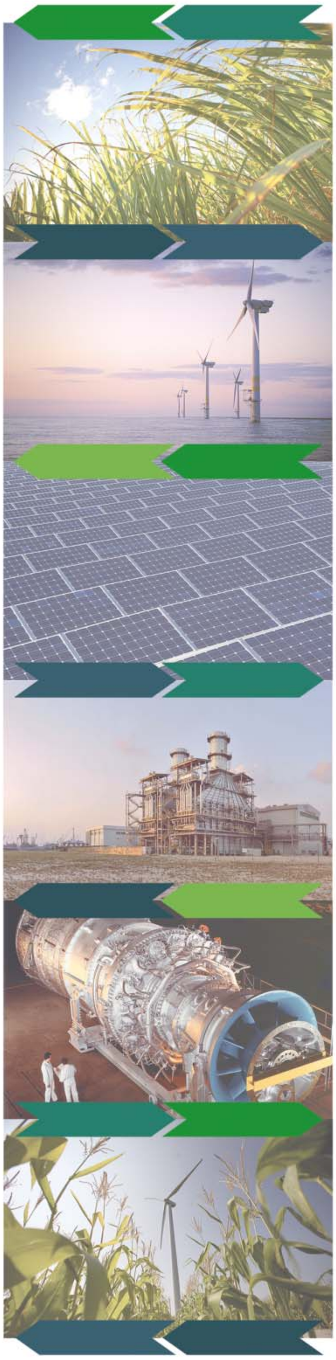
Navigating the Roadmap for Clean, Secure and Efficient Energy Innovation



D.5.8: WP5 Summary report - Energy Systems: Demand perspective

Author(s): Michael Hartner, Sebastian Forthuber, Lukas Kranzl, Sara Fritz, Eric Aichinger, Andreas Müller (TU Wien)

Andrea Herbst, Tobias Fleiter, Matthias Rehfeldt (Fraunhofer ISI)

Stephanie Heitel, Michael Krail, Jonathan Köhler (Fraunhofer ISI)

Christiane Bernath, Frank Sensfuß, (Fraunhofer ISI)

03 / 2019

A report compiled within the H2020 project SET-Nav (work package 5)

www.set-nav.eu

Project Coordinator: Technische Universität Wien (TU Wien)

Work Package Coordinator: TU Wien

SET-Nav

Strategic Energy Roadmap

The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 691843 (SET-Nav).

Project coordinator:

Gustav Resch

Technische Universität Wien (TU Wien), Institute of Energy Systems and Electrical Drives, Energy Economics Group (EEG)

Address: Gusshausstrasse 25/370-3, A-1040 Vienna, Austria

Phone: +43 1 58801 370354
Fax: +43 1 58801 370397
Email: resch@eeg.tuwien.ac.at
Web: www.eeg.tuwien.ac.at

Dissemination leader:

Prof. John Psarras, Haris Doukas (Project Web)

National Technical University of Athens (NTUA-EPU)

Address: 9, Iroon Polytechniou str., 15780, Zografou, Athens, Greece

Phone: +30 210 7722083
Fax: +30 210 7723550
Email: h_doukas@epu.ntua.gr
Web: http://www.epu.ntua.gr

Lead author of this report:

Michael Hartner

Technische Universität Wien (TU Wien), Institute of Energy Systems and Electrical Drives, Energy Economics Group (EEG)

Address: Gusshausstrasse 25/370-3, A-1040 Vienna, Austria

Phone: +43 1 58801 370379
Fax: +43 1 58801 370397
Email: hartner@eeg.tuwien.ac.at
Web: www.eeg.tuwien.ac.at

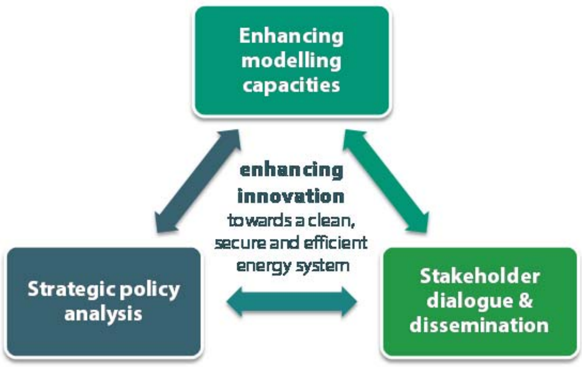
SET-Nav
Strategic Energy Roadmap

Project duration:	April 2016 – March 2019
Funding programme:	European Commission, Innovation and Networks Executive Agency (INEA), Horizon 2020 research and innovation programme, grant agreement no. 691843 (SET-Nav).
Web:	www.set-nav.eu
General contact:	contact@set-nav.eu

About the project

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

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



Who we are?

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

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

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1 Introduction

1.1 Overall goals of modelling work in SET-Nav

The goal of the modelling work in the SET-Nav project is to quantify potential pathways towards a low carbon energy system in EU28 Member States (MS) until the year 2050. We aim at quantifying the majority of energy flows on the demand and supply side by linking several models dedicated to different sectors. Work package 5 of the SET-Nav project was dedicated to modelling the demand side of the energy system covering the sectors buildings, industry and transport and it´s link to the electricity system and gas sector.

This report presents the main results that have been derived from the modelling activities on the demand side. They have been derived from 3 case studies with a focus on to the building, industry and transport sector in which each sector was analysed individually and model runs for the SET-Nav pathways in which all models were used to generate an almost complete picture of a low carbon energy system until the year 2050.

1.2 Structure of this report

The report is structured as follows: Chapter 0 describes the overall approach of the modelling work in case studies and the SET-Nav pathways. Then the main methodologies and results for each sector individually are presented. Chapter 3 is dedicated to the building sector, it´s link to the electricity system and potential developments of renewable heating options as well as the role of thermal efficiency. The results on modelling potential developments in the industry sector are presented in Chapter 4 with a focus on technology options for the main carbon emitting industrial processes and resulting electricity demand from industry including the flexibility potential from an electricity system perspective. Chapter 5 is dedicated to the transport sector, illustrating decarbonisation options for vehicles categories and their impact on demand for alternative energy carriers for transport. In chapter 6 the main results from all pathway runs are summarized and the overall development of final energy demand and CO_2 emissions in demand sectors for all pathways are presented.

2 Methodology, data flows and scenario definitions

Within this section the general methodological approach is briefly presented. A more detailed description will be given within the chapters dedicated to the individual sectors.

2.1 Overall approach and data exchange concept

The overall methodology of analysis within the SET-Nav project was to first conduct case studies for individual research questions focusing on different sectors. However already at this stage a common data exchange concept for all involved models and sectors was established (see deliverable 5.1). The core of each case study within WP5 was a specific model focusing on simulating the demand side of the building, industry, and transport sector respectively. Within each case study the data exchange concept was applied to link these core models with several other models to link the demand side with the supply side of the energy system. The focus was particularly to link the demand models with the electricity system to study the impacts of developments on electricity demand and potentials to supply additional demand with renewable energy sources as well as to analyse flexibility potentials on the demand side. Figure 1 illustrates this approach which will further be explained for each case study in the following chapters.

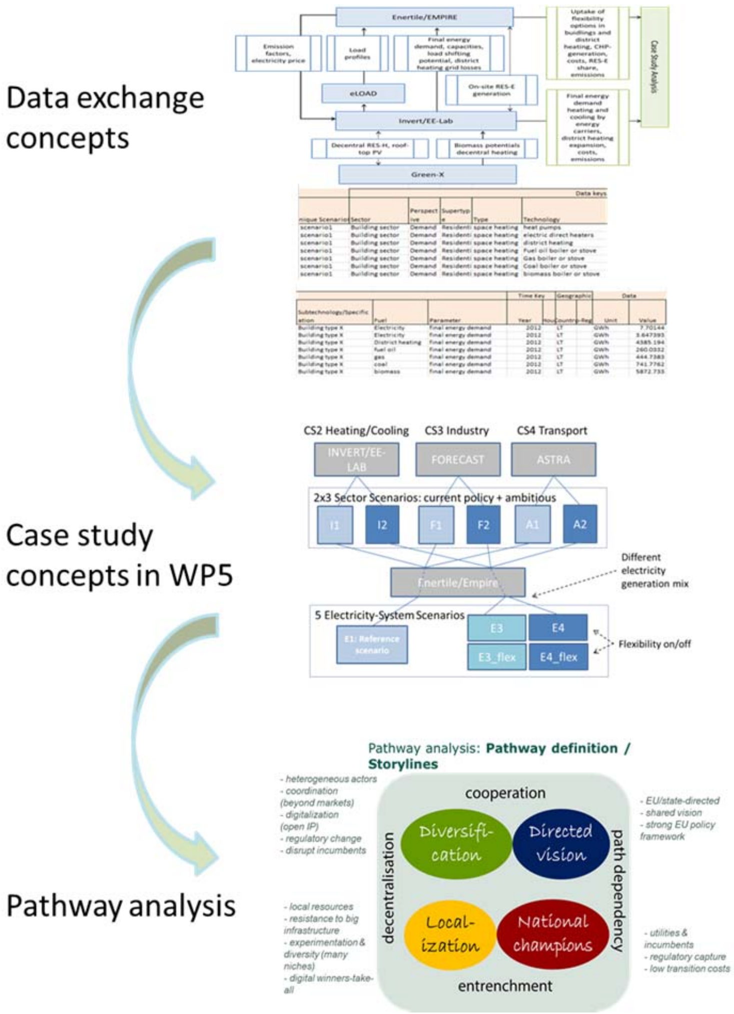


Figure 1: Overall concept of modelling the demand perspective in the SET-Nav project

2.2 Case studies on demand perspective

Within the first stage of the SET-Nav project 11 case studies have been conducted – see Figure 2 for an overview on all case studies. 3 case studies (red circles) were dedicated to analysing energy demand and quantifying potential developments until the year 2050. Those case studies are:

- Energy demand and supply in buildings and the role of RES market integration (building sector see chapter 3 or Case study report (deliverable 5.2))
- The contribution of innovative technologies to decarbonise industrial process heat (industrial sector see chapter 4 or Case study report (deliverable 5.4))
- Ways to a cleaner and smarter transport sector (transport sector see chapter 5 or Case study report (deliverable 5.6))

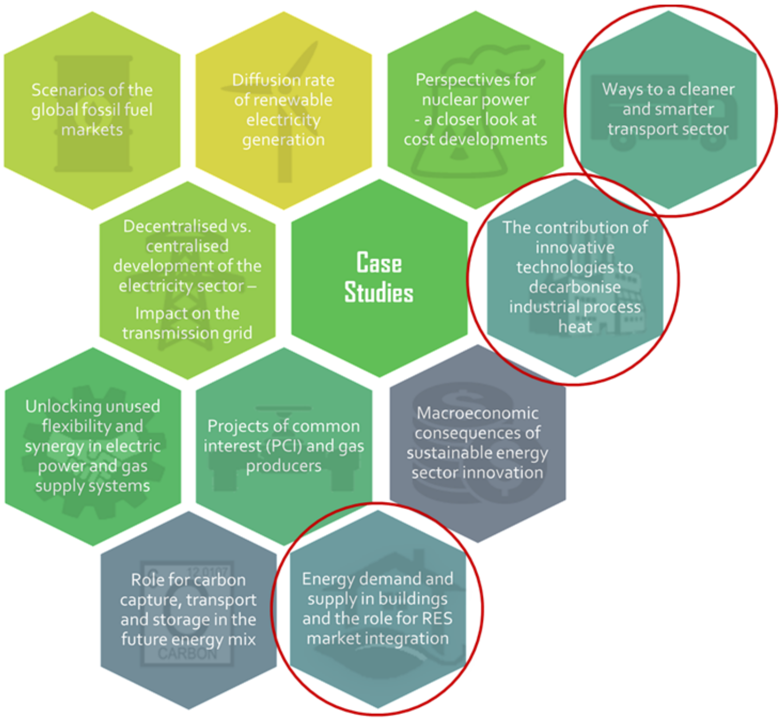


Figure 2: Overview of all case studies in the SET-Nav project. Case studies on the demand side in WP5 within red circles

Detailed results for each case study can be found in the Case study reports. In addition, the following chapters will summarize the main results of each case study, in particular the lessons learned for the pathway analysis presented at the end of each chapter. Within WP5 all demand models where linked with the electricity system models Enertile© and Empire. Each sector model (INVERT/EE-Lab – buildings, FORECAST – industry, ASTRA – transport) calculated a current policy and an ambitious scenario with higher CO_2 emission reductions. Those results where then integrated (using the data exchanged concepts and data formats developed at the early stage of the project) into the electricity supply models. Each supply model calculated several scenarios to analyse the impact on the electricity system and evaluating the importance of flexibility options on the demand side. The links established within the case studies were also used in the following pathway analysis.

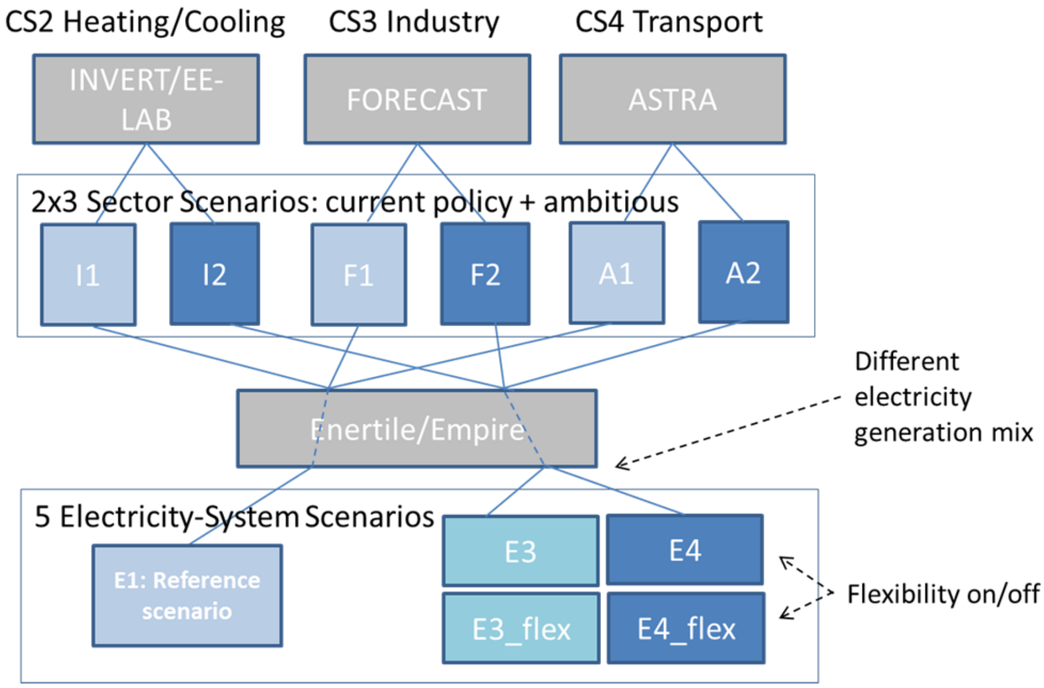


Figure 3: Overview on scenarios within the case studies conducted in WP5

2.3 SET-Nav Pathways from demand perspective

The lessons learned from the case studies where used to define the SET-Nav pathways in WP9 where all sectors and models were linked to quantify potential developments towards low carbon energy supply across all sectors. From the overall pathway definition the demand models in WP5 derived assumptions which were then translated into different inputs for each model, depending on the characteristics of each pathway. While some overall assumptions for the pathways (e.g. the availability of CCS in the directed vision and national champions pathway) were directly integrated in the sector models other characteristics were interpreted individually by each sector model. In a discussion process among all demand side and supply side modellers within the project the assumptions were collected and finetuned to avoid inconsistencies between the sectors. Furthermore the framework conditions on energy prices, population growth, economic developments and ranges of emission reduction targets for each model were defined and harmonized. Figure 4 and Table 1 provide an overview of the pathway definition including the main characteristics from an overall perspective. The interpretation of each pathway and the derived assumptions are presented in chapter 3 to 5 for each sector.

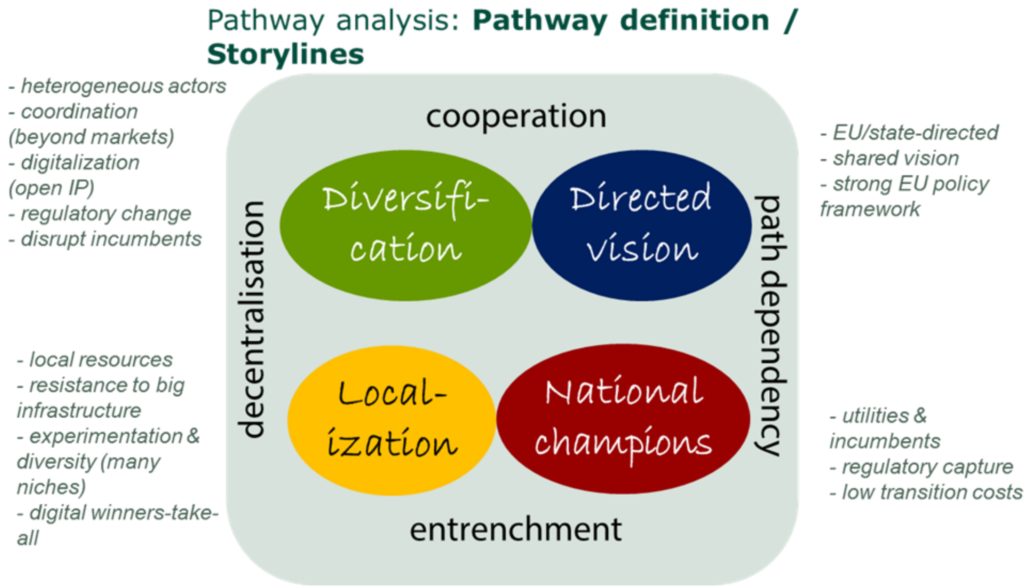


Figure 4: Overview of pathway definitions in the SET-Nav project

Table 1: Examples for overall key elements and characteristics of each pathway

	Diversifi-cation	Directed vision	Local-ization	National champions
dimensions of uncertainty	**cooperation decentralisation**	**cooperation path dependency**	**entrenchment decentralisation**	**entrenchment path dependency**
alternative acronyms	proliferation	direction	localisation	continuation
key elements of scenario storyline	- many new entrants - heterogeneous actors - support for coordination (beyond markets) - digitalisation and open platforms - active consumers - regulatory opening (for new business models) - disruption of incumbents	- shared vision for direction of change (buy-in to targets & EU as global leader) - strong guiding role of state (EU) - engagement with stakeholders (but favouring large actors) - durable and stable policy framework - strong coordination between member states	- exploitation of local resources - differences in national strategies - public resistance to big new infrastructure - experimentation & diversity (many market niches) - digitalisation and national coordination (winner-takes-all)	- minimisation of transition costs - strong role for incumbent firms & utilities - regulatory capture of new policy - large-scale projects - low transition costs
broad policy framework derived from storyline	regulatory opening up market to new entrants, mechanisms to ensure grid capacity	strong market guidance (regulations, standards, taxes), cross-country harmonisation	differentiated policies, variation between countries, weak EU harmonisation	policies minimise transition costs & disruption, favouring centralised systems & incumbents
SET Plan emphasis: Priority Areas (WP3)	(decentral) renewables, efficiency, smart grid, e-mobility	(central) renewables, efficiency, (new) nuclear, CCS, e-mobility	(decentral) renewables, efficiency, (existing) nuclear, CCS (localised), e-mobility	(central) renewables, efficiency, (new and existing) nuclear, CCS, e-mobility

3 Energy demand in buildings

This chapter is dedicated to describing the modelling activities within the building sector and the main results that can be derived from the various scenario runs that have been conducted to quantify potential developments of energy demand in the building sector until 2050.

3.1 Methodology and scenario definitions

3.1.1 Model description Invert/EE-Lab

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

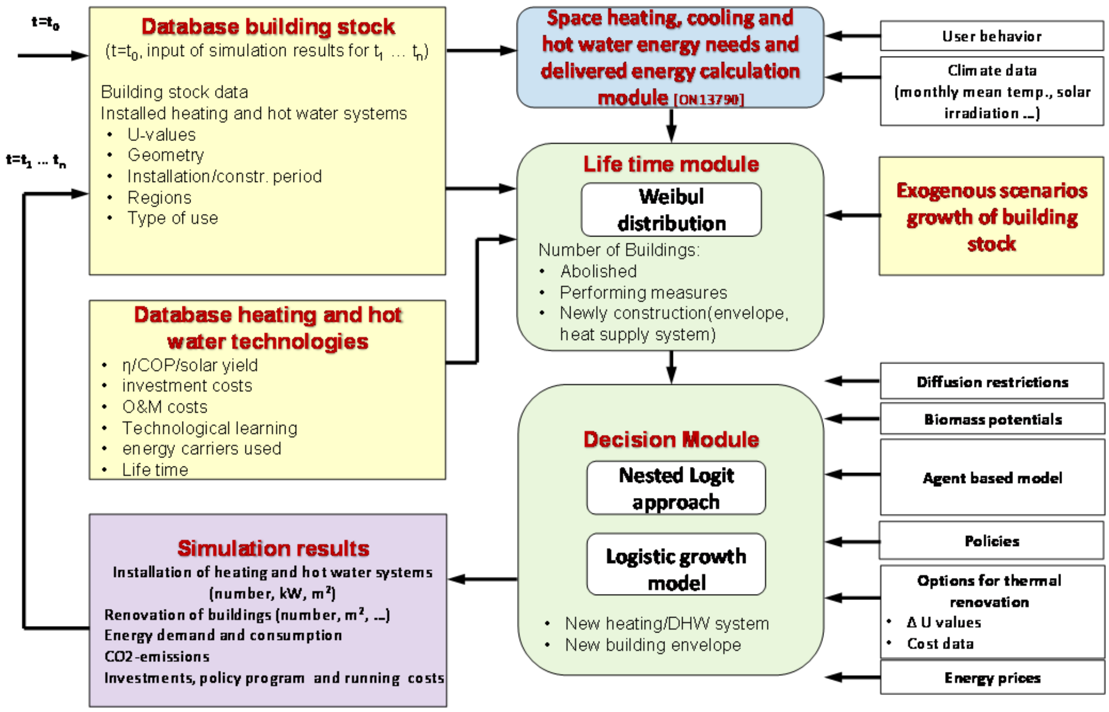


Figure 5: Overview structure of Simulation-Tool Invert/EE-Lab

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

3.1.2 Scenario assumptions in case study on buildings

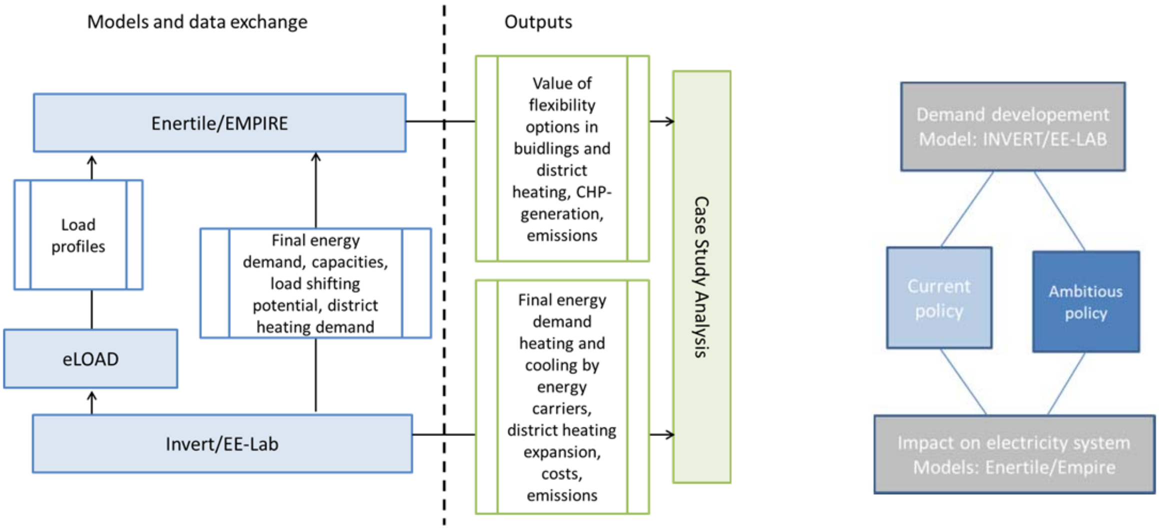


Figure 6: Data exchange concept, model links and general scenario design in case study 5.2

The starting point of the analysis of this case study was the computation of 2 scenarios calculated with the building stock model INVERT/EE-Lab. A current policy scenario was calculated assuming that all existing policy measures related to the European building stock are implemented in their current form and continue to be valid until the year 2050. In the ambitious policy scenario measures already implemented in the current-policy scenario were intensified to reach stronger energy demand reductions and increasing shares of renewables in the building stock.

The results on annual energy demand for heating and cooling from both scenarios were transformed into hourly profiles and fed into the electricity system models for further analyses. The electricity system models followed different scenario approaches within their simulation runs and focused on specific aspects of the link between heating and cooling and the electricity system. Biomass use in all involved models are finally compared with model results from the Green-X model to analyse the feasibility with respect to overall available biomass potentials. The results from Green-X were also used to set maximum biomass potentials in the building stock model.

3.1.3 Assumptions for pathway modelling – buildings

In a first step the assumptions on the framework conditions for all pathway calculations were harmonized across all models involved in the pathway calculations. Table 2 shows an overview of the framework conditions that were relevant for modelling the pathways in the building sector.

- The overall CO_2 emission reduction target for the whole energy system was roughly -85% in the year 2050 compared to the year 2015. To reach such an overall target it was assumed that the building sector would have to reach emission reduction targets of more than -90% in all pathways.
- The pathway narratives as described in Table 1 define overall tendencies of developments which are translated into inputs for the building stock model. This will be further evaluated below and is shown in Table 3.
- Population growth per country and economic growth are derived from the Primes – EU Reference Scenarion 2016 and translated into developments of gross floor areas in the residential and service sector for each country.

- Wholesale prices for fossil fuels (gas, oil and coal) are derived from the IEA new policy scenario 2016, while wholesale electricity prices are derived from model runs with the electricity system model Entertile©. From those wholesale prices end-user prices had to be estimated. A tool developed by Fraunhofer ISI is used to calculate retail prices for each energy carrier including retail margins as well as taxes until the year 2050. The CO_2 price is included in the taxes and is therefore not a direct input to the building stock model used for the pathway scenarios. The resulting retail prices are interpreted as end-user prices and are used for calculating the energy costs for heating and cooling in the pathway calculations.

Table 2: Overview of assumptions on framework conditions for the pathways in the building sector.

		SET-Nav			
		Buidlings (Final energy demand for heating and cooling excluding industrial buildings)			
		Diversification	**Directed Vision**	**Localisation**	**National champions**
GHG targets	**GHG reduction targets across sectors**	85% GHG reduction as default target in 2050 --> for buildings this would imply GHG emission reductions of more than -90% compared to 2015			
Frame-work conditions	**Basic socio-technical** *Europe*	**cooperation / decentralisation**	**cooperation / path dependency**	**entrenchment / decentralisation**	**entrenchment / path dependency**
		- many new entrants - heterogeneous actors - active consumers - coordination, digitalisation, open platforms - regulatory opening -challenges to incumbents	- clear shared vision - EU in guiding role - buy-in of (large) stakeholders - durable and stable policy framework - strong coordination between member states	- local resources - national differentiation - resistance to big infrastructure - experimentation & diversity (but weak spillovers) - winner-takes-all digitalisation	- low transitional risks (the devil you know) - strong role for incumbents - regulatory capture - large-scale projects & balance sheet
	Population growth	*PRIMES EU Reference Scenario*			
	Economic growth	*PRIMES EU Reference Scenario*			
	Energy carrier prices	*Retail price tool – Fraunhofer ISI*			
	Electricity prices	*Provided by ENERTILE*			
	Coal, gas, oil	*IEA scenario*			
	CO2 prices	*Not directly implemented in Invert/EE-Lab - goes through taxes and retail prices*			

Table 3 shows an overview of the main assumptions for each pathway that were implemented in the building stock model. The most important characteristics of each pathway are highlighted in red. We distinguish assumptions and settings for the model runs along policies and technologies. The main assumptions are:

- The **starting point for all pathways** the settings in the model is the **ambitious policy scenario** which has been calculated in the case studies. In all pathways we assume country specific subsidies for renewable heating systems and thermal renovations as well as obligatory building standards. We also calculated a **reference scenario** in which we assumed the same settings as in the **current policy scenario** and only adjusted the overall framework conditions including the energy carrier prices to the settings of the pathways.
- **Natural gas:** Following the lesson learned from the case study results that it is very likely that with the remaining stock of heating systems fuelled by natural gas CO_2 emission reductions of more than 90% in the building stock are not feasible, we simulated a phase out from natural gas in the building sector in 3 of the 4 pathways. Only in the National Champions pathway we allowed natural gas to stay in the mix, assuming that the remaining gas demand could be delivered by biogas or Power to Gas.
- **Diversification pathway:** We interpreted the higher level pathway characteristic for the building sector as a world where we expect to have a highly electrified and digitalized building stock. In the model this translates into high subsidies and low diffusion barriers for heat pumps.

We also assume a linear 40% cost reduction for heat pumps until the year 2040. Furthermore it is assumed that smart thermostats are the norm which we simulate by decreasing the average indoor temperatures by -1°C until the year 2050.

- **Directed vision:** In the Directed Vision scenario we assume that the clear shared vision leads to a world where very ambitious thermal renovation activities can be enforced. This is simulated assuming higher subsidies for deep renovation activities as well as enhanced renovation obligations and buildings standards beginning in the year 2025. Furthermore the preconditions were interpreted in a way that district heating would also be strongly supported. We assume enhanced investment subsidies for district heating connections and optimistic diffusion barriers as a result of clear district heating zoning policies which are assumed to lead to high connection rates in urban areas.
- **Localization:** This pathway was interpreted as a scenario with higher diffusion of solar thermal and photovoltaic systems. The subsidies for these technologies where increased compared to the other pathways. Furthermore the diffusion restrictions for both technologies are lower than in other pathways. It was decided not to directly set the settings of the model to support more diffusion of biomass heating system as they take over a large share even with standard settings in the model. Furthermore an increased need of biomass in the industry and transport sector is anticipated which sets limits to an increased use in the building sector.

