importance with increasing market shares.

[21] 133 TWh is the sum of excess electricity in the individual counties. If the electricity could be traded limitless over all EU28+2, the excess would be merely 4.3 TWh.

Table 17: Share of process in shifted amount of electricity per year, distinguished by demand-side sector

Sector	Process	2020	2030	2040	2050
HH	Ventilation & Air-conditioning	<1%	<1%	<1%	<1%
	Heat pumps	16%	36%	16%	21%
TE	Ventilation & Air-conditioning	<1%	<1%	<1%	<1%
	Heat pumps	5%	4%	3%	2%
	Circulation pumps and other heating auxiliaries	<1%	<1%	<1%	<1%
	Refrigeration	59%	27%	34%	34%
IND	Cement grinding	<1%	<1%	<1%	<1%
	Electric arc furnace	14%	24%	17%	4%
	Mechanical pulp	5%	4%	2%	2%
TRANS	e-Mobility	1%	4%	28%	38%
	∑	100%	100%	100%	100%

Source: eLOAD

In total, the applied DSM reduces the negative residual load of the EU28 + NO + CH by 16 % in 2050 over the individual countries, integrating an additional 22 TWh of RES. Table 18 shows the negative residual load for the largest EU countries plus the entire EU28 + NO + CH next to the integrated RES (i.e. reduced negative residual load). The integration of RES in this scenario is executed on a national level, without cross-border exchange of electricity. Thus, the shown RES integration by DSM is possible without the extensive use of interconnectors. However, the results of the Mod-RES scenario clearly show that particularly in Spain only a small share of the excess RES can be integrated with DSM, leaving room for additional flexibility options and/or the promotion of DSM to evoke a higher willingness in consumers to participate in DSM.

Table 18: Negative residual load vs. integrated RES for the largest EU countries and the entire EU28 + NO + CH

		FR	DE	ES	IT	NL	PL	UK	∑ EU28 + 2
Neg. residual load	*TWh*	9.2	18.3	68.3	13.3	0.7	1.2	2.4	**133**
Integrated RES	*TWh*	4.4	4.6	4.4	4.3	0.5	0.3	0.9	**22**

Source: eLOAD

Besides the reduction of negative residual load, the aim of DSM is the smoothing of the residual load curve to further reduce the flexibility requirements and/or allow for high full load hours of conventional electricity generation capacities, thus reducing efficiency losses when ramping power plants up and down and allowing for cost efficient base-load generation capacities. In the Mod-RES scenario, DSM reduce the standard deviation of the residual load by an average of 11 % over the individual EU28 + NO + CH countries.

An example of the effect of DSM is depicted in Figure 37, which shows system and residual load with and without DSM for Germany in 2050. It shows that the negative residual load, which occurs particularly in summer, is reduced and the residual load is overall flattened. Since the objective of DSM is the smoothing of the residual load, the peak load of the system load curve increases in midday hours in order to integrate additional RES.

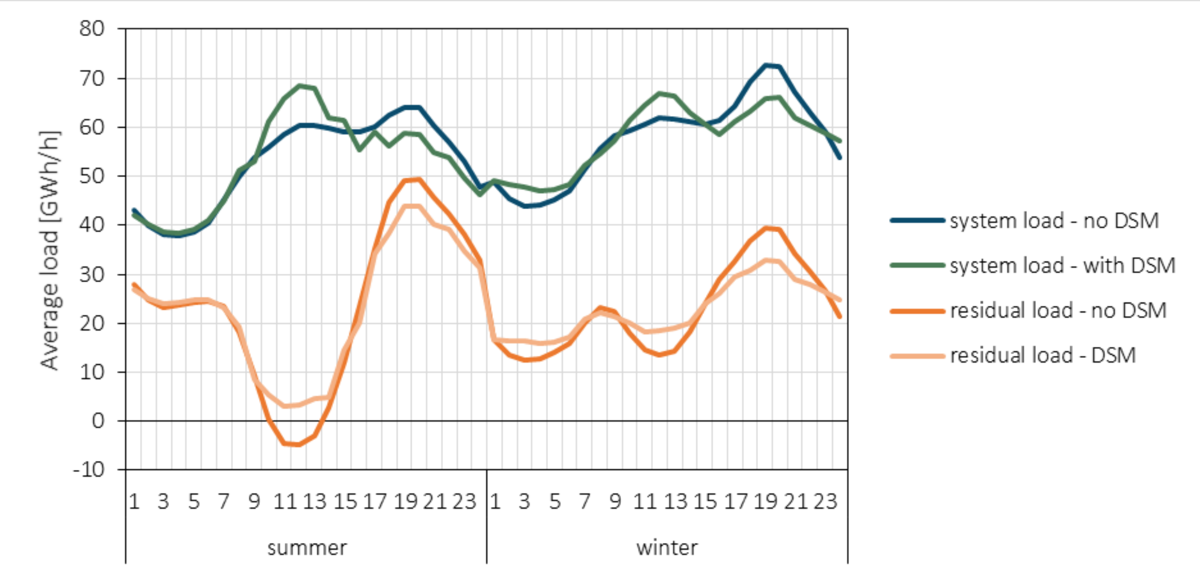

Figure 37: German average system and residual load with and without DSM in 2050 in summer (left) and winter (right)

Source: eLOAD

4.1.2.2 The High-RES scenarios – Possibilities of DSM

Compared to the Mod-RES scenario, the electricity consumption in the High-RES scenarios is higher, due to a more ambitious electrification of the demand-side sector. This ambitious transformation is also reflected in the system load curves. Figure 38 depicts the system load of Germany in 2050 for the three scenarios, clearly showing the on average higher system load in the High-RES scenarios. The large difference between the High-RES centralized and the decentralized scenario stems from the assumption that in the decentralized scenario, hydrogen, for the transport sector as well as for feedstock and fuel in the industry sector, is produced via electrolysis decentralized in the fuel stations and industrial plants. Therefore, the electricity consumption for electrolysers is included in the system load (in the centralized scenario, hydrogen is produced as part of the electricity sector and is therefore no part of the electricity demand-side). Besides the effect of the electrolysers, that feature a band-like profile with high full load hours, the structural changes in the system loads are similar in both High-RES scenarios. Both High-RES system loads also feature load peaks on midday and in the evening from the electric vehicle charging, which occurs in the High-RES scenario not only after the last trip at home, but additionally at the workplace due to a higher number of charging points in the more ambitious transformation scenarios (Figure 38).

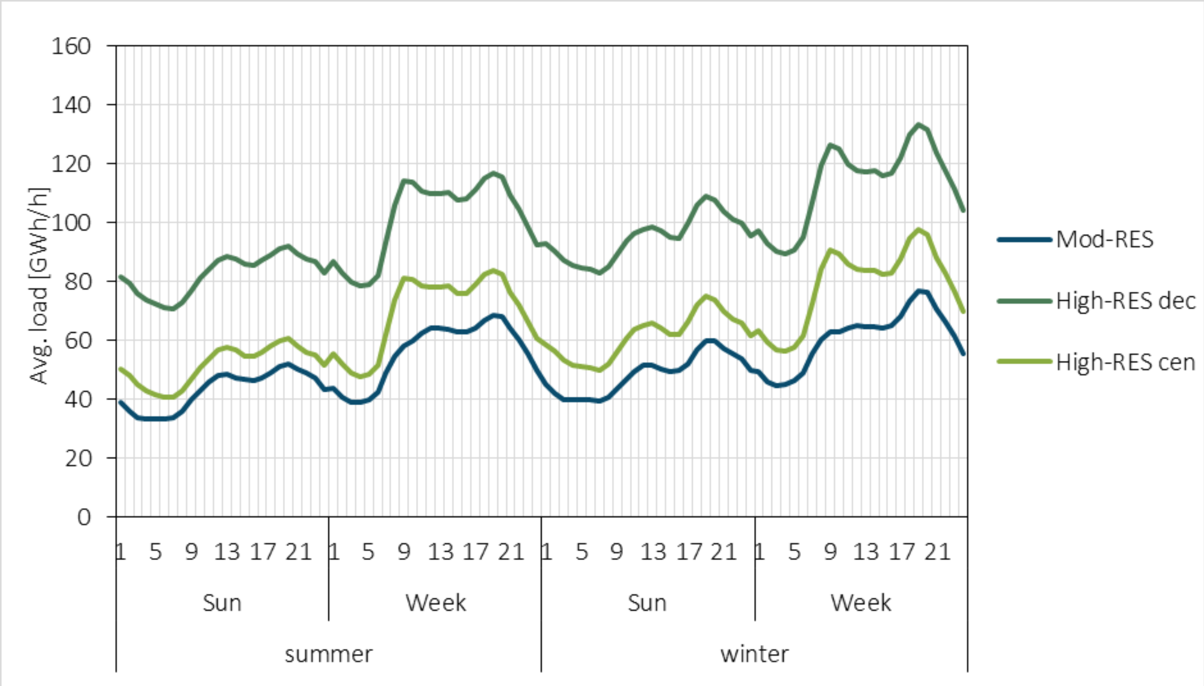

Figure 38: German average load in summer (left) and winter (right) on Sundays and weekdays in 2050 in the Mod-RES and High-RES scenarios (centralized and decentralized)

Source: eLOAD

The higher electricity consumption in the High-RES scenarios together with a higher amount of RES generation, results in highly fluctuation residual loads and a high amount of negative residual load. The fluctuating residual load corresponds with equally highly fluctuating electricity prices, leaving room for DSM to exploit the arbitrage.

Figure 39 shows the shifted load as the sum of load shifting in the EU 28 + NO + CH in the High-RES centralized scenario. For a better readability, the DSM processes are grouped: Ventilation and air-conditioning (V&AC) contains the loads of the household and tertiary sector, the same for heat pumps (HP). “Industry” groups all industrial DSM processes, i.e. electric arc furnace, cement grinding, mechanical pulp. Equally, private and commercial electric vehicles (EV) are grouped.

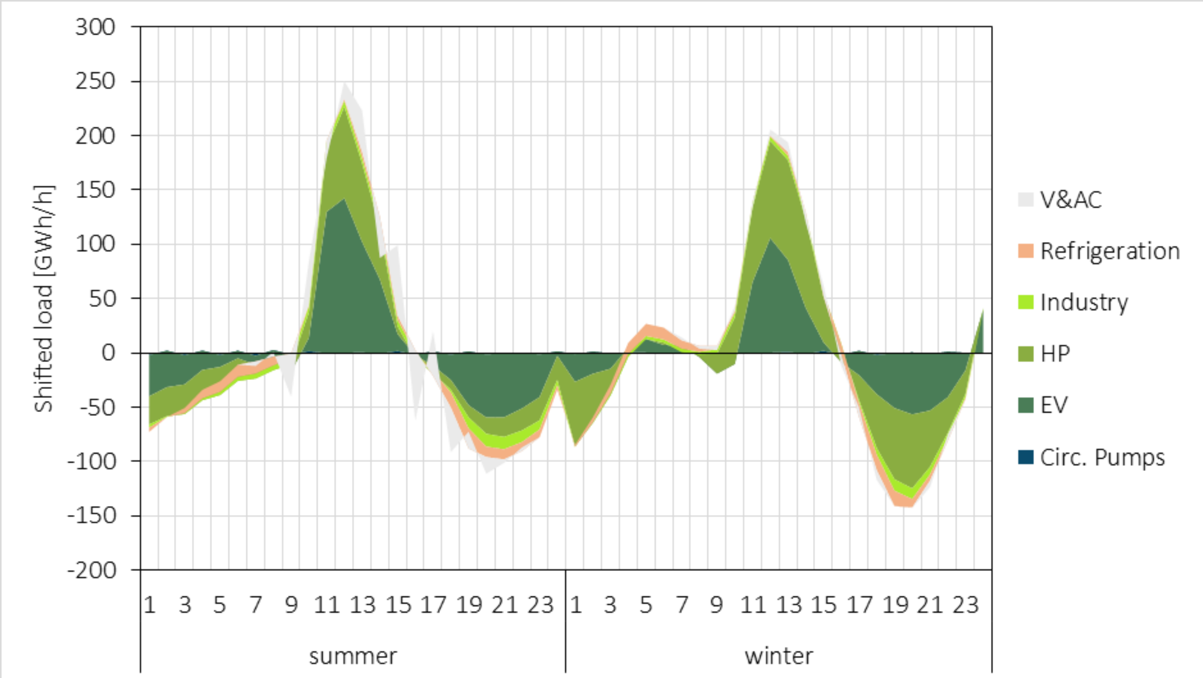

Figure 39: Shifted load in the EU28 + NO + CH in 2050 for summer (left) and winter (right) in the High-RES centralized scenario, distinguished by DSM process

Source: eLOAD

The Figure 39 shows that, in 2050, load is shifted mostly from night hours towards the middle of the day with high PV production and low or negative residual loads. In total, the negative residual load can be reduced by 35 TWh.

Table 19: Negative residual load vs. integrated RES for the largest EU countries and the entire EU28 + NO + CH in the High-RES centralized scenario

High-RES cen		FR	DE	ES	IT	NL	PL	UK	∑ EU28 + 2
Neg. residual load	*TWh*	46.3	73.4	81.2	45.7	40	21.3	62.2	**420**
Integrated RES	*TWh*	7.7	5.2	4.6	6.3	0.4	1	4.5	**35**

Source: eLOAD

In comparison to the centralized scenario, the decentralized scenario features a higher amount of DSM, mainly due to the available flexibility from decentralized batteries and electrolysers. However, due to the higher electricity consumption for hydrogen production, the amount of excess RES is small, in particular in large countries with a high electricity demand (see Table 20). Due to the high amount of flexible demand, the negative residual load can be reduced by large quantities. In Germany, e.g. negative residual load is almost omitted entirely.

Table 20: Negative residual load vs. integrated RES for the largest EU countries and the entire EU28 + NO + CH in the High RES decentralized scenario

High-RES dec		FR	DE	ES	IT	NL	PL	UK	∑ EU28 + 2
Neg. residual load	*TWh*	0.3	1.6	0.0	0.0	22.2	--	26.7	**55**
Integrated RES	*TWh*	0.3	1.5	0.0	0.0	9.5	--	14.8	**27**

Source: eLOAD

The high amount of DSM, including substantial amounts of stationary residential battery storage capacities (see calculations of their diffusion below), in the decentralized scenario leads to an extremely smoothed residual load: for example in Germany, the residual load's standard deviation is reduced by 75 % (compared to a reduction of 9 % in the centralized scenario). Figure 40 depicts the average German residual load in 2050 for the two High-RES scenarios.

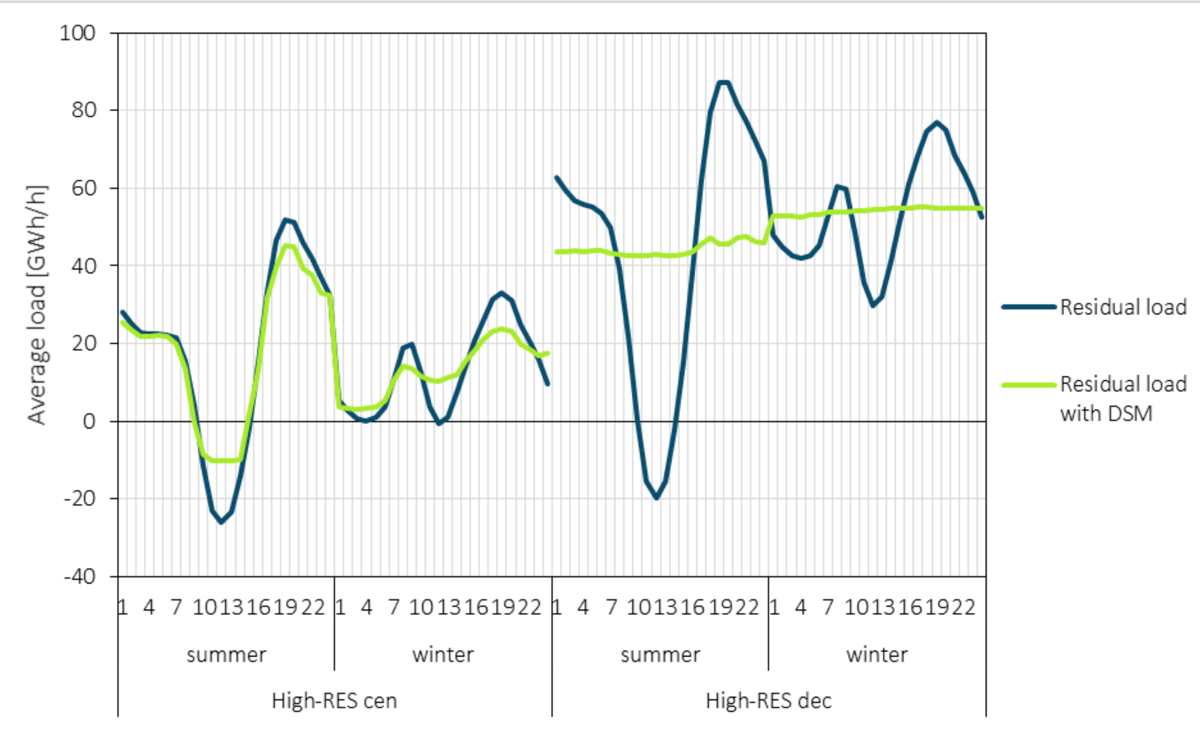

Figure 40: German residual load in 2050 with and without DSM in the High RES centralized (left) and decentralized (right) scenario

Source: eLOAD

In Figure 41, the shifted load in the decentralized High-RES scenario is compared to the centralized scenario.

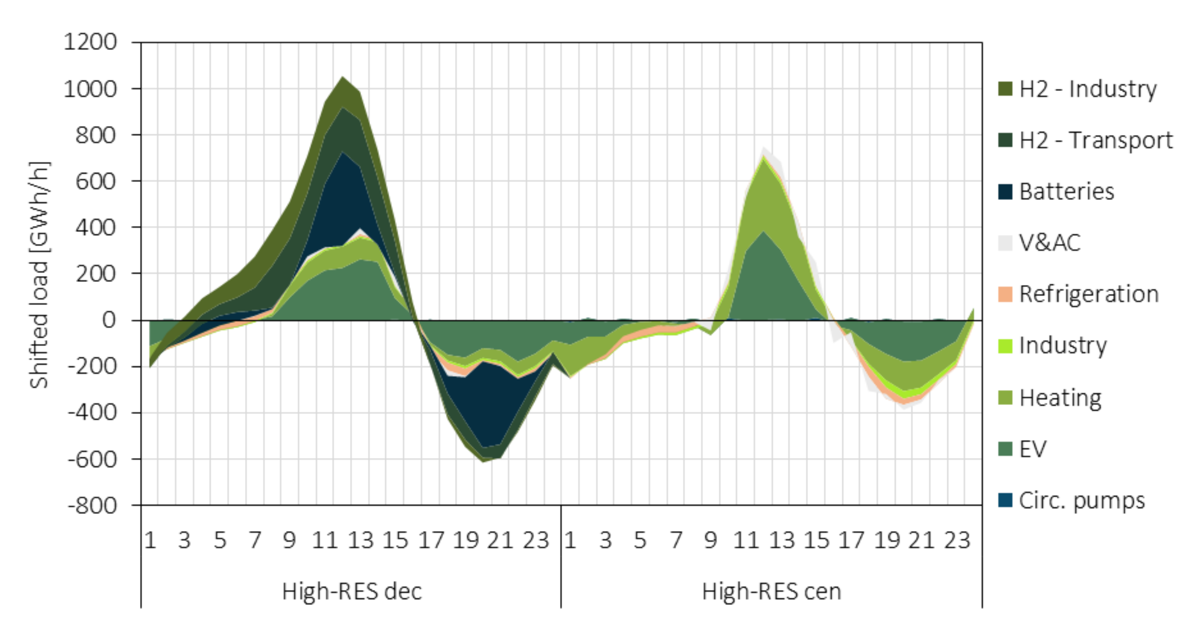

Figure 41: Shifted load in the EU28 + NO + CH in 2050 in the High RES decentralized (left) and centralized (right) scenario, distinguished by DSM process

Source: eLOAD

While in the centralized scenario, heat pumps and electric vehicles are the dominant DSM option, these technologies are complemented by the new flexibility options of the electrolysers and the stationary batteries in the High-RES decentralized scenario. Electrolysers together with stationary and mobile batteries make up 87 % of the DSM potential in the decentralized scenario in 2050 (see Table 21).

Table 21: Share of processes to the load shifting potential in the High-RES scenarios in 2050

	High-RES dec	High-RES cen
Circ. pumps	0%	2%
Electric vehicles	19%	37%
Heat pumps	8%	40%
Industry processes	1%	5%
Refrigeration	2%	6%
V&AC	2%	10%
Batteries	18%	--
H2 - Transport	26%	--
H2 - Industry	24%	--
∑	**100%**	**100%**

Source: eLOAD

Stationary batteries are, unlike electric vehicles and electrolysers, not driven by the necessary fuel switch, but by consumers' desire to optimize their own electricity supply with a PV system and a combined stationary battery. Since the technology is one of the most important flexibility options in the decentralized scenario, the applied methodology for the assessment of its market diffusion and the resulting installed capacities are explained in the following in more detail.

Market diffusion of stationary batteries

The market diffusion of decentralized battery systems in households is calculated in 5 steps:

(i) Calculation of battery operation

The battery operation is calculated for an average (individual) household with a PV system of the average installed power of the considered country. The load profile is taken from for all EU28 + NO + CH countries from a German source, i.e. (VDI 2008), and scaled according to the countries' average yearly residential electricity consumption. The average size of residential PV rooftop system for the EU countries is taken from (GfK Belgium consortium 2017) and the PV electricity production profile is calculated based on the analysis in Chapter 3.3.

The battery operation is calculated for three different battery capacities: no battery, 2.5 kWh, 5 kWh, and 7.5 kWh. Subject to the technical restrictions of the installed battery as well as the household's electricity consumption and PV production profile, charging and discharging loads are determined for each hour of the optimization interval *h* for each user by minimizing the objective function (4.1):

$$\text{Min} \sum_{\text{h}=\text{h}_{\text{min}}}^{\text{h}_{\text{max}}} C_h\left(\eta^{-1}\, P_{Batt,pos,h} + \eta\, P_{Batt,neg,h}\right) \tag{4.1}$$

with the control variables $P_{Batt,pos}$ (charging) and $P_{Batt,neg}$ (discharging). Efficiency losses due to energy conversion in the battery and the AC-DC inverter are considered via the efficiency factor $\eta = \eta_{Batt} \cdot \eta_{AC-DC} \coloneqq 88\,\%$. The objective function is subject to technical restrictions, such as capacity limits. For all battery sizes, a maximum charging rate of 0.5C is assumed, and a minimum state of charge (SoC) of 10 %.

For both technologies, heat pump and battery, the consumption of self-generated electricity is favoured with the implementation of the following cost function ($A < B$) (4.2):

$$C_h \coloneqq \begin{cases} A, & P_{HH,h} + P_{Batt,h} + P_{ls,h} \leq P_{PV,h} \\ B, & \text{else} \end{cases} \tag{4.2}$$

with the household's electricity demand P_{HH} that includes the non-optimized heat pump consumption, battery load $P_{Batt} = P_{Batt,pos} + P_{Batt,neg}$, shifted heat pump load P_{ls}, and the PV production P_{PV}. Note that the amount of A and B is in this case not important, as long as A < B the battery operation is optimized to maximize self-consumption.

The electricity supply is simulated for each country with the battery operation model described above. The results are aggregated into two indicators for each individual household and PV + battery system configuration: the household's remaining *electricity purchase* from the public grid and its (remunerated) *PV feed-in*. Both indicators are applied within the subsequent economic assessment.

(ii) Calculation of economic benefit

In a subsequent step, economic benefit of each of the battery system is calculated. In the calculation we consider the annuity of the investment I_0 (see Chapter 3.4) and the annual cost of electricity supply, which is calculated as the sum of electricity purchased from the grid e_p in kWh times the end-user electricity price for households P_{HH} in EUR/kWh over the course of one year. The cost of electricity purchase is reduced by the amount of excess electricity feed-in e_f in kWh per year times the feed-in remuneration, which is set to be the trading electricity price P_T in EUR/kWh (4.3):

$$\min_{\tau}\left\{\left[\frac{(1+i)^n \cdot i}{(1+i)^n - 1} I_0\right]_{\tau\, a} + \sum_{t=1}^{8760}\left(P_{HH} \cdot e_p - P_T \cdot e_f\right)_{\tau\, a}\right\}_c \quad (4.3)$$

In a case of high electricity trading prices, the cost of electricity supply can also become negative. In each year a the economics are calculated for each battery size τ and the most economical battery (or no battery) is selected.

A battery lifetime n of 15 years is assumed and an internal discount rate i of 2 %.

(iii) Calculation of share of battery adopters (s-curve)

Following Rogers' (2003) adopter groups, it is assumed that the adopter group of "innovators" installs a battery before the average person does. Accordingly, it is assumed that in the first year, in which a battery is economically feasible for the average household, the market share of batteries (within the population of households with a PV rooftop system) is 2.1 % (share of "innovators" in the population).

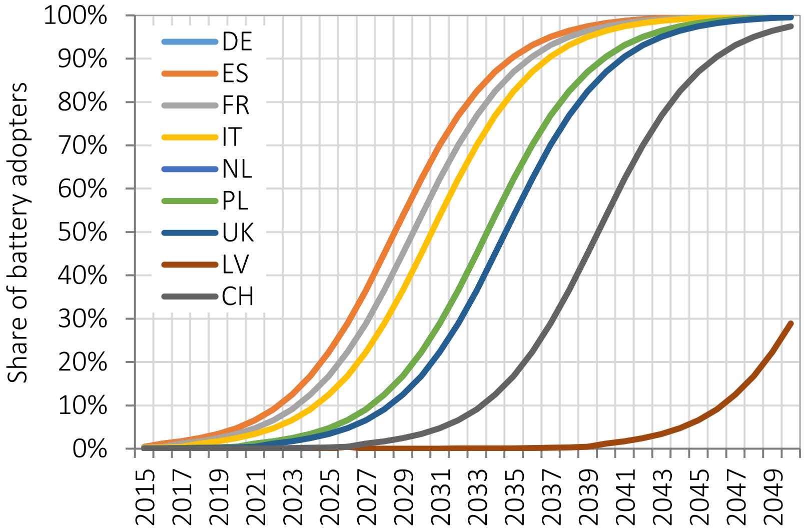

Figure 42: Diffusion curves for selected EU countries[22]

Source: eLOAD

[22] The lines for DE and ES have the same pattern, therefore are overlapping

An optimistic logistic diffusion trajectory is taken from another innovative technology (the same so-called s-curve was applied in Elsland et al. 2016). The fixed s-curve is shifted so that the first year, in which battery is economically feasible for the average household shows a market share of about 2 %. Figure 42 shows the resulting diffusion curves for selected EU countries and Switzerland.

(iv) Calculation of population of adopters

The entire population of battery adopters ($N_{adopter}$) equals the number of PV rooftop systems on residential buildings. It is calculated as the installed power of PV rooftop systems ($P_{PV\ rt}$) (calculated in Chapter 3.3) times the share of residential buildings of the PV rooftop potential ($r_{residential}$) (taken from (EEG TU Wien) and divided by the average installed power for PV rooftop systems ($P_{avg\ PV\ rt}$) in the individual countries (GfK Belgium consortium 2017) (see equation (4.4)).

$$N_{adopter} = \frac{P_{PV\ rt} \times r_{residential}}{P_{avg\ PV\ rt}} \tag{4.4}$$

With the described assumptions and the development of PV rooftop systems, the residential PV systems for all EU countries + CH are calculated, resulting in 19 million in 2015 and 93 million in 2050.

(v) Calculation of battery capacity

In a final step, the total installed battery capacity (C_{Batt}) is calculated as the product of the share of battery adopters in the population ($r_{adopters}$, see step 3), the population ($N_{adopters}$, see step 4) and the installed battery capacity of the average household ($C_{avg\ batt}$, see step 2).

$$C_{Batt} = r_{adopters} \times N_{adopters} \times C_{avg\ batt} \tag{4.5}$$

The results of the calculation of the market diffusion of decentralized batteries can be found in Table 22 and Table 23. The following table shows the most economic batteries size resulting from the technology cost and the financial benefit of increasing self-consumption.

Table 22: Most economic battery capacity in kWh for the average household in selected countries in the years 2015-2020, 2030, 2040, and 2050

country	*unit*	2015	2016	2017	2018	2019	2020	2030	2040	2050
DE	*kWh*	0	0	2.5	5	5	5	5	5	5
ES	*kWh*	0	0	5	5	5	7.5	7.5	7.5	7.5
FR	*kWh*	0	0	2.5	5	5	7.5	7.5	7.5	7.5
IT	*kWh*	0	0	2.5	2.5	5	5	5	5	5
NL	*kWh*	0	0	0	2.5	2.5	2.5	5	5	5
PL	*kWh*	0	0	0	0	2.5	2.5	2.5	2.5	5
UK	*kWh*	0	0	0	2.5	5	5	7.5	7.5	7.5

Source: eLOAD

In the mid- to long-term future, relatively large batteries are installed in residential PV self-consumption systems, due to relative low technology costs. The application of the experience curves (see REFLEX work package 3) result in substantially decreasing specific investment, from 1250 EUR/kWh in 2017 to 346 EUR/kWh in 2050. The technological learning in stationary batteries is primarily limited to the cell technologies, since other system components such as inverters or control elements are already rather mature. The specific investment is therefore expected to remain above a certain level.

Regarding the resulting battery installations, note that the low electricity prices in Norway inhibited the batteries in this country to gain an economic case, even in the long-term future. This cost development allows for a high diffusion and large systems. In 2050 we expect over 80 million batteries in the EU28 + 2, i.e. over 90% of the households with a PV roof-top system own a battery.

Table 23 shows the resulting installed battery capacity for selected EU countries and the entire EU28 + NO + CH. In total, the High-RES decentralized scenario is characterised by almost 470 GW of stationary residential batteries in the year 2050.

Table 23: Expected installed battery capacity in MWh for selected EU countries and the entire EU28 + CH based on the assumptions described in steps 1 to 5 in the years 2020, 2030, 2040, and 2050

country	***unit***	**2020**	**2030**	**2040**	**2050**
DE	*MWh*	2,404	39,003	54,865	63,861
ES	*MWh*	162	14,186	45,873	68,563
FR	*MWh*	1,264	36,108	73,182	100,286
IT	*MWh*	250	13,067	28,725	62,404
NL	*MWh*	0	2,000	6,392	5,329
PL	*MWh*	0	829	7,671	10,236
UK	*MWh*	0	6,053	36,033	45,942
EU28+CH	*MWh*	**4,145**	**126,765**	**319,267**	**467,567**

Source: eLOAD

4.2 Energy Technology Portfolios for System Flexibility on the Supply Side

In this section, the results regarding the energy technology portfolio for system flexibility in the electricity and heat sector are discussed. Therefore, the two sectoral based models ELTRAMOD and TIMES-HEAT-EU are applied to analyse the developments in the electricity and heat sector under consideration of the given scenario framework and assumptions of Chapter 3. In the following sub-sections the scenario specific key assumptions and input parameters are presented, followed by the model result analyses regarding the capacity, generation and cost developments as well as regarding the trend in CO_2 emissions for the electricity and heat sector.

4.2.1 Electricity Sector

The power sector is responsible for around 25 % of total GHG emissions in Europe (European Commission 2011a). Regarding the overall emission reduction targets, the European power sector is assigned a crucial role since several low-carbon technologies are already technically available at comparably affordable cost. Additionally, the electrification of the demand side sectors increases the importance of ambitious decarbonisation measures for the transformation of the electricity system. Within this framework, emission reduction goals for the electricity sector are beyond the overall 80 % reduction target to enable the decarbonisation of the other sectors. Besides, efficiency measures and the expansion of RES are therefore enforced by the European energy policy (European Commission 2011a).

With ELTRAMOD, optimal combinations of relevant technologies are calculated to assess the role of different flexibility options against the background of the scenario specific assumptions discussed before. In contrast to the approach applied in the demand side models, in ELTRAMOD no CO_2 emission reduction target is applied but scenario specific CO_2 prices, which reflect the frameworks discussed in Chapter 3. In the following, further key assumptions concerning ELTRAMOD are presented before the model results are discussed.

Scenario assumptions

When applying the electricity market model ELTRAMOD, mainly the two input parameter RES generation and electricity demand have a strong impact on the model outcomes. The differences in these input parameters are defined by scenario specific assumptions discussed before and will be summarised briefly to increase the understanding of the model results.

Concerning the weather dependent renewable electricity generation from PV and wind power plants differences between the scenarios arise due to the lower RES based electricity generation in the Mod-RES scenario compared to the High-RES scenarios as well as due to the different technologies generating RES electricity in the central versus decentral High-RES scenarios (see Chapter 3.3).

Regarding the electricity demand, further input factors resulting from the model coupling with TIMES-HEAT-EU, ASTRA, FORECAST and eLOAD have an impact on ELTRAMOD's outcome. Although electrification of the heating sector, i.e. the investment in heat pumps, is a model endogenous result, the heating demand available for power-to-heat applications is restricted and derived from TIMES-HEAT-EU results. Also the combined heat and power plant (CHP) capacities result from the model interface with TIMES-HEAT-EU and are implemented in ELTRAMOD as minimum fuel-specific power plant installations. Furthermore, there are differences in the developments of the electricity demand and energy efficiency measures, between each scenario due to the model coupling with ASTRA, FORECAST and eLOAD. As can be seen in Figure 43, the scenario specific assumptions result in a comparably lower electricity system load in the Mod-RES scenario due to less electrification of the energy demand sectors. Additionally, the higher electricity demand in the High-RES scenarios shows differences between the central and the decentral scenario regarding their composition as well as the assumed coupling of the demand side sectors. The system load itself is composed in each scenario by direct electricity use in the industry, residential, tertiary and transport sectors. In the High-RES decentral scenario, a stronger increase in electricity demand from the industry and transport sector can be observed. In the High-RES decentral scenario, hydrogen demand for industry and transport is satisfied directly via decentral electrolysis and therefore increases electricity demand in the industry and transport sector. In contrast, in the High-RES central scenario, the hydrogen demand is covered model-endogenously in ELTRAMOD via central electrolyzers taking part in the electricity market. In total, exogenous electricity demand for ELTRAMOD is around 75 % higher in the High-RES scenario compared to the Mod-RES scenario, while High-RES decentral has a slightly higher electricity demand compared to the central scenario.