Table 3: Translation of pathway narratives into assumptions for the building sector.

	SET-Nav			
	Diversification	**Directed Vision**	**Localisation**	**Nat. champ.**
Financial support of RES heating systems	direct investement subsidies for all renewable heating systems	moderate direct investment subsidies for thermal efficiency measures	direct investement subsidies for all renewable heating systems More subsidies for PV and solar thermal	country dependent
Obligations for renewable shares for heating per building	new installations of fossil heating systems prohibited from 2030	new installations of fossil heating systems prohibited from 2030	new installations of fossil heating systems prohibited from 2030	country dependent
Thermal efficiency improvement	LOW - investment subsidies - enhancement of building codes as in ambitious scenario	HIGH - enhanced investment subsidies for deep renovation - enhanced renovation obligations from 2025	MODERATE - moderate investment subsidies - moderately enhanced renovation obligations from 2025	country dependent
Biomass	LOW - reference scenario potentials - pessimistic diffusion of biomass - investment subsidies for pellets as in ambitious scenario - no investment subsidies for wood log, wood chips	LOW - reference scenario potentials - very pessimistic diffusion of biomass - investment subsidies for pellets as in ambitious scenario - no investment subsidies for wood log, wood chips	LOW - reference scenario potentials - very pessimistic diffusion - no investment subsidies	country dependent
District heating	LOW - pessimistic diffusion of district heating	HIGH - optimistic diffusion of district heating (zoning and connection obligations, cost reduction) - enhanced investment subsidies	MODERATE - moderately optimistic diffusion rates	country dependent
Heat pumps	HIGH - significant cost reduction (-20% until 2040) - high subsidies, as in ambitious scenario	MODERATE - moderate cost reduction (-10% until 2040) - moderate diffusion of heat pumps - moderate investment subsidies	MODERATE - moderate cost reduction (-10% until 2040) - moderate investment subsidies	country dependent
Green gas	LOW	LOW	LOW	country dependent
PV	HIGH - high diffusion - investment subsidies as in ambitious scenario	MODERATE - moderate diffusion - moderate investment subsidies	HIGH - high diffusion - investment subsidies as in ambitious scenario	country dependent
Solar thermal	MODERATE - moderate diffusion of solar thermal systems - investment subsidies as in ambitious scenario	LOW - low diffusion - investment subsidies as in ambitious scenario	HIGH - high diffusion rates - investment subsidies as in ambitious scenario	country dependent
Efficiency improvements through smart technologies	HIGH - strong support and acceptance of smart thermostats from 2025	HIGH - strong support and acceptance of smart thermostats from 2025	MODERATE - moderate support and acceptance of smart thermostats from 2025	country dependent

- **National Champions:** While in all other pathways the same tendencies where assumed for all countries, the National Champions pathway represents a scenario in which different developments per country are assumed. Based on the settings in the other pathways different settings for technologies per country were defined. Table 4 provides an overview of the assumptions per country. "Yes" means that the most optimistic assumptions for the diffusion of a technology from the other 3 pathways were applied, "No" means that the standard settings from the ambitious scenario in the case study were used for the model runs. The settings were based on the assessment of the current status in each country. E.g. countries with currently high shares of district heating were defined as "High district heating"- countries and vice versa. Within this pathway it was also assumed that countries where natural gas currently has very high market shares will not follow the phase out. It is further assumed that the remaining gas demand in those countries could be covered by biogas or power to heat.

Table 4: Country specific assumptions in the National Champions pathway

	Ambitious renovator	High district heating	High electricification	biomass country	Solar country	Smart heating	Allow Gas (green Gas)
AT	yes	yes	yes	yes	no	yes	no
BE	no	no	yes	no	no	yes	yes
BG	no	yes	no	yes	no	yes	no
CY	no	no	yes	no	yes	no	no
CZ	yes	yes	yes	no	no	yes	no
DE	yes	yes	yes	no	no	yes	yes
DK	no	yes	yes	no	no	yes	no
EE	no	yes	no	yes	no	yes	no
ES	no	no	yes	no	yes	no	no
FI	yes	yes	no	yes	no	yes	no
FR	yes	no	yes	no	no	yes	yes
GB	yes	no	yes	no	no	yes	yes
GR	no	no	yes	no	yes	no	no
HR	no	no	yes	no	yes	no	no
HU	yes	yes	no	yes	no	no	yes
IE	no	no	yes	no	no	yes	no
IT	no	no	yes	no	yes	yes	no
LT	yes	yes	no	yes	no	no	no
LU	yes	no	yes	no	no	yes	yes
LV	yes	yes	no	yes	no	no	no
MT	no	no	yes	no	yes	no	no
NL	yes	no	yes	no	no	yes	yes
PL	no	yes	no	yes	no	no	yes
PT	no	no	yes	no	yes	no	no
RO	yes	yes	no	yes	no	no	no
SE	yes	yes	yes	yes	no	yes	no
SI	yes	no	yes	yes	no	yes	no
SK	yes	yes	no	no	no	no	yes

3.2 Case study on buildings - main results and lessons learned

Within this section an overview of the main results from the case study on buildings and the lessons learned for the following pathway analysis is given. Detailed results can be found in the Case study report (deliverable 5.2 of the SET-Nav project).

3.2.1 Summary of results from case studies

Figure 7 shows the modelling results for total final energy demand in the EU28 member states from 2012 to 2050 for the calculated current and an ambitious scenario, differentiated by the main end use categories domestic hot water, space heating, cooling and auxiliary devices. In both scenarios total final energy demand is expected to decrease significantly.

In the current policy scenario final energy demand is expected to decrease from 3815 TWh in 2012 to 2754 TWh in 2050 which corresponds to a decrease of around -28%. The more ambitious policies implemented in the model are expected to lead to a further decrease to 2483 TWh in 2050 which is equivalent to a -35% reduction of final energy demand. In both scenarios the decrease is a result of increased investments in the thermal efficiency of the European building stock, which lead to lower space heating demand. Space heating accounts for about 84% of the overall heating demand and cooling demand in 2012, which amounts to about 3204 TWh, whereas hot water accounts for around 13% (497 TWh).

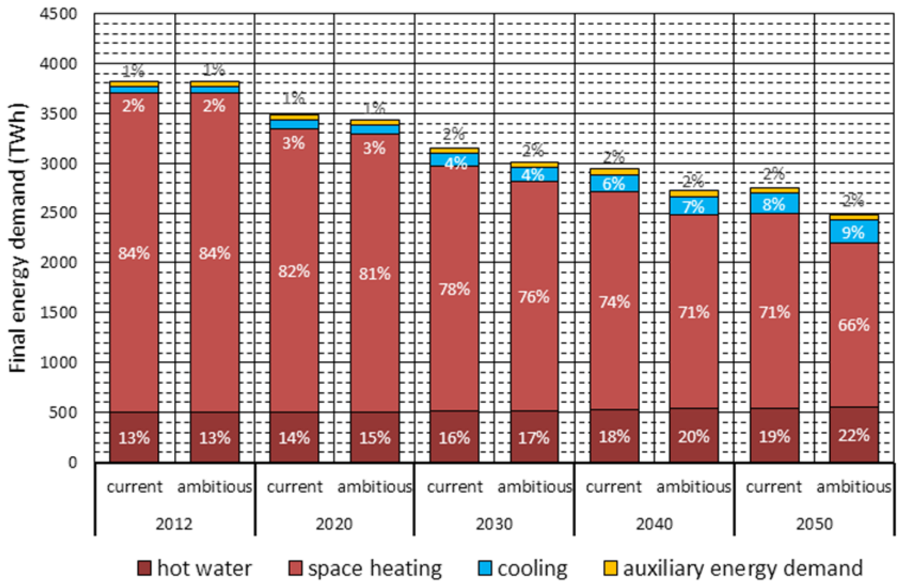


Figure 7: Total final energy demand by usage types for *current and ambitious* scenario for EU28 in TWh

The decrease of the space heating demand is expected to be around -39% in the current and -48% in the ambitious scenario. Hot water demand is expected to increase by about 8% (current scenario) respectively 11% (ambitious scenario) due to population growth and increase of total floor area. This leads to an increase in the end use share for hot water from 13% to 19% (current scenario) and 13% to 22% (ambitious scenario) respectively. The demand for auxiliary energy to operate heating systems is expected to increase but is expected to amount to only around 2% by 2050. The results suggest that while energy demand for hot water and auxiliary devices stay rather constant in absolute terms, a noticeable shift in the total shares from space heating to water heating can be observed.

Table 5: Final energy demand by usage types in TWh and change of final energy demand by usage types for *current and ambitious* scenario in % for EU28

Final energy demand (TWh)	hot water		space heating		cooling		auxiliary energy demand		TOTAL	
Scenario	current	ambitious	current	ambitious	current	ambitious	current	ambitious	current	ambitious
2012	497	497	3204	3204	67	67	47	47	***3815***	***3815***
2020	500	503	2847	2786	88	90	51	50	***3485***	***3429***
2030	512	519	2457	2297	127	135	55	54	***3150***	***3005***
2040	526	538	2187	1942	171	184	57	56	***2941***	***2720***
2050	536	554	1953	1651	207	222	58	56	***2754***	***2483***
Share 2012	13%	13%	84%	84%	2%	2%	1%	1%	100%	100%
Share 2050	19%	22%	71%	66%	8%	9%	2%	2%	100%	100%
Change 2012/2050	8%	11%	**-39%**	**-48%**	210%	232%	23%	20%	***-28%***	***-35%***

Figure 7 also reveals that final energy demand for space cooling, which is assumed to be covered by electricity, increases significantly from 67 TWh in 2012 to more than 200 TWh in 2050. The share of space cooling in total energy demand for heating and cooling the EU28 building stock increases from around 2% in 2012 to around 8%-9% in 2050 indicating that space heating and hot water will still account for the main share of final energy demand, despite the strong increase in cooling needs.

Figure 8 illustrates the development of final energy demand per energy carrier. Figure 9 shows the corresponding shares for each scenario. It can be clearly seen that the use of fossil energy carriers decreases substantially in both scenarios.

Fuel oil and coal nearly disappear from the heat generation mix and are mainly substituted by biomass boilers, but also heat pumps and solar thermal systems. Despite a significant decrease of around -52% to -63%, natural gas still makes up for a large share of heat supply until 2050 in both scenarios. Even in the ambitious policy scenario natural gas is expected to account for around 25% of final heating and cooling supply in the EU28 building stock.

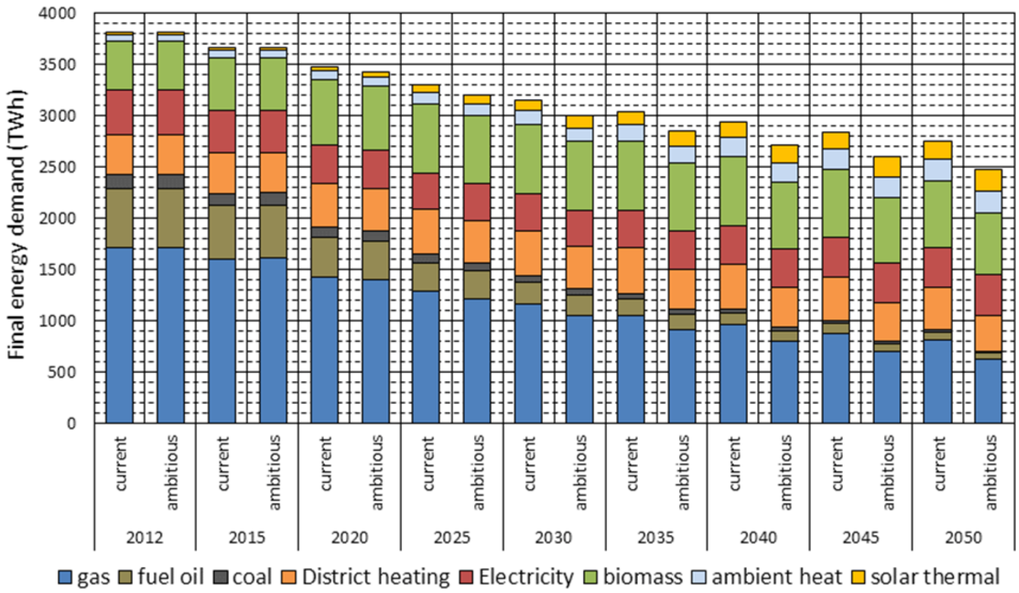


Figure 8: Total final energy demand by energy carrier for current and ambitious scenario for EU28 in TWh

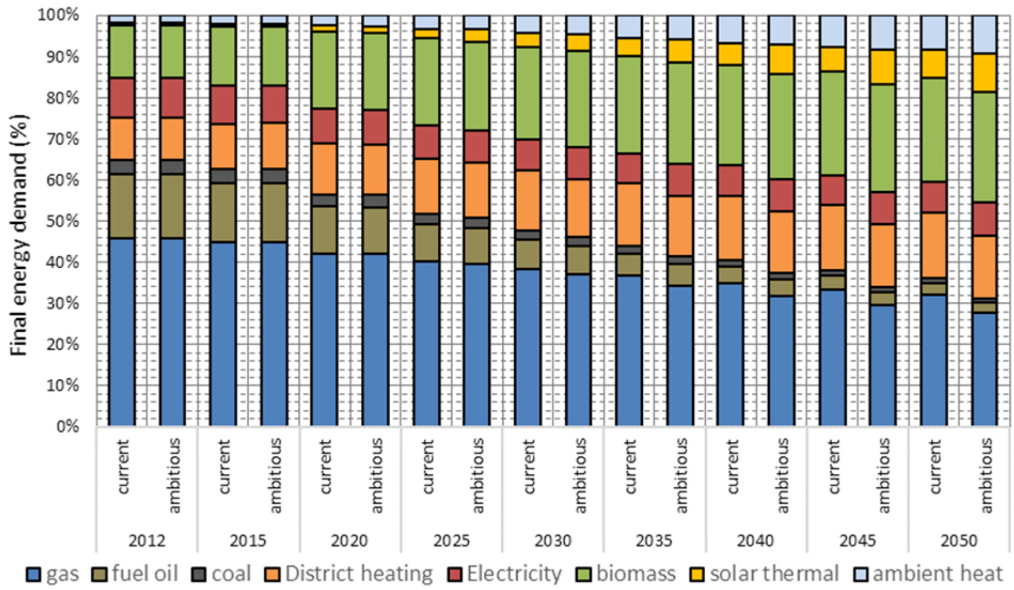


Figure 9: Share on total final energy demand per energy carrier for *current and ambitious* scenario for EU28 in %

Although district heating is expected to increase its market share, total energy demand from district heating networks is expected to stay rather constant (slight increase in current, moderate decrease in ambitious scenario) due to higher efficiencies of connected buildings.

Table 6: Final energy demand by energy carrier for *current and ambitious* scenario for EU28 in TWh and corresponding shares in %

Final energy demand	2012		2050				2050	2050
Scenario			current		ambitious		current	amb.
unit	(TWh)	(%)	(TWh)	(%)	(TWh)	(%)	(+/- %)	(+/- %)
Gas	**1717**	45%	**819**	30%	**627**	25%	-52%	-63%
Fuel oil	**580**	15%	**74**	3%	**59**	2%	-87%	-90%
Coal	**133**	3%	**26**	1%	**18**	1%	-80%	-86%
District heating	**388**	10%	**408**	15%	**349**	14%	+5%	-10%
Electricity	**431**	11%	**397**	14%	**402**	16%	-8%	-7%
Biomass	**480**	13%	**643**	23%	**603**	24%	+34%	+26%
Ambient heat	**67**	2%	**216**	8%	**209**	8%	+225%	+213%
Solar thermal	**20**	1%	**172**	6%	**216**	9%	+766%	+988%
TOTAL	3815	100%	2754	100%	2483	100%	-28%	-35%

Electricity demand for heating and cooling in European buildings is expected to stay more or less constant, or slightly decreases (-7% to -8%). However there is a noticeable shift from space heating to space cooling. Electricity demand for space heating and hot water supply is expected to decrease by around -60%, despite a significant increase of market shares of electricity powered heat pumps that allow for exploiting ambient heat for space heating and hot water supply. Heat pumps are expected to be deployed in particular in new buildings but also as substitution of existing direct electric heating systems. In the scenarios cooling will accounts for more than 60% of electricity demand for heating and cooling.

Figure 10 summarizes the results by showing aggregated shares of fossil and renewable energy carriers as well as shares of the secondary energy carriers electricity and district heating in final energy supply for heating and cooling. The share of fossil energy carriers is strongly reduced from 64% in 2012 to 33% in 2050 for the current policy scenario settings and 28% in the ambitious policy scenario respectively. Note that natural gas accounts for more than 90% of fossil energy carriers in 2050 because as described above coal and fuel oil are expected to disappear due to the implemented policies and assumptions on energy price developments. Renewable energy carriers (biomass, ambient heat and solar thermal) are expected to increase from 15% in 2012 to 37% in the current policy scenario and 41% in the ambitious policy scenario. The increasing shares of final energy supply from electricity are a result of increasing cooling demand while the share of electricity supply for heating is expected to decrease. The share of district heating is expected to increase from 10% to 15% in the current policy and 14% in the ambitious policy scenario respectively.

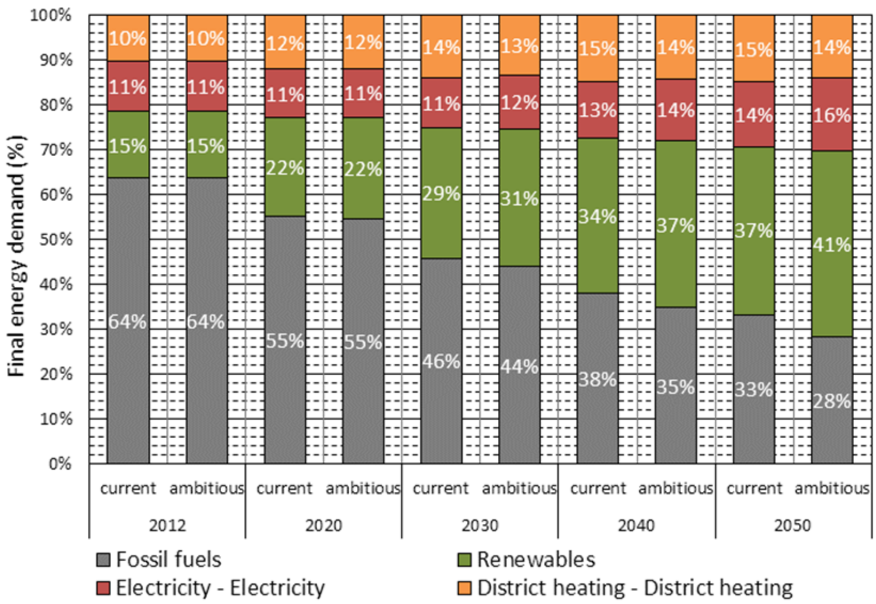


Figure 10: Shares of fossil fuels, renewables, electricity and district heating on final energy demand for space heating, hot water and space cooling supply in EU28 until 2050

It has to be noted that also heat from district heating and electricity is partly supplied by renewable energy carriers. The total share of renewables in primary energy for heating and cooling depends on developments in the energy carrier mix for electricity and district heating which is not modelled in INVERT/EE-Lab. With respect to CO_2 emission reductions the results indicate that while emissions decline significantly, reductions of more than -80% until 2050 constitute a major challenge. Even if it is assumed that district heating and electricity supply is almost fully decarbonized until 2050, emission reductions amount to around -77% in the current policy scenario and -83% in the ambitious policy scenario. To reach emission reductions of more than 90% which is assumed to be necessary to reach ambitious climate goals, the use of natural gas would have to be reduced even more than in the calculated scenarios. Given the high market shares of natural gas in particular in urban areas and the relatively long lifetime of heating systems in the European building stock this can be seen as the major challenge for decarbonizing heating and cooling supply.

Energy expenditures

Following the reduction of final energy for space heating, energy expenditures for households and the service sector are expected to decrease significantly. Figure 11 shows energy expenditures from an end user perspective for space heating, hot water, space cooling and auxiliary energy in the EU28 until 2050.

Annual Energy expenditures amount to about 340 billion € in 2012 and are reduced by around -25% in the current policy scenario and -35% in the ambitious policy scenario respectively. That amounts to around 250 billion € and 220 billion € respectively in the year 2050. Model results indicate that the expenditures for space heating will be strongly reduced by about -40% to -50%, mainly as a result of thermal renovation measures in the building stock. On the contrary a growing demand for space cooling and therefore increasing energy expenses for electricity for air conditioning from about 15 billion € in 2012 to more than 50 billion € in 2050 annually are estimated in the scenarios. Space heating expenses will still account for the biggest share (around 55% to 60% of the total energy expenses) while cooling will cover around 25%. The energy expenses for water heating are expected to decrease despite an increase in total energy demand, mainly because of the increased deployment of solar thermal systems.

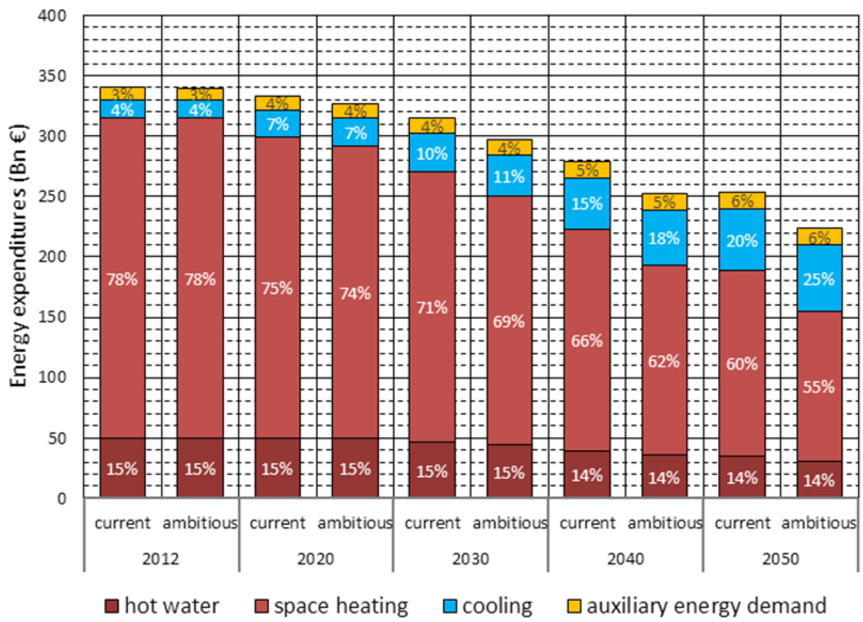


Figure 11: Energy expenditures by usage types for current and ambitious scenario for EU28 in Bn €

Figure 12 shows energy expenditures from an end user perspective on the main energy carriers for heating and cooling in EU28 until 2050. The reductions mainly stem from a decrease in expenses for fossil energy carriers while expenses for biomass and district heating slightly increase.

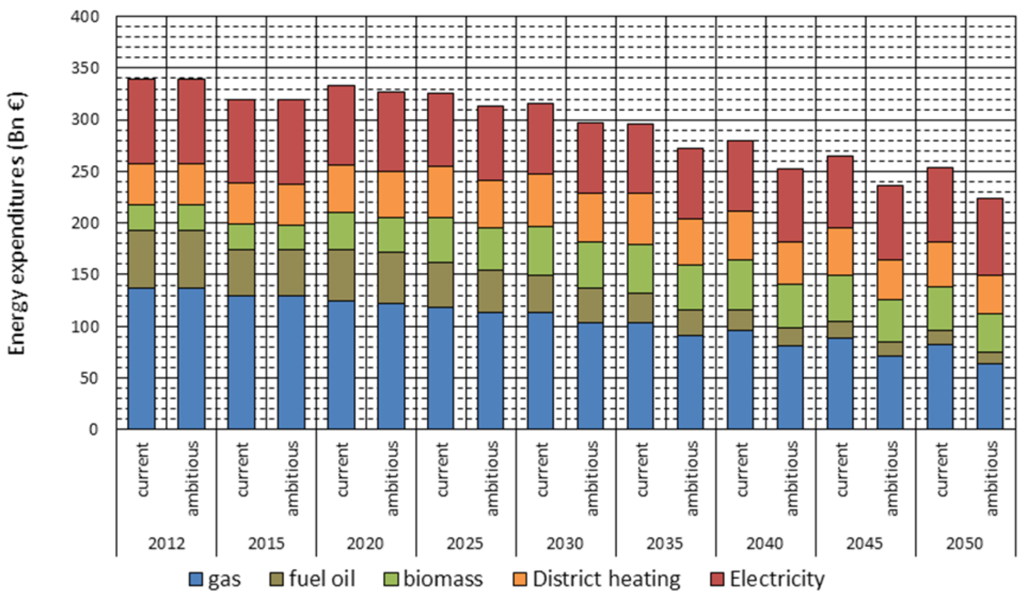


Figure 12: Energy expenditures by energy carriers for *current and ambitious* scenario for EU28 in Bn €

Investments

Total annual investments in heating systems and thermal refurbishments are estimated to be between 100 billion € and 120 billion € in the current policy scenario in the period between 2015 and 2050. The additional measures applied in the ambitious policies result in an increase in annual investments of around 20 billion € to 25 billion € resulting in about 120 billion € to 135 billion € in total annual investments across the EU28 throughout the whole period. The additional investments are mainly a result of higher investments in thermal retrofit measures and (to a lower extent) higher investments in heating systems in particular solar thermal systems.

Investments in retrofit measures, illustrated in Figure 13 amount to about 50 billion € to 70 billion € annually, whereas investments for heating systems, illustrated in Figure 14 amount to about 40 billion € to 50 billion €.

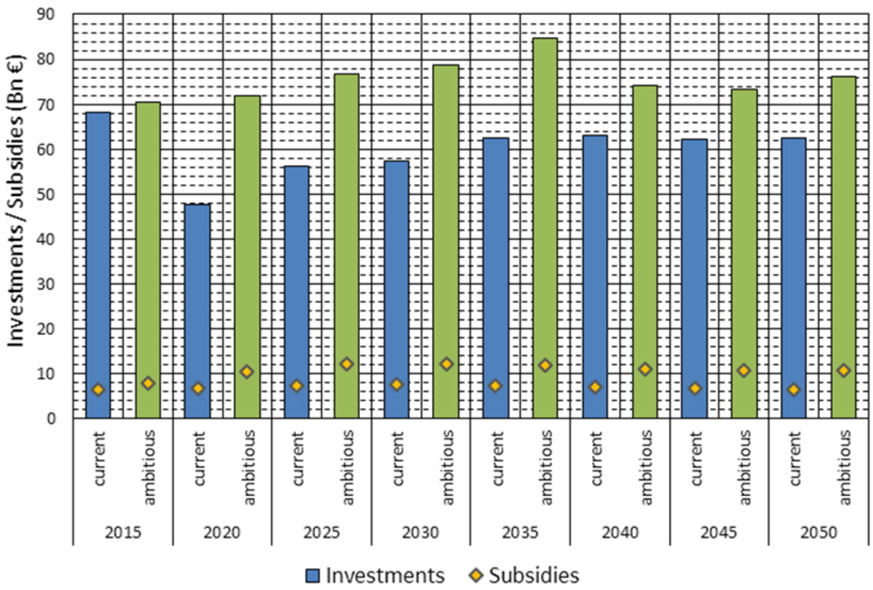


Figure 13: Investments and subsidies for building renovation for current and ambitious scenario for EU28 in Bn €

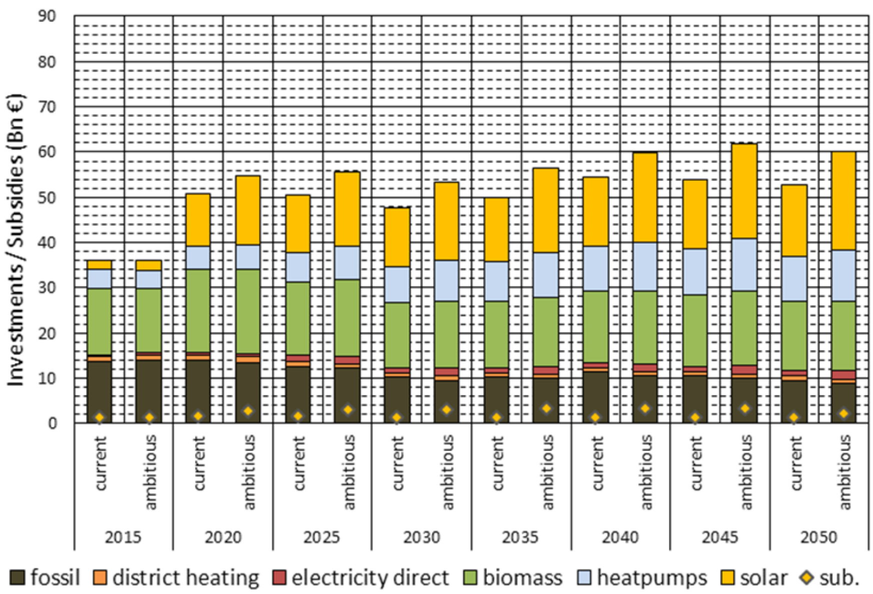


Figure 14: Investments and subsidies for heating systems by energy carriers for current and ambitious scenario for EU28 in Bn €

The subsidies granted for renovation actions according to the assumed subsidy regimes in each member state account for about 7 billion € to 12 billion € annually, whereas subsidies for heating system investments amount to about 1,3 billion € to 3,2 billion €.

Figure 14 differentiates investments in heating systems from an end user perspective per energy carrier. The scenario results indicate that renewable heating systems account for the main share of investments. Investments in fossil heating systems (mainly natural gas boilers) only account for less than 20% of investments throughout the period between 2015 and 2050.

Note that investments in district heating systems are to a large extend covered by the network operator and are therefore reflected in the energy costs from an end user perspective which is why investments shown in Figure 14 are low although the number of buildings connected to a district heating network increases in both scenarios. Investments in direct electric heaters are low in both scenarios as most installed electrical heating system in the model are more efficient heat pumps.