For the scenario specific model calculations with ELTRAMOD, the total system load is transformed into hourly load profiles smoothed by DSM measures from eLOAD. As shown in Chapter 4.1.2, the potential of different DSM processes to flatten the residual load can be substantial. Since these applications are assumed to be applied decentral (mainly to increase self-consumption), thus not participating in the wholesale electricity market, the value of additional market-based flexibility options represented in ELTRAMOD (see e.g. Müller and Möst 2018) is restricted.

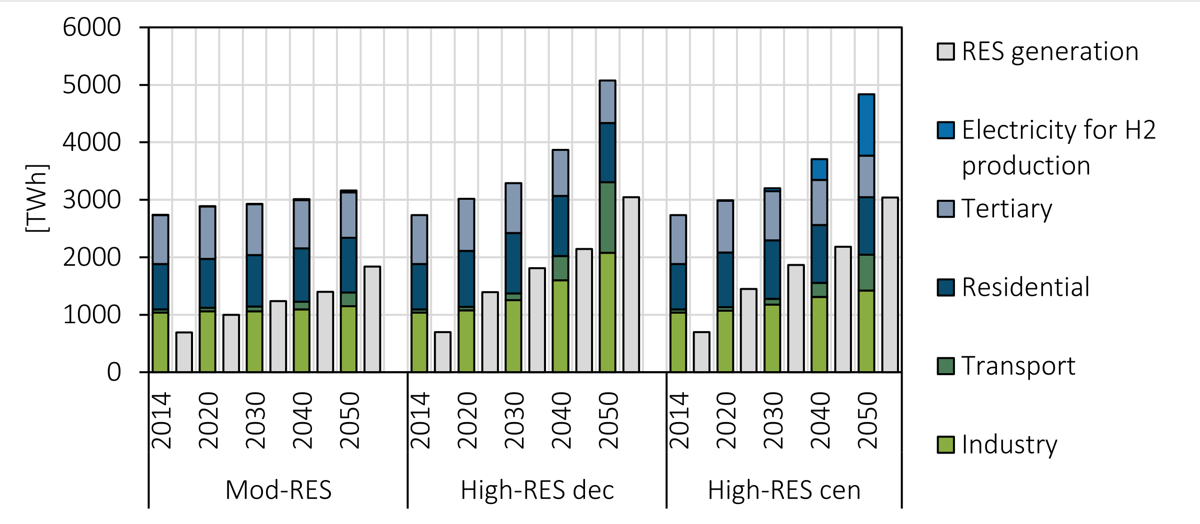

Figure 43: Yearly composition of electricity demand and RES generation in the REFLEX scenarios across all modeled countries

Source: FORECAST, eLOAD, ASTRA

Based on the yearly values summarised above the scenario specific hourly parameters for RES feed-in and electricity demand (see Chapter 4.1.2) are exogenous input for ELTRAMOD as well. With these fluctuating time series, the demand for flexibility in the electricity system is characterised by the residual load defined as the hourly difference between the system load and the intermittent RES electricity generation. By applying ELTRAMOD, an optimal investment and hourly dispatch of available flexible technologies is calculated to meet these scenario specific flexibility requirements. The different assumptions for the input parameters result in diverging developments for the residual load in the scenarios. In Figure 44, the aggregated hourly residual load for all countries is sorted from its yearly maximum to minimum for the Mod-RES as well as for the two High-RES scenarios. This is done to estimate the yearly flexibility requirements in the whole region, without taking limited interconnector capacities into account, as it is done for the model calculations. In the Mod-RES scenario, the sorted residual load is decreasing from 2014 to 2050 due to the faster increase in RES generation compared to the system load. In contrast, the significant increase of system load in the High-RES scenarios overlaps the increase of RES generation and leads to a diverging development. The strong increase of system load in the High-RES decentral scenario from the year 2030 on leads to an increase of the total residual load from 2030 to 2050. Furthermore, the decentral hydrogen production increases the electricity demand especially in times when there is a high RES feed-in and thus increases the lower parts of the residual load. For the High-RES central scenario, this effect is less strong since there is a lower increase in system load as well as no decentral electrolysis use. Therefore, in 2050, the residual load is negative in around 600 hours where the overall RES generation in the 35 countries is higher than the system load.

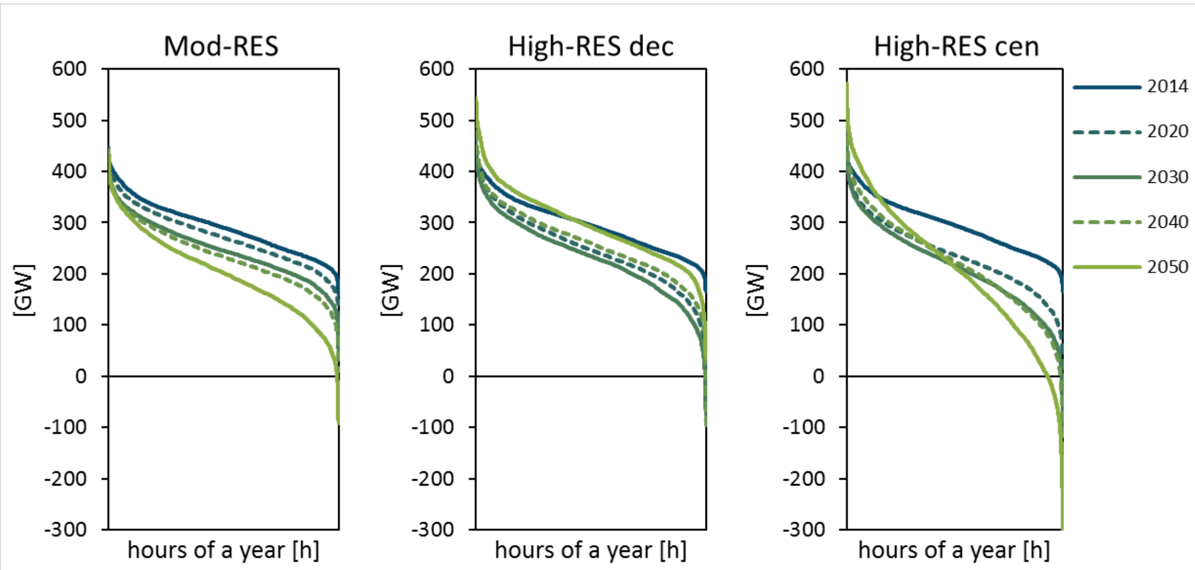

Figure 44: Development of the aggregated sorted residual load in the REFLEX scenarios across all modeled countries

Source: FORECAST, eLOAD, ASTRA

Besides the renewable expansion pathways, further central assumptions within the REFLEX scenario framework (see Chapter 3) have an impact on the outcome of ELTRAMOD. The input regarding the fuel and CO_2 prices as well as the cost developments based on the technological learning curves strongly influence the model endogenous decision on optimal flexible technology combinations. Additionally, existing power plant decommissioning is assumed to be exogenously based on power plant age. In Table 24, the main differences in input assumptions are summarised.

Table 24: Scenario assumptions and input parameter for the electricity sector

	Source	Mod-RES	High-RES dec	High-RES cen
RES capacity and profiles		Calculated based on PRIMES **Reference Scenario Data**	Calculated based on PRIMES **High Renewable Scenario Data with higher PV share**	Calculated based on PRIMES **High Renewable Scenario Data with higher wind share**
Heating demand	**TIMES-Heat** (own calculations, see Chapter 4.2.2)	Scenario specific available heating demand for power-to-heat	Scenario specific available heating demand for power-to-heat	Scenario specific available heating demand for power-to-heat
Hourly electricity load profiles	**eLOAD** based on **FORECAST** (own calculations, see Chapter 4.1.2)	Scenario specific load profiles	Scenario specific load profiles **including hydrogen demand for industry**	Scenario specific load profiles **without hydrogen demand for industry**
Yearly hydrogen demand for transport	**ASTRA** (own calculations, see Chapter 4.1.1.4)	Scenario specific hydrogen demand	Scenario specific hydrogen demand	Scenario specific hydrogen demand
CO_2 prices	Assumption based on Capros et al. (2016)	**Moderate CO_2 prices**	**High CO_2 prices**	
Investments	Assumptions and based on own learning curve model (see Chapter 3.4)	**Lower learning rates** for selected technologies	**Higher learning rates** for selected technologies	
Power plant decommissioning	Power plant database	Based on power plant age		

Source: ELTRAMOD

While keeping the assumptions presented before in mind in the following the results of ELTRAMOD regarding optimal investments in and dispatch of flexibility options in the electricity market are discussed.

Scenario results regarding the electricity sector

Figure 45 summarises the overall capacity mix including the exogenously added RES capacities in the three scenarios. Wind and PV capacities become the dominant electricity generation plants until 2050. The strongest overall increase shows the High-RES decentral scenario with a total capacity of more than 2,000 GW, while the Mod-RES scenario adds up to around 1,300 GW. When looking at the fossil fuel based power plants, a decrease in emission intensive capacities can be observed. In total coal, lignite and oil but also nuclear power plants show a constant decrease from 2014 to 2050 in each scenario, although no complete phase out of these technologies can be observed in any of the scenarios. The figure additionally shows the aggregated minimum CHP capacities separately received from TIMES-HEAT-EU. Due to the before mentioned higher CO_2, prices the decrease in gas capacities without CCS is higher in the High-RES scenarios. Again, the increase in system load does not lead to substitution of conventional power plant mix at the end of the observed period of time. After a decline until the year 2030, mainly the new installed CCS capacities cause an increase in total conventional capacity until 2050.

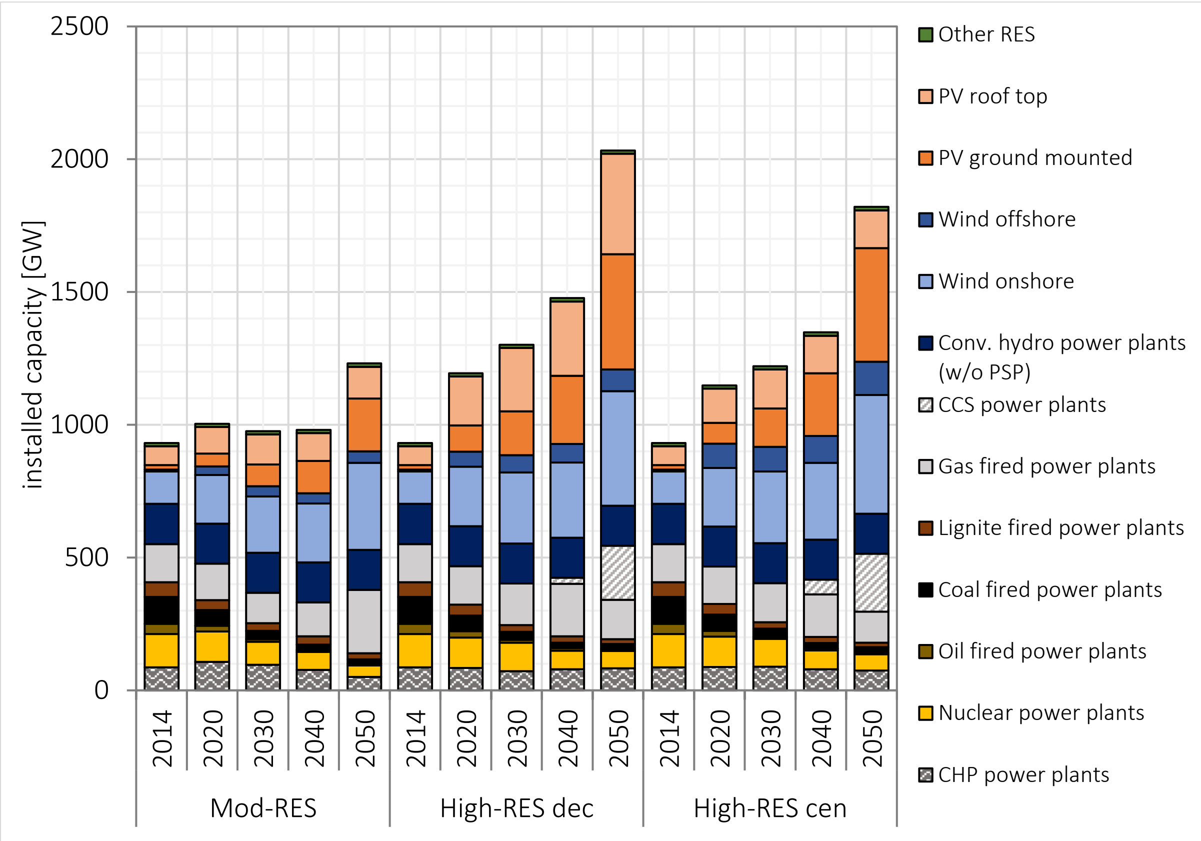

Figure 45: Overall capacity mix in the REFLEX scenarios across all modeled countries

Source: ELTRAMOD

In Figure 46, the corresponding model-endogenously added technology specific capacities are presented. Additionally, the negative values show the exogenous capacity decommissioning based on the power plant age, which is identical for the Mod-RES as well as for the two High-RES scenarios, because the existing power plant mix in the observed regions is the same for each scenario. Since RES are exogenous input for ELTRAMOD without an assumed decommissioning, these technologies are excluded in the figure to focus on the model outcomes. Particularly in the years 2020 to 2040 overall increasing decommissioned capacities can be observed mainly for nuclear, coal, lignite and gas based power plants. New model endogenously calculated power plant capacities are characterized by a fuel switch to less emission intensive fuels like gas. Until 2030, each scenario shows a net decommissioning in dispatchable generation capacity. In the years after 2030, the CO_2 prices as well as the increase of the system load have a major impact on the resulting power plant mix. While in the Mod-RES scenario new capacities in 2040 and 2050 are mainly composed of nuclear and gas (closed cycle and open cycle gas turbine, CCGT and OCGT) based power plants, the higher CO_2 prices in the High-RES scenarios lead to investments in gas CCS technologies as well. Additionally, the amount of new installed capacities is around 75 % higher compared to the Mod-RES scenario. The strong increase in system load and high CO_2 prices result in around 203 GW and 218 GW gas CCS capacities in the year 2050 in the High-RES decentral and central scenario, respectively. For the same reason, investments in nuclear power plants between 42 and 63 GW in the years 2030 to 2050 are optimal (yet exogenously restricted) under the given assumptions. As mentioned in the model description in Chapter 2.2.4, the investment in new nuclear power plants is restricted only to countries where specific plans for new nuclear power plants exist. This assumption increases the value of alternative low carbon technologies like CCS to cover the additional electricity demand. In total, the aggregated results for nuclear and CCS based power plants in REFLEX are in between the range of the aforementioned studies. However, the development paths of low-carbon conventional capacities in existing studies tend to have higher shares of nuclear power plants compared to CCS. For instance, compared to the EU Roadmap (European Commission 2011a), 120 GW for nuclear based plants and 160 GW for CCS plants are estimated. For the EU Reference Scenario, Capros et al. (2016) calculate an European energy system with around 93 GW nuclear power plants and 19 GW CCS technologies for the year 2050. As it also can be seen in Figure 46, in the High-RES decentral scenario, higher conventional fuel based capacities are installed since the higher system load as well as the more flattened residual load (due to the stronger application of DSM) allows for more electricity generation capacities.

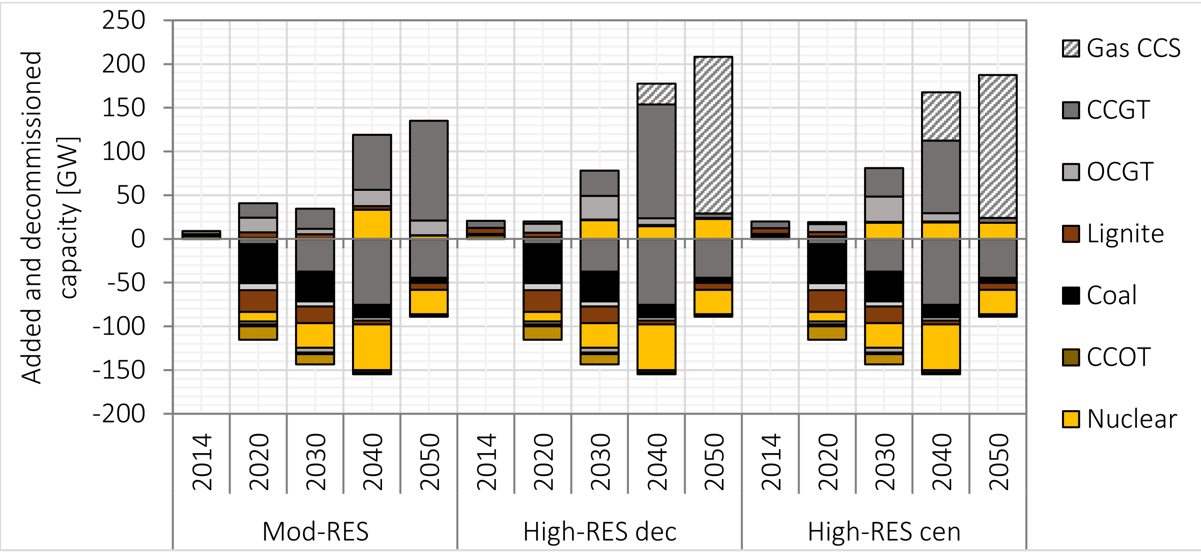

Figure 46: Added and decommissioned capacity in the REFLEX scenarios across all modeled countries

Source: ELTRAMOD

Besides the existing but not expansible pump storage plant (PSP) capacities and the residential storages, significant investments in additional storage capacities can only be observed in the Mod-RES scenario from the year 2040 on, particularly small lithium-ion battery (around 19 GW) and to a lesser extent adiabatic compressed air energy storages (A-CAES) (4 GW). The negligible investments in storage capacities in the High-RES scenarios (in total 0.2 GW and 0.8 GW in the decentral and central, respectively) are attributed to the substantial storage capacities not participating in the electricity market (see Chapter 4.1.2.2). In the High-RES decentralized scenario, there are installations of stationary residential batteries up to

470 GW. In contrast the High-RES centralized scenario is characterised by a higher share of mobile batteries in electric vehicles. Since the hourly system load profiles are therefore already exogenously smoothed by DSM applications, missing balancing requirements are decreasing the value of storages. As in the Mod-RES scenario, with less non-electricity-market based DSM as well as less electrification of the different energy demand sectors, the pattern of the residual load allows for the shifting of electricity from phases with high RES feed-in to phases with RES deficits and investments in storages become optimal, particularly with high RES shares and CO2 prices (see e.g. Zöphel and Möst 2017). In contrast, the development of the residual load in the High-RES scenarios particularly for the years 2040 and 2050 is less optimal for storage applications. Additionally the competition regarding the times with low and negative residual load between the increased use of demand side sector coupling via power-to-heat as well as power-to-gas and storages further limit the value of the latter ones.