3.2.2 Lessons learned for SET-Nav pathways

Thermal refurbishment and development of final energy demand for heating and cooling

The scenario calculations demonstrate that the final energy consumption for space heating and hot water can be significantly reduced until 2050 through thermal refurbishments of the existing building stock. While existing policy measures already incentivize efficiency increases in the European building stock more ambitious policies are needed to reach climate targets in line with the Paris agreement.

Our modelling results show that policies regarding the efficiency in the building can significantly influence the investment decision of building occupants and owners. They also show that measures need to be taken early because of the long life time of the building stock.

Since also the ambitious scenario does not achieve renovation activities in line with the Paris targets, even more ambitious measures were implemented in some of the pathways.

Uptake of renewable heating systems and energy carrier mix

The scenario calculations performed within this case study result in a significant uptake of renewable heating systems. Biomass heating systems, heat pumps and solar heating systems can substitute the use of fuel oil and coal for decentral heat supply until 2050. The main fossil energy carrier left in the heat supply mix by 2050 in both calculated scenarios is natural gas which currently shows high market shares in particular in urban areas. With regard to ambitious climate targets those high market shares of natural gas are critical as natural gas will be the main source for CO_2 emissions in the European heat supply. Again, it should be noted that resulting emissions in the calculated ambitious policy scenario are higher than the required reduction of 90% or more to reach the Paris climate targets.

Biomass use for heating increases in both scenarios but lies within available potentials under the precondition that thermal efficiencies of the buildings` envelopes increase substantially. For very ambitious overall CO_2 emission targets however potentials for biomass supply for space heating and hot water still have to be seen critical. Biomass will also be heavily used in other sectors where higher temperature levels are needed (e.g. process heat for industry or electricity production from biomass). This is considered in the pathway implementation by not specifically enhance the support for biomass heating systems compared to the case studies. Note that other policy measures, in particular a phase out of natural gas or obligations for renewable heating systems can indirectly lead to higher shares of biomass.

Also heat pumps play an important role in the energy transition. Provided that they substitute existing direct electric heating systems and that the use of heat pumps is restricted to heat distribution systems with low temperature levels (below 50°C) the electricity demand for space heating does not increase significantly in both scenarios. Increasing shares of heat pumps therefore appear to be feasible from an electricity system perspective. However it has to be noted that the use of electrical heat pumps will only lead to substantial CO_2 reductions if the electricity system is decarbonized as well. In the pathway analysis the diversification and localization pathways show significantly higher diffusion of heat pumps (see following section).

Future role of district heating:

Due to building refurbishment, heat demand will strongly decrease in ambitious decarbonisation scenarios. Of course, the economic effectiveness of district heating grid is correlated also to the heat densities. In rural areas, this leads to the fact that district heating may lose attractiveness. However, our analysis show that also in scenarios with strong uptake of renovation activities, a large share of the heat demand can be covered by heat distribution costs below cost threshold that allow district heating to compete with decentral heating options.

District heating can be an enabler for decarbonisation as it is a substitute for the use of natural gas in urban areas. District heating networks allow for the integration of waste heat and other local renewable energy sources. Furthermore it can provide flexibility for the electricity system if CHPs in combination with large scale heat pumps are applied for generating heat. The analysis in the case study conducted together with the electricity system Enertile© indicate that a combination of large scale heat pumps, boilers and to a lower extent CHPs could be the preferred option at least for large heat networks. This flexible heat generation approach is already demonstrated in several heat networks in Denmark.

Within the pathway analysis the Directed vision pathway and in some countries the National champions pathway represent scenarios with very optimistic diffusion and cost assumptions for district heating.

3.3 SET-Nav pathways in the building sector

In this section the results for the SET-Nav pathways in the building sector are presented. First the development of final energy demand, renewable shares and CO_2 emissions are shown, then the resulting investments in building envelopes and heating systems as well as expected energy expenditures are discussed.

3.3.1 Development of final energy demand,

Figure 15 and Table 7 illustrate the development of final energy demand in the pathways compared to a reference scenario. The reference scenario is based on the current policy scenario from the case studies using harmonized assumptions on GDP, population growth and energy prices to be comparable with the pathways. County specific results for the building sector can be found in the Annex.

Total final energy demand decreases significantly in all pathways compared to the year 2015 and also compared to the reference scenario. The additional final energy demand reductions are considered to be a precondition for a strong decarbonisation scenario. The highest reductions from 2015 to 2050 are achieved in the directed vision scenario where the most ambitious renovation measures in combination with smart heating technologies are assumed. Here total final energy demand reductions are more than -36% compared to around -25% in the reference scenario. Even in the Localization pathways, which reaches the lowest demand reductions final energy demand is reduced by around -32%. As already discussed in the case study section reductions are only achieved for space heating, while final energy demand for hot water stays more or less constant and space cooling increases significantly in all pathways.

It can be clearly seen that the main difference in all pathways compared to the reference scenario is the use of natural gas. As already discussed in the case study section it is expected that without strong measures like strict renewable obligation or restrictions on the use of fossil heating systems natural gas will still cover large shares of heat demand by 2050. In the reference scenario natural gas still covers 38% of total final energy demand by 2050. In the diversification, directed vision and localization pathway this share is reduced to 5%. Note that in those pathways a complete phase out from natural gas starting in the year 2030 is simulated. In the National Champions pathway where gas-fired heating systems are allowed in several countries gas makes up for 23% of total final energy supply. Note that to reach CO_2 emission reductions of more than 90% this gas demand has to be supplied by non-fossil supply chains (biogas or power to gas). Similar to the results in the case studies fuel oil and coal fired heating systems almost completely disappear in the supply mix. The remaining demand stems from old heating systems which are not replaced after the year 2030.

The strong decrease of gas-fired heating systems in combination with the policy settings in the pathways trigger the diffusion of other heating systems. Depending on the pathway supply is covered by a mix of heat pumps (reflected by ambient heat and electricity), biomass heating systems, district heating, direct electric heaters and solar thermal systems. Solar thermal systems are assumed to cover around 9% to 10% of final energy demand in all pathways compared to only around 1% in the year 2015.

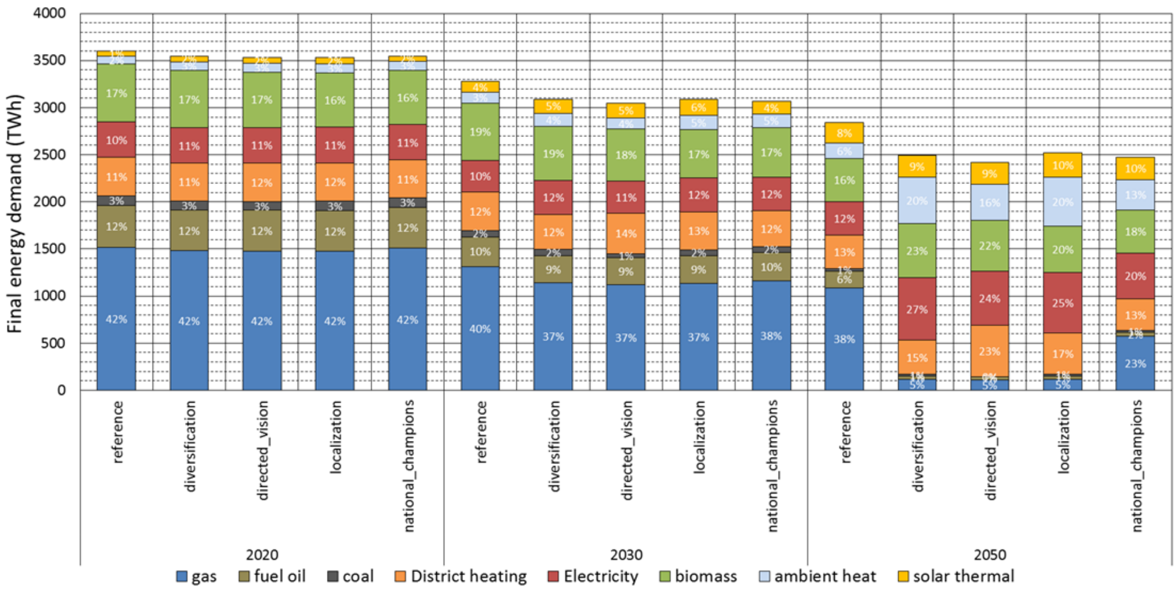


Figure 15: Development of final energy demand per energy carrier for heating and cooling in EU28 for all SET-Nav pathways

Table 7: Development of final energy demand per energy carrier for heating and cooling in EU28 for all SET-Nav pathways

Final energy demand (TWh)	2015		2050									
Scenario	reference		reference		diversification		directed vision		localization		national champions	
	(TWh)	(%)	(TWh)	(%)	(TWh)	(%)	(TWh)	(%)	(TWh)	(%)	(TWh)	(%)
gas	1664	45%	1090	38%	116	5%	110	5%	118	5%	571	23%
fuel oil	515	14%	176	6%	33	1%	33	1%	34	1%	43	2%
coal	122	3%	24	1%	20	1%	3	0%	20	1%	20	1%
District heating	394	11%	360	13%	362	15%	547	23%	438	17%	333	13%
Electricity	410	11%	351	12%	663	27%	573	24%	641	25%	490	20%
biomass	520	14%	459	16%	578	23%	540	22%	495	20%	456	18%
ambient heat	73	2%	164	6%	489	20%	383	16%	514	20%	319	13%
solar thermal	22	1%	216	8%	232	9%	229	9%	260	10%	241	10%
TOTAL	3720	100%	2840	100%	2493	100%	2417	100%	2520	100%	2473	100%

Figure 15 shows the final energy demand for District heating, electricity and biomass in 2050 compared to the year 2015 for all pathways. Please see Annex for country results.

In all pathways and also in the reference scenario the share of district heating in final energy supply is considered to increase. However, absolute final energy demand in 2050 for district heating is only considered to increase in the Directed Vision (547 TWh, 23%) and Localization (438, 17%) pathways. Although district heating is considered to be an efficient substitute for natural gas in urban area the pathway analysis suggests that final energy demand will not increase drastically due to reductions in space heating demand. The results also suggest that existing networks could be expanded without significantly increasing the total heat generation capacity. Note however that it also has to be assumed that district heat supply is largely decarbonized until 2050 to reach emission reductions of more than 90% for the building sector.[1]

A similar development is simulated for biomass heating systems. The share of biomass increases significantly from 14% in 2015 to at least 18% in the National Champions pathway and up to 23% in the

[1] District heating and electricity supply mix in the SET-Nav pathways is presented in the summary report of WP7

Diversification pathway. The reason why decentral biomass systems are highest in the Diversification pathway is that within this pathway non-fossil decentral heating systems cover larger shares due to lower shares of district heating or gas networks (only in National Champions pathway). But even in the Diversification pathway the increase of biomass use is moderate (578 TWh in 2050 compared to 520 TWh in 2015). This is due to the thermal renovation measures that help to preserve biomass resources for heating but also due to the biomass potential restrictions in the model. The restricted potentials lead to higher biomass prices which also limit a stronger diffusion of biomass systems. It should be noted that the overall demand for biomass increases significantly due to demand increases in the transport and industry sector – see overall results in chapter 6.

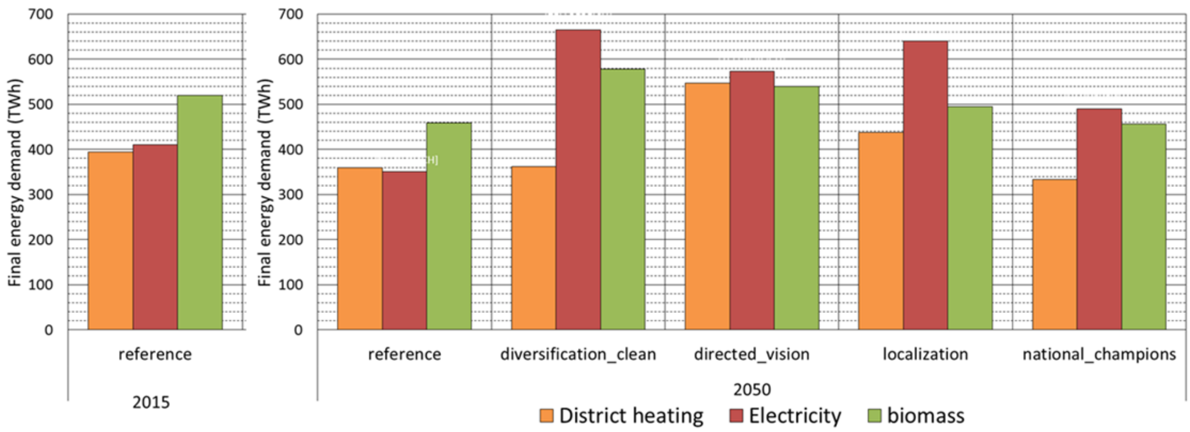


Figure 16: Development of final energy demand for district heating, electricity and biomass in the year 2050 compared to the 2015

Figure 16 also illustrates the level of electrification for heating and cooling in the building sector in contrast to the case study scenarios electricity demand increases significantly due to a stronger diffusion of heat pumps. In buildings with higher heat supply temperatures also direct electric heater are installed at the end of the simulation period. This is also due to the restrictions on biomass use which are originally the preferred option for higher temperature decentral heating systems. The highest increase of total electricity demand is observed in the Diversification pathway where electricity demand for heating and cooling increase from around 410 TWh in 2015 to 663 TWh in 2050. Within those pathways a flexible control of heat pumps and direct electric heating systems becomes even more important, also considering the additional increase in electricity demand in the transport and industry sector as well as the high shares of fluctuating renewables (see WP7 report). Figure 17 further illustrates the development of electricity demand for heating and cooling showing the development per end use category and technology. The figure reveals that by 2050 around 200 TWh of electricity is needed to cover cooling demand in buildings. Despite the higher efficiency of heat pumps also electricity demand for space heating and hot water increases compared to the base year. Also note that this is in contrast to the reference scenario where electricity demand for heating is supposed to decrease substantially due to the substitution of direct electric heaters with heat pumps. The main increase of electricity demand takes place after 2030 in parallel to gas phase out. Such a development would also be in line with overall CO2 emission reductions given that also the electricity sector is less decarbonized before 2030.

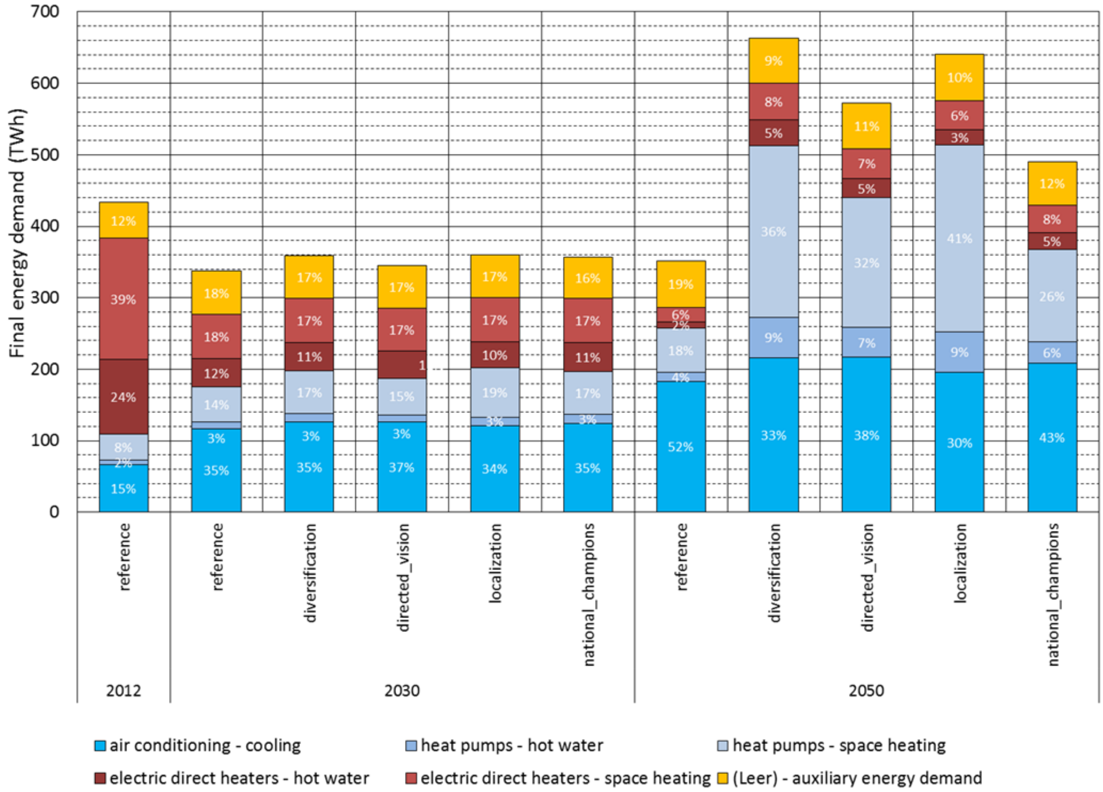


Figure 17: Electricity demand in SET-Nav pathway per technology and end-use.

3.3.2 Renewable shares and CO_2 emissions

Figure 18 illustrates the development of renewable shares as well as the shares of the secondary energy carriers electricity and district heating. The shares of fossil fuels in the National Champions scenario include the remaining gas consumption. Note that in the supply scenarios it is assumed that natural gas can be substituted by biogas or power to gas which was not included in the building stock model Invert/EE-Lab. It can be seen that the main part of the transformation to a decarbonized buildings stock happens between 2030 and 2050. By 2030 fossil fuels still account for around 50% of final energy. This share is reduced to 7% in the Diversification and Localization pathway and 6% in the Directed Vision pathway. The remaining share of 26% in the National Champions pathway represents results from the gas demand in the countries where new installations of gas systems are still allowed after 2030. This is close to the remaining natural gas demand which resulted from the assumptions implemented in the ambitious policy scenario for the case studies. Also the high share of 45% fossil supply in the reference scenario indicate that very ambitious and strong measures are needed for a strong decarbonisation of the building stock. It also has to be noted that district heating and electricity make up for more than 1/3 of energy supply in all pathways and up to 47% in the directed vision scenario. Therefore those pathways only reach the goal of -90% CO_2 emission reductions if these sectors are highly decarbonized as well.

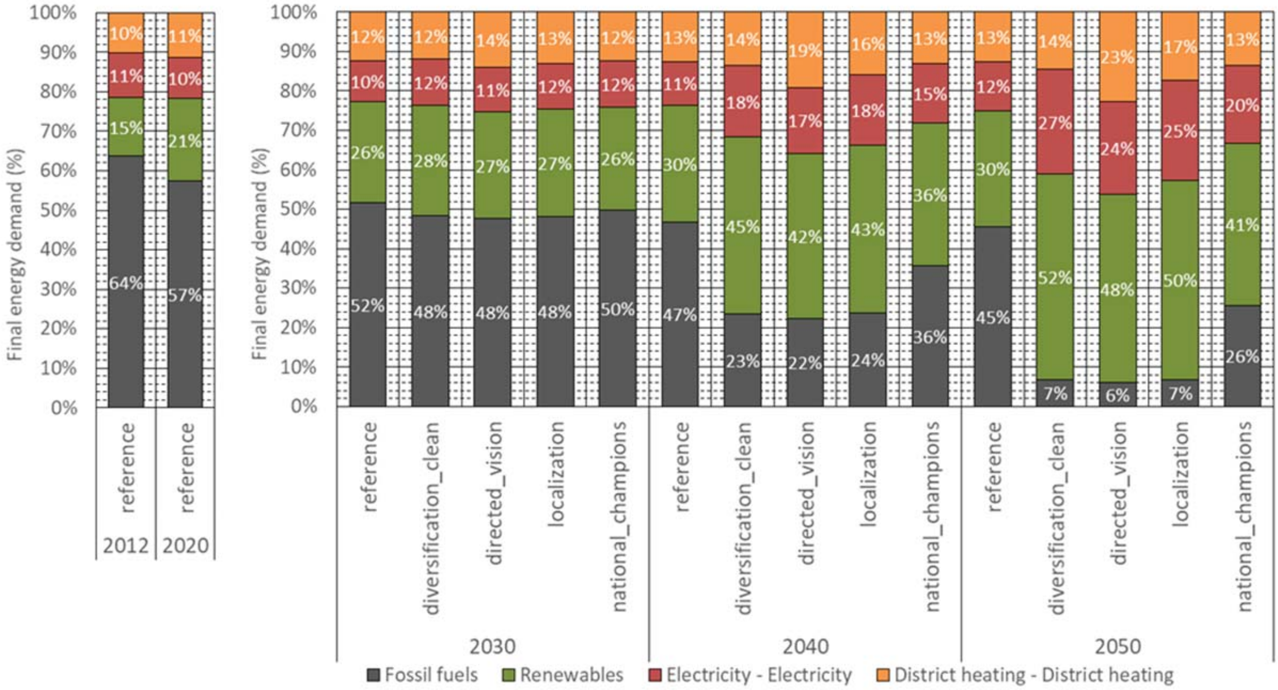


Figure 18: Shares of fossil fuels, renewables, electricity and district heating in all SET-Nav pathways.

This also has to be considered in the interpretation of Figure 19 which shows the development of CO_2 emission from fossil heating systems in 2050 compared to the year 2015. Indirect emissions resulting from the supply of district heat and electricity are not included in this figure. As in Figure 18 natural the emissions in the National Champions pathway have to be interpreted as the CO_2 emissions that would result if the natural gas supply is not substituted by biogas or power to gas. The emission factors used for estimating CO_2 emissions from fossil energy carriers used for heating and cooling are provided in Table 8. Under these assumptions fossil CO_2 emissions combusted in heating systems across EU-28 are reduced from around 540 million tons CO_2 in 2015 to around 40 million tons CO_2 in 2050 in the Localization, Diversification and Directed Vision pathway. This amounts to a reduction of more than -90% in these pathways. The theoretic result of remaining 138 million tons in the National Champions scenario once again highlight the need to substitute natural gas in this pathway to reach reductions in the range of -90%. The figure also shows that in 2015 and 2030 around 2/3 of direct fossil emissions in the heating and cooling sector results from the combustion of natural gas indicating that very ambitious emission reduction targets in the building stock would also mean a phase out of natural gas for heating in the building sector.

Table 8: CO_2 emission factors assumed for energy carriers

	Emission factor [kgCO_2/kWh primary]
Coal	0.342
Fuel oil	0.288
Natural gas	0.198

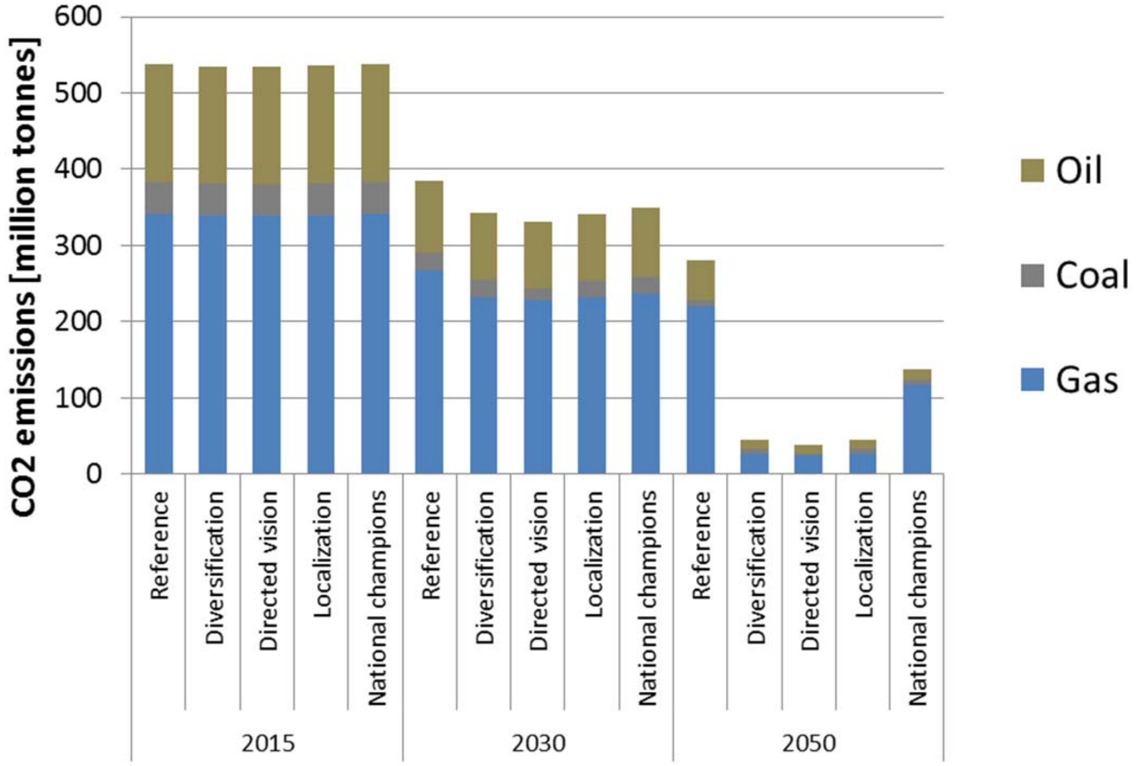


Figure 19: Development of CO_2 emissions from fossil heating systems in all SET-Nav pathways (assuming the use of natural gas also in the National champions pathway)

3.3.3 Development of investments in thermal efficiency measures, heating systems and energy expenditures.

This section provides an overview of the investments in heating systems, building envelope and on energy expenditures simulated for the building sector in the SET-Nav pathways.

Figure 20 shows average annual investments in thermal renovation measures (investments in pure maintenance measures of building are excluded) and heating systems for all pathways. The points in the figure illustrate the amount of subsidies for heating systems and thermal renovation measures respectively. It can be clearly seen that all pathways require significantly higher investments than the reference scenario. The highest investments result from the policy settings in the directed vision scenario due to significantly higher investments in thermal renovation measures. Table 9 shows that those additional investments are partly triggered by higher subsidies for deep thermal renovation. On average subsidies cover around 28% of the investments in those measures in the directed vision pathway while subsidy shares are between 11% and 14% in the reference scenario. Subsidies levels are much lower for heating systems as the transition towards renewable heating systems is mainly triggered through renewable obligations and restrictions on new fossil heating systems rather than financial support.

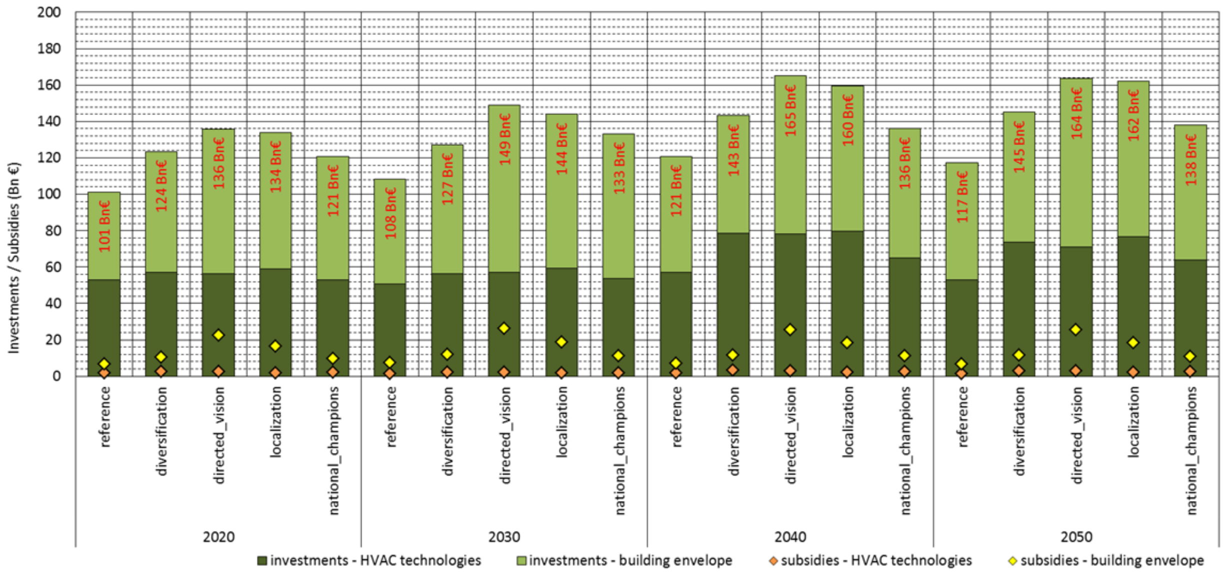


Figure 20: Average annual investments and subsidies for heating systems (HVAC technologies) and thermal renovation measures (building envelope) in SET-Nav pathways – EU28.

Table 9: Average annual investments and subsidies for thermal renovation measures (building envelope) in pathways

	2020					2030					2040					2050				
scenario	reference	divers.	dir. vision	localization	nat. champ.	reference	divers.	dir. vision	localization	nat. champ.	reference	divers.	dir. vision	localization	nat. champ.	reference	divers.	dir. vision	localization	nat. champ.
Investments	48.3	66.5	79.5	75.1	67.8	57.7	70.9	92.2	84.5	79.6	63.8	64.8	86.8	80.0	70.9	64.3	71.5	92.6	85.5	74.1
Subsidies	6.7	10.3	22.4	16.3	9.8	7.5	11.8	26.1	18.8	11.2	6.9	11.4	25.4	18.5	11.0	6.8	11.4	25.5	18.3	11.0
Subsidy share	*14%*	*15%*	*28%*	*22%*	*14%*	*13%*	*17%*	*28%*	*22%*	*14%*	*11%*	*18%*	*29%*	*23%*	*16%*	*11%*	*16%*	*27%*	*21%*	*15%*

Figure 21 shows investments in heating systems per technology. The figure reveals that the phase out from natural gas triggers higher investments into other heating systems. While in the period until 2030 investments for heating systems in the pathways are only slightly higher than in the reference scenario. After 2030 around 20 billon € of annual investments are required to replace gas fired systems. Note that those costs also include energy carrier change costs that are implemented in the building stock model (Additional costs are assumed when buildings change from one energy carrier to another one). This also explain the lower investments in the national champions pathway in which not all countries move away from gas fired systems. Note that this assumes that the existing gas fired systems can also be operated with alternative gas sources. It should also be noted that the additional costs to set up an infrastructure to deliver alternative "green" gas is not reflected in those figures. This is also the case for district heating for which investments in the building stock model are defined as the costs for connecting a building to the grid, while the costs for constructing and maintaining the heat networks is reflected in the energy expenditures.