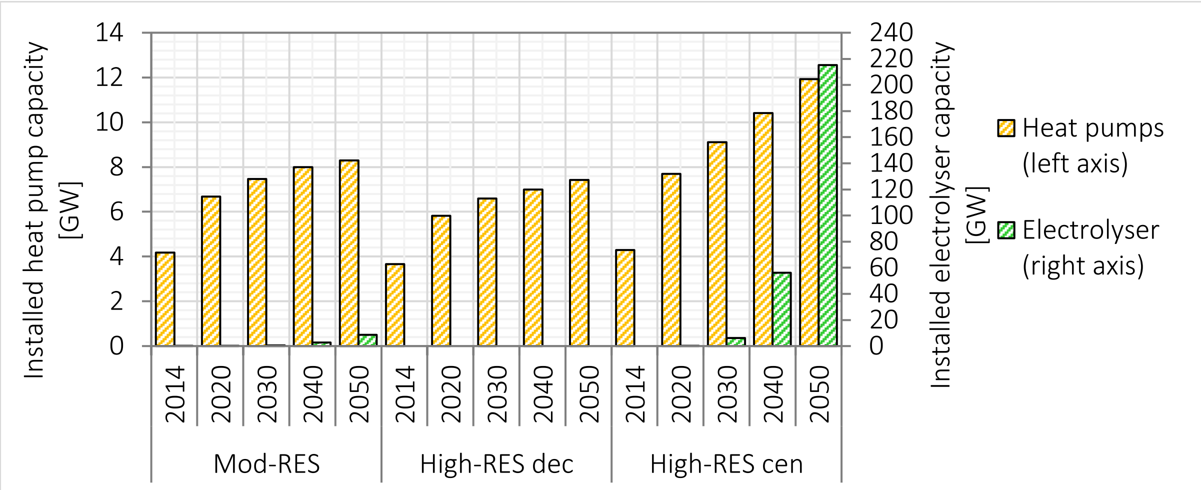

Figure 47: Installed power-to-x technologies in the REFLEX scenarios across all modeled countries

Source: ELTRAMOD

The input assumptions for sector coupling, by applying power-to-heat and power-to-gas, restrict and enforce the investments in heat pumps and electrolysers respectively. The limited available yearly heating demand as result of the model coupling with TIMES-HEAT-EU (see Chapter 4.2.2 for further insights) limits the installation of huge amounts of heat pump capacities as can be seen in Figure 47 left axis. Additionally, by including gas boilers as benchmark processes in ELTRAMOD, there is a competition between gas based heat generation and heat pumps relying on low electricity prices for an economical use. The higher amounts of RES surplus in the Mod-RES scenario as well as in the High-RES central scenario results in slightly higher heat pump capacities of 8 GW and 12 GW, respectively, compared to the decentral one (7 GW) in the year 2050. In contrast, the central hydrogen demand based on the model coupling with ASTRA (transport) and FORECAST (industry) enforces the investment in electrolysers in ELTRAMOD (see Figure 47 right axis). While there is no central hydrogen production by scenario definition in the High-RES decentral scenario, a significant increase in power-to-gas capacities can be observed from 2030 on in the High-RES centralized scenario and to a lesser extend in the Mod-RES scenario. The highest capacities are in the year 2050 in the central scenario (215 GW). Apart from this enforced hydrogen production, there is no additional investment in power-to-gas-to-power technologies. Thus, the competitiveness of power-to-gas in an electricity market perspective can therefore be assessed as limited (see for further discussions, e.g. Brunner et al. (2015)).

Based on the model results from ELTRAMOD INVEST and under consideration of the assumptions described before, the optimal dispatch of the calculated installed capacities is estimated in a second optimization step with the model ELTRAMOD DISPATCH. Figure 48 presents the aggregated electricity generation and electricity demand for all years of the three scenarios. The negative y-axis illustrates the electricity that is demanded by the system load (exogenous input from eLOAD, see Chapter 4.1.2), including electrolysis (power-to-gas for transport and industry) and heat pumps (power-to-heat to cover the remaining district heat) as well as charging of storages and the curtailed feed-in of variable RES (VRES). The electricity supply side is displayed on the positive y-axis with the conventional electricity generation, the feed-in of RES (variable and controllable) as well as with the discharging of storages.

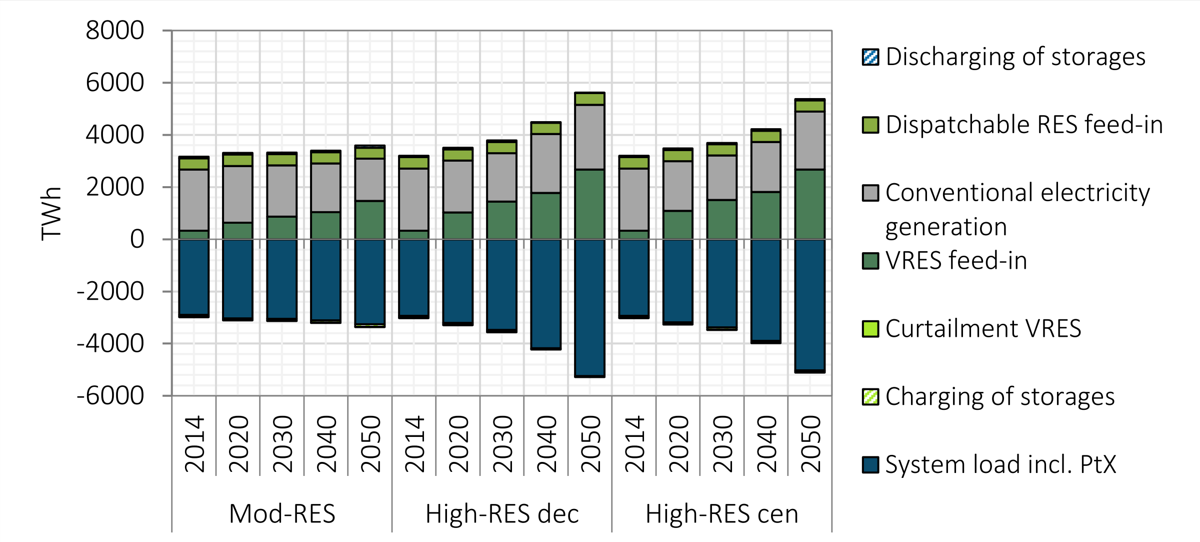

Figure 48: Aggregated electricity generation and electricity demand in the REFLEX scenarios across all modeled countries

Source: ELTRAMOD

In the Mod-RES scenario, Figure 48 illustrates the slightly increasing system load. While the electricity feed-in of intermittent RES is 3.5 times higher in 2050 than in 2014 (328 TWh_{2014} to 1474 TWh_{2050}), the conventional electricity generation is decreasing by 31 % due to decommissioning of power plants as well as higher operational costs because of higher fuel and CO_2 prices. With higher electricity feed-in of RES, more storage is required from a system-optimal perspective. The electricity charged and discharged by storages is growing by ca. 40 % from 2014 to 2050 in the Mod-RES scenario. Further, the feed-in of controllable RES as biomass, run-of-river plants and technologies is quite constant in all years and scenarios. In all three scenarios, the amount of curtailed RES is low, thus the RES integration is almost 100 %.

In the High-RES decentralized and centralized scenario, the system load is increasing more significantly. With growing RES feed-in, the conventional generation is decreasing from 2014 to 2030, while additional conventional generation is needed from 2040 to 2050. Due to increasing electrification in the demand side sectors, the installed RES feed-in cannot provide the additional required electricity. Therefore, low-carbon generation technologies as gas power plants (CCGT, Gas CCS) are constructed and operating from 2040 to 2050 in the High-RES decentralized scenario. The generated electricity exceeds the electricity demand in all years and scenarios due to grid and storage losses that are considered for each country. Due to the lower system load in the High-RES centralized scenario, lower conventional electricity generation is needed compared to the decentralized scenario. While the RES feed-in is the same in both of the scenarios, the amount of wind and PV feed-in differs as the decentralized scenario is a PV dominated system and the centralized scenario a wind dominated system.

The model results of the capacity investments (see Figure 45) depict that the need for additional storages towards 2050 is marginal under the given scenario assumptions. However, there are pumped storage plants and reservoir storages installed with a total discharge capacity of 116 GW. Figure 49 illustrates the charged and discharged electricity by storages (pumped storage plants, reservoir, batteries and A-CAES) for all scenarios. The storage requirements in the Mod-RES scenario are the highest in 2050 due to lower electrification in other sectors and thus more value for the residual load balancing potential of storages. Compared to the decentral scenario, more charging and discharging of electricity by storages is needed in the central scenario due to higher fluctuations of the residual load from 2030 onwards. The system load in the decentral scenario is already flattened significantly by DSM measures as well as the optimal dispatch of electrolysers in the industry sector (see Chapter 4.1.2.2). Therefore, the residual load of the decentral scenario is more constant than the residual load of the central scenario, which leads to more storage dispatch requirements in the central scenario.

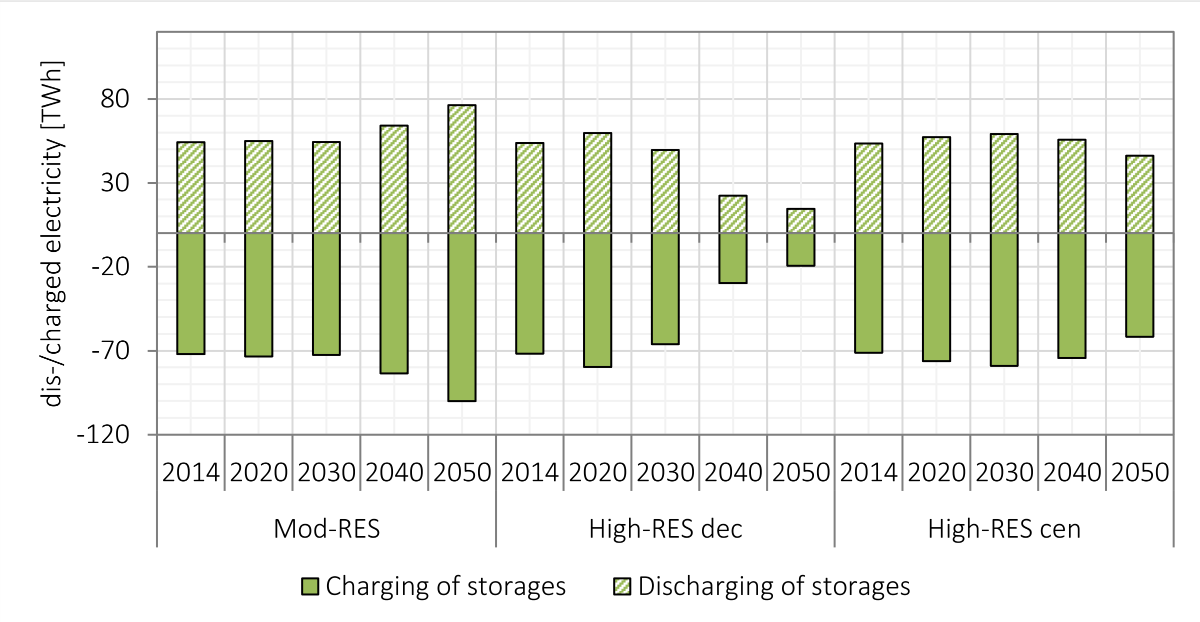

Figure 49: Amount electricity charged and discharged in the REFLEX scenarios scenarios across all modeled countries

Source: ELTRAMOD

Figure 50 summarises the technology specific electricity generation of the three scenarios. Despite the increasing electricity generation of power plants with CCGT (particularly in the Mod-RES scenario), the electricity generation by conventional technologies is decreasing due to lower generation of lignite and coal fired power plants as well as nuclear power plants. This results from higher fossil fuel and CO_2 prices as well as from national energy policy strategies (see ELTRAMOD model description in Chapter 2.2.4). Some of the EU28 + NO + CH + Balkan countries agreed on the phase-out of coal power plants by joining the Coal-Powering-Alliance and on the nuclear phase-out (e.g. declaration of Germany to phase-out nuclear power plants until 2022 after Fukushima's catastrophe). However, in other countries new nuclear power plants are planned to be constructed (e.g. Bulgaria, Hungary, and Poland). While the use of uranium is constrained by national energy policies, lignite and coal are not further used due to their emission intensity. Additionally, oil fired power plants are not playing a crucial role in future years as peak load power plants. In all scenarios, a fuel switch from lignite, coal and uranium to gas is obvious[23]. Conventional generation technologies are needed in future years, even with high feed-in of RES, due to the electrification of the demand side sectors. Gas is used as a conventional fuel alternative which is dispatched in high efficient CCGT or in low-carbon gas CCS power plants. Figure 50 illustrates a technology shift from CCGT to gas CCS power plants from 2040 to 2050 in the High-RES scenarios, again mainly driven by the CO_2 price (ca. 150 EUR/tCO_2 in 2050 in High-RES scenarios). Since CCS technologies are low-carbon technologies with an assumed CO_2 capture rate of 88 %, these technologies become cost-optimal under the given assumptions.

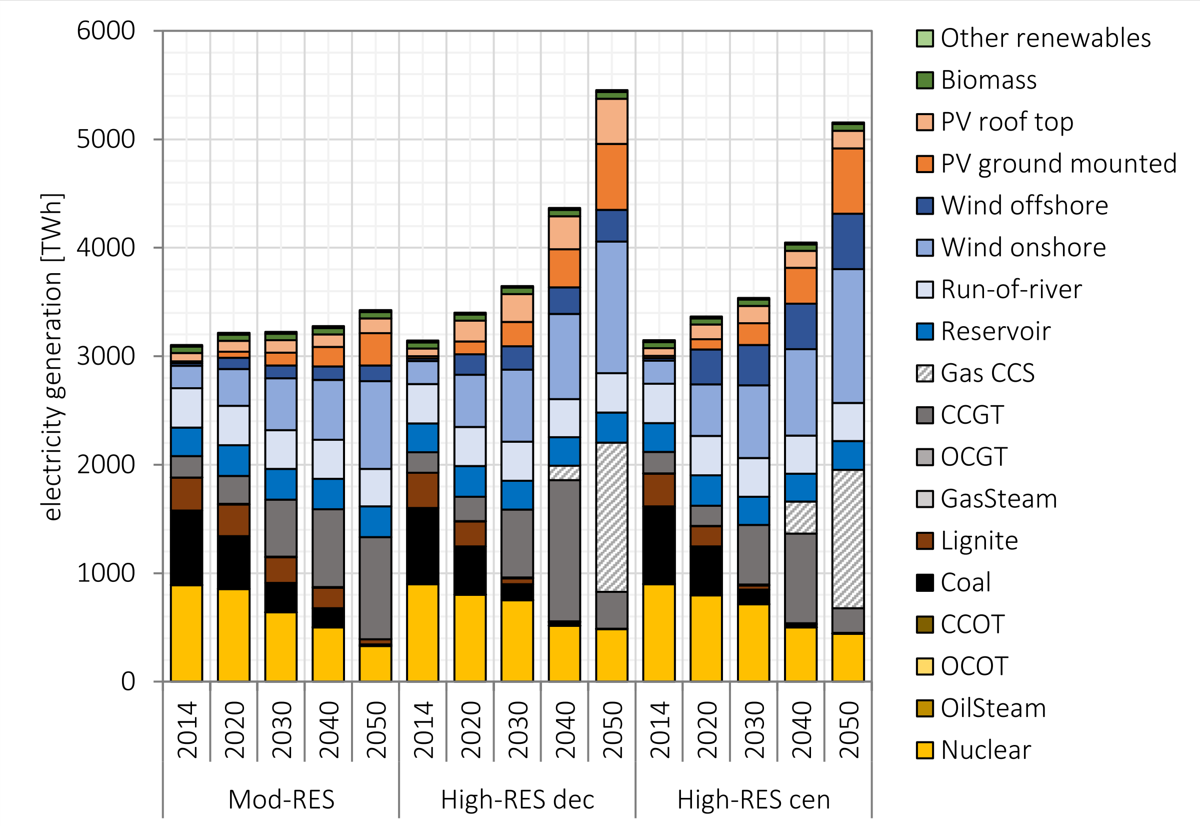

Figure 50: Overall electricity generation in the REFLEX scenarios scenarios across all modeled countries

Source: ELTRAMOD

In Figure 51 the annualized investment costs for new conventional power plants, storages, RES, NTC and for power-to-x-technologies as electrolysers and heat pumps as well as the fixed operational and generation costs are illustrated. The annualised investment costs for the NTC are the same for each scenario, since the assumed exogenous transnational interconnector capacity extension is the same. However the figure illustrates, that grid extension costs have a relatively small share of the total system costs, with the highest value

[23] A comprehensive discussion about the development and interactions of the European natural gas demand and different natural gas supply strategies can be found, e.g. in Riedel et al. (2017)

of 2.5 bn. EUR in the year 2020. In all three scenarios, the generation costs of conventional power plants are increasing due to higher fuel and CO_2 prices, while in the High-RES scenarios, the generation costs are also increasing because of higher electricity generation of conventional power plants as CCGT and gas CCS plants by 2030. The annualized investments of conventional plants and storages are developing differently across the scenarios. In the Mod-RES scenario the annualized investments of conventional power plants and storages are 10 times higher in 2040 than in 2030 (20.14 bn. EUR in 2040 and 2.31 bn. EUR in 2030 respectively). Further, in 2050 the investments are decreasing by ca. 50 %. In 2040, the investments for conventional power plants are mainly consisting of investments in OCGT, CCGT, nuclear power plants and lithium-ion batteries (see Figure 46). In the High-RES scenarios the costs for investments in new conventional capacities are increasing quite similar. In contrast to the model endogenous investment decisions for flexible technologies, additional RES capacities are driven by the exogenous input of the RES expansion pathways (see Chapter 3.3). The highest RES investments are transacted by 2020 for all scenarios (18 bn. EUR Mod-RES, 38 bn. EUR High-RES dec and 42 bn. EUR High-RES cen). While the investments in 2030 and 2040 for new RES capacities are decreasing, a further increase occurs by 2050 (16 bn. EUR and 29 bn. EUR High-RES dec/cen). In contrast to the RES and conventional power plant investments, the investments in power-to-x-technolgogies are marginal. To summarize, there are no significant differences in the total system costs until 2030 for all scenarios. By 2050, the total system costs are 1.7 times higher in the decentral and the central scenario than in the Mod-RES scenario, mainly because of the significant increase of generation costs.