Figure 21 also highlight the dramatic increase of investments in heat pumps after 2030. It can also be seen that while investments in biomass systems increase from 2030 to 2040, new investments slow down until 2050 which is due to the restricted biomass potentials assumed in the model. On the other hand direct electric heaters are increasingly installed again after 2030. All pathways result in high investments of solar thermal and PV systems and in combination with other heating systems. (Solar includes solar thermal and PV systems)

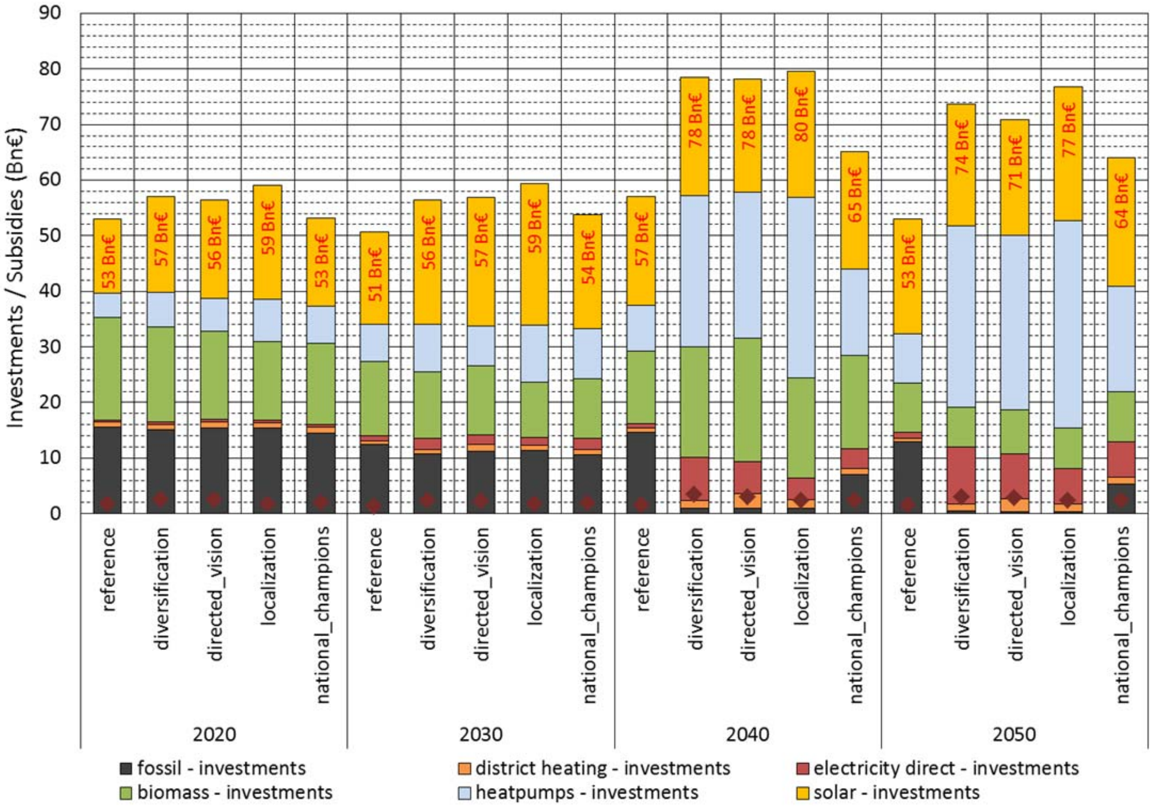


Figure 21: Investments in heating systems per technology in SET-Nav pathways and total subsidies for heating systems (red diamonds)

Figure 22 shows the development of energy expenditures per end use category. It is expected that costs for cooling will account for around 20% of energy expenditures. The share of space heating decreases from around 73% in 2020 to around 60% or lower in all pathways. Energy expenditures for hot water supply decrease from 50 billion € in 202, to around 40 billion € due to the contribution of hot water supply by solar thermal systems and the use of efficient heat pumps. Figure 22 also shows that despite lower total energy demand compared to the reference scenario, energy expenditures are more or less on the same level. This is a result of higher costs for biomass and the switch from natural gas to electricity with typically higher end-user prices.

This effect can be seen in Figure 23 which shows energy expenditures per energy carrier. In all pathways expenditures for electricity account for the largest share of energy expenditures for heating and cooling in the year 2050 compared to only 32% in the reference scenario. These figures reveal the strong link between the electricity sector and heating/cooling sector in strong decarbonisation scenarios. Figure 24 provides more insights into those electricity expenditures by showing the split between cooling, space heating, hot water and auxiliary energy demand for all heating systems.

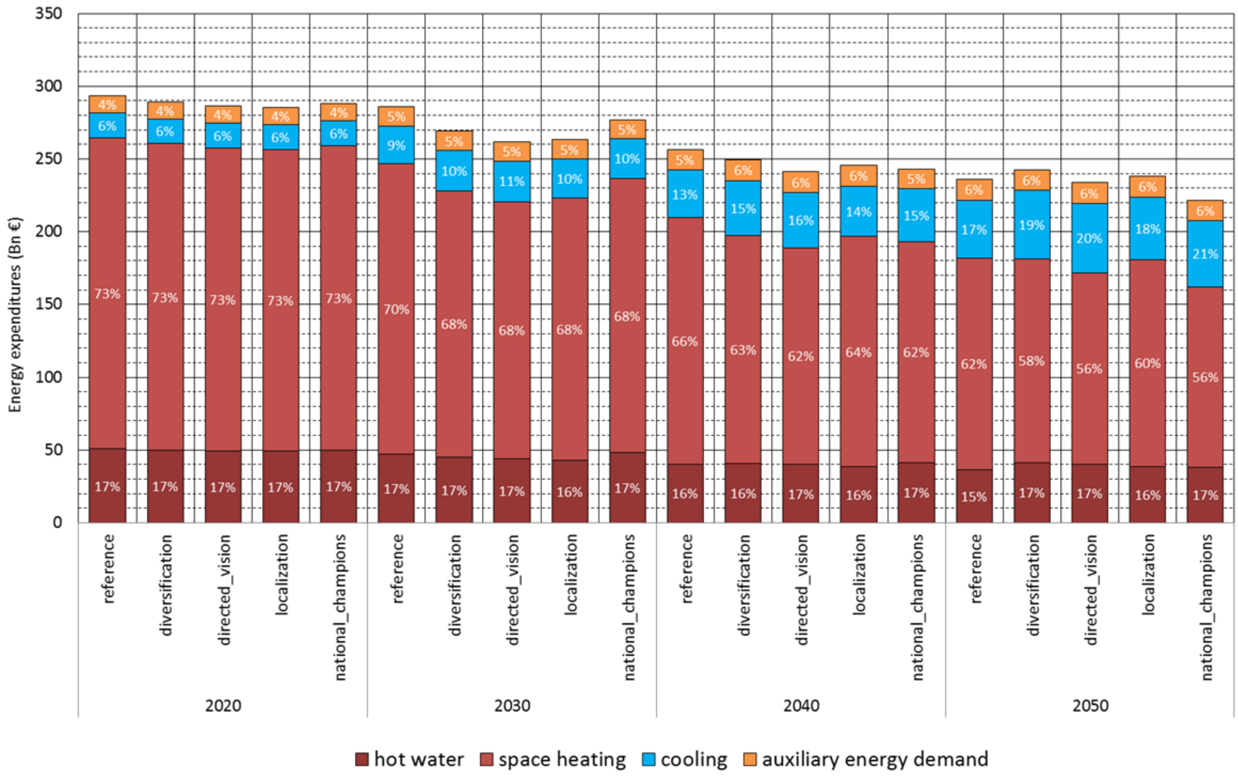


Figure 22: Development of energy expenditures per end use in SET-Nav pathways.

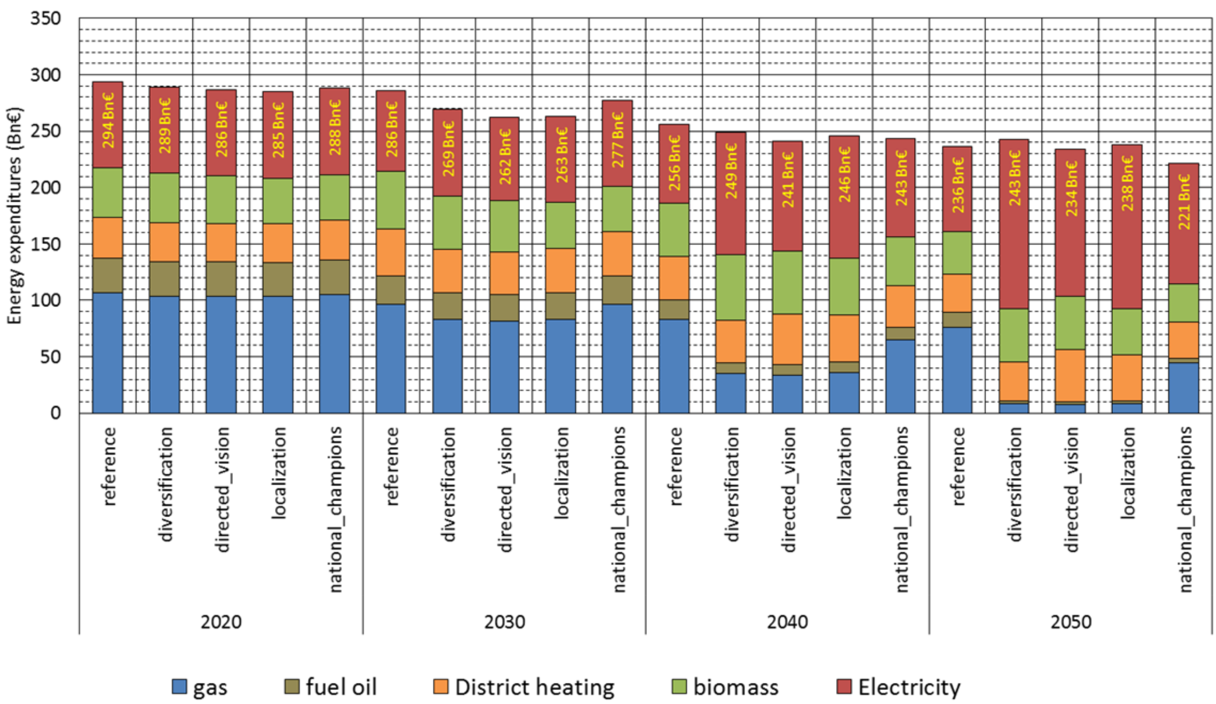


Figure 23: Development of energy expenditures per energy carrier in SET-Nav pathways

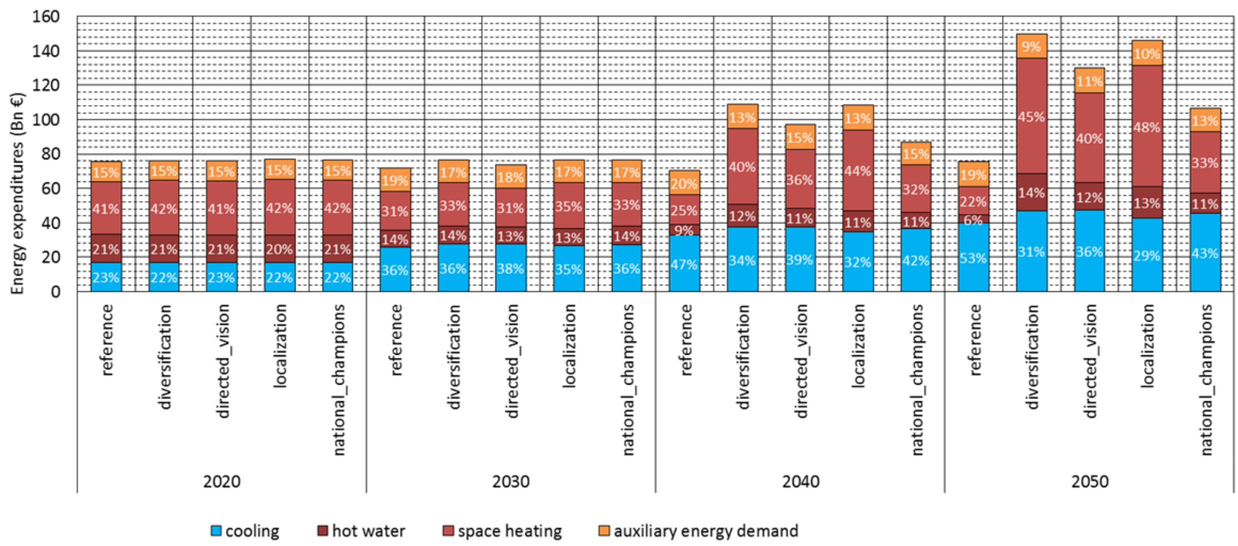


Figure 24: Expenditures on electricity in SET-Nav pathways per end use category

3.4 Conclusions and policy recommendations

From the case study and pathway analysis the following conclusions can be drawn:

- The pathway analysis show that ambitious CO_2 emission targets of more than 90% until the year 2050 can be reached. However strong measures to increase the thermal efficiency of the building stock and to promote a high diffusion of low carbon heating systems are needed.
- Very ambitious decarbonisation scenarios also go hand in hand with a phase out of natural gas in the long term. Given the currently high market share and competitiveness of natural, the existing gas infrastructure in Europe, and planned supply infrastructure project such a development can be considered as a big challenge and would require strong policy measures. Considering the long lifetime of heating systems such a phase-out would have to start latest in the year 2030 to reach CO_2 emission reductions beyond -90% in the building stock. A phase out of natural gas heating systems triggers large investments in alternative technologies for heating. Only if natural gas can be substituted by a form of low carbon "green gas" (e.g. biogas, power to gas) the preservation of a gas supply infrastructure for buildings is in line with high CO_2 mitigation targets.
- District heating can be a substitute for natural gas in urban areas and allows to integrate low carbon heat sources which cannot be integrated in decentral heating system. E.g. waste heat, solar thermal in combination with large storage, or large scale heat pumps that exploit mid to high temperature heat sources. To ensure the competitiveness of district heating high market shares within district heating supply areas are needed. These could be achieved by regulatory measures (e.g. zoning) that go hand in hand with a phase of fossil heating systems in urban areas.
- Heat pumps and solar systems are key technologies to reach low emissions in the building stock. Both technologies show a strong increase in all calculated scenarios.
- The use of biomass is also crucial in strong decarbonisation scenarios. However biomass potentials are limited and demand for biomass is also expected to strongly increase in the industry and transport sector. Although the number of installed biomass heating systems

increases significantly the increased efficiency of the building stock leads to only moderate increases of biomass use for buildings in the pathways.

- Thermal renovation measures are needed to conserve renewable resources, in particular biomass. Furthermore thermally renovated buildings support the integration of heat pumps as typically higher efficiency can be reached in thermally efficient buildings. In addition, the more the overall energy demand for space heating can be reduced the less additional electricity demand resulting from the diffusion of heat pumps can be expected in ambitious decarbonisation scenarios.
- Cooling demand is expected to increase significantly until the year 2050. Measures to increase the efficiency of cooling systems or the promotion of district cooling gain importance to reduce electricity demand and the resulting pressure on the electricity system.
- The decarbonisation of the buildings stock is strongly linked to the electricity system. A substantial share of heating and cooling demand is expected to be covered by electricity. Only if the electricity system is decarbonized in parallel overall CO_2 emission reduction targets can be reached. The analysis shows, that while for moderate CO_2 emission reduction targets electricity demand for heating is reduced or stays constant in the long term, very ambitious targets in combination with a phase out of natural gas triggers a significant increase of electricity demand for heating in the building stock.

4 Energy demand in industry

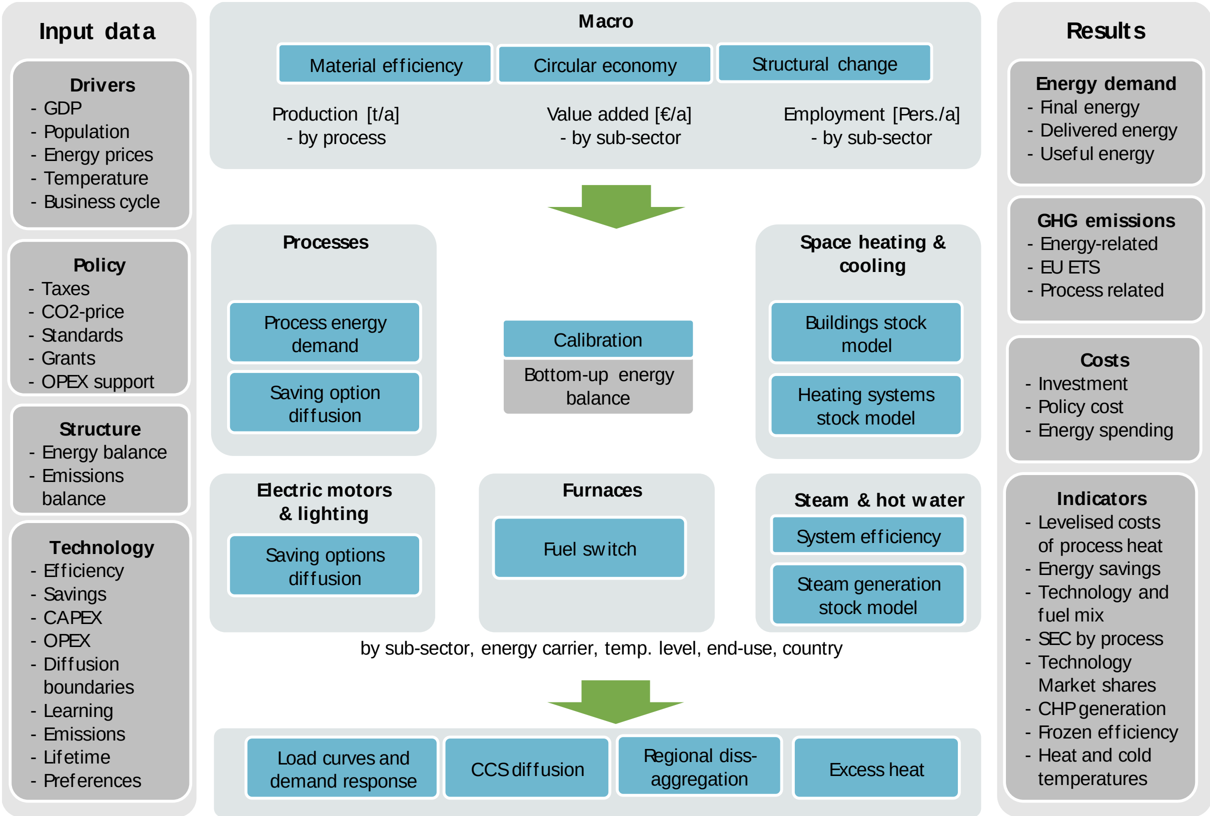
Industry accounts for about 25% of EU final energy demand and its dominant energy carriers are gas, electricity, coal, and oil. This means the sector is critical for the achievement of European climate goals. The EU Roadmap for moving to a competitive low-carbon economy in 2050 has set a target of -83 to -87% emission reductions in industry by 2050. Several analyses show that industry is unlikely to meet this target without a major change in the policy framework. This report presents possible mitigation pathways for the EU28 that achieve an ambitious reduction in GHG emissions of between 70 and 79 percent by 2050 compared to 2015 in the industrial sector - which equals an emission reduction of 82 and 87% compared to 1990. The transition scenarios contain a variety of different mitigation options including higher energy efficiency, fuel switching to RES, CCS, power-to-heat, secondary energy carriers based on RES, innovative production technologies and new products, material efficiency, substitution and circular economy elements. Thus, the scope of mitigation options is very broad, particularly compared to other studies, which are often based on CCS for the industrial sector. The results show that RES and energy efficiency offer huge potentials for decarbonisation, but that additional measures are also necessary, such as changes in the production structure resulting in new innovative technologies like renewable hydrogen-based direct reduction in the steel industry or low carbon cement types. These scenarios reflect a radical change to be achieved in less than 35 years. Even if many mitigation options are only implemented on a large scale after 2030, policies need to be in place soon to drive this transition. (Herbst et al. 2018)

4.1 Methodology and scenario definitions

4.1.1 Model description Forecast-Industry

The **FORECAST** modelling platform aims to develop long-term scenarios for future energy demand of individual countries and world regions until 2050. It is based on a bottom-up modelling approach considering the dynamics of technologies and socio-economic drivers. The model allows addressing various research questions related to energy demand including 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 and ex-ante policy impact assessments. Energy-intensive processes are explicitly considered, while other technologies and energy-using equipment are modelled as cross-cutting technologies. FORECAST is a simulation model used to support investment decisions, taking into consideration barriers to the adoption of energy efficient technologies as well as various policy instruments such as standards, taxes and subsidies. Different approaches are used to simulate technology diffusion, including diffusion curves, vintage stock models and discrete choice simulation.

Figure 25 shows the simplified structure of FORECAST-Industry. Main macro-economic drivers are industrial production for over 70 individually modelled basic materials products, gross value added for less energy-intensive sub-sectors and the employment numbers. Five sub-modules cover: basic materials processes, space heating, electric motor systems, furnaces and steam systems.



Source: FORECAST

Figure 25: Overview of the bottom-up model FORECAST-Industry

For this study, the three sub-modules related to the CO2-intensive industries are of high importance:

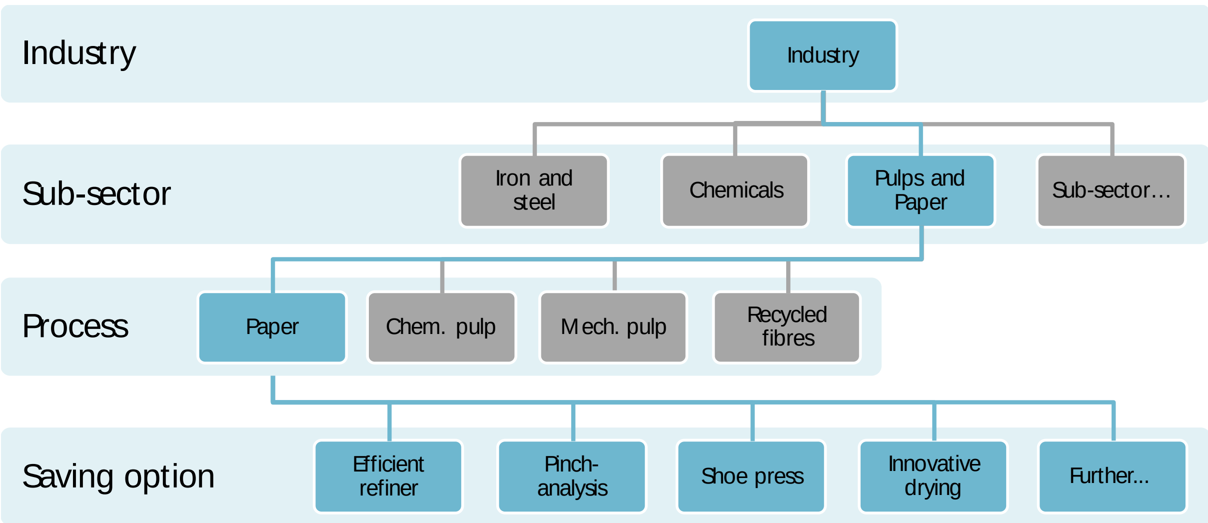
1. **Energy-intensive processes**: This module covers 76 individual processes/products via their (physical) production output and specific energy consumption (SEC). The diffusion of about 200 individual saving options is modelled based on their payback period (Fleiter et al. 2013; Fleiter et al. 2012). Saving options can represent energy efficiency improvements, but also internal use of excess heat, material efficiency or savings of process-related emissions.
2. **Space heating and cooling**: Space heating accounts for about 9% of final energy demand in the German industry. We use a vintage stock model for buildings and space heating technologies. The model distinguishes between offices and production facilities for individual sub-sectors. It considers the construction, refurbishment and demolition of buildings as well as the construction and dismantling of space heating technologies. Investment in space heating technologies such as natural gas boilers or heat pumps is determined based on a discrete choice approach (Biere et al. 2014).
3. **Electric motor systems and lighting**: These cross-cutting technologies (CCTs) include pumps, ventilation systems, compressed air systems, machine tools, cold appliances, other motor appliances and lighting. The module captures individual units as well as the entire motor-driven system, including losses in transmission between conversion units. The diffusion of saving options is modelled in a similar way to the approach used for process-specific saving options.
4. **Furnaces**: energy demand in furnaces uses the bottom-up estimations from the module “energy-intensive processes”. Furnaces are found across most industrial sub-sectors and are very specific to the production process. Typically, they require very high temperature heat. The

furnaces module simulates price-based fuel switching using a random utility model (for more details, see Rehfeldt et al. 2017).

5. **Steam and hot water systems**: the remaining process heat (<500°C) is used in steam (and hot water) systems. The module covers generation and distribution of steam and hot water. For distribution, efficiency improvements for each scenario are based on available literature. Steam generation is modelled using a vintage stock model simulating the replacement of the entire steam generation technology stock. More than 20 individual technologies are taken into account including natural gas boilers, CHP units, biomass boilers, heat pumps, electric boilers and fuel cells. Fuel switch is determined as a result of competition among the individual technologies using the total cost of ownership (for more details, see Biere 2015).

In the following, the **sub-module for energy-intensive processes** is described in detail. For additional model descriptions, we refer to the FORECAST website.[2]

The hierarchical structure of the sub-module is presented in **Figure 26**. For each country, the industry as a whole is the highest level of aggregation. Using the sectoral definition from Eurostat energy balances, the industry is divided into sub-sectors like the iron and steel industry or the pulp and paper industry. Within each sector, more than 70 processes are defined that represent major products or industrial production processes (e.g. steel finishing or wood grinding for the production of mechanical pulp). For each process, saving options are defined, which reduce the specific energy consumption and process related GHG emissions by diffusing through the technology stock. Diffusion depends on boundaries and payback time.



Source: FORECAST

Figure 26: Hierarchical structure of the FORECAST sub-module for energy-intensive processes

For process-specific technologies, the main driver is the projection of physical production (e.g. tons of crude steel from blast furnaces). The 70 most energy- and green-house-gas-intensive processes are considered separately in the model. For each of these processes, the specific energy consumption/GHG emissions, temperature ranges and the physical production output per country are important modelling parameters.

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

Table 10: Overview of products covered in FORECAST-Industry for bottom-up calculation by sub-sector

Non-metallic minerals	Chemicals	Non-ferrous metals	Iron and steel
Container glass	Adipic acid	Aluminium, primary	Sinter
Flat glass	Ammonia	Aluminium, secondary	Oxygen steel
Fibre glass	Calcium carbide	Aluminium extruding	Electric steel
Other glass	Carbon black	Aluminium foundries	Rolled steel
Houseware, sanitary ware	Chlorine, diaphragma	Aluminium rolling	Coke oven coke
Technical, other ceramics	Chlorine, membrane	Copper, primary	Smelting reduction
Tiles, plates, refractories	Chlorine, mercury	Copper, secondary	Direct reduction
Clinker Calcination-Dry	Ethylene	Copper further treatment	DR H2 plasma steel
Clinker Calcination-Semidry	Methanol	Zinc, primary	DR RES electrolysis steel
Clinker Calcination-Wet	Nitric acid	Zinc, secondary	DR H2 + EAF
Preparation of limestone	Oxygen		
Gypsum	Polycarbonates		
Cement grinding	Polyethylene		
Lime milling	Polypropylene		
Bricks	Polysulfones		
Lime burning	Soda ash		
RES electric melting	TDI		
Less carbon cement (30%)	Titanium dioxide		
Low carbon cement (50%)	RES H2 Ammonia		
Low carbon cement (70%, recarbonating)	RES H2 Methanol		
Low carbon cement (95%, recycled concrete)	Ethylene, RES H2 methanol-based		
Petrochemicals	**Food drink and tobacco**	**Pulp and paper**	**Others**
Refinery type 1	Sugar	Paper	Plastics: Extrusion
Refinery type 2	Dairy	Chemical pulp	Plastics: Injection moulding
Refinery type 3	Brewing	Mechanical pulp	Plastics: Blow moulding
Refinery type 4	Meat processing	Recovered fibres	
	Bread & bakery		
	Starch		

Source: FORECAST

Depending on the data availability, processes can consist of small individual production steps (e.g. burning of clinker in the cement industry) or entire production lines for individual products or product groups (e.g. production of paper). In total, FORECAST currently considers more than 70 individual process as listed in Table 10 allowing for a huge level of detail.

The production data for the individual processes is collected by country and is regarded as the backbone of the FORECAST model. While no individual data source is available that provides data for all products, production data is collected from a variety of sources (e.g. Cembureau, Worldsteel).

4.1.2 Mitigations options in FORECAST

The FORECAST model covers the complete Eurostat final energy demand and EU ETS sector. As such, the model also aims to covers a broad scope of mitigation options ranging from incremental energy efficiency improvements via innovative new processes to downstream material efficiency in the end-use sectors. The following table gives an overview how the various types of mitigation options are included in FORECAST.

Table 11: Type of mitigation options and inclusion in FORECAST

Clusters of mitigation options	Implementation in FORECAST
Incremental and BAT energy efficiency improvement	The model explicitly considers the diffusion of more than 200 energy efficiency measures included in the sub-modules on *processes* and on *electric motor systems*. These include for **example excess heat use, optimised control systems, high-efficiency electric motors, variable speed drives**, or very sector specific technologies like **coke dry quenching in steel** or the **shoe press in paper-making**. Diffusion is modelled based on the payback time and assumptions about min and max diffusion boundaries.
Advanced energy- and resource efficient processes	More radical process innovations are included in the model similarly to the above energy-efficiency measures. Their diffusion, however, starts later by defining an earliest market introduction. In addition, options that only mitigate process emissions can be included. Examples are new types of **cement clinker with better energy performance or thin slab or strip casting in steel finishing**.
Fuel and feedstock switching	Fuel and feedstock switching is simulated in the sub-modules on furnaces and steam systems by explicitly taking energy and CO2 prices and the profitability of alternative technologies into account (example: **switch to biomass or electric boilers to provide steam in paper and chemicals industries**). If fuel switching is strongly related to the introduction of new production processes, it is also included in the sub-module for energy-intensive processes (e.g. diffusion of **RES-H2 direct reduction to replace basic oxygen furnace route in steelmaking**).
CCS	Industrial carbon capture and storage (CCS) is modelled in FORECAST on a process level. The model allows identifying the major GHG point sources most appropriate for CCS **(e.g. integrated steelworks, cement plants, ammonia or ethylene plants**). The diffusion of CCS is based on techno economic assumptions including earliest market entry, CAPEX and OPEX, capture rate, energy consumption, etc.
Recycling and re-use	Recycling and circular economy can be modelled with FORECAST for the major energy-intensive processes and products (**e.g. steel, aluminium, copper, paper, glass, plastics or potentially cement**). The model works with projecting past recycling rates in a baseline scenario, while an ambitious circular economy scenario includes higher recycling rates that are capped by availability of recovered materials (e.g. steel-scrap availability).