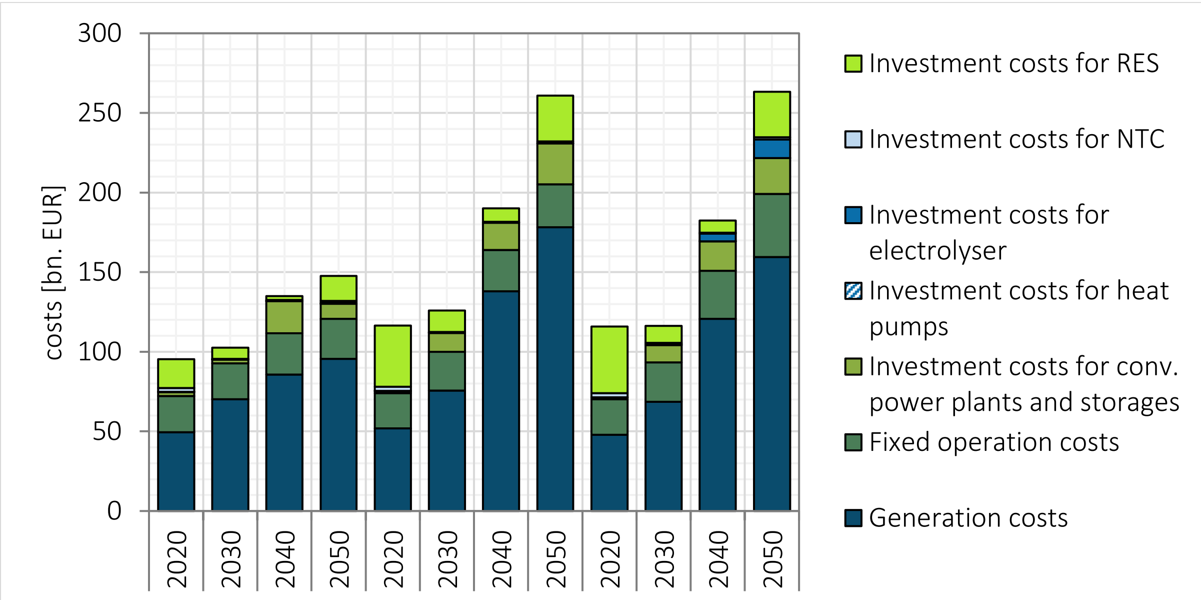

Figure 51: Annualised total system costs in the REFLEX scenarios scenarios across all modeled countries

Source: ELTRAMOD

As mentioned before, the CO_2 emission reduction targets for the electricity sector are implicitly considered by the increase of the CO_2 price. Figure 52 represents the CO_2 emissions for each scenario as well as an approximation of the EU CO_2 reduction target for the electricity sector by 2050 (European Environment Agency 2018). The CO_2 emissions in the Mod-RES scenario are the highest for all years compared to the High-RES scenarios due to higher generation by technologies with greater CO_2 emission factors, particularly from lignite and coal fired power plants (see Figure 50). In the decentralized scenario, more CO_2 is emitted than in the centralized scenario due to more conventional generation. The increase (+25 %) of CO_2 emissions by 2040 in the decentralized scenario can be explained by the increase of electricity generation from gas fired power plants as CCGT due to higher electrification of demand side sectors compared to the centralized scenario (see Figure 43). The further decrease of CO_2 emissions by 2050 results from the gas technology switch from CCGT to gas CCS generation. In the centralized system the emitted CO_2 emissions are the lowest in 2050 with 141 Mt-tCO2eq due to the lower system load and therefore lower conventional electricity generation compared to the decentralized scenario (231 Mt-tCO2eq). The approximately estimated CO_2 reduction target of the EU for the electricity sector is about 236 Mt-tCO2eq, which can be achieved in both High-RES scenarios.

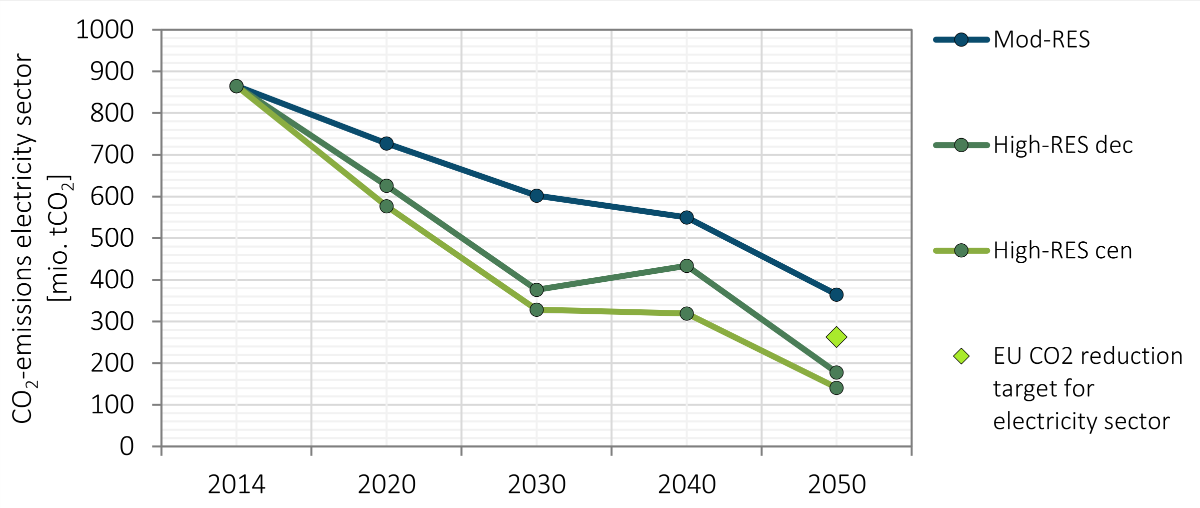

Figure 52: Development of total CO_2 emissions in the electricity sector in the REFLEX scenarios

Source: ELTRAMOD

Conclusions for the electricity sector

While the differences between the Mod-RES scenario and the High-RES scenarios are significant, the optimal mix of flexible power plants in the High-RES central and decentral scenario is rather similar. Regarding the capacities installed, differences occur mainly depending on the amount of electricity system load as well as additional electricity demand from the demand side sectors, leading to aggregated fossil fuel and nuclear based capacities of around 590 GW in the High-RES decentralized and 510 GW in the centralized scenario across all observed countries. Thus, under the given assumptions and input from the coupled models within the REFLEX framework, the optimal installations to provide flexible electricity generation is less affected from a central and a decentral scenario with ambitious climate protection goals. This is true although the weather dependent RES generation as well as the direct and indirect electricity demand show different patterns in each scenario. In contrast and based on the scenario framework, there are different developments regarding the sector coupling, leading to significantly more capacities of power-to-x-technologies, particularly electrolysers, in the electricity market in the centralized scenario.

The discussed differences between the dispatches of the technologies show a varying application of the flexibility options resulting in more low-carbon electricity generation by gas fired power plants with CCGT and CCS in the High-RES scenarios due to higher CO_2 and fuel prices. In an energy policy perspective, these high prices are necessary to avoid investments in emission intensive technologies in the presence of an increasing electrification of other demand side sectors. In the Mod-RES scenario, the electricity generation in 2050 by carbon intensive lignite and coal-fired power plants is reduced but still relevant. However, the future electricity generation with high feed-in of renewable energy sources will be characterised by low-carbon conventional electricity generation due to nuclear, CCGT and gas CCS power plants. Further, the mix of electricity charging and discharging by pump storage plants, reservoirs, A-CAES and battery storages, the Europe-wide electricity exchange as well as the application of demand-side technologies as power-to-gas and power-to-heat are covering the required system flexibility while integrating the intermittent RES generation amounts. Since the electrification of other demand side sectors is more pronounced in the decentralized scenario, the system load is higher and consequently more conventional electricity generation is needed than in the centralized scenario. Hence, the electricity system of the decentralized scenario is more cost intensive than a centralized system under the given scenario assumptions.

4.2.2 HEAT SECTOR

At present about half of the final energy consumption is associated with heating and cooling (European Commission 2016b) and these energy services will still have a substantial share in energy consumption in the future. In many EU countries in particular in Scandinavia, Central and Eastern Europe, a significant proportion of the heat demand in high-density urban areas is covered with the use of district heating networks in which pressurized hot water, normally with temperature below 100˚C is used as the heat carrier (Lund et al. 2014). District heating (DH) has the benefits of integrating local heat resources, including waste heat and renewables, better control of (especially local) emissions, and together with combined heat and power (CHP) plants, it not only generates higher overall efficiency but also increases the flexibility of local power systems. However, DH development requires high initial investments and its economic feasibility is often constrained by the size of the local market. Still in the 2000s district heat has been produced in large extent based on fossil fuels such as gas, coal or oil. This notwithstanding, the transformation towards achieving low-carbon (or even carbon-free) DH systems has already begun and DH systems are in the focus of a sustainable energy system development. Such transformation is possible by a fuel and technology switch to RES (e.g. in Sweden bioenergy accounts for 34 % of the current final energy, making this country a world bioenergy leader) but also requires further integration of district heat and power system to enlarge their flexibility. TIMES-HEAT-EU is used to explore the evolution of the district heat generation mix in EU member states for the scenarios considered in the REFLEX project.

Scenario assumptions

Like in the previous chapters, in the following major factors influencing the development of future district heating systems are briefly described before presenting and discussing the results. One of the most important input parameters is the change in the future district heat demand which is exogenously provided to TIMES-HEAT-EU by the FORECAST model.

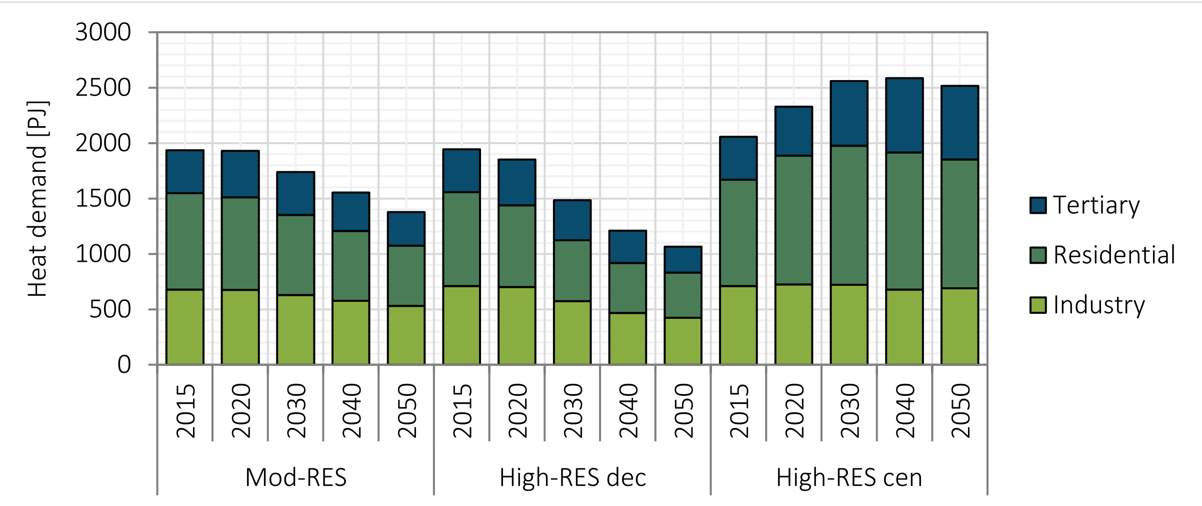

Figure 53: Development of district heat demand in REFLEX scenarios across all modeled countries

Source: TIMES-HEAT-EU, FORECAST

As depicted in Figure 53, the demand for district heat in 2050 is expected to be lower than today in the Mod-RES and High-RES decentral scenario, mainly due to low-energy and refurbished buildings. The more significant drop in the High-RES decentral scenario is due to the fact that in addition individual (and thus non-central) heating systems play a more important role in this scenario. Only the High-RES central scenario assumes an increase in the DH demand mainly because of supporting measures assumed in this scenario (further details are described in Chapter 4.1). In addition, it was assumed that in the Mod-RES and High-RES central scenario the overall EU-wide relative share of electricity produced in cogeneration will be the same as today, i.e. ca. 12 %.

The others factors influencing the model results are: prices of CO_2 emission allowances on the EU ETS market, techno-economic parameters of processes employed in DH systems as well as potential and costs of fuels and energy resources. Further key assumptions include the CHP annual overall efficiency requirements, the share of electricity generated in highly efficient cogeneration as well as the ramping constraints for generation units. The coupling of the power and heating sectors are introduced by enabling CHPs having income from electricity sales. At the same time, the use of power-to-heat technologies causes electricity costs. To complete the picture, all DH-generating technologies get the income from district heat sales according to the average annual DH price. Thus, the electricity price signals on the wholesale market derived in an iterative model coupling process with ELTRAMOD played an important role not only in dispatching of CHPs, heat storage systems and power-to-heat technologies but also in the investment decision regarding new generation capacities. One should be aware that the obtained results take into account the competition that exists between the actors (DH generation technologies), which is not always straightforward. For instance, reacting to the low electricity prices, power-to-heat technologies may want to produce DH and thus augment the residual load contributing to upward flexibility (giving a chance for increasing the power production). However, with limited overall DH demand, this heat cannot be any longer produced in CHPs and thus it is not only a losing opportunity to obtain an income from DH and electricity sales, but it has also consequences on their general activity due to the annual overall efficiency requirements.

Scenario results regarding the heat sector

Figure 54 depicts the development of electricity generating capacities of CHPs in the different REFLEX scenarios. In general a switch towards natural gas and bioenergy-fuelled plants can be observed. In the Mod-RES scenario there are some capacities of coal, but these are plants ending their operation in 2045 and are then decommissioned (see also fuel input in Figure 59). In the case of the High-RES scenarios, no other fossil fuels than natural gas are installed from 2030 on, due to higher CO_2 prices. In case of CHPs it is often practiced that the capacity represents the electrical capacity only and a special coefficients are introduced representing the ratio of electricity lost to the heat gained and the heat to power ratio. As a result of that approach, CHP capacity is driven by the electricity demand. That is why the highest capacities are observed in High-RES centralized scenario. Despite the fact that both High-RES scenarios have the same electricity demand, in the decentral scenario even lower growth in CHP plants occurs, due to the different assumption regarding the electricity share from CHP plants in total electricity production, as discussed above.