Material efficiency and substitution	FORECAST includes product innovation and substitution as exogenous assumption in the production output. E.g. **replacing cement and bricks by wood** results in lower cement production and consequently lower energy demand and emissions. Similarly, material efficiency and switch to business models are considered: E.g. in the construction industry new **concrete mix designs** might save cement as might **optimized construction designs** that require a minimum of cement and steel**.** However, downstream mitigation options can show a huge degree of heterogeneity and are difficult to include systematically and comprehensively in energy system models. E.g. capturing all emission-related effects along the value chain (e.g. energy needed for the collection of recovered materials) is particularly challenging and not possible in today's energy system models. For the basic materials products, anyhow, major source of CO_2 emissions is the production process, which is included in FORECAST in detail.

Source: FORECAST

4.1.3 Assumptions for pathway modelling - industry

The four above mentioned pathways (for details see section 2.3) can be translated into two pathways for the industrial sector (see Table 12):

- **Directed Vision/National champions:** a mitigation pathway strongly focusing on the use of CCS in industry
- **Diversification/Localisation:** a mitigation pathway using a portfolio of many different mitigation options including low-carbon innovations, ambitious material efficiency and circular economy, hydrogen as an energy carrier and feedstock as well as electricity for process heating.

In the all pathways, any remaining energy efficiency potentials 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, financial support for RES and RES based electricity is assumed to support fuel switching to biomass, power-to-heat and power to gas. Furthermore, a CO_2 price increase to 150 euros/t CO_2 in 2050 is assumed. Companies in the pathways 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.

Table 12: Pathway characterization by mitigation option

		Diversification	Directed Vision	Localisation	National champions
GHG targets	GHG reduction targets across sector	based on the EU Roadmap, minimum of -83 to -87% reduction compared to 1990 reduction to be achieved by industry			

	Diversification	Directed Vision	Localisation	National champions
Mitigation options				
Incremental efficiency improvements	Faster diffusion of incremental process improvements (BAT & INNOV ≥TRL5).	Faster diffusion of incremental process improvements (BAT & INNOV ≥TRL3 5).	Faster diffusion of incremental process improvements (BAT & INNOV ≥TRL3 5).	Faster diffusion of incremental process improvements (BAT & INNOV ≥TRL3 5).
Fundamental process improvement	Radical process improvements (INNOV ≥TRL 5)	-	Radical process improvements (INNOV ≥TRL 5)	-
Fuel switching to RES	Stronger fuel switching to biomass, power-to-heat and power-to-gas technologies. Radical changes in industrial process technologies take place (e.g. **switch to hydrogen**). Low demand for district heating.	Fuel switching to power-to-heat (<500°). Use of existing equipment (no radical changes in industrial processes technologies). More district heating demand.	Stronger fuel switching to biomass, power-to-heat and power-to-gas technologies. Radical changes in industrial process technologies take place (e.g. **switch to hydrogen**). Low demand for district heating.	Fuel switching to biomass and electricity (<500°). Use of existing equipment (no radical changes in industrial processes technologies). More district heat demand
Carbon capture and storage	No CCS	CCS for major energy-intensive point sources.	No CCS	CCS for major energy-intensive point sources.
Recycling and re-use	Stronger switch to secondary production (e.g. electric steel, secondary aluminium).	Stronger switch to secondary production (e.g. electric steel, secondary aluminium).	Stronger switch to secondary production (e.g. electric steel, secondary aluminium).	Stronger switch to secondary production (e.g. electric steel, secondary aluminium).
Material efficiency and substitution	Decrease in clinker factor. Increase in material efficiency & substitution.	Less effort in material efficiency & substitution.	Decrease in clinker factor. Increase in material efficiency & substitution.	Less effort in material efficiency & substitution.

In terms of physical production, blast furnace steel, electric arc steel, cement and ethylene are among the most important industrial products. In the Directed Vision/National champions scenario only the cement production shows an clearly increasing trend due to needed investment in infrastructure, refurbishment and renewable energy sources (e.g. wind) for the achievement of an ambitious mitigation target (see). Production in the European steel industry is stagnating assuming a constant development in established steel producing countries (e.g. Austria, Germany) as well as a decoupling of value added and physical production based on historic trends while for selected new member states, still slight increase in steel production is assumed. In the Diversification/Localisation pathway increased efforts in material efficiency and substitution as well re-use are assumed leading to a lower crude steel and cement production in 2050 compared to the Directed Vision/National champions pathway. Recycling and secondary production routes are considered for steel, aluminium, copper, paper and glass. For cement production, a reduction of the clinker ratio (share of clinker input compared to cement output) is considered. Especially in the steel industry, a strong increase of secondary production substituting blast furnace steel production is assumed. In the Diversification/Localisation pathway all remaining EAF potentials will exploited under the assumptions of improve scrap collection/quality and broader applications for EAF steel compared to today.

In the **chemical industry** two main products are discussed exemplarily: methanol and ethylene. While in the Reference and the Directed Vision/National champions pathway the demand for ethylene is still increasing, ethylene production is assumed to remain on the level of 2015 in the Diversification/Localisation pathway due to improvements in plastic recycling and the substitution by bio-based products. In addition, large shares of conventional methanol and ethylene production are substituted until 2050, using RES hydrogen based methanol production and RES H2 methanol based ethylene production.

Illustrations of production data for steel, cement, methanol and ethylene are provided in Figure 27, Figure 28, and Figure 29.

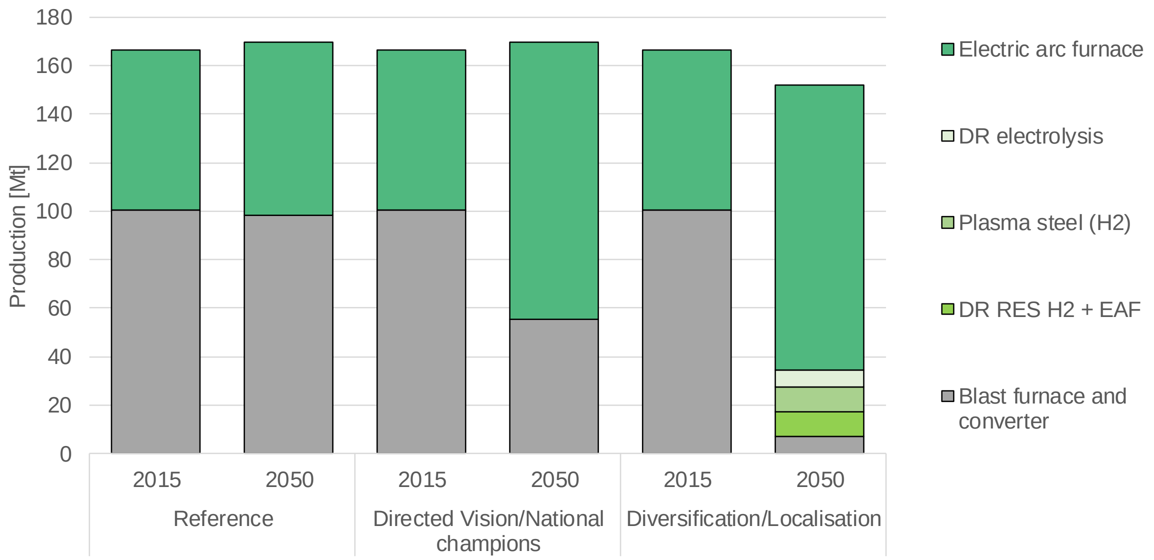


Figure 27: EU28 crude steel production by process in Mt. (2015-2050)

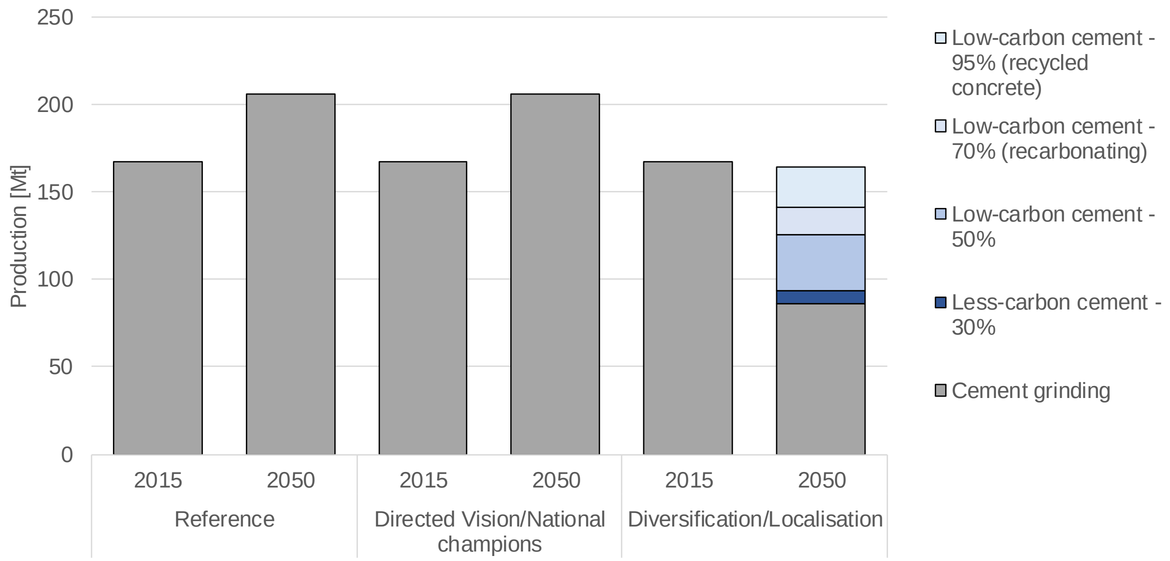


Figure 28: EU28 cement production by process in Mt. (2015-2050)

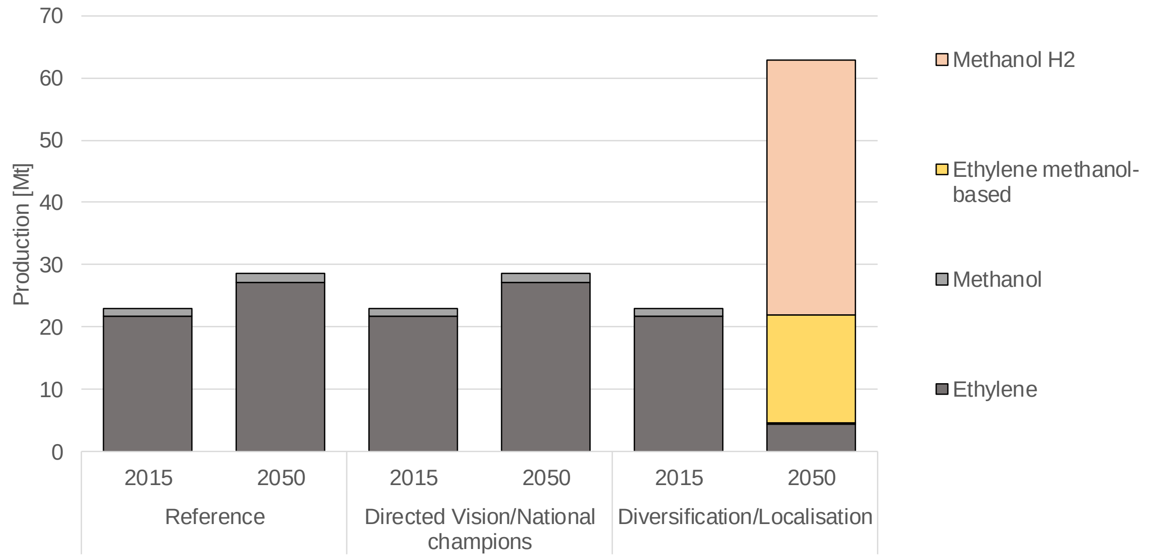


Figure 29: EU28 methanol & ethylene production by process in Mt. (2015-2050)

4.2 Main results and lessons learned from Case studies

4.2.1 Summary of results from case studies

The case studies carried out in the SET-Nav project have shown that today's policies are not on the right track towards decarbonisation, although a slow but continuous decrease of industrial CO_2 emissions is expected in the EU28 up to 2030 and 2050. The two transition scenarios TRANS-CCS and TRANS-IPT have shown a reduction of industrial CO_2 emissions by **70% reduction compared to 2015** translating to **82% reduction compared to 1990**. Detailed results for the case studies can be found in *D5.5 Case study report on decarbonisation in industry*[3].

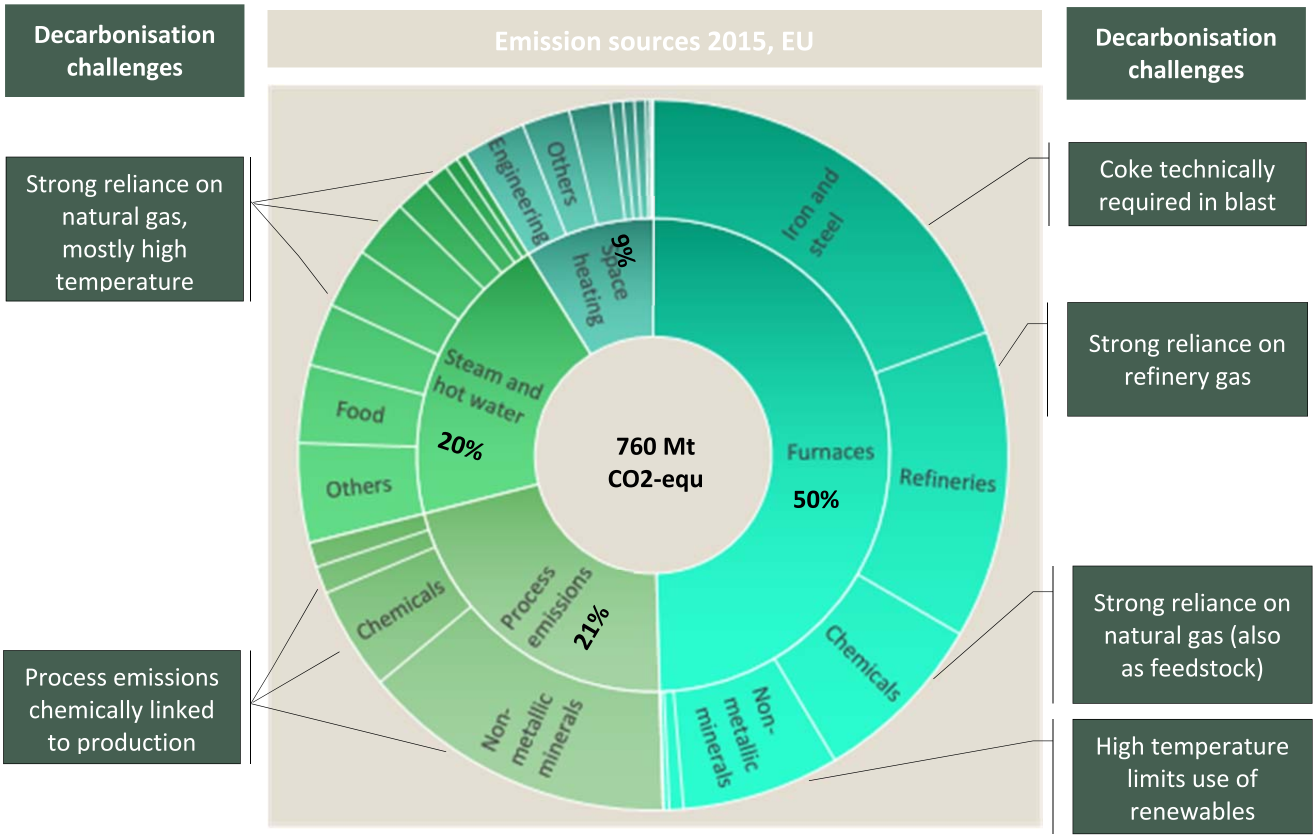


Figure 30: EU28 direct industrial emissions by end-use and challenges of industrial decarbonisation

The results presented in the case studies discussed the impacts of different mitigation options, such as incremental and BAT energy efficiency improvements, advanced energy and resource efficient processes, fuel switching, recycling and re-use, as well as material efficiency and substitution on EU industrial energy demand and CO_2 emissions. However, the processes currently used to produce energy-intensive basic material products have been optimised over many decades. The **remaining energy efficiency potentials** due to applying the best available technology (BAT) are **limited**. For example, even the most efficient clinker furnace will not be able to reduce its energy demand by much

[3] http://www.set-nav.eu/sites/default/files/common_files/deliverables/wp5/D5.5%20Case%20study%20report%20on%20decarbonisation%20in%20industry.pdf

more than 10% compared to today's average. In addition, **fuel switching** from fossil fuels like natural gas to renewable sources 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 would require policies that are more specific. **Improved material efficiency and the circular economy** have a huge mitigation potential. However, it is still unclear what an effective policy mix would look like and this probably encompasses a wide range of individual measures.

4.2.2 Lessons learned for SET-Nav pathways

As industry is not right on track for deep decarbonisation the current policy mix needs to be adjusted in order to effectively support R&D activities directed at the decarbonisation of industrial production.

- **EU Emissions Trading Scheme** (ETS): Extending the ETS with a minimum price path (i.e. a floor price) to provide more long-term clarity and the certainty needed for investors in low-carbon innovations.
- **Public RD&I funding** can play an important role in accelerating the market introduction of innovative low-carbon processes. The current proposal of the European Commission to establish an EU Innovation Fund as a follow-up to the ongoing NER300 programme is an important step in this direction.
- **Targeted public procurement** to support the market introduction of low-carbon products by establishing niche markets.
- **CO_2 tax** as the central element of a broader energy tax reform could provide the incentives needed for fuel switching for companies outside the ETS. This must avoid any double burden on companies inside the ETS.
- Boosting **material efficiency and a circular economy** approach along the value chain requires a broad policy mix.
- 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.
- **Industrial excess heat to nearby district heating networks**. 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 immission control acts, strengthening local heat planning and providing investment grants.

4.3 Energy demand and CO2-emissions in industry in SET-Nav pathways

The following 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 the European CO_2 emissions and energy demand until 2050. As discussed in section 4.1.3 the four SET-Nav pathways did translate into two scenarios for the industry sector:

- **Directed Vision/National champions:** a mitigation pathway strongly focusing on the use of CCS in industry
- **Diversification/Localisation:** a mitigation pathway using a portfolio of many different mitigation options including low-carbon innovations, ambitious material efficiency and circular economy, hydrogen as an energy carrier and feedstock as well as electricity for process heating.

These two pathways are shown below in comparison to a reference development, which reflects a future development based on current policies and past trends. In both pathways, significant direct emission reductions of 70 to 79 percent compared to 2015 can be achieved. This corresponds to an 82 to 87% direct emissions reduction compared to 1990. Final energy demand also decreases in both pathways for the EU28 by 16 and 27% in 2050 compared to 2015 - using electricity as dominant energy carrier.

4.3.1 CO_2 emissions

The achieved emission reduction in 2050 of **-87 to -82% compared to 1990** in the SET-Nav pathways in line with the target of the European Roadmap for moving to a competitive low carbon economy in 2050 of -83 to -87% emission reductions for the industry sector in 2050 (European Commission 2011a). Compared to the Reference Scenario - which only shows a slight decrease in direct CO_2 emissions of -11% in 2050 compared to 2015 for the EU28 - the Directed Vision/National champions pathway and the Diversification/Localisation pathway achieve a **reduction in direct emissions compared to 2015 of -79 (761 to 163 Mt CO2-equ.) and -70% (761 to 228 Mt CO2-equ.)** (see Figure 31).

Industrial direct emissions can be split into direct energy-related CO_2 emissions from fossil fuel combustion and direct process-related CO_2 emissions from chemical reactions within the productions process. Emission reductions in the Directed Vision/National champions pathway are mainly caused by large scale diffusion of CCS throughout the whole industry sector as well as BAT and innovative energy efficiency measures. Most captured emissions stem from cement and lime production, primary steel production and the basic chemicals industry. However, also smaller point sources like glass and paper production plants contribute to the 294 Mt captured CO2 emissions in 2050 in the pathway (Figure 31).

In the Diversification/Localisation pathway energy related emissions decrease drastically from 598 Mt. in 2015 to 148 Mt in 2050 (-75%) due to higher energy efficiency, fuel switching to RES, power-to-heat, secondary energy carriers, innovative processes and new products as well as improved material strategies and increased recycling. Consequently, the weight of process related emissions in the Diversification/Localisation Scenario increases from 21% of total direct emissions in 2050 to 35% of total direct emissions in 2050 followed by emissions from the use of natural gas (32%) (Figure 31).

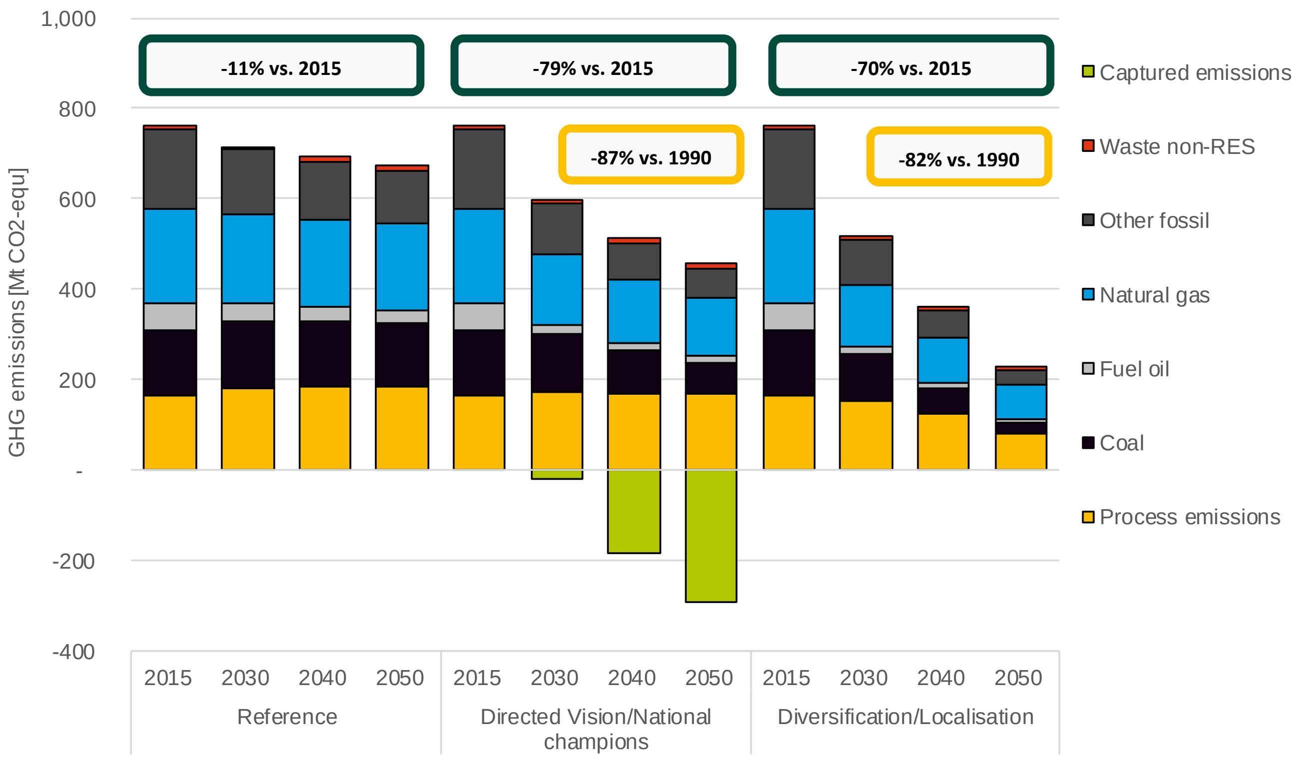


Figure 31: EU28 direct CO2 emissions by source in Mt CO2-equ. (2015-2050)

The non-metallic minerals sector is the biggest contributor of direct industrial CO_2 emissions. It is dominated by the production of cement clinker, which emits about 0.5 tonnes of process CO_2 emissions per tonne of clinker produced. Other CO_2-intensive products of the non-metallic minerals sector include lime, the calcination of dolomite/magnesite, glass, bricks and ceramics. The production of pig iron or steel in the iron and steel industry is the second largest emitter of direct industrial CO_2 emissions in 2015. The main emissions are from the (technically required) use of coal and coke in blast furnaces. In addition, chemical processes such as ammonia, ethylene or methanol production contribute to industrial emissions, making the chemical industry the third biggest emitter of direct CO_2 emissions (see Figure 32).

In 2050 the **non-metallic minerals** sector remains the largest contributor to industrial CO_2 emission in both pathways. While in the Directed Vision/National champions pathway nearly all emissions of the sector (-80% compared to 2015) can be mitigated - using CCS for cement, lime and glass production - the remaining emissions from non-metallic minerals in the Diversification/Localisation pathway remain considerably higher. In the Diversification/Localisation pathway conventional Portland cement production is partly substituted by innovative low carbon cement sorts using new binders. These new cement sorts can reduce the specific energy- and process-related cement emissions by between -30 and -70%. However, this implies that even innovative cement production still emits process-related CO_2. In addition, material efficiency and recycling improvements in the construction industry contribute to the achieved emission reductions of the sector. Further potentials in the non-metallic minerals sector are 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. Overall, the direct emission reductions in the non-metallic minerals sector amount to -54% in 2050 compared to 2015.

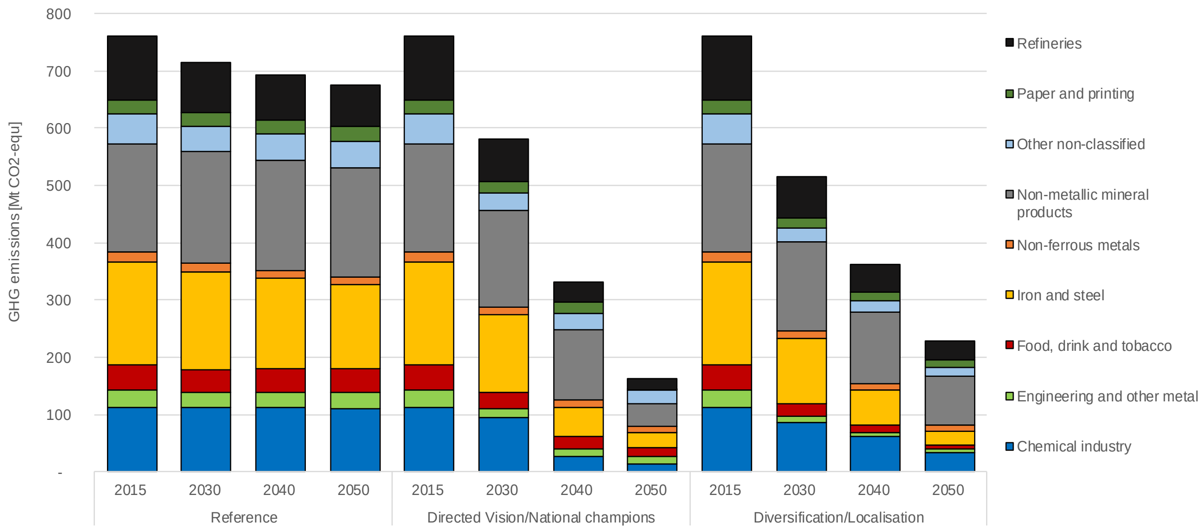


Figure 32: EU28 direct CO2 emissions by subsector in Mt CO2-equ. (2015-2050)

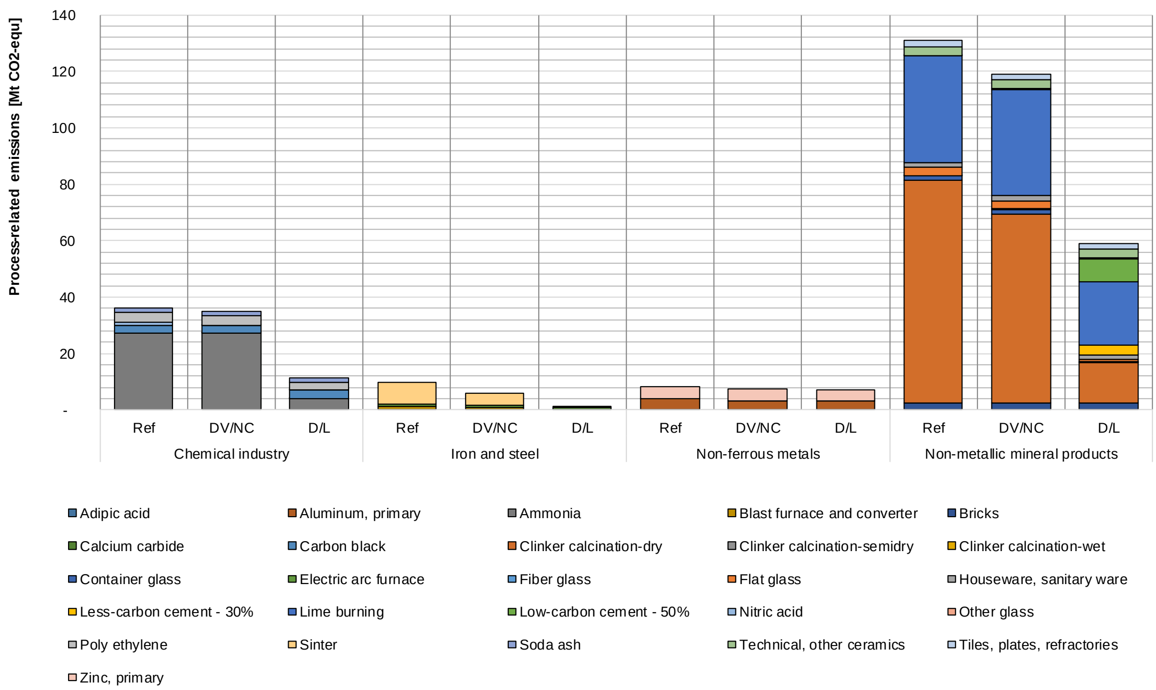


Figure 33: EU28 process emissions by subsector and product/process in Mt CO2-equ. (2050)

In the Directed Vision/National champions pathway, emissions from the **iron and steel industry** are reduced by 85% in 2050 compared to 2015. This emission reduction is mainly achieved by replacing oxygen steel (BOF[4]) with electric steel (EAF[5]) in combination with the use of CCS as major mitigation option. In the Diversification/Localisation pathway, an even stronger switch to secondary steel production (EAF) takes place. In addition, the remaining oxygen steel production is completely substituted with innovative steel production technologies until 2050 using either renewable hydrogen (DR H2+EAF or DR H2 plasma) or renewable electricity (DR electrolysis). This leads to an emission reduction of 87% in 2050 compared to 2015 in the Diversification/Localisation pathway.

In the **chemical industry** fuels - especially natural gas - are not only used for energy uses but also as feedstock for the production of e.g. olefins (ethylene, propylene, others), ammonia and methanol. Using CCS in the Directed Vision/National champions pathway leads to an emission reduction of 87% in 2050 compared to 2015. In the Diversification/Localisation scenario substantial emission cuts of about 71% take place, mainly by using hydrogen-based processes in ammonia, ethylene and methanol production and switching process heat generation to the direct use of electricity. Figure 33 shows the remaining emissions from smaller sources in the chemical industry.

On country level, GHG emissions reflect the industrial structure of the country. Germany, France, United Kingdom, Italy and Spain are currently the largest CO_2 emitters in the European Union. Together they account for 59% of total EU28 direct industrial CO_2 emissions in 2015. Germany being by far the largest emitter with 165 Mt CO_2-equ. (22% of total EU28) in 2015. In comparison, France has emitted 79 Mt CO_2-equ. in 2015 (see Figure 34).

[4] Basic oxygen furnace route

[5] Electric arc furnace route

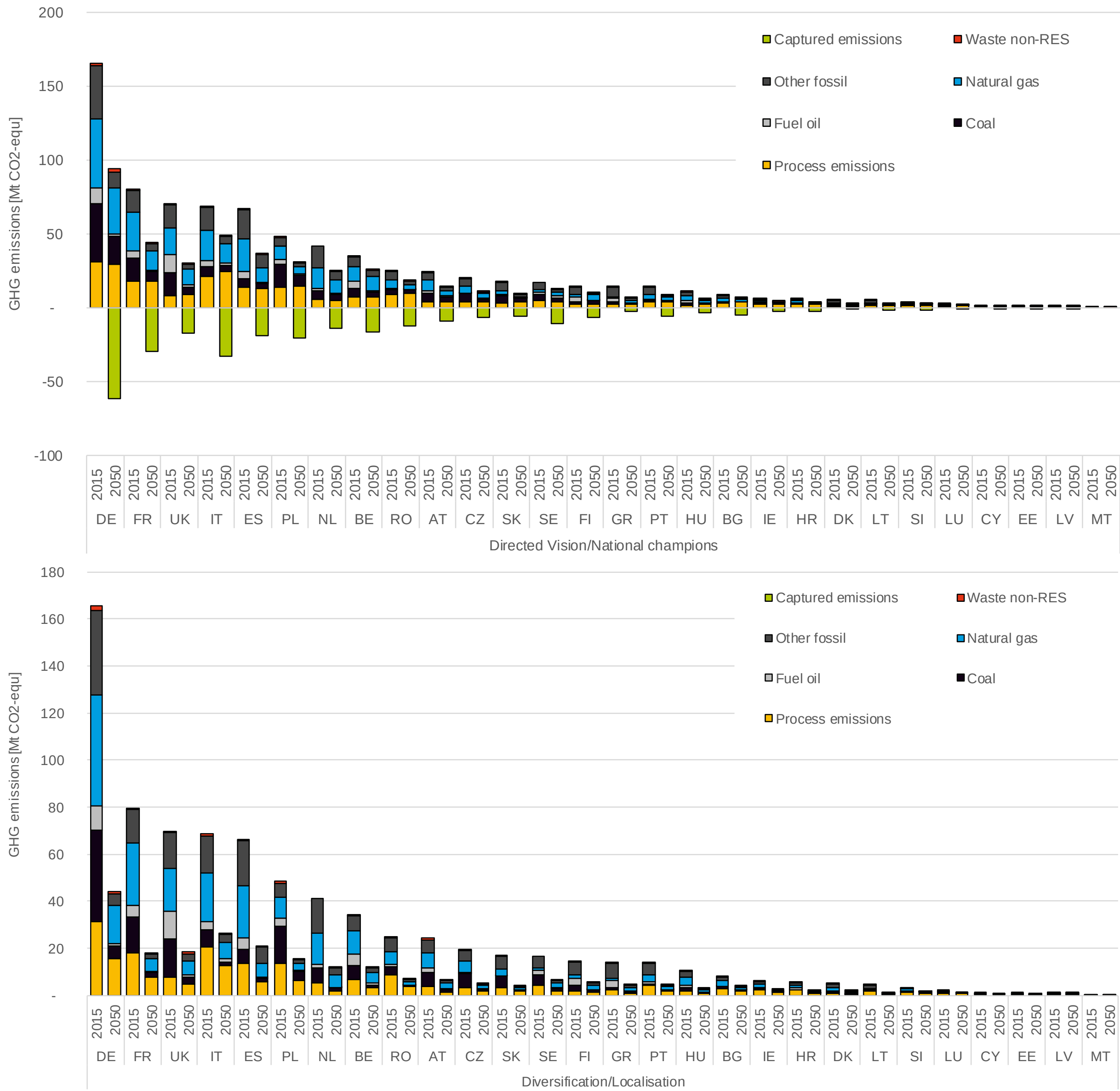


Figure 34: Direct CO2 emissions by country, source and scenario in Mt CO2-equ. (2015, 2050)

4.3.2 Final energy demand

In the reference case industrial final energy demand (FED) for the EU28 is stagnating as efficiency effects are nearly equalled out by activity effects (e.g. gross value added growth) from 3739 TWh in 2015 to 3707 TWh in 2050. In the decarbonisation pathways, FED is decreasing in both scenarios until 2050, however a lot slower than GHG emissions (Figure 35).

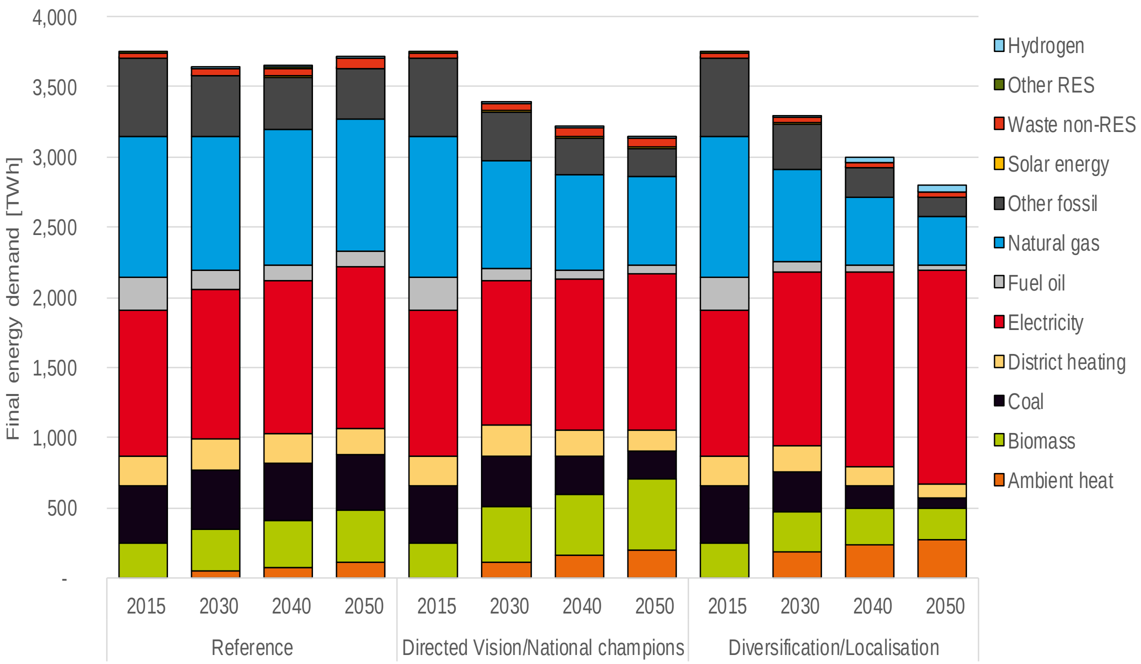


Figure 35: EU28 Final energy demand by energy carrier in TWh (2015-2050)

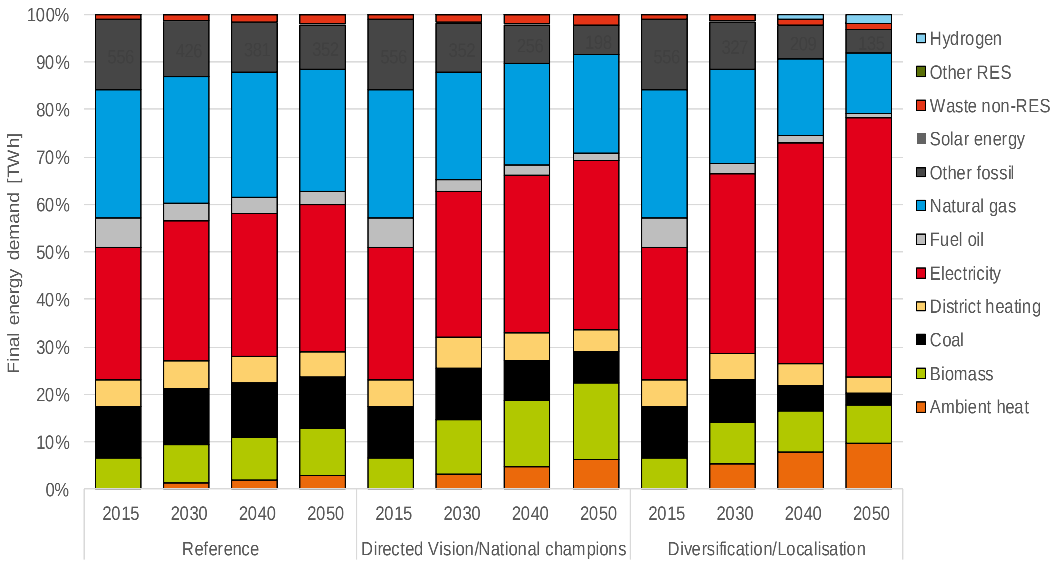


Figure 36: EU 28 Final energy demand by energy carrier in percent of Total (2015-2050)

In the Directed Vision/National champions pathway final energy demand decreases by 16% compared to 2015 to 3137 TWh including energy demand for industrial CCS. The decrease in FED in the Directed Vision/National champions pathway is mainly driven by energy-efficiency innovations. Biomass and ambient heat gain shares while fuel oil is nearly phased out by 2050 and coal demand is falling substantially (Figure 35, Figure 36). In the Diversification/Localisation pathway, FED decreases by 27% compared to 2015 to 2806 TWh in 2050. In this pathway, electricity becomes the dominant energy carrier in 2050 while the use of biomass is limited on current level. In addition, final energy demand for hydrogen (58 TWh) mainly from the steel industry becomes relevant until 2050. As in Directed Vision/National champions fuel oil is nearly phased out by 2050 and coal demand is falling substantially. In both pathways, natural gas still plays an important role in 2050.

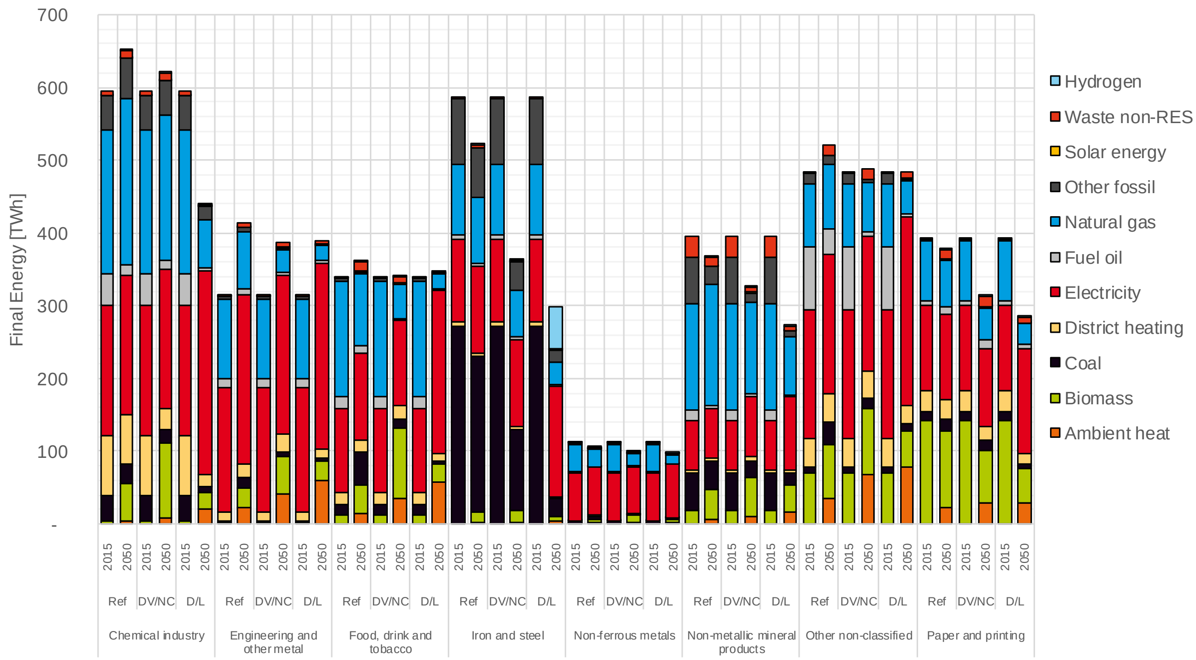


Figure 37: EU 28 Final energy demand by sub-sector and energy carrier in TWh (2015-2050)

The picture at country level is similar to that for emissions. Germany, France, Italy, United Kingdom and Spain are currently the countries with the highest energy demand in the European Union (see Figure 38). Together they account for 59% of total EU28 final energy demand in 2015. It is interesting to note that Italy and the United Kingdom have switched places in the ranking of the highest final energy demand compared to the ranking of emissions. This means that Italy has a higher final energy consumption but only a similar high emission level of CO_2 as the United Kingdom in 2015. This is partly due to Italy's production structure. Italy mainly produces electric steel, which is much less energy- and CO_2-intensive than the blast furnace route (see Figure 38).

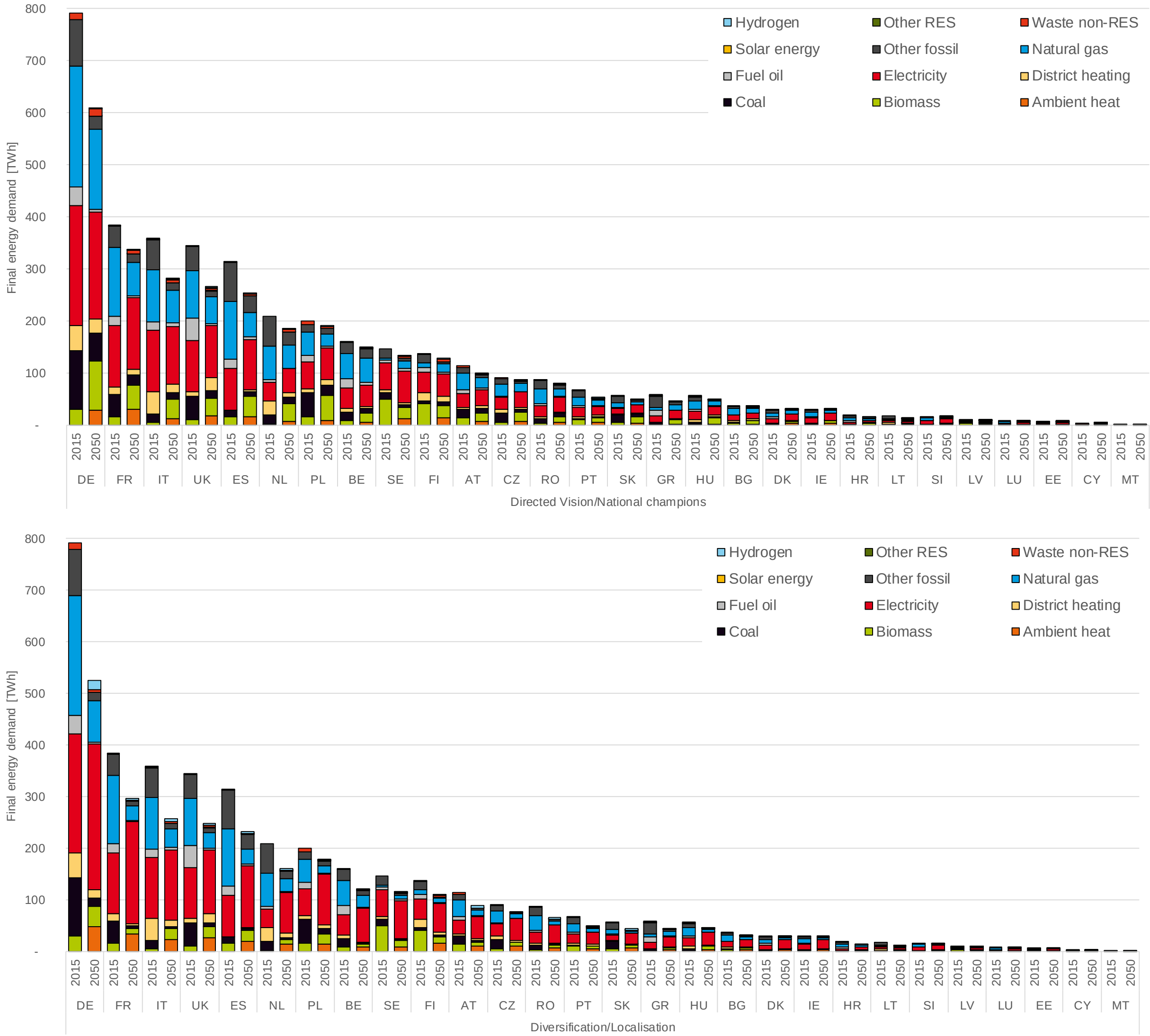


Figure 38: Final energy demand by country and energy carrier in TWh (2050)

4.3.2.1 Feedstock demand

In addition to the final energy demand already shown, the Diversification/Localisation pathway creates an additional demand for renewable hydrogen, which is needed as feedstock for the chemical industry for the production of ammonia, methanol and consequently ethylene (see Figure 39). Total hydrogen feedstock demand for the EU28 adds up to 384 TWh in 2050 in the Diversification/Localisation pathway. In the Directed Vision/National champions pathway feedstock for chemicals is still based on fossil fuels: natural gas feesdstock and naphtha feedstock (Figure 40).

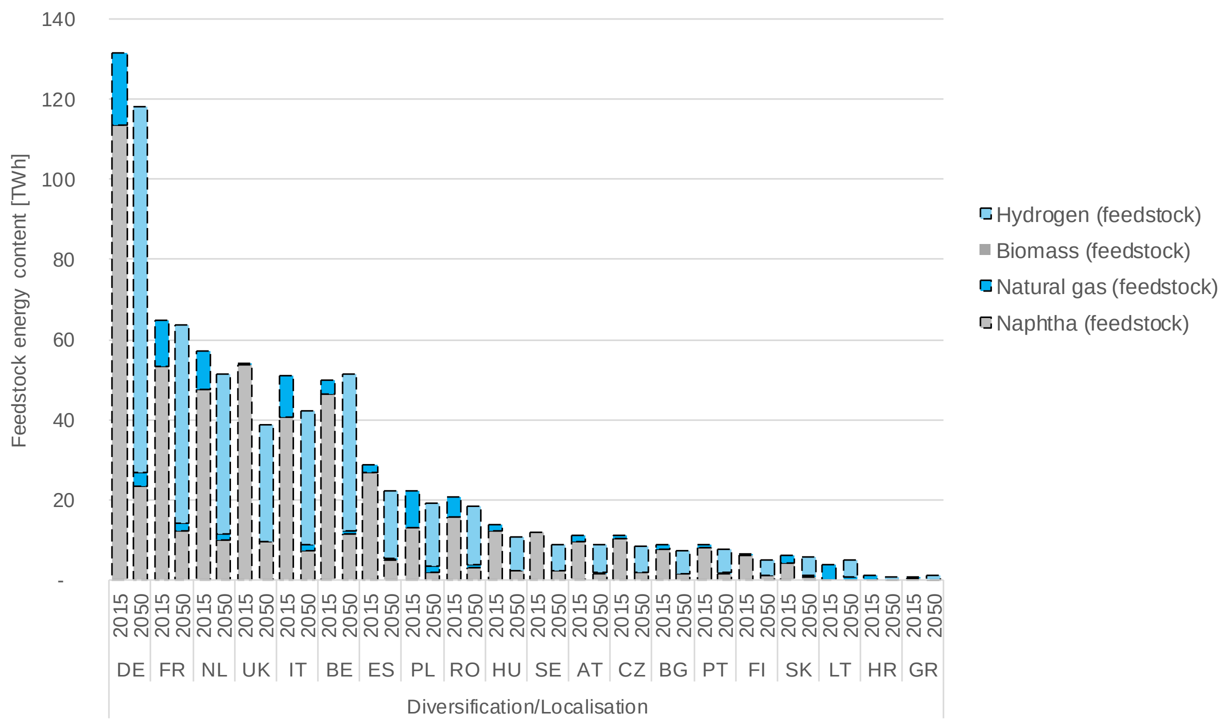


Figure 39: Feedstock energy content by country in TWh (2050)

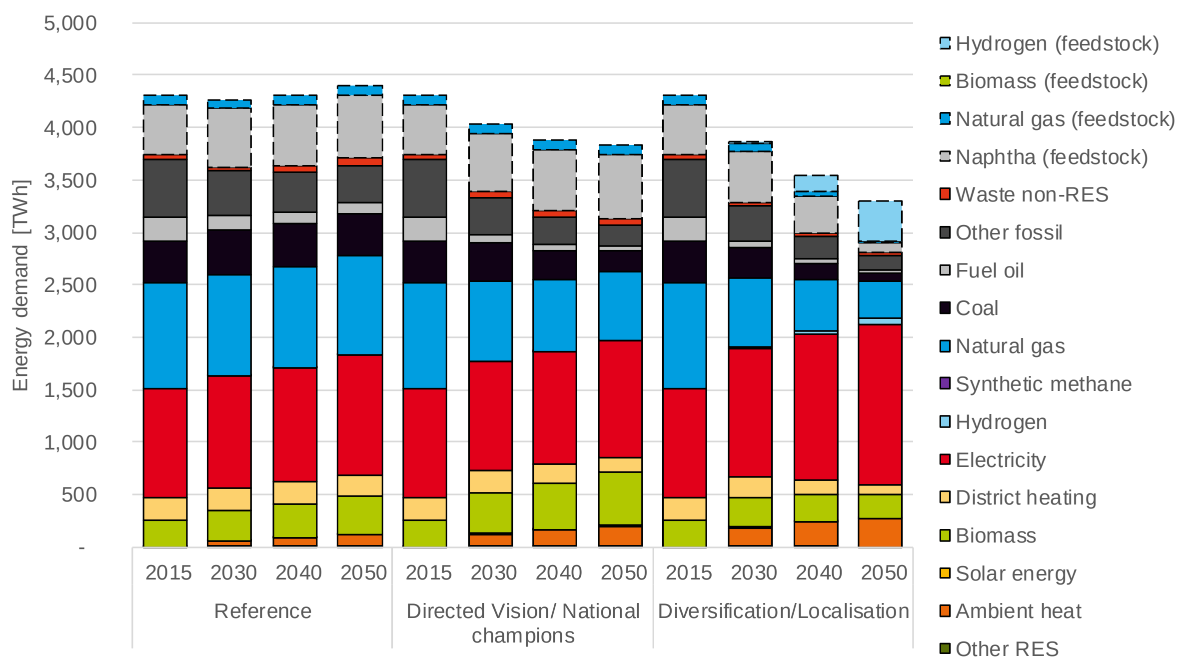


Figure 40: EU28 Total energy demand by energy carrier incl. feedstock in TWh (2015-2050)

4.3.2.2 Electricity and biomass

Two types of electricity demand can be distinguished in the following. On the one hand, there is direct electricity use as final energy mainly for mechanical energy and heating (e.g. electric furnaces, DR electrolysis steel). On the other hand, is the indirect use via secondary energy carriers - in this case hydrogen. The Reference case (+11% from 1041 to 1152 TWh) and the Directed Vision/National champions pathway (+7% to 1118 TWh) only slight increases in electricity demand takes place until 2050 compared to 2015 (Figure 41).

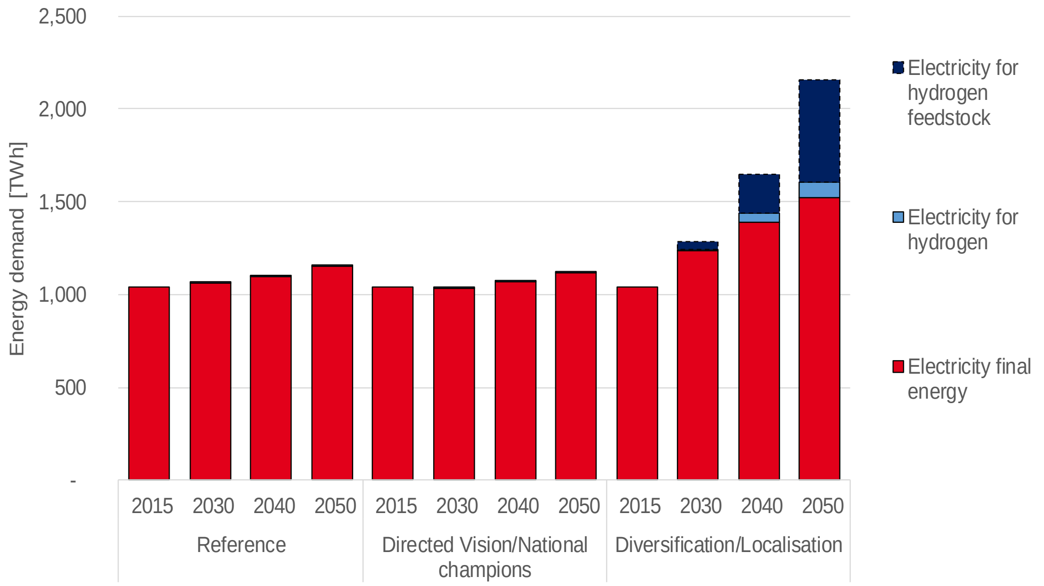


Figure 41: EU28 Total electricity demand from FED and hydrogen in TWh (2015-2050)

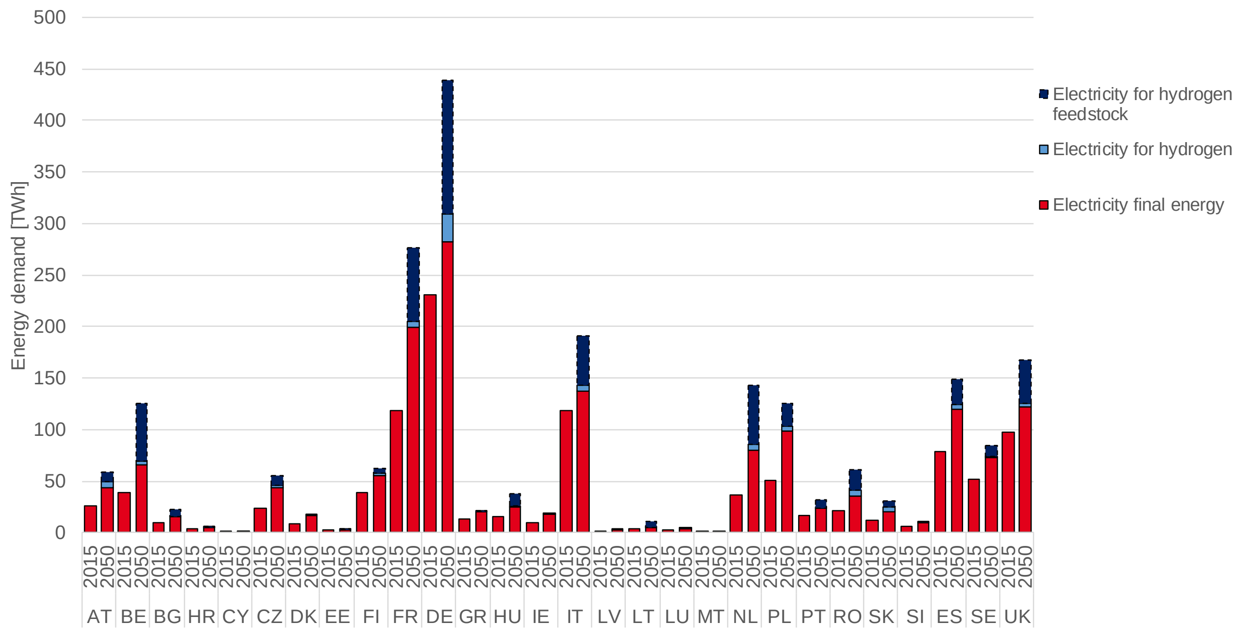


Figure 42: EU28 Total electricity demand from FED and hydrogen by country for the Diversification/Localisation pathway in TWh (2015-2050)

The drastic increase in electricity demand (+107% from 1041 to 2157 TWh) in the Diversification/Localisation pathway is driven by the large-scale use of electricity for process heating: this includes heat pumps where applicable, but also electric boilers for industrial steam generation and electric furnaces e.g. in glass melting or even electric clinker kilns. As well as the use of hydrogen: 549 TWh electricity for hydrogen feedstock plus 83 TWh electricity for hydrogen in the steel industry. In the chemical industry, innovative processes using hydrogen enter the market in 2030 and substitute large shares of the conventional methanol and ammonia production in 2050. However, these mitigation options can only exploit their full potential if renewable electricity is used.