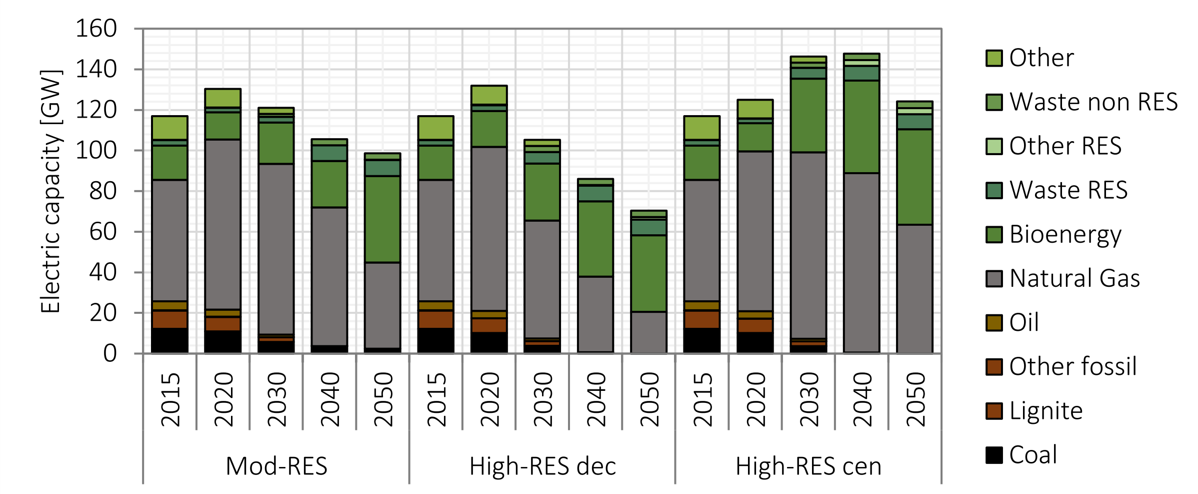

Figure 54: Overall electric capacity of CHP plants in the REFLEX scenarios across all modeled countries

Source: TIMES-HEAT-EU

In case of heat-only plants (HOPs) the existing thermal capacities are decommissioned until 2030. In general, HOPs are losing competition with CHPs as they can only profit from heat sales, whereas plants operating in high efficient cogeneration can make profit from both electricity and heat. The heat-only technology for which there are new capacity additions in the High-RES scenarios is large solar thermal plants, mainly in the centralized case where the heat demand is higher (Figure 55). Power-to-heat technologies in TIMES-HEAT-EU include electric boilers and large scale heat pumps. Both power-to-heat types are running based on electricity purchased on the wholesale electricity market. However, the power-to-heat technologies can be differentiated by their operational patterns. Heat pumps are more capital intensive but have higher efficiencies (the minimum value of COP is set to 3). Both types are assumed to operate constantly within seasons following and do not actively react to the changes of the electricity price. In contrary, electric heaters are assumed not only to serve as peak load units, but predominantly to actively respond to electricity price variations and generate DH that can be stored. Furthermore, power-to-heat technologies are benefiting from RES surplus electricity that otherwise would have been curtailed.

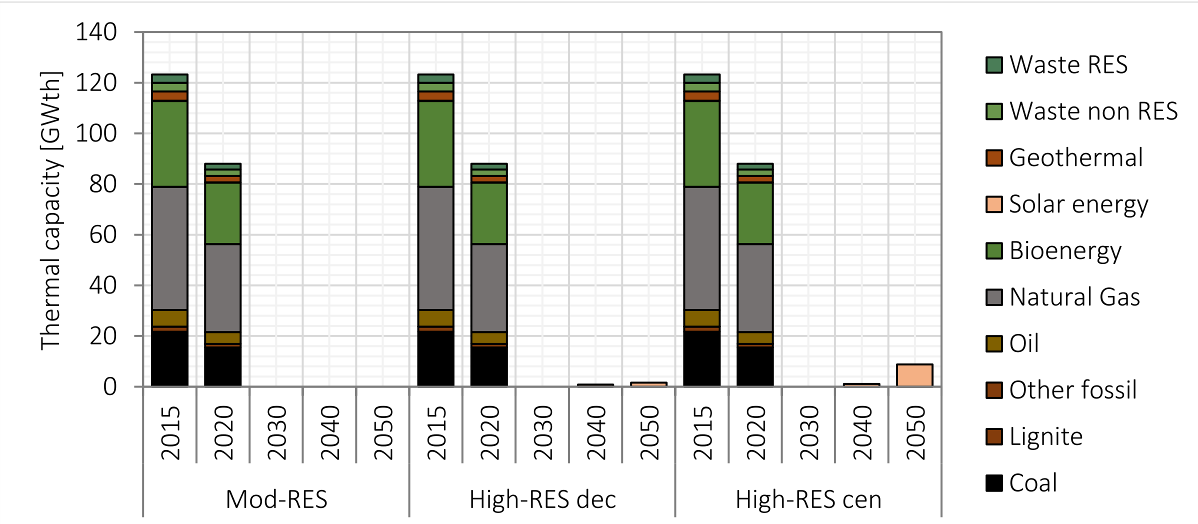

Figure 55: Overall thermal capacity of HOPs in the REFLEX scenarios across all modeled countries

Source: TIMES-HEAT-EU

Figure 56 presents the cumulative thermal capacities installed of power-to-heat technologies. The greatest addition of power-to-heat capacities, mainly electric heaters, is observed in the High-RES central scenario, in which electricity prices variate more than in other scenarios (meaning that there are quite many time-slices with low electricity price) and the overall DH demand is greater. The generated heat is subsequently stored. It is obvious that the TIMES-HEAT-EU results for power-to-heat are different from those of ELTRAMOD (see Chapter 4.2.1), this is due to the fact that both models represents different power-to-heat modelling approaches. While TIMES-HEAT-EU is focused on the centralized heat sector and represents electricity-only power plants as exogenous source of energy, ELTRAMOD focuses on the electricity generation and distribution sector.

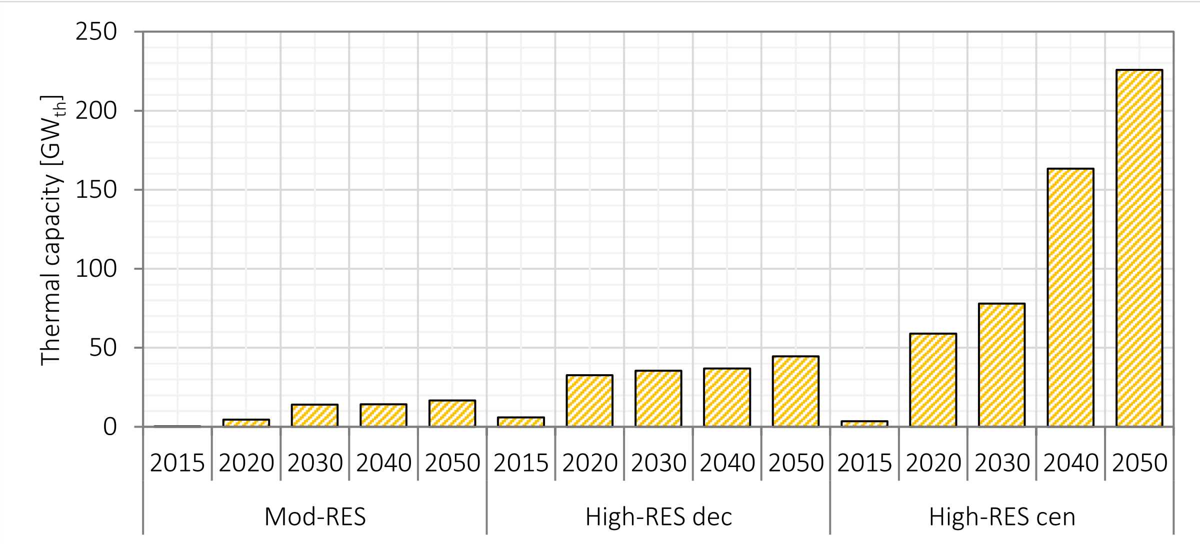

Figure 56: Overall heat generation capacity of power-to-heat technologies in the REFLEX scenarios across all modeled countries

Source: TIMES-HEAT-EU

In TIMES-HEAT-EU, thermal energy storages (TES) allow the short-term and seasonal storage, helping to balance heat demand and supply. Three main kinds of TES systems are distinguished, i.e. sensible thermal energy storage (STES), latent heat storage by phase-changing materials (PCM) and thermal-chemical storage (TCS). TIMES-HEAT-EU considers only STES as PCM and TCS are still at a research and development stage and therefore require high investments (the advantage lies in higher storage capacity per unit media). More specifically, water tanks have been selected for short-term storage whereas borehole TES are assumed for the seasonal storage. Figure 57 presents the overall amount of heat that flows out of TES in the different REFLEX scenarios. The highest flows can be observed in the High-RES scenarios, especially in the centralized one. This is because on the one hand in the High-RES scenarios the demand is more variable than in the Mod-RES scenario which increases the potential of short term storage. Additionally, there is more activity of variable power-to-heat applications in case of low electricity prices in the High-RES centralized scenario. Inter-seasonal storages depend more on the total head demand, resulting in a higher heat flow from long term storages in the centralized scenario. The storage technology to accumulate more energy is limited since it is not economically viable to install very large capacity available to react to peaks in energy production in power-to-heat technologies.

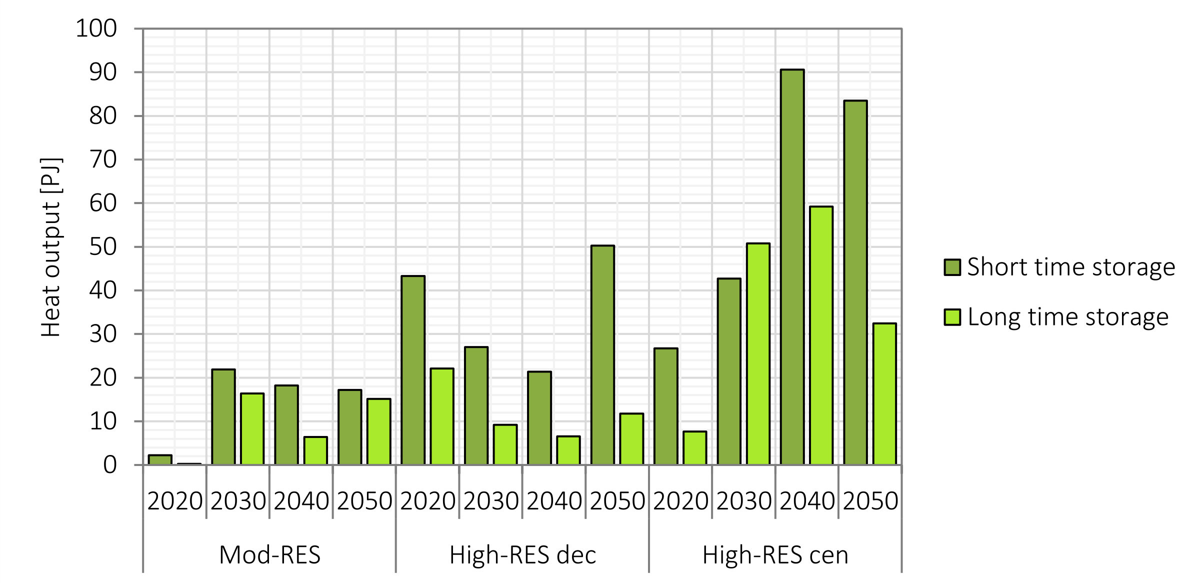

Figure 57: Heat flow out of TES in the REFLEX scenarios across all modeled countries

Source: TIMES-HEAT-EU

TIMES-HEAT-EU calculates the weighted average annual DH generation costs (WA-DH generation costs). At first, the unit DH generation costs are calculated for each heat generation technology. These costs include fuel, fix and variable O&M, annualized investments as well as costs of CO_2 emission allowances. Then, the total costs are divided by the amount of heat produced to calculate unit cost of heat generation. This calculation is straightforward in case of HOPs. In case of CHPs, the total costs are split into two parts and assigned to power and heat generated. Finally, the unit generation costs are weighed by heat production. The evolution of the WA-DH generation costs for selected countries (with the biggest DH demand) is presented in Figure 58. The average DH generation costs are, in general, lower than the reported overall district heat price for the end-users (usually local DH operators are adding distribution and other fees) (Euroheat & Power 2017).

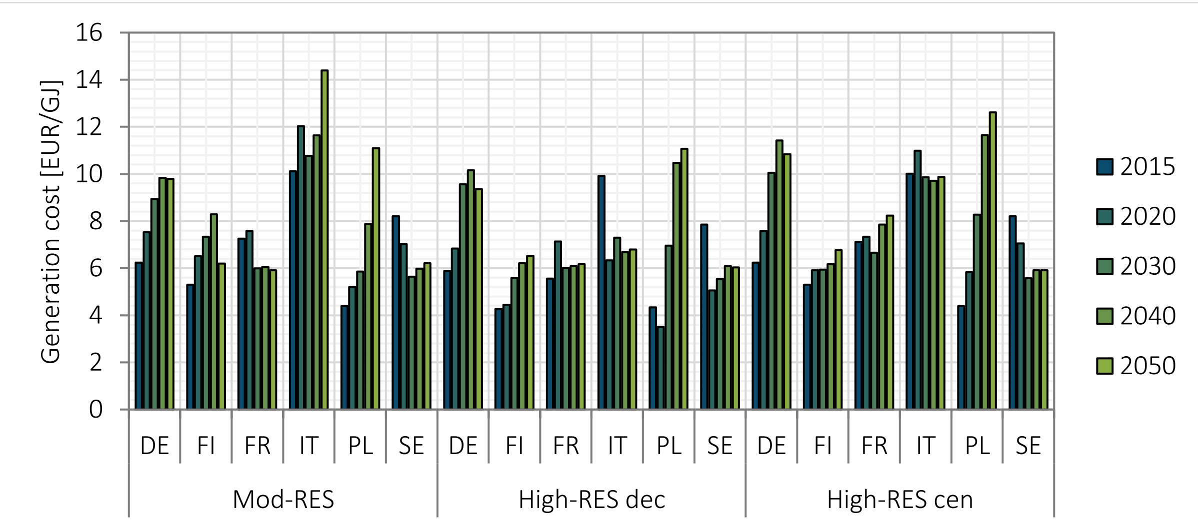

Figure 58: Average district heat generation costs in Mod-RES scenario for selected countries

Source: TIMES-HEAT-EU

As one can see WA-DH generation costs are increasing as compared to the base-year in most of the member states. This is due to the investments in new capacities, rising prices of CO_2 emission allowances and fuel costs. It should be also mentioned, that investments for units that already existed in 2015 are considered as sunk costs. The existing heat-only plants are replaced in future years with CHP plants. This also has an impact on DH costs as in case of CHPs total costs are only partly assigned to heat. In case of Sweden, because of very high biomass potential, a decrease in DH generation cost in every scenario is observed, due to the zero-emission coefficients for biomass. In general, if renewable fuel potential is high enough to cover significant amounts of DH demand, heat generation cost decline, as in case of France in the Mod-RES scenario.

As presented in Figure 59, in all scenarios fuel and technology switches toward bioenergy (mainly biomass[24]) and natural gas as well as towards heat production in cogeneration occur. Clearly, bioenergy-based CHP units are replacing existing solid fuel fired HOPs and CHPs. Natural gas units are utilised in countries with low bioenergy potentials.

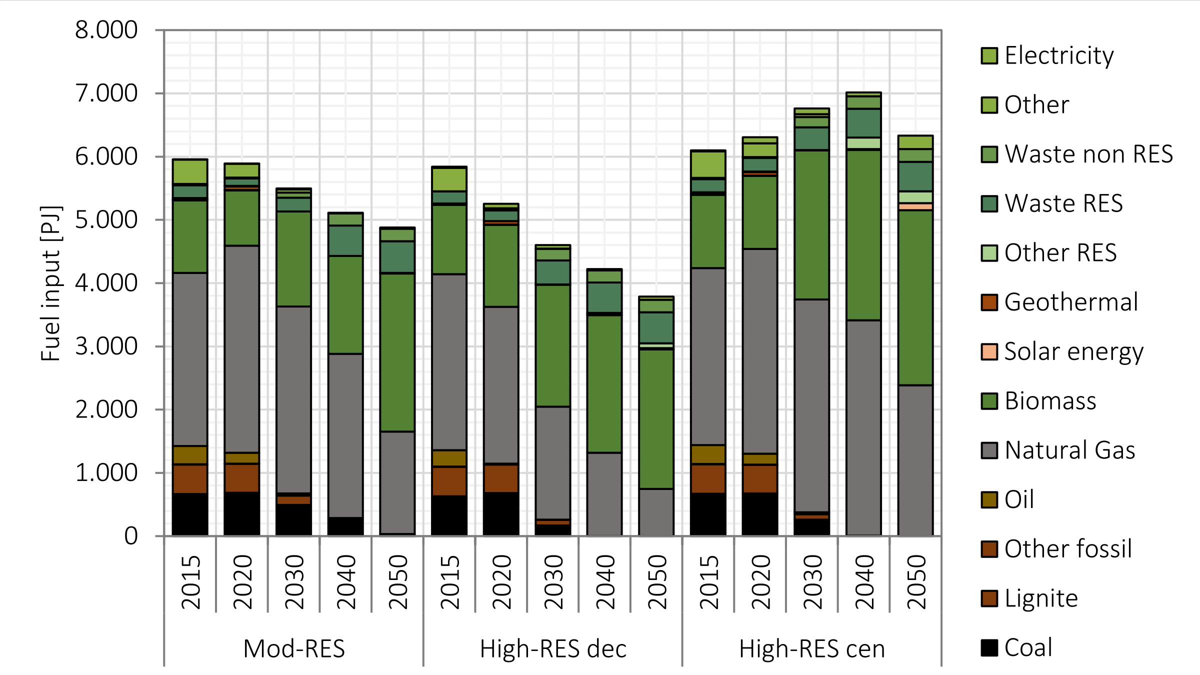

Figure 59: Fuel input for DH generation in the REFLEX scenarios across all modeled countries

Source: TIMES-HEAT-EU

Figure 60 presents the amount of electricity produced in cogeneration for the REFLEX scenarios. As mentioned earlier, in case of the Mod-RES and High-RES centralized scenario the constraint to maintain about 12 % of the total electricity production by CHP plants is set, which is not the case in the High-RES decentralized scenario. Thus, the highest electricity production occurs in the High-RES centralized scenario. In the High-RES decentralized case, the amount of electricity produced reflects the lower DH demand, thus it is the amount of electricity that is needed to be produced by CHP plants to achieve high efficiency cogeneration goals.

[24] See Annex C for information about the calculation of the biomass potential.

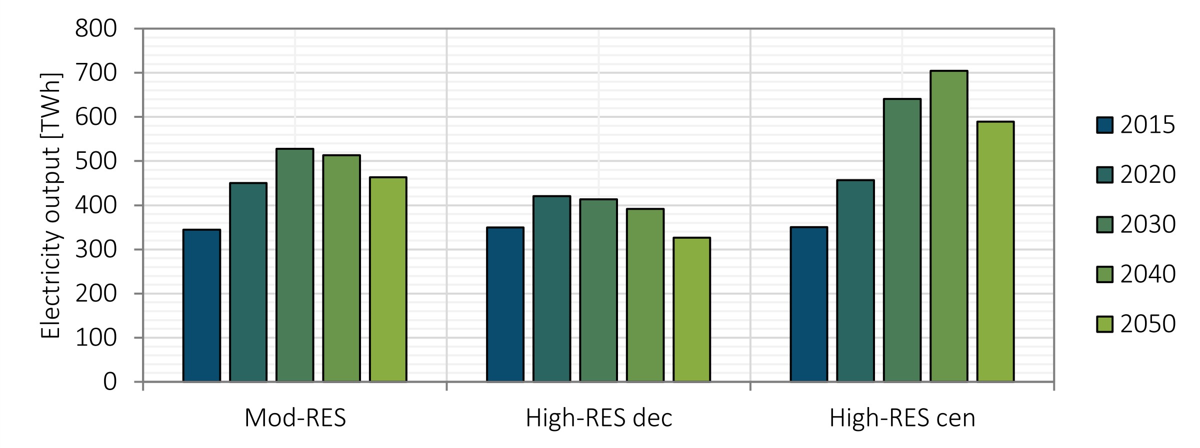

Figure 60: Electricity generation of CHPs in the REFLEX scenarios across all modeled countries

Source: TIMES-HEAT-EU

CO_2 emissions in the heat sector

The switch in DH generation mix towards renewables and cogeneration results in decreasing CO_2 emissions in all scenarios as depicted in Figure 61.

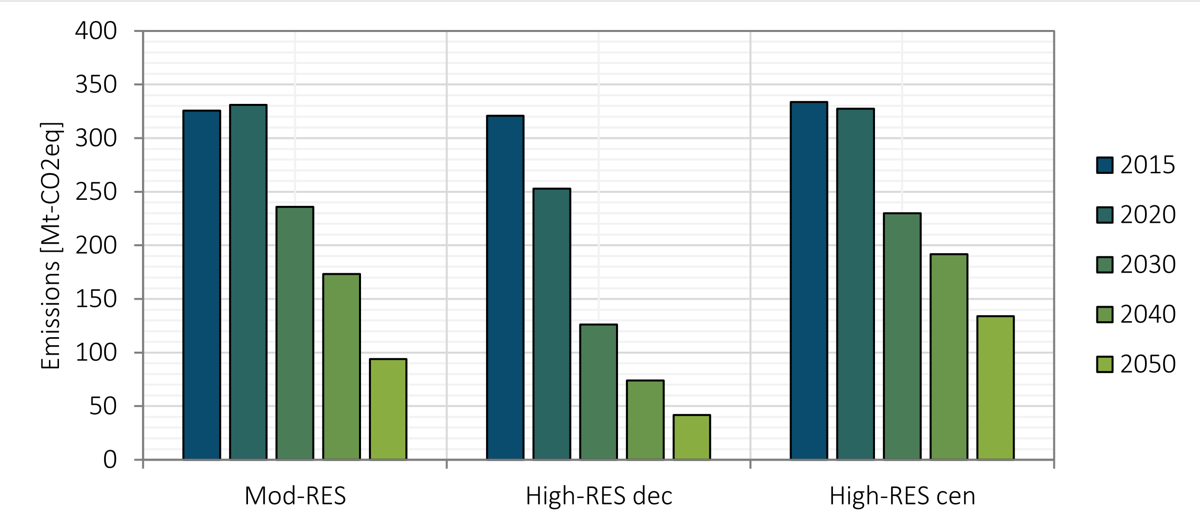

Figure 61: CO2 emissions from district heat generation in the REFLEX scenarios across all modeled countries

Source: TIMES-HEAT-EU

Since the total amount of energy (both heat and electricity) is the highest in the High-RES centralized scenario, the corresponding CO_2 emissions are the highest in this scenario. As presented in Table 25, the CO_2 emission factor per total energy output in 2050 is in the High-RES centralized scenario only slightly higher than in the Mod-RES scenario. The reason for this is the high DH demand and because of the fact that all zero-emission fuels are used up to their limits, whereas the remaining DH demand has to be fulfilled by fossil fuels. That also explains why in the decentralized scenario this factor is the lowest (see fuel input structure in Figure 59).

Table 25: Summary of the key results of TIMES-HEAT-EU

	Mod-RES			High-RES cen			High-RES dec		
Year	2015	2030	2050	2015	2030	2050	2015	2030	2050
Electricity generation [TWh]	344	528	464	351	641	589	350	413	327
DH generation [PJ]	3291	2893	2541	3360	3669	3641	3144	2627	2230
Fuel input [PJ]	5957	5495	4881	6097	6761	6331	5840	4601	3787
CO_2 emissions [Mt]	326	236	94	334	230	134	321	126	42
Total system efficiency [%]*	76	87	86	76	88	91	75	89	90
CO_2 emission per total energy output [kt/PJ]	72	49	22	72	38	23	73	31	12
Share of CHP in total electricity generation [%]	12	18	15	12	20	15	12	13	7

* calculated as a ratio between total electricity and heat output (including P2H) to fuel input.

Source: TIMES-HEAT-EU

Conclusions for the heat sector

The presented results show that under the given scenario framework, CHPs are more convenient in the future than HOPs. Bioenergy (mainly biomass) capacities are increasing significantly. Therefore, biomass can play an important role in substituting fossil fuels in DH generation in particular in the EU member states where the DH networks are already well developed. Natural gas is still used due to high flexibility also in terms of the power-to-heat production ratios. Seasonal heat storages and short-term heat storages help to smooth the generation profiles and increase the heat production in summer times. The use of power-to-heat technologies including large heat pumps depends on electricity prices but certainly helps to manage the RES electricity surplus that otherwise would be curtailed. With decreasing district heat demand and with a simultaneous increase in electricity demand – as in case of High-RES decentral scenario – it is impossible to maintain the current relative share of electricity produced in cogeneration while meeting the cogeneration efficiency goals. In fact, in this scenario the share decreases from the current 12 % to 7 % in 2050. In general district heat costs are increasing in future years. This is mainly due to the investments in new capacities, rising prices of EAUs and increasing fuel costs. Therefore, it is necessary to maintain the existing or new implemented policy measures that will guarantee necessary profits for generators and keep the DH end-user prices at competitive levels. Only then it will be possible to have an increase in DH demand as in case of High-RES central scenario. With the development of low-energy buildings, DH networks should be expanded in regions where sufficient spatial heat density exist in order to maintain the current DH demand. Otherwise with decreasing DH demand, as e.g. in case of the Mod-RES and High-RES decentral scenario, CHPs are exposed to lower DH sales but also to lower electricity sales. In case of the High-RES central scenario, the increased DH demand has to be associated with developments of new district heat systems. It is also important to design them for low-temperature sources such as renewables. The transition towards higher use of bioenergy (mainly biomass) requires sustainable organizational (logistic) solutions that will minimize energy and CO_2 emissions embedded in processing and transportation.

4.3 CO_2-EMISSIONS

According to the Annual European Union greenhouse gas inventory, the total GHG emissions (excluding land use, land use change and forestry) in Europe accounted to 4,290 Mt-CO_2eq in the year 1990 (EEA 2016). The European Roadmap for moving to a competitive low-carbon economy aims a domestic emission reductions of 80 % in 2050 across all sectors compared to 1990 (European Commission 2011a). This target is also set as a threshold value for the emission reduction in the ambitious High-RES scenarios of the REFLEX project. Figure 62 summarises the results regarding the emissions analysed in detail in Chapter 4.1.1 of the energy demand sectors transport, industry, residential and tertiary as well as of the energy supply sectors electricity and heating for all scenarios. Additionally, the total GHG emissions from 1990 are presented as dotted line as well as the scenario specific percentage of reduction compared to this value for each year observed. Starting with an overall reduction of 21 % compared to 1990 this value increases to 47 % in the year 2050 for the Mod-RES scenario, thus it is not achieving the GHG emission reduction targets. In contrast, the targeted emission reductions of 80 % are achieved in both High-RES scenarios resulting in overall emissions of 870 Mt-CO_2eq in the decentral and of 860 Mt-CO_2eq in the central scenario. In the Mod-RES scenario, total direct emissions are already decreasing by 34 % between 2014 and 2050, due to energy efficiency progress and fuel switch driven by electricity, fuel and CO_2 prices. In contrast to the High-RES scenarios, particularly the energy demand sectors (except the tertiary sector) are not contributing significantly to emission reductions in the Mod-RES scenario since less ambitious policy measures and technology roll-outs are assumed. In the High-RES scenarios, the emission decrease is stronger and rather similar for these sectors. In total, the transport, industry, residential and tertiary sector are reducing their emissions to 597 Mt-CO_2eq and 585 Mt-CO_2eq in the decentral and central scenario, respectively. Regarding the energy supply sector, differing developments of the electricity and heating sector can be observed in Figure 62. Although the sum of their emissions decreases to around 274 Mt-CO_2eq in both scenarios in 2050, the electricity sector is contributing more in the central scenario than in the decentral scenario and vice versa for the heating sector. In conclusion, it can be stated that a price of at least 150€/t in 2050 (as assumed in the model calculations) is necessary to achieve the emission reduction target.

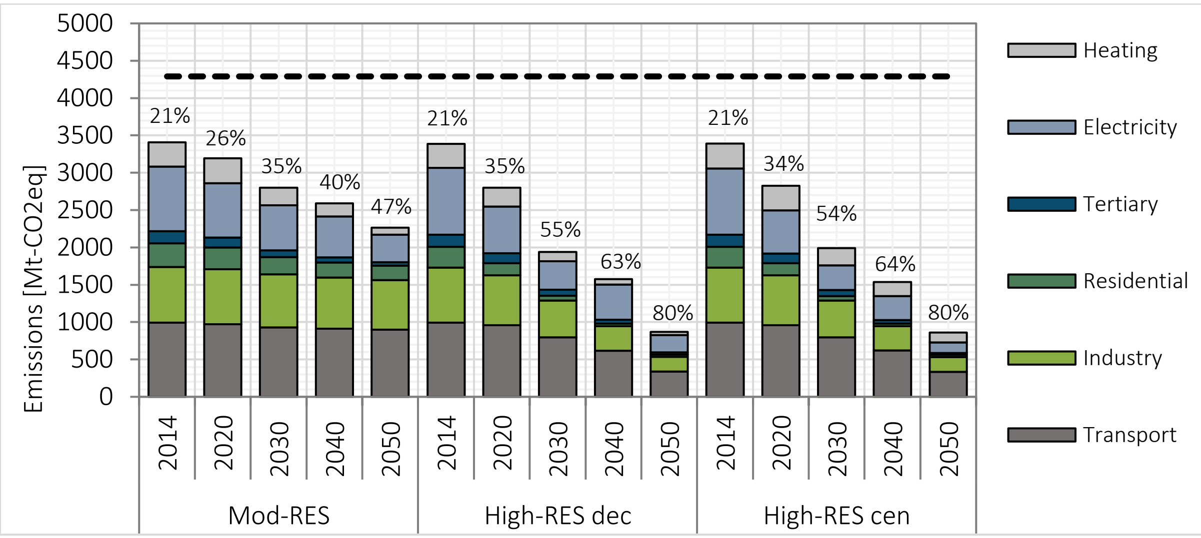

Figure 62: EU28 total direct emissions from transport, industry, residential, electricity and heating sector

Source: FORECAST, ASTRA, ELTRAMOD, TIMES-HEAT-EU

These developments can also be analysed in Figure 63, presenting the percentage of emission reduction compared to 2014 for each of the sectors. Since the allocation of emissions from the sectors analysed in REFLEX to the European emission inventory is not trivial, the reference year 2014 is chosen. Nevertheless, to estimate the contribution of each sector compared to the year 1990, the sector specific share of CO_2eq emissions of the year 2014 are assumed to be the same for the year 1990 and additionally presented with dotted lines in Figure 63. Regarding the energy demand sectors, the strongest decrease in emissions between 2014 and 2050 occurs in the residential (91% in both High-RES scenarios) and the tertiary sector (79-83 %) in the High-RES scenarios. However, as aforementioned, these sectors already show comparably high emission reduction potentials in the Mod-RES scenario (37 % residential and 68 % tertiary) reflecting the impact of current policies on the appliance and building sectors (e.g. RED, EED, EPBD, Ecodesign, etc.). Industrial emissions decrease by 74 % in the High-RES centralized scenario and 73 % in the High-RES decentralized scenario between 2014 and 2050. The transport sector reduces its direct emissions by 66 % in both ambitious policy scenarios in 2050 compared to 2014. In the electricity sector, reductions of 74 % and 84 % in the decentral and central High-RES scenario, respectively are realised compared to the year 2014. For the heating sector, these values are 87 % (decentral) and 60 % (central). Resulting from overall differences in the scenario framework assumptions in total the highest influence on emission reduction between the High-RES decentral and central scenarios occurs for the heating sector, followed by the electricity and tertiary sector.

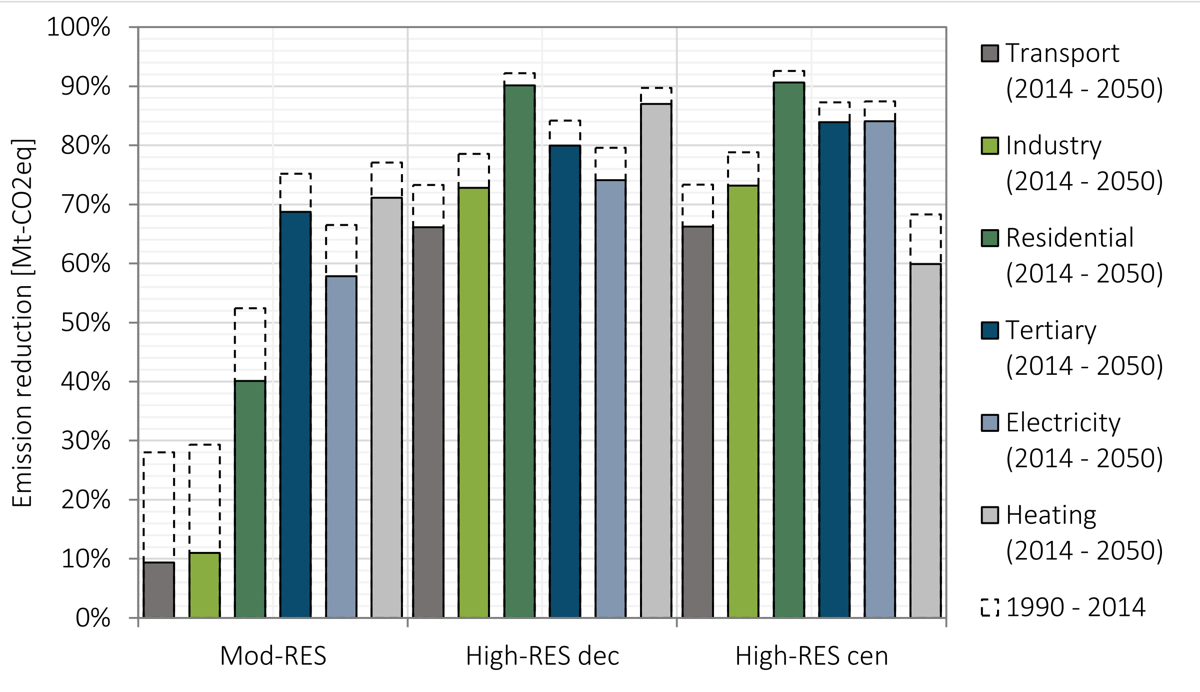

Figure 63: Percentage of emission reductions in 2050 compared to 2014 (1990) in the REFLEX scenarios

Source: FORECAST, ASTRA, ELTRAMOD, TIMES-HEAT-EU

5 Summary and Policy Recommendations for a Cross-Sectoral Energy System

The results presented above support existing analyses and policy recommendations (e.g. EU Roadmap), such as the improvement of the EU Emissions Trading Scheme (ETS) to enable high CO_2 prices, to provide more long-term clarity and the certainty in price developments and to include more CO_2 emitting sector into the ETS. Additionally, in the context of a highly uncertain environment and large potential investments, public RD&I funding can play an important role in accelerating the market introduction of innovative low-carbon processes (e.g. EC Innovation Fund). Apart from these general recommendations, the detail and the number of coupled models involved in REFLEX enables a comprehensive view on the effort necessary to achieve a transformation of the European energy system.