In the Directed Vision/National champions pathway high financial support for biomass leads to a use to broad use of biomass where it is technical feasible (e.g. cement and lime production). In the Directed Vision/National champions pathway the demand for biomass increases from 251 TWh in 2015 to 506 TWh in 2050. In comparison the demand for biomass decreases in the Diversification/Localisation pathway to 229 TWh in 2050 (see Figure 43).

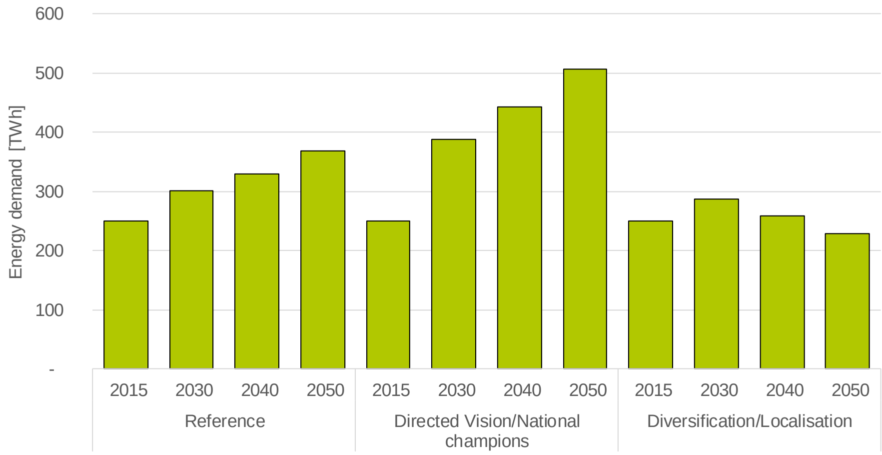


Figure 43: EU28 final biomass demand in TWh (2015-2050)

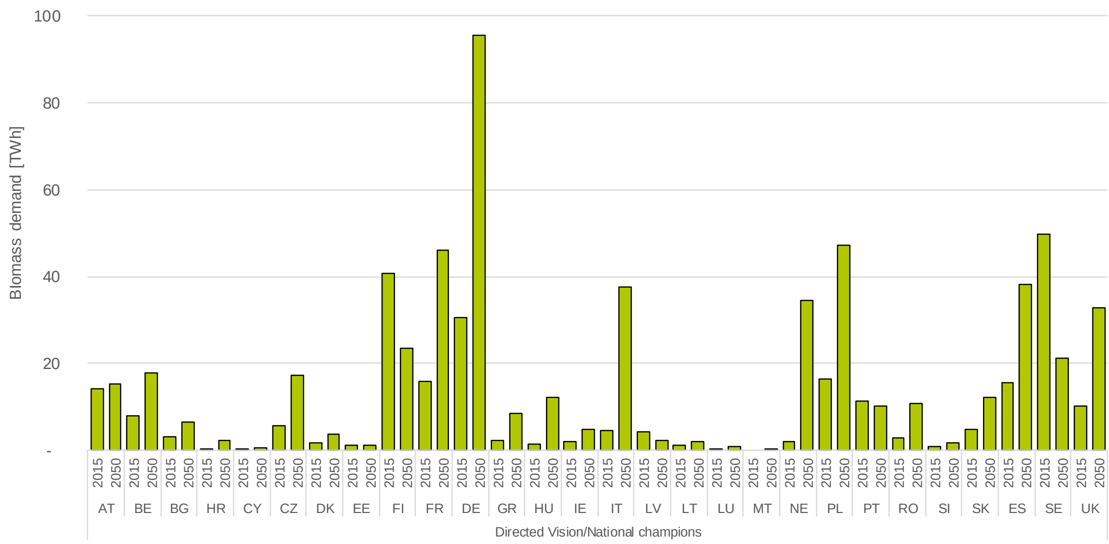


Figure 44: EU28 final biomass demand by country in the Directed Vision/National champions pathwayin TWh (2015-2050)

4.3.2.3 Fuel switch

Steam and hot water generation is used across all industries, but has very high demands in chemicals, pulp and paper as well as the food industry. It covers a temperature range of up to 500°C and uses relatively comparable technologies in all sectors. The temperature range allows the use of combined heat and power (CHP) technologies. In total, final energy demand for steam and hot water accounts for about 25% of industrial final energy demand in the EU28.

The following graph (Figure 45) show the evolution of the fuel mix in the final energy demand used for steam and hot water generation in the Directed Vision/National champions pathway and the Diversification/Localisation pathway. It can be seen that the share of biomass in the Directed Vision/National champions pathway increases in nearly all sectors, due to higher financial support for RES. The share of electricity (power-to-heat) is increasing in both pathways, while the increase is much higher in the Diversification/Localisation scenario. Again, this is due to financial support, which is also provided for RES-based PtH.

The use of fossil fuels on the other side is decreasing in both scenarios. Coal and fuel oil are nearly completely phased out and also natural gas is decreasing drastically. Still, in 2050, some natural gas is remaining in most sectors. The main reason is a slow turnover of the technology stock in combination with new gas-based capacities being constructed in the coming years. A more drastic phase-out of gas would require a stronger policy frame, which could include either stronger financial incentives or a ban on the use of fossil fuels even before 2030.

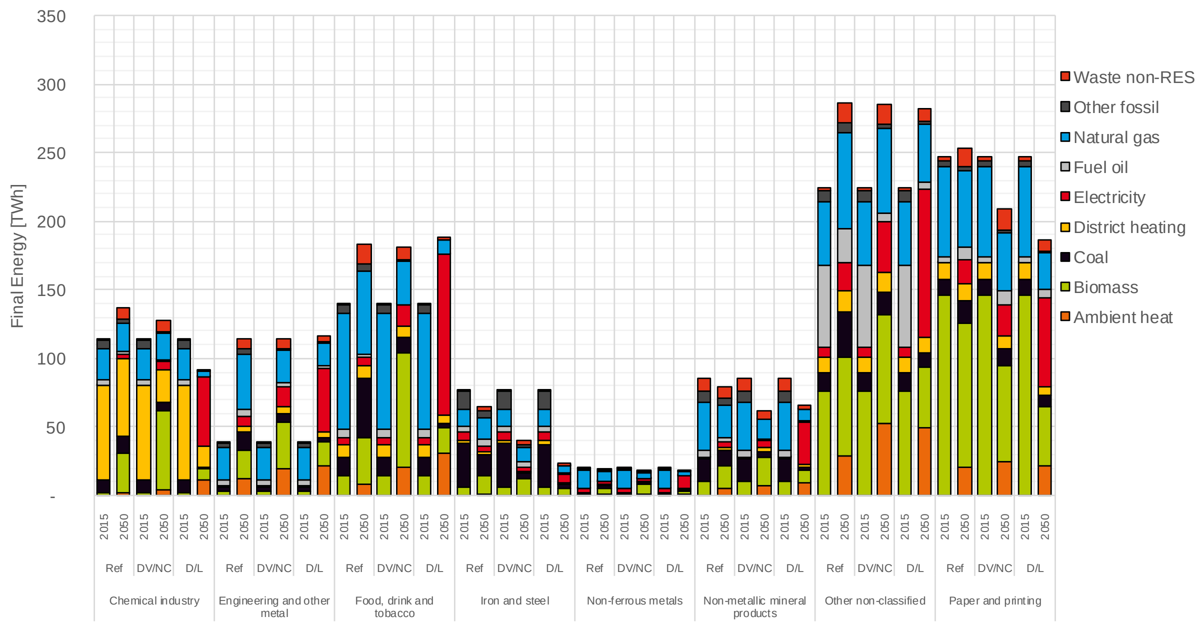


Figure 45: EU 28 Final energy demand for steam and hot water by energy carrier (2015-2050)

Another important field for fuel switching are industrial furnaces. Comparted to steam systems, furnaces are very diverse and specific to the related production process. They 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 more technical restrictions and RES are sometimes difficult to integrate.

Figure 46 show the fuel shares in final energy demand for process heating via furnaces in the three main industries: Chemicals, iron and steel and non-metallic minerals (cement, lime and glass). It can be observed that even in the Directed Vision/National champions pathway, coal is reduced substantially and only remains in the iron and steel industry, where it is needed as a reduction agent. On the other hand, biomass gains shares in the chemicals and the non-metallic minerals sector, where it is already today used in clinker kilns. In the iron and steel industry, the shift away from oxygen steel towards electric steel drives down coal demand and increases electricity demand. Due to the lower final energy demand of electric steel, this shift also drives down total final energy demand in the iron and steel industry.

The Diversification/Localisation pathway experiences an even stronger shift towards electricity and hydrogen. The increase in electricity demand is driven by a shift away from oxygen steel towards electric steel and process changes that include for example electric furnaces in the glass industry and RES DR electrolysis in the steel industry. Across all sectors and scenarios, also in 2050 still a substantial amount of natural gas is used.

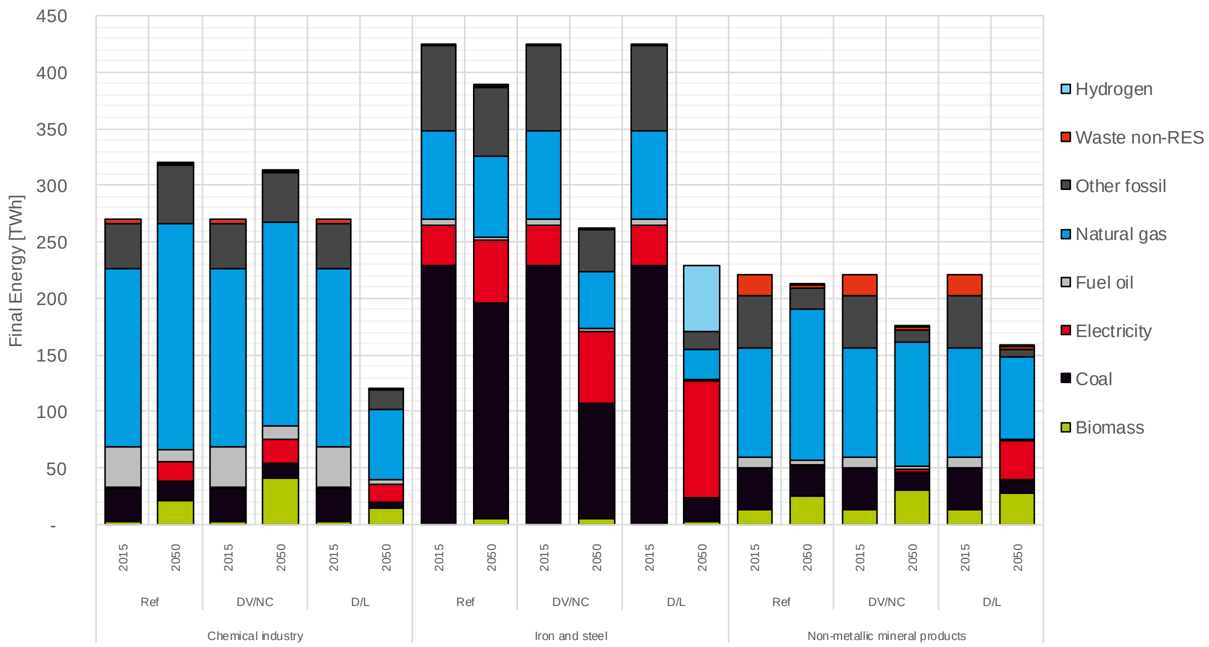


Figure 46: EU 28 Final energy demand for process heating (>500°C) by energy carrier in TWh (2015-2050)

4.4 Energy expenditures and investment

In the following, investment expenditures (CAPEX) and energy cost spending (OPEX) are discussed for investments in the industry sector. Investments and costs are reported as the difference compared to Reference case. Only costs related to the technical energy system are reported. This excludes e.g. external costs, macro-economic effects, etc.

Additional investments from 2015 to 2050 compared to the reference case are dominated by energy efficiency investments in building renovation, process optimisation and steam distribution systems in all scenarios. Investment in the Directed Vision/National champions pathway is higher than in the Diversification/Localisation pathway, driven by the CCS capture, transport and storage infrastructure costs (see Figure 47). Innovative low-carbon production processes like low-carbon cement, hydrogen-based chemicals or steel production routes have a lower need for additional investment expenditures. This is caused by the assumption that investment cycles are unchanged and that investment in innovative technologies takes place when re-investment would be undertaken anyway. In addition, it is assumed that H2 is produced centralized and industry does not bear the costs of large scale hydrogen electrolysers. Furthermore, before 2030 investments in low-carbon production processes are marginal, main activity is R&D, which is not reflected in the cost assessment. In addition, due to the lower production of some of the relevant energy-intensive products (e.g. steel, cement) in the Diversification/Localisation pathway investments is lower as smaller or no additional capacities will be needed.

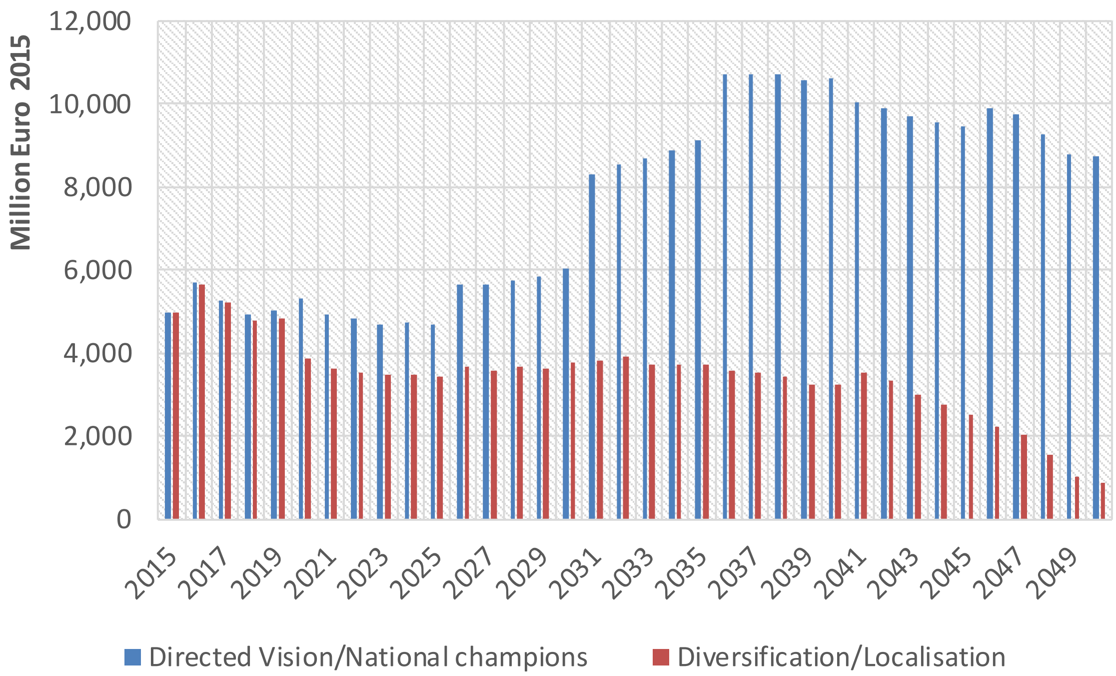


Figure 47: EU 28 annual differential investment by scenario compared to reference (2015-2050)

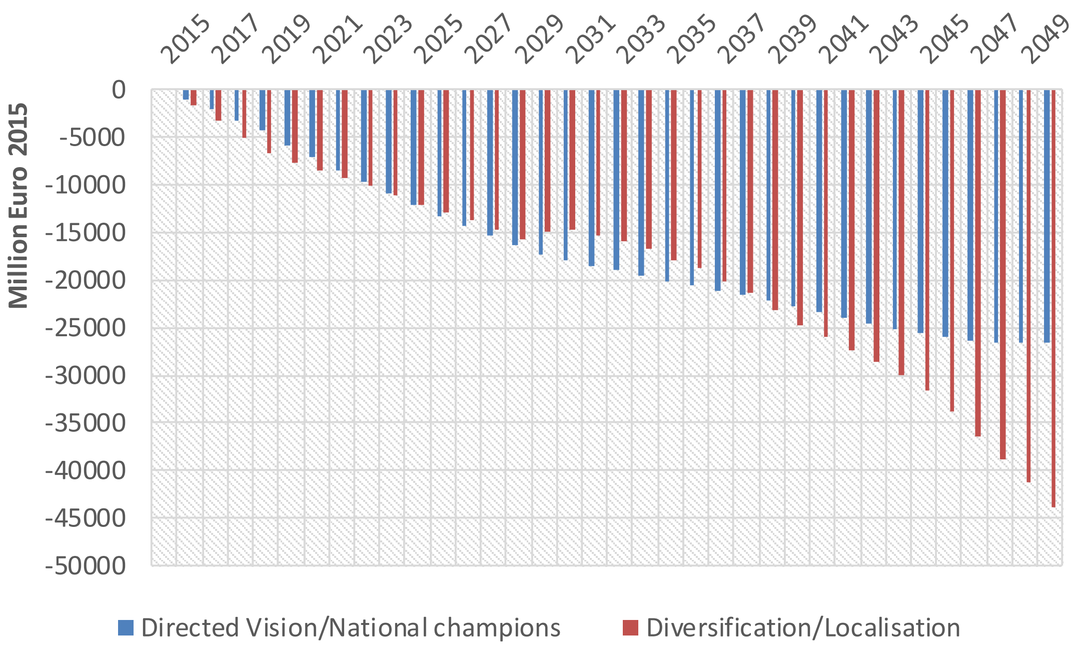


Figure 48: EU28 annual differential energy expenditures by scenario compared to reference (2015-2050)

While the switch to electricity increases energy expenditures in the Diversification/Localisation scenario, the material efficiency progress in this scenario overcompensates this increase (Figure 48). The combination of energy and material efficiency, recycling and increasing fossil fuel prices compensates for the extensive use of high-value energy carriers like hydrogen and electricity resulting lower energy expenditures as in the reference scenario. It has to be underlined that the costs of improvements of material efficiency and circular economy have not been included in this assessment.

Finally, it needs to be underlined that the energy expenditures are highly sensitive to energy price assumptions, which per definition are very uncertain and not predictable and the assumed support for RES. The assumed increase in fossil fuels prices reduces the additional costs of the decarbonisation scenarios compared to the reference scenario. Thus, results have to be interpreted in the light of these assumptions and uncertainties.

4.5 Conclusions & recommendations

From the case study and pathway analyses the following conclusions can be drawn:

- Even if remaining energy efficiency potentials are ambitiously exploited, the basic materials industries will still remain major energy consumers and the possible contribution to CO_2 mitigation is limited.
- Efficiency potentials in cross-cutting technologies are still higher and can substantially reduce electricity demand - if effective policies are implemented.
- When fundamentally new production technologies enter the market, efficiency improvements and optimisation of existing technologies has no effect in the long-term, when these technologies are anyway replaced. Such efficiency improvements, however, reduce cumulated emissions along the pathway. Thus, for fundamental transition scenarios, the role of energy efficiency optimisation needs to be discussed.
- Biomass has a large potential at relatively low cost (if sustainable resources are available).
- RES electricity can contribute substantially:
    - For steam generation it requires high financial support due to high electricity prices compared to fossils or biomass. Due to the high importance of OPEX (compared to CAPEX), financial support needs to address running costs. Investment grants are less effective.
    - For furnaces, using electricity requires fundamental process and technology changes like e.g. a new steel production route. The use of electricity is also strongly related to the use of hydrogen and power-to-gas. Also here, high operation costs are a major barrier and need to be addressed by the policy frame.
- Other technologies based on RES like solar thermal or heat pumps only have limited applications due to high temperature levels needed in furnaces.
- In general, long lifetime of capital (>20 years) requires early changes, if fossil fuels should be phased out by 2050.

In the Diversification/Localisation pathway, radical changes to industrial production systems like innovative processes and large-scale power-to-heat for steam generation mainly enter the market 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 10 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 policy mix needs to be adjusted in order to effectively support R&D activities directed at the decarbonisation of industrial production. This includes the following elements:

- **EU Emissions Trading Scheme** (ETS): At the current level of certificate prices (EUAs), the ETS is not effective in reducing industrial emissions. For investments in low-carbon technologies, companies' expectations of future prices are even more important than the current price levels. If companies cannot rely on rising EUA prices, they will not invest in CO_2 abatement technologies. Extending the ETS with a minimum price path (i.e. a floor price) could provide more long-term clarity and the certainty needed for investors in low-carbon innovations.
- 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. The current proposal of the European Commission to establish an EU Innovation Fund as a follow-up to the ongoing NER300 programme is an important step in this direction.
- In addition, **targeted public procurement** can support the market introduction of low-carbon products by establishing niche markets. For example, considering life-cycle CO_2 emissions when procuring building materials might encourage the cement industry to develop and provide more low-carbon alternatives.
- Although a major share of industrial GHG emissions is covered under the EU ETS emissions cap, a **high amount of industrial CO_2 emissions remains outside the ETS** and thus does not receive a CO_2 price signal. These companies currently have no incentive to switch to renewable or low-carbon fuels for heat generation. A **CO_2 tax** as the central element of a broader energy tax reform could provide the incentives needed for fuel switching. This must avoid any double burden on companies inside the ETS.
- Boosting **material efficiency and a circular economy** approach along the value chain requires a broad policy mix. Examples of individual policies include:
    - Re-evaluation of value added tax according to the carbon-footprint of products and a lower value added tax for repair services.
    - Reform the EU ETS to keep CO_2 price signals along the value chain visible for downstream consumers and companies.
    - Evaluate building codes and the regulative framework in the construction industry to facilitate the use of sustainable building products and the efficient use of materials.
    - Sector-specific measures to increase recycling rates where these are still very low like in plastics or concrete.
- 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. On the EU level, the Energy Efficiency Directive already provides important incentives by requiring regular energy audits for large enterprises, asking for national measures to support audits in small companies and setting up national energy efficiency obligation schemes. Some countries go beyond the Directive and implement

additional measures. For instance, in Germany, companies receive **tax discounts for using a certified energy management system**, which has led to a drastic increase in ISO 50001 certifications here. Further, the country supports so-called **learning energy efficiency networks**. Both measures could be used as a blueprint for EU initiatives.

- 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 immission control acts, strengthening local heat planning and providing investment grants.

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.

5 Energy demand in the transport sector

Introduction: Greenhouse gas emissions and reduction targets

In 2015, the transport sector accounted for around 30% of the European greenhouse gas (GHG) emissions. The EU Roadmap for moving towards a competitive low-carbon economy sets the target to reduce GHG emissions from transport[6] compared to 1990 by -54% to -67% in 2050 in order to achieve an overall reduction of 80% for all domestic emissions across sectors (European Commission (2011a)). Analyses show that transport is likely to miss this target by a long way without major changes in the policy framework and the adoption of new technologies.

In 2005, the transport sector even showed an increase of +30% GHG emissions compared to the base year in contrast to all other sectors that were able to decrease emissions. One reason is that the efficiency increase achieved for conventional technologies is outweighed by a strong increase in transport activity both for freight and for passengers due to GDP growth and higher incomes of the population.

Therefore, further strategies are required to decarbonise the transport sector. According to the EU Transport White Paper (European Commission (2011b)), the key strategies to decarbonise the transport sector until the year 2050 are:

1) Shift to more efficient transport modes
2) Diffusion of low/zero-emission technologies
3) Alternative fuels

The main purpose of this study is the analysis of measures to accelerate the transition from a fossil fuel based towards an energy efficient and low-carbon transport sector in Europe that achieves its GHG emission reduction targets. For the Case Study Scenarios and the Pathways, the three main EU strategies will be combined by varying their relevance and the priorities of alternative options within a strategy. Furthermore, the impact of the transition on the power sector will be analysed in the case study due to a strongly increasing electricity demand from transport.

5.1 Methodology and scenario definitions

5.1.1 Model description ASTRA

ASTRA (ASsessment of TRAnsport Strategies) is an integrated assessment model applied since more than 20 years for strategic policy assessment in the transport and energy field. The model is based on the System Dynamics approach and built in Vensim®.

The model covers all EU28 member states plus Norway and Switzerland. A strong feature of ASTRA is the ability to simulate and test integrated policy packages and to provide indicators for the indirect effects of transport on the economic system. The ASTRA model covers the time period from 1995 until 2050. Results in terms of main indicators are available on an annual basis.

ASTRA simulates the development of passenger and freight transport per mode with an adapted classical four stage modelling approach. The model is calibrated to match major indicators for the time

[6] including international aviation, excluding international maritime shipping

series from 1995 until 2015 such as transport performance, fuel consumption, CO_2 emissions and GDP according to the main European reference sources such as Eurostat. For future trends until 2050, the EU Reference Scenario (Capros P. et al. 2016) provides parameters like the development of GDP, population and energy prices and serves for validation of the ASTRA model behaviour (e.g. transport performance and fleet development) in the Reference scenario.

Model structure

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

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

A key feature of ASTRA as an integrated assessment model is that the modules are linked together. An overview on the modules and their main linkages is presented in the following figure. A more detailed description of the ASTRA model can be found in Krail (2009) and Fermi et al. (2014) or on the ASTRA website (www.astra-model.eu).

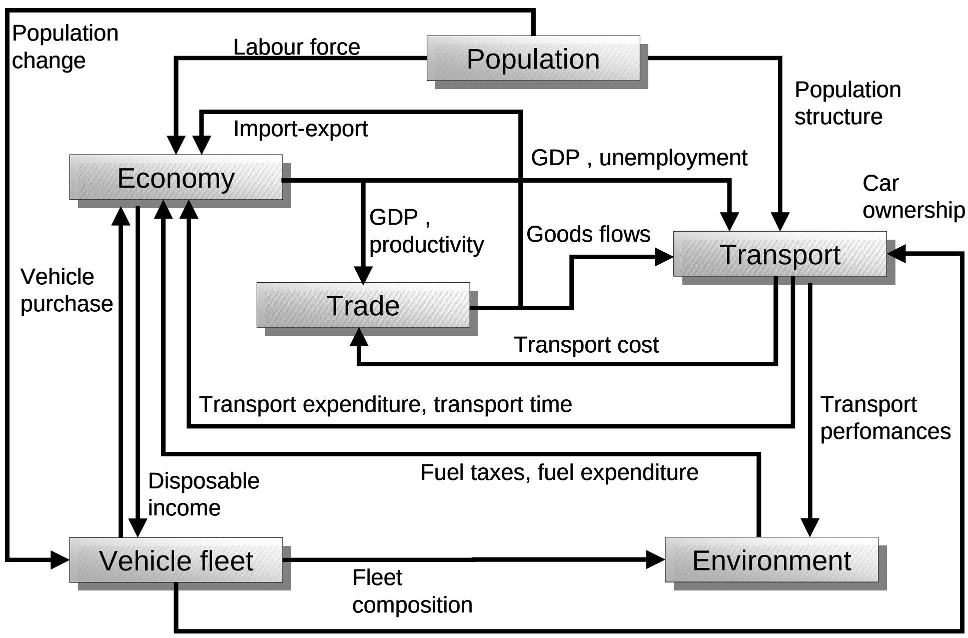


Figure 49: Model structure of ASTRA

Vehicle fleet and technology diffusion

The diffusion of alternative drive technologies in the *road vehicle fleet* is simulated separately for different vehicle categories. These categories comprise private and commercial cars, light duty vehicles

(LDV), heavy duty vehicles (HDV) 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, CNG, LNG, 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. Within the SET-Nav project, new low-emission powertrain options were added in particular for the road freight modes and for buses. Technology diffusion is based on an adapted total cost of ownership (TCO) approach. Besides the TCO, an important issue of the diffusion of new technologies is the deployment of charging and filling station infrastructure and the development of ranges of alternative fuel vehicles.

Non-road vehicle fleets like inland waterways, maritime ships, airplanes 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. Synthetic fuels based on Power-to-Gas (PtG) and Power-to-Liquid (PtL) could be taken into account as a sustainable substitute for biofuels and were not modelled separately.

Model outputs

ASTRA can produce a wide range of impact categories; in particular transport system operation, economic, environmental and social indicators. Standard outputs from ASTRA are for example:

- Transport performance
- Technology share of the vehicle stock
- Final energy consumption
- Greenhouse gas and air pollutant emissions
- Investments

Results are available in several levels of detail, depending on the output e.g. by country or region, by mode, by vehicle category, by energy carrier or by emission type.

Methodology: model coupling

For the case study (see description on assumptions and results below), ASTRA was coupled with three other models in order to analyse the impact of the transition towards a low-carbon transport sector on the energy system and to include simulations on technological progress.

ASTRA simulations provided the development of the final energy consumption by energy carrier for each transport mode and year. The final electricity demand was converted into hourly consumption by using load profiles and day specific traffic load curves for each mode. The impact of the electricity and hydrogen demand from transport on the electricity system was finally analysed by the energy supply models Enertile® and EMPIRE. More details on the involved models and the model coupling can be found in the comprehensive Case Study Report (Heitel et al. 2018).

5.1.2 Scenario assumptions in the case study on transport

To identify and describe potential decarbonisation pathways towards an energy-efficient transport system largely based on renewable energy carriers by 2050, we conducted a model-based analysis of three different scenarios. For each scenario, a set of transport and energy policy packages was defined as well as a techno-economic framework setting the parameters for energy-efficient and alternative fuel technologies (e.g. learning rates, infrastructure deployment).

The following three scenarios were defined:

- A **Reference scenario**, which reflects the effects of current policies and serves as a benchmark to compare the more ambitious scenarios.
- Two ambitious Policy scenarios that aim at achieving GHG emission reductions of 60% to 65% by 2050 compared to 1990. They are mainly differentiated by infrastructure decisions:
  1) **Direct electrification**: Hybrid trolley truck infrastructure is deployed in all European countries on highly-used motorways.
  2) **Hydrogen scenario**: Hydrogen fuelling infrastructure is expanded comprehensively and market entry supported.