While summarising the results presented above, more specific policy recommendations can be made based on the insights of the energy system models. To achieve the ambitious decarbonisation targets, the role of the energy demand side becomes crucial, as it is shown in the REFLEX High-RES scenarios. In general, energy demand reductions can be achieved by several options, of which one of them is energy efficiency improvements. Additionally, electricity becomes the most important energy carrier in the model calculation based on the given framework conditions enabling the substitution of fossil fuels. This leads to significant emission reductions in the industry, residential, tertiary and transport sector. Remaining emissions mainly stem from the use of gas as a less emission intensive fossil fuel in all energy demand sectors.

Key measures enabling the decarbonisation in the industry are radical process improvements as well as the use of electricity and hydrogen in the steel and glass industry. Changes to industrial production systems, such as innovative processes and large-scale power-to-heat for steam generation, are mainly envisaged in the time horizon after 2030. Before 2030, energy efficiency improvements combined with fuel switching to biomass and progress towards a circular economy are the main mitigation options that drive CO_2 emissions downward. However, in order to have new process technologies and innovations ready by 2030, substantial research, development and innovation activities need to take place in the coming decade. In general, it is necessary to set incentives towards a low-carbon industry as early as possible to accelerate the market entry of efficient and innovative processes as increases of CO_2 price probably will take place after 2040 and consequently will affect only a small share of investment decisions taken. Pilot and demonstration plants need to be built to prepare for market introduction. It might easily take ten years for new processes in the materials industry to progress from lab-scale to market. Certification processes such as those needed for new cement types can prolong the time taken even more. To further promote material efficiency and a circular economy approach along the value chain broad policy mix is required. Implementing policies to overcome barriers to energy efficiency (energy management schemes, audits, soft loans, and energy service market) is a prerequisite for other (price-based) policies to work effectively as well. Energy-intensive industries can also help other sectors to decarbonise, e.g. by providing excess heat to nearby district heating networks. While large potentials are available here throughout Europe, various barriers are preventing its uptake. Policies can support the uptake by e.g. hedging high risks in individual projects, engaging top management by offering adequate incentives, regulating excess heat release in national emission control acts, strengthening local heat planning and providing investment grants.

In the residential and tertiary sector, the improvement of energy efficiency in buildings and applications are crucial as well as increasing renovation rates. Together with the technology choice for the heating supply (DH in High-RES centralized scenario and heat pumps in decentralized scenario), this leads to significant decrease in the final energy demand for space heating which currently accounts for the main part of emissions in these sectors. Efficiency progress in residential sector is mainly driven by EU regulations like Ecodesign Directive and Building Performance Directive. Tapping additional efficiency potentials requires additional efforts, subsidies as well as removal of barriers and changes of personal preferences. Especially for residential buildings, space heating demand is a main contributor to GHG emissions. To reduce these, combined efforts in refurbishment rates, depths and technology change are needed. It can be shown, that refurbishment is a prerequisite for the deployment of RES energy sources, which will be the main contributor to emission reduction. However, reaching the EU targets includes major efforts from all actors and stakeholders as well as additional regulatory framework. EU-wide regulations for building standards in tertiary sector are already in force as of today and a main driver in the long run until 2050 to reduce heating demand and related GHG emissions. Additionally, the results do not show a strong reduction in electricity demand for appliances and processes, leaving space for additional efficiency gains. To allow for a more centralized provision of renewable heat, financial incentives as well as connection regulations and strategies are needed to tap the full potential. Heat pumps can play a certain role for decarbonising heat demand in the tertiary sector, but specific support measures such as geothermal potential zones need to be managed as well as further cost reductions achieved for tapping ground sources for ambient heat gains.

Ambitious policy measures are required also to achieve the 2050 target of -60 % GHG emission reduction for the transport sector compared to 1990. The main drivers are efficiency improvements, the diffusion of low-and zero-emission road vehicles and alternative fuels, in particular for aviation and navigation. In addition, modal shift from using individual cars to more efficient modes like public transport, cycling and walking can contribute to decarbonisation. Therefore, a bundle of complementary measures is required to support and accelerate this transition. This includes strict fuel efficiency standards for all types of road vehicles, tax and pricing strategies (e.g. road charges, fuel taxes and registration taxes all dependent on CO_2 emissions) and sufficient and timely infrastructure deployment (in particular charging stations and hydrogen filling stations) to reduce range anxieties and extra efforts for refuelling actions. If low-emission vehicles do not diffuse fast enough regardless of the implemented measures due to soft factors of technology acceptance, phase-out decisions for pure fossil-fuel based cars could be made by 2030 for completion in the subsequent five to ten years. In addition, ICT-based integrated multimodal mobility systems have to be promoted in order to make using public transport more attractive.

The results regarding the flexibility provision in the electricity market show that the assumed increase in electricity demand can only be served with additional dispatchable power plants. Sector coupling contributes to an increase as well as a flattening of the residual load and this way helps to balance the flexibility needs in the electricity market. To reach ambitious decarbonisation goals, the CO_2 intensive electricity generation must be significantly reduced. Since conventional electricity generation capacity will be needed to some extent also in High-RES scenarios, high CO_2 prices result in strong emission reductions. Here mainly natural gas power plants will play an important role in reducing emissions (due to the switch from CO_2-intensive energy carriers, such as coal and lignite, to gas). In the model, the need for CCS technologies occurs from 2040 on, depending on the carbon price policy. In general, CCS should therefore be developed as a further option. If the policy makers, want to deploy these technologies the effort on increasing the competitiveness of CCS technologies as well as on doing research on challenges regarding the storage of CO_2 should be applied from now on. Nevertheless, a faster RES capacity expansion together with an enforced coupling of the energy end use sectors is preferable to reach the climate policy goals as well as to avoid stranded investments in conventional power plants. Therefore, the integrated cross sectoral developments should be considered to account for possible trade-offs. In general, since emissions reductions in other sectors are comparably challenging, the sector coupling by electrification should be enforced. As it was mentioned above, an ambitious decarbonisation of the energy demand sectors increases the system costs of electricity generation. Nevertheless, the importance of the electricity to decarbonise the European energy system is of crucial importance. Additionally, regarding the central versus decentral High-RES scenarios, the conventional power plant mix as well as the total system costs in the electricity sector do not show very huge differences. In this perspective, the future development to a more central or decentral energy system can be based on realisable cost reductions for RES technologies without strongly affecting the electricity system. Additionally, the involvement of other important aspects like public acceptance (for a more central or decentral RES expansion) can be discussed without techno-economical limitations in the electricity system. The role of additional storages in the electricity system cannot finally be assessed, since the scenario and model coupling framework enforce the application of competing technologies and applications respectively (DSM, demand side sector coupling). In contrast, it is shown that residential storage applications have a high potential to decrease the flexibility requirements. Nevertheless, regarding the characteristics and the additional value of storage technologies, besides their application within the REFLEX project (e.g. system services), their importance can in general be assessed as high. If policy makers want to increase the role of storages, major cost reductions for batteries have to happen and have to be enforced. If cost reductions can be realised, fossil fuel based generation can further be decreased.

Furthermore, significant GHG emission reductions are possible in the district heat generation sector from 60 % to ca. 85 % in 2050 depending on the REFLEX scenarios. Bioenergy (mainly biomass) technologies are increasing their role becoming a key technology in heat supply. Natural gas units are utilised in countries with low bioenergy potentials, but also in other countries they help to fulfil the technical and operational constraints. Heating only plants, except large solar thermal plants, are losing competition with CHPs. At the same time, power-to-heat technologies actively respond to electricity price variations and to generated DH that can be stored. Furthermore, RES electricity surpluses can be used, instead of being otherwise curtailed. Seasonal and short-term heat storages help to smooth DH generation profiles and increase heat production in summer times. In general, district heating costs will increase in the future. This is mainly due to investments in new capacities, rising CO_2 and fuel prices. Besides, it is necessary to maintain the existing or new implemented policy measures that will guarantee profits for generators and keep the DH end-user prices at competitive levels.

The results regarding the cumulated CO_2 emissions show that the REFLEX High-RES scenarios achieve the ambitious decarbonisation targets formulated by the EU Roadmap. Although the contribution of different sectors differs between the decentralized and centralized scenario, the overall effect on emission reductions is the same. Therefore, when assessing the target achievement and comparing the two High-RES scenarios, the decision about a more central or decentral transformation of the European energy system is not bound to a better or worse performance regarding their ability to decarbonise the energy demand and supply. It is rather a question about an adequate mix of ambitious energy policy targets and measures like it is discussed in the summary above. However, it has to be mentioned that the both High-RES scenarios are more normative scenarios instead of being on track. This means that significant additional efforts are necessary, if such scenarios shall be achieved. Since the interactions between the energy sectors involved are complex, the results of the REFLEX project may help to give an in-depth understanding about optimal pathways to a low-carbon European energy system.

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Annex

A Model References

A.1 FORECAST

The model has been applied for national as well as EU-wide studies. Some exemplary researches are:

- Study evaluating the current energy efficiency policy framework in the EU and providing orientation on policy options for realising the cost-effective energy efficiency/ saving potential until 2020 and beyond; study performed for the European Commission DG ENER; (Fraunhofer ISI 2014)
- Determination of a German energy and climate strategy: „Klimaschutzszenario 2050" for the German Ministry for the Environment (Repenning et al. 2014)
- Scenarios for electricity demand in the EU27+2 countries until 2035, determined for different European energy utilities
- Study on the contribution of Energy Efficiency Measures to Climate Protection within the European Union until 2050; study performed for the German Federal Ministry for the Environment (Boßmann et al. 2012)
- ADAM adaptation and mitigation strategies: Supporting European climate policy – 2 Degree Scenario for Europe – Policies and Impacts (client: European Commission)

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A.2 eLOAD

The model has been applied for national as well as EU-wide studies. Some exemplary researches are:

- Determination of electricity system load curves of selected EU Member States (ESA², 2013)
- Scenario-based analysis of the national electricity demand, load curves and DR potentials until 2035 for different European energy utilities.

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A.3 ASTRA

The model has been applied for national as well as EU-wide studies. Some exemplary researches are:

- FUTRE (2012-2014) – Future prospects on transport evolution and innovation challenges for the competitiveness of Europe
- ASSIST (2011-2013) – Assessing the social and economic impacts of past and future sustainable transport policy in Europe
- GHG-TransPoRD (2009-2012) – Reducing greenhouse-gas emissions of transport beyond 2020: linking R&D, transport policies and reduction targets
- iTREN-2030 (2006-2009) – Integrated transport and energy baseline until 2030
- TRIAS (2005-2007) – Sustainability impact assessment of strategies integrating transport, technology and energy scenarios

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A.4 ELTRAMOD

The model has been applied for national as well as EU-wide studies. Some exemplary researches are:

- Grid and storage expansion in the European electricity system until 2050 and the impact of renewable feed-in obligation on these investments (ESA² 2013; Müller et al. 2013a)
- Analysis concerning the trade-off between grid and storage expansions as well as on flow calculation based on Net Transfer Capacity (Gunkel et al. 2012)
- Development of the German price duration curve until 2030 considering different policies concerning the priority feed-in of renewable energies (Müller et al. 2013b)
- The impact of market integration of renewable energies on power plant dispatch and investment decisions (Müller et al. 2013a)

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A.5 TIMES-HEAT-EU

Up to the present the model has been applied for national studies. Some exemplary researches are:

- Analysis of the consumption of natural gas by individual and district heating technologies in Poland till 2035 (Wyrwa et al., 2013)
- Indepth analysis of the residential heat system in Poland with the special focus on district heating (ESA², 2013)
- Modelling the development of the Polish domestic heat sector with the focus on small biomass installations (Pluta et al., 2013)

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B INVESTMENT PAYMENT ASSUMPTIONS WITHOUT TECHNICAL LEARNING

Table 26: Investment payment assumptions without technical learning

Technologies without learning progress	Investments in EUR/MW$_{el}$ Mod-RES and High-RES 2014-2050
CCGT	800,000
CCOT	800,000
Coal	1,800,000
GasSteam	920,000
Lignite	1,500,000
Nuclear	6,000,000
OCGT	400,000
OCOT	400,000
OilSteam	400,000
PSP	1,667,000
Reservoir	1,446,000

Source: data based on Schröder et al. (2013)

C Biomass Potential

The available biomass potential has been estimated in (Elbersen et al. 2012; Ruiz et al. 2015). In (Elbersen et al. 2012) the spatially detailed and quantified overview of EU biomass potential is presented taking into account the main criteria determining biomass availability from different sources. Biomass resources have been mapped to quantify the technical potential which subsequently has been translated into economic potential. Finally, the distinction has been made between a Reference and Sustainable scenarios. In the current EU law only biofuels have to meet the mandatory sustainability criteria whereas for solid and gaseous biomass sources the Commission has put forward only the recommended sustainability criteria which can be adopted by Member States, but are not binding. In the Sustainable scenario it was assumed that for all bioenergy sources consumed in EU (including solid and gaseous) there are environmental constraints. In (Ruiz et al. 2015) input data to the JRC-EU-TIMES model are described in terms of availability of bioenergy for EU and neighbouring countries. The evaluation of bioenergy potentials has been carried under three scenarios: High, Medium and Low bioenergy availability. The High bioenergy scenario reflects a situation where stimulation measures are in place and/or demand for biomass is high and there is a willingness to pay a (higher) price for it. This enhances the mobilisation of biomass production and harvesting opportunities and stimulates the use of biomass above alternative uses. The Medium bioenergy scenario corresponds to a reference case, and specifies the most likely future development of bioenergy leading to a continuation of current trends. There is stimulation of bioenergy production, but taking account of sustainable and resource efficient use of biomass. The mobilisation of biomass production and harvesting is not as strongly stimulated as in the High scenario. Stimulation and policy measures can be assumed to be in line with currently agreed policies and targets. In the Low bioenergy scenario biomass use in the energy sector is not a key priority, but rather its efficient use. This implies that there are fewer stimulation measures in place for mobilisation of domestic biomass supply and sustainability criteria are strict putting limits to the removal of residues from forests and the production of dedicated cropping potential both for biofuels and ligno-cellulosic crops. In both reports at the top level of aggregation biomass is categorized according to its origin i.e. biomass from agriculture, forestry and waste. These three categories are then split into different biomass types: 17 and 30 types for (Elbersen et al. 2012) and (Ruiz et al. 2015), respectively.

In order to combine the information from these two sources each type of biomass was assigned with a label indicating if it is supposed to be used as a feedstock for biofuel production or not. Subsequently, the biofuel-labelled types were rejected (as in this Chapter we are mainly focused on biomass-for heating), whereas the others have been summed for each scenario described above. Finally, the results of the comparison were showed on the figures with mean and min, max values from the set of the scenarios. Figure 64 presents the biomass potentials for selected countries according to different scenarios. The countries with the highest biomass potential include Germany, France, Poland and Sweden.

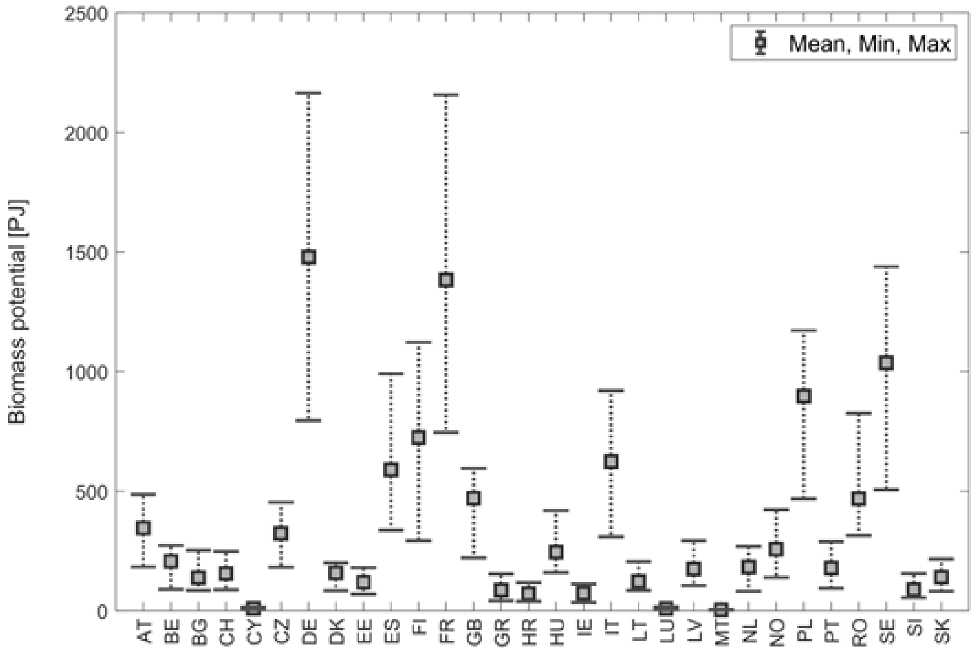

Figure 64: Biomass potentials

Source: AGH