The Reference Scenario assumes that all policy measures related to the European transport sector existing at the end of 2017 are implemented in their current form and continue to be valid until the year 2050. This comprises in particular regulations on CO_2 standards for cars and light duty vehicles and the directive on renewable energy. In addition, the directive on the deployment of alternative fuels infrastructure (AFID) is assumed to be implemented to the extent that the member states defined in their National Policy Frameworks as response to this directive. Furthermore, guidelines on the Trans-European Transport Network (TEN-T) are considered. TEN-T is a European Commission policy directed towards the development of a Europe-wide network of roads, railway lines, inland waterways, maritime shipping routes, ports, airports and rail-road terminals. Its implementation 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.

In the ambitious Policy scenarios that should meet the European GHG emission reduction targets, measures of the Reference Scenario were partly intensified and complemented by further regulations in order to achieve a stronger shift to more-efficient modes, to low- and zero-emission vehicles and to alternative fuels.

Measures that support the diffusion of low- and zero-emission vehicles include more ambitious CO_2 standards for new cars and light duty vehicles and the extension of standards to busses and trucks, pricing based on CO_2 emissions - in particular road charges, fuel taxes and vehicle registration taxes, and subsidies during the market entry phase of new technologies. In addition, phase-out decisions for pure internal combustion engine (ICE) vehicles were assumed with completion in 2030 for new buses and in 2035 for new cars and light duty vehicles. Besides the investment costs at the time of vehicle purchase and the running costs, sufficient charging and filling station infrastructure is key for technology diffusion to reduce range anxieties and the effort for refuelling or recharging. Therefore, a further deployment of infrastructure was assumed.

Furthermore, the Policy scenarios comprise more intensive measures to shift traffic from individual road transport to more efficient transport modes like trains, public transport, cycling and walking. Such measures include the improvement of local public transport and cycling and walking infrastructure, the promotion of sustainable mobility and making multi-modal transport more convenient by providing common electronic multi-modal information platforms and services that reduce waiting times and enable seamless electronic ticketing and real-time trip information.

Compared to road transport, aviation and maritime and inland waterway navigation have far less potential to decarbonise by diffusion of new technologies until 2050 because the operating life of aircraft and ships is long, leading to low substitution rates. The technological alternatives, especially for aircrafts, are not mature and will be very expensive to develop. Therefore, measures for these non-road modes focus on emission standards for new aircrafts and ships and a higher share of alternative fuels, in particular LNG and biomethane for ships and biokerosene for aviation. For railways, electrification is further increased.

Overall, the policy scenarios set a focus on the electrification of road transport while biofuels are used in particular for non-road modes having less decarbonisation options. Nevertheless, the share of biofuels blended in diesel and gasoline was assumed to increase also for road-modes. CNG and LNG were not further promoted as alternative technologies because their CO_2 emission reduction potential is limited unless natural gas is replaced by biomethane.

Table 13 provides an overview of the key policies and measures for the three scenarios. The interventions for the policy scenarios are considered to be additional to the existing measures in the reference case.

Table 13: Overview on the main characteristics of the Reference and the two Policy Scenarios

<table>
<tr><th rowspan="2"></th><th rowspan="2">Reference Scenario</th><th colspan="2">Policy Scenarios</th></tr>
<tr><th>Direct Electrification</th><th>Hydrogen</th></tr>
<tr><td rowspan="7">Policies for the diffusion of low/zero-emission technologies and alternative fuels</td><td rowspan="2">Passenger car CO_2 EC regulation 443/2009</td><td colspan="2">CO_2 regulation for new buses and trucks,
stricter regulation for cars and light duty vehicles</td></tr>
<tr><td colspan="2">Vehicle registration tax depending
on the CO_2-emissions of the vehicle</td></tr>
<tr><td rowspan="2">Van CO_2 EC regulation 510/2011</td><td colspan="2">Road charging based on emissions</td></tr>
<tr><td colspan="2">Subsidies for electric vehicles in early market phases</td></tr>
<tr><td rowspan="3">Renewable Energy Directive 2009/28/EC (10% share of renewable energy in the transport sector final energy demand)</td><td></td><td>Subsidies and R&D initiatives for market entry of FCEVs</td></tr>
<tr><td colspan="2">Increased energy taxation for conventional fuels and reduced fuel tax for electricity, biofuels, hydrogen and renewable synthetic fuels</td></tr>
<tr><td colspan="2">Phase-out of new pure internal combustion engine vehicles for urban buses as of 2030, for cars and light duty vehicles as of 2035</td></tr>
<tr><td rowspan="2">Filling and charging stations for alternative fuels</td><td rowspan="2">As defined by National Policy Frameworks provided by member states as response to the AFID directive 2014/94/EC</td><td colspan="2">Continuously increasing public charging infrastructure</td></tr>
<tr><td>-</td><td>Dense hydrogen infrastructure</td></tr>
<tr><td>Trolley truck infrastructure</td><td>-</td><td>Hybrid Trolley-Truck infrastructure on highly-used motorways in all EU countries</td><td>-</td></tr>
<tr><td>Non-road transport</td><td rowspan="2">TEN-T guidelines (core network completed by 2030, comprehensive completed by 2050, increasing the competitive advantage of railways and inland waterways)</td><td colspan="2">Increased electrification for railways, emission standards for new aircrafts and ships, higher share of LNG for ships, higher share of bio-kerosene for aviation</td></tr>
<tr><td>Shift to more efficient transport modes</td><td colspan="2">More intensive efforts to shift traffic from cars to trains, public transport, cycling and walking, e.g. by improving local public transport</td></tr>
<tr><td>Alternative fuels</td><td></td><td colspan="2">Higher share of bio-fuels, supplemented by synthetic PtX-fuels if not enough sustainable biomass should be available</td></tr>
</table>

5.1.3 Assumptions for the pathway modelling

General method

The ambitious policy scenarios investigated in the case study assume a strong cooperation between all European countries with joint decisions on effective transport policy measures and on technology choice leading to a comprehensive electrification of road transport. Under different conditions, the relevance of the different decarbonisation strategies for transport will vary. Within the SET-Nav project, four holistic transformation pathways are simulated within the modelling framework of the whole SET-Nav consortium to achieve EU GHG reduction targets across all sectors. Each pathway represents specific framework conditions and trends that might evolve in the upcoming decades varying the two key uncertainties (1) degree of cooperation and (2) degree of decentralisation. The key elements and general storyline of the four SET-Nav pathways are described in section 2.3 above. This chapter explains how these general scenario descriptions have been interpreted to develop assumptions for the transport modelling with the ASTRA model for each of the four SET-Nav pathways.

The pathways were developed based on the insights gained in the case study for transport (results are summarised in section 5.2 below). While the case study defined two extreme policy scenarios assuming all countries using either hybrid trolley trucks in the first scenario or FCEV in the second scenario as decarbonisation option for trucks, the pathways include much more variation of technologies between countries depending on the characteristics of the four pathways. Thus, biofuels, LNG and CNG vehicles are also foreseen as alternatives for road transport, even if they seem less preferable compared to electrification via BEV, PHEV, FCEV or trolley vehicles.

In addition, two limitations of the case study scenarios were considered for the pathway simulations. The first limitation of the case study was that automated vehicles were not included. As their diffusion seems relevant for some of the pathway storylines, scenarios for automated vehicles were integrated in the model based on the study by Krail et al. (2019). The market entry of automated and driverless cars is expected after 2035. Driverless vehicles have a higher fuel efficiency of 15-18%. Overall effects on emissions will depend on its application - e.g. using driverless cars only as part of public transport, as shared vehicles in car sharing fleets or permitting them also for private use. Driverless trucks and buses are assumed to diffuse faster into vehicle fleets compared to cars due to higher cost saving potentials with the reduction of driver costs and increased fuel efficiency gains. For the pathways, two scenarios for connected and automated driving were applied based on the study by Krail et al. (2019). The first scenario assumes a „World of vehicle ownership“, while the second scenario represents a "World of mobility services“, in which automated ride sharing for passengers increases and shared automated vehicles for freight lead to increased load factors and more multi-modal transport. This most recent implementation in the model includes effects of connected and automated driving on fuel consumption, occupancy rates, load factors, costs and time required per kilometre. Implications for the number of new vehicles per year are assumed to be minor as higher annual kilometres of shared vehicles lead to faster scrapping and substitution.

The second limitation mentioned for the scenario simulation in the case study was that changes in behaviour and technology choice that are not mainly cost-driven are hard to predict and depend on multiple factors including societal trends and the perceived attractiveness and convenience of more sustainable alternatives. Thus, depending on the characteristics of the pathways, the acceptance levels for car sharing and the active modes walking and cycling, for the diffusion of specific technologies and investments in local public transport were varied. It was also assumed that home-owners with roof-top PV have a higher probability to buy a BEV or PHEV car which becomes relevant in particular for scenarios in which RES electricity supply is deployed with decentral solutions. A reduction of transport activity via complete avoidance of trips was not considered while mode shifts can occur within the model simulation to a certain extent.

Storyline for the transport sector by pathway

In the following, the interpretation on how the transport sector develops based on the individual SET-Nav pathway characteristics is described by highlighting the main differentiation factors.

- **Diversification:**
  The Diversification pathway envisions a future in which the transport system transforms into a "mobility as a service" system where multi-modal information platforms and services are deployed fast. New business models based on shared vehicles lead to higher occupancy and load factors for passenger and freight transport and increase the overall efficiency of the system. Car ownership declines in general while the trend towards car sharing increases. An early market entry of autonomous driving further intensifies multi-modal transport solutions and usage. Several alternatives to conventional power train technologies and a range of different policies are adopted varying between different countries in Europe. The described developments are enabled by a prevailing openness for new technologies, a regulatory opening, high levels of digitalization and experimentation by diverse heterogeneous actors including many new entrants.

- **Directed Vision:**
  In the Directed Vision pathway, centralized policy and investment decisions across all EU countries provide a strong, common direction for low carbon transport. Pure ICE vehicles for passenger and light freight road transport are phased out. Trolley infrastructure for trucks is undertaken in most countries with good access to the EU power grid while islands with limited interconnections adopt fuel cells instead. There is considerable support for public transport and rail freight also for national and international distances enabling a significant modal shift to more efficient modes. Biofuels are mainly foreseen for non-road modes for which alternative low-emission technologies seem not sufficiently mature to prevail substantially by 2050. Behaviour change plays a relatively minor role, the private ownership of cars is still prevalent.

- **Localization:**
  The Localization pathway moves towards transport systems for localized and sharing economies. The role of car sharing, public transport, walking and cycling increases for local mobility. Urban planning measures provide adequate infrastructure for active modes and investments for local public transport are made. The adoption of new technologies differs between countries; big infrastructure projects such as trolley truck infrastructure are avoided. Decentral electricity production via roof-top PV increases incentives for households to buy electric cars. Overall, technological learning is slower due to more diversity and weak spillovers. Therefore, and due to the focus on local resources, the demand for biofuels is relatively high to achieve the GHG reduction targets for transport.

- **National Champions:**
  The National Champions pathway has elements in common with the Directed Vision pathway, as some countries adopt strong policies to achieve decarbonisation, however, emphasizing national development of new technologies instead of international links. Biofuels are adopted on a large scale also for road transport. Only urban ICE buses are phased out. Internal combustion engine

vehicles with the strategy to substitute fossil fuels by alternative fuels are considered as acceptable technology solution for many areas of application. This strategy implies supporting technological progress for sustainable biofuel production including advanced biofuels and an optimal use of biomass. While existing filling station infrastructure can be maintained, supply with biofuels has to be established. The institutions of mobility remain based on car ownership; car sharing is not a major part of transportation. There is relatively little modal shift from road to rail.

Figure 50 summarizes the main characteristics for the underlying development of the transport sector by pathway.

Diversification	Directed Vision
"Mobility as a service" system with new business models, shared and increasingly autonomous vehicles for freight and passengers. Range of various technologies and policies adapted across EU countries.	Joint infraststructure and policy decisions across EU countries. Strong electrification of road transport with trolley truck infrastructure and phase-out of pure ICE vehicles. Biofuels mainly used for non-road modes.
Localization	**National Champions**
Strong role of car-sharing, public transport, walking and cycling for local mobility. Technologies differ between countries. Decentral roof-top PV installation incentivizes electric car purchases for households. Biomass as local resource is part of the decarbonization strategy.	National development of new technologies and policies. Low- and zero-emission technologies diffuse relatively slowly. Biofuels adopted on a large scale, also for road transport. Low changes in modal split and car ownership.

Figure 50: Main characteristics of the transport sector development for the SET-Nav pathways

Model assumptions for pathways

In order to achieve the overall GHG reduction target across all sectors, it is intended that the transport sector reduces GHG emissions by -65% in 2050 compared to 1990 for all pathways.

This strong decarbonisation of the transport sector requires ambitious and effective policy measures. Thus, several measures that were elaborated in the case study were also applied in all pathways, but to a different extent depending on the pathway. These measures include:

- policies to improve the efficiency of vehicles for all road modes,
- measures to increase costs for conventional vehicles while decreasing them for low-emission vehicles (vehicle registration tax and fuel tax based on emissions, R&D and subsidies for new technologies),
- the deployment of charging stations and alternative fuelling infrastructure,
- measures for non-road modes, in particular increased electrification for railways and emission standards for aircrafts and ships,
- policies to increase the share of biofuels for road and non-road modes, and

- measures to achieve a modal shift from driving by individual cars to public transport, car sharing and active modes (assuming e.g. urban planning measures, electronic multi-modal platforms and services, etc.).

The main distinctive assumptions of the individual pathways are described in the following:

Trolley truck infrastructure is deployed for the Directed Vision pathway for all countries with good access to the EU power grid, for the pathways Diversification and National Champions only for selected countries with higher probability of deployment based on current pilot studies, while no deployment takes place in the Localization pathway due to public resistance to new big infrastructure. Hydrogen infrastructure deployment and support for FCEV takes place to different levels in the Diversification and the Localization pathway, for the Directed Vision pathway only for countries without trolley truck infrastructure. The diffusion of CNG and LNG is not further supported in the pathways Directed Vision and National Champions while there are moderate measures promoting these technologies in selected countries in the two more decentralised pathways. The level of biofuel shares varies depending on the country, in particular for the pathways Diversification and Localization. For road transport, the biofuel shares were assumed to increase strongly in the National Champions pathway, while they rise least in the Directed Vision pathway. The highest average biofuel share for aviation in 2050 is reached in the Directed Vision pathway with 55%, while all pathways have a share above 40%.

Phase-out of pure internal combustion engine vehicles for new cars, vans and urban buses is implemented in the Directed Vision pathway across all European countries by 2035 while this strong policy measure plays a minor role in the other pathways for which its implementation varies concerning vehicle scope, affected countries and year of completion.

Based on the storyline of the pathways, automated and connected driving was implemented with the scenario "World of mobility services“ for the Diversification pathway, while the scenario „World of vehicle ownership“ was chosen as most adequate for the three other pathways. Several parameters that affect mode shifts towards car sharing, walking, cycling and public transport were varied according to the described storyline of each pathway. The improvement of public transport was defined highest in the Directed Vision pathway, the acceptance of car sharing lowest in the National Champions pathway, and the trend for e-bikes has the highest level in the Localisation pathway, just to name a few examples.

Table 14 provides a summary of the main differentiating assumptions between the pathways.

Table 14: Summary of varied technology and policy assumptions for the SET-Nav pathways

	Diversification	Directed Vision	Localization	National Champions
Trolley truck infrastructure	DE, NL, DK, FI, SE, NO	Trolley trucks in most countries (wo islands)	-	DE, DK, FI, SE, NO
Measures for FCEV diffusion	Different levels	in countries wo trolley trucks →UK, IE, CY, MT	Different levels	Very low, selected countries only
Measures for CNG/LNG diffusion	Different levels	Very low, selected countries only	Different levels	Selected countries only
Biofuel share	Different levels low to high	Low for road modes, very high for aviation	Different levels low to high	Very high in all countries also for road modes
Phase-out ICE vehicles	Urban buses, cars & LDV in selected countries 2030-40	Urban buses in 2030, cars & LDV in 2035	Urban buses in 2030 for EU15/NO/CH, cars/LDV in selected countries in 2035/40	Urban buses in 2030 for EU15/NO/CH, in 2040 for EU13
Autonomous driving	Scenario „World of mobility services“	Scenario „World of car ownership“		
Car sharing, active modes	Variations of levels for several parameters, e.g. highest level of improvement of public transport in Directed Vision, lowest diffusion of car sharing in National Champions, highest level of e-bike penetration in Localization.			

5.2 Main results and lessons learned from Case studies

5.2.1 Summary of case study results

Development of GHG emissions

The case study differentiated two ambitious policy scenarios due to two promising low carbon technologies for road freight transport: (1) Direct electrification achieved by hybrid-trolley trucks on motorways, and (2) Power-to-Hydrogen based fuel cell electric vehicles. Both policy scenarios exceed the current European GHG reduction targets for the transport sector in 2030 and meet the aimed reduction range of -60% to -65% in 2050 compared to 1990.

In 2015, road transport accounted for approximately 80% of CO_2 emission from transport. While this share decreases only slightly to 75% in the Reference Scenario in 2050, a share of less than 50% is achieved in the Policy scenarios. Due to limited options for decarbonisation for aircrafts and ships, these modes represent around half of the emissions in 2050 in the Policy scenarios.

Development of the share of alternative fuel vehicles in the vehicle stock

In the Reference scenario, pure diesel and gasoline-fuelled vehicles still constitute around 70% of the European car fleet in 2050, while battery electric cars (BEV & PHEV) represent a quarter of the fleet. The development is driven by a planned increase in charging stations as well as by decreasing prices and longer ranges due to technological learning. In the Policy scenarios, cost advantages of conventional cars in relation to low-emission cars were reduced by introducing road charges, fuel taxes and registration taxes that are dependent on CO_2 emissions. In addition, pure gasoline, diesel, LPG and CNG cars were phased out as of 2035. This leads to more than 90% electric cars in 2050, therein around 30% pure battery-electric vehicles. In the Hydrogen policy scenario, the fleet consists of more fuel cell electric vehicles (FCEV) that substitute PHEVs for cars driving long-distances in comparison to the Direct electrification scenario due to experience curve effects and the intensive deployment of hydrogen fuelling infrastructure.

While diesel trucks dominate in the Reference Scenario with less than 3% alternative powertrains in 2050, diesel trucks decrease in the Direct electrification scenario to a share of 53% in the fleet and in the Hydrogen scenario to even 44%. Assuming a deployment of the trolley truck overhead cable infrastructure as of 2020 in the direct electrification scenario, trolley technology starts diffusing from this time onwards for the road tractors and long-distance trucks. Market penetration of fuel cell electric trucks in the Hydrogen scenario starts later due to challenges related to the technology, the hydrogen production and its distribution to refuelling stations. Despite this later start, the fleet composition shows a higher share of FCEVs in 2050 compared to trolley trucks in the Direct electrification scenario because fuel cell technology is used for all truck weight classes not only for the long-distance trucks. In 2050, trolley trucks represent 32% of the truck vehicle stock in the Direct electrification scenario, while FCEVs represent 47% of the truck fleet in the Hydrogen scenario.

For the bus fleet, scenario results show similar developments. The bus fleet remains 86% diesel in 2050 in the reference scenario. By introducing ambitious policies, Diesel share declines further as conventional buses are replaced by BEVs and FCEVs with different proportions depending on the policy scenario.

Development of the transport performance and the modal split

Transport performance in form of passenger and freight kilometers increases steadily towards 2050 mainly due to GDP growth and the development of the population and the income per household.

Current measures defined in the Reference scenario already result in a shift from car use to trains for passenger transport. In the Policy scenarios an even stronger shift is achieved assuming further improvements in public transport in combination with higher costs for driving a car due to policies like higher taxes on conventional fossil fuels. For freight transport, only a slight modal shift was achieved as elasticities are lower and modal shifts even more difficult to obtain. Towards 2050, road freight transport starts regaining share as new vehicle technologies become cheaper due to learning and economies of scale.

Development of the final energy demand for transport

In the Reference Scenario, final energy demand decreases until 2030 due to efficiency improvements, but increases again towards 2050 as transport activity grows continuously. 85% of the final energy demand is still provided by fossil fuels in 2050, only 15% by the renewable energy carriers electricity, hydrogen and bio-fuels.

The Policy scenarios achieve a stronger and steady reduction of final energy demand that continues even until 2050 because battery electric vehicles and trolley trucks have considerably higher efficiency factors compared to conventional ICE vehicles. The share of renewable energy reaches more than 40% in 2050.

The consumption of biodiesel and bioethanol decreases due to the strong electrification of road transport. As biokerosene was chosen as main decarbonisation option for aviation, it constitutes around 65% of total biofuel consumption from transport in 2050.

The electricity demand from transport increases strongly over time due to the diffusion of BEV, PHEV, FCEV and hybrid trolley trucks. While electricity consumption constituted 1% of the total final energy demand of transport in 2015, it develops in the policy scenarios to around 30% in 2050 with more than 850 TWh. Therein, cars will be the transport mode with the highest electricity consumption in 2050. In the Hydrogen scenario, around 270 TWh hydrogen are needed in 2050.

Role of flexibility provided to the electricity system

Battery charging of BEV and PHEV and hydrogen production for FCEV can provide flexibility to the electricity system. If load shifting for battery charging is accepted and charging infrastructure deployed in public areas and at company sites, a certain flexibility potential can be provided by BEV and PHEV and peak loads in the early evening hours can be reduced. Hydrogen for FCEV can be produced via electrolysis, in particular in times of surplus electricity, and be used as electricity storage with the option of reconversion.

The results of the electricity system models Enertile® and EMPIRE indicate that flexibility options in the transport sector can contribute to balancing the variable supply of renewable electricity generation and can significantly reduce the need for back-up capacity in the electricity system. Curtailment, transmission losses and conversion losses in power storage systems can be interpreted as proxies for the utilization of flexibility options. Results show that the presence of load shifting options and the possibility of hydrogen reconversion reduce the utilization of pump storages, the electricity exchange between countries and the amount of curtailed renewable power. If the flexibility options in the Direct electrification scenario of the transport sector are used, the annual CO_2-emissions in the electricity sector are reduced by up to 16% in the year 2050. This reduction can be almost entirely attributed to less natural gas-fired electricity generation.

5.2.2 Lessons learned for SET-Nav pathways

The major strategies for decarbonising the transport sector are (1) shifting to more efficient transport modes, (2) diffusion of low/zero-emission technologies, and (3) bio & synthetic fuels. The case study results for transport show that all three strategies for decarbonisation have to be combined to achieve the SET-Nav GHG emission reduction goals.

The shift away from road to more energy efficient modes is partly restricted by limited capacities of public transport systems and railways, and depends heavily on behavioural change and organisational change in logistics and supply chain systems. Changes in behaviour are hard to predict and can depend on multiple factors such as societal trends. For passenger transport, further developments could enable an even stronger shift to more efficient and active modes. Examples are fully automated vehicles that bridge the 'last-mile' and thus improve access to public transport, higher familiarity with digitalization and thus stronger affinity to use multi-modal information platforms and services or a stronger development towards a sharing-economy.

The new powertrain technologies for road transport offer substantial potentials for decarbonisation. The diffusion of these technologies has to be supported with packages of measures including stricter CO_2 emission standards, sufficient deployment of the filling and charging infrastructure, stronger R&D and subsidies. Phase-out policies of pure internal combustion engine vehicles should also be considered as an effective measure to accelerate the transition.

Furthermore, technological alternatives for decarbonisation have to be assessed for their flexibility potential that they provide for the electricity system and on the overall efficiency because sector coupling is key to achieve the overall energy system transformation in a cost-efficient way. There is a tendency that the higher the flexibility potential the lower the overall efficiency: The best overall efficiency can be achieved by direct electrification with power generation from renewable energy sources either as battery-electric vehicles or as powered overhead-cable solutions. Based on well-to-wheel analyses, BEVs can achieve an overall efficiency factor of around 80%, FCEVs of more than 40%. The results from the electricity system models indicate that flexibility options provided by the transport sector can significantly reduce the need for back-up capacity in the electricity system. For a cross-sector optimisation, flexibility should only be a relevant criteria as long as it supports a secure and cost-efficient energy system, but above this level, overall energy efficiency might be a main decision criteria.

In the case study, biofuels were mainly considered for aviation for which other low-emission alternatives are expected to remain prohibitively expensive until 2050. For pathways with a lower degree of electrification of road transport, alternative fuels might become more important to achieve the GHG reduction targets. The available quantities of sustainable biomass for biofuel production have to be taken into account. If not enough sustainable biomass is available, the potential of synthetic fuels should be further investigated.

5.3 Energy demand and CO_2-emissions in the transport sector in SET-Nav pathways

5.3.1 CO_2 emissions

The development of the CO_2 emissions for the four pathways is depicted in Figure 51. All pathways exceed the European reduction targets for the transport sector in 2030 and in 2050. In 2050, the targeted GHG reduction of - 65% compared to 1990 is achieved for all pathways.

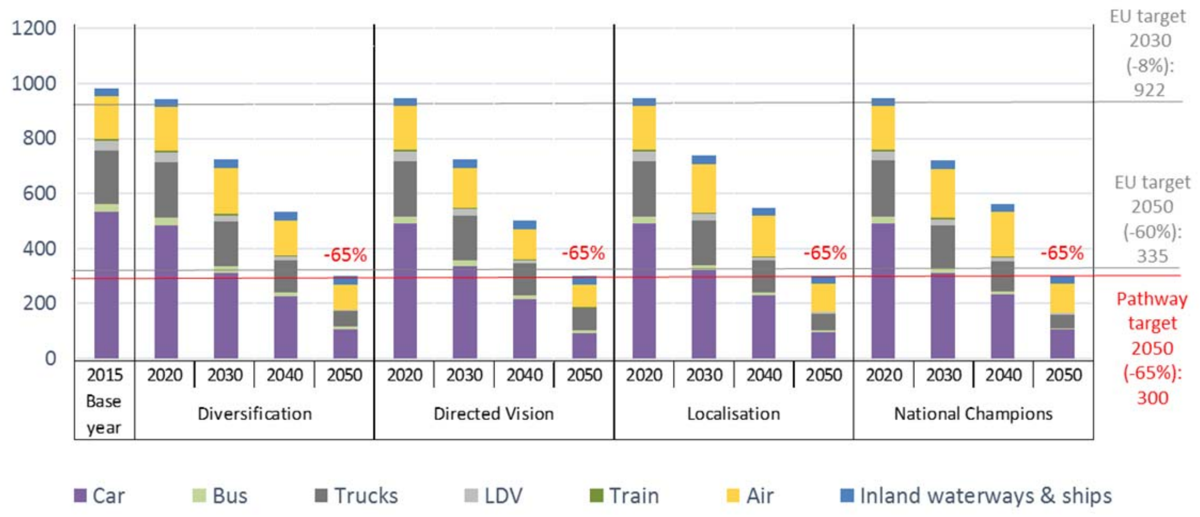


Figure 51: CO_2 emissions by transport mode in EU28 until 2050 in Mt CO_2-equivalent

5.3.2 Technology diffusion in the vehicle stock

Figure 52 shows the development of the powertrain technologies in the European car fleet for the four pathways. The highest share of electric cars (BEV and PHEV) in 2050 with over 90% is achieved in the Directed Vision pathway due to the phase-out decision for pure ICE cars with completion for new sales by 2035 for all European countries. In the Diversification and the Localisation pathway battery electric car share reaches around 50% in 2050. The diffusion over time is supported in these two scenarios by the more decentral deployment of RES: Households with roof-top PV have a higher probability to purchase a BEV or PHEV vehicle due to financial incentives as they generate the electricity for charging the batteries with their PV system and due to stronger technical familiarity. In addition, phase-out decisions were assumed in some countries. In the National Champions pathway, the share of battery electric cars is about a third in 2050. The ratio of PHEV to BEV is with 2:1 relatively high in the Directed Vision pathway as result of the phase-out decision. It was assumed that this strong intervention leads to higher PHEV purchases as it forces all new car buyers to choose an electric car even if they have reservations about battery electric vehicles.

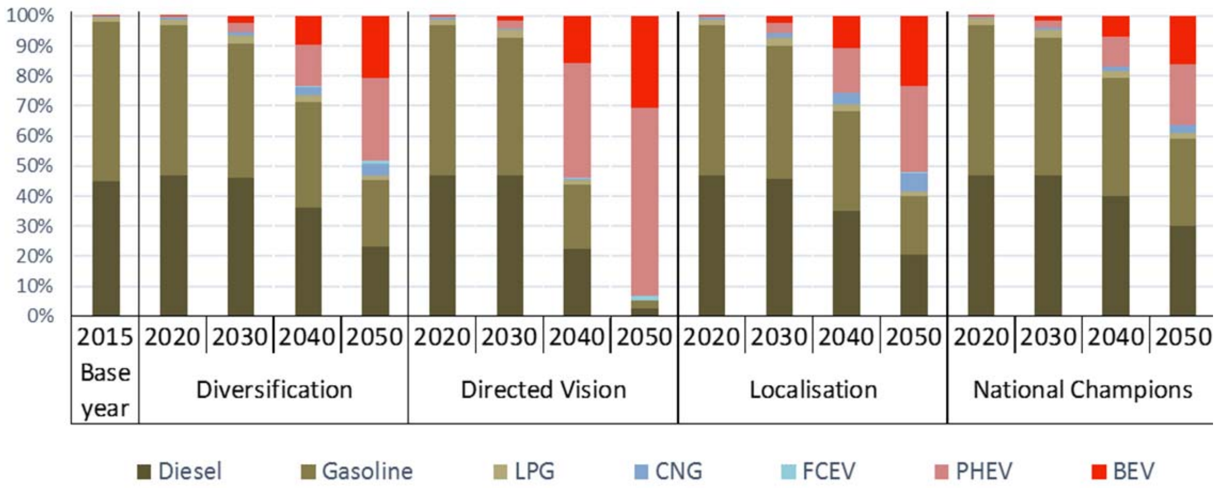


Figure 52: Car fleet composition by technologies in EU28 until 2050

Figure 53 depicts the technology diffusion in the light duty vehicle fleet. The development trends are similar to the diffusion in the car fleet as similar policies apply, but result in higher shares of battery electric vehicles. One reason is the increasing fleet of CEP (courier, express mail and parcels) operators delivering parcels in cities that already tend to change to vehicles with electric drive. Also other vehicle owners like craftsmen want to ensure that they can enter cities to get to their clients.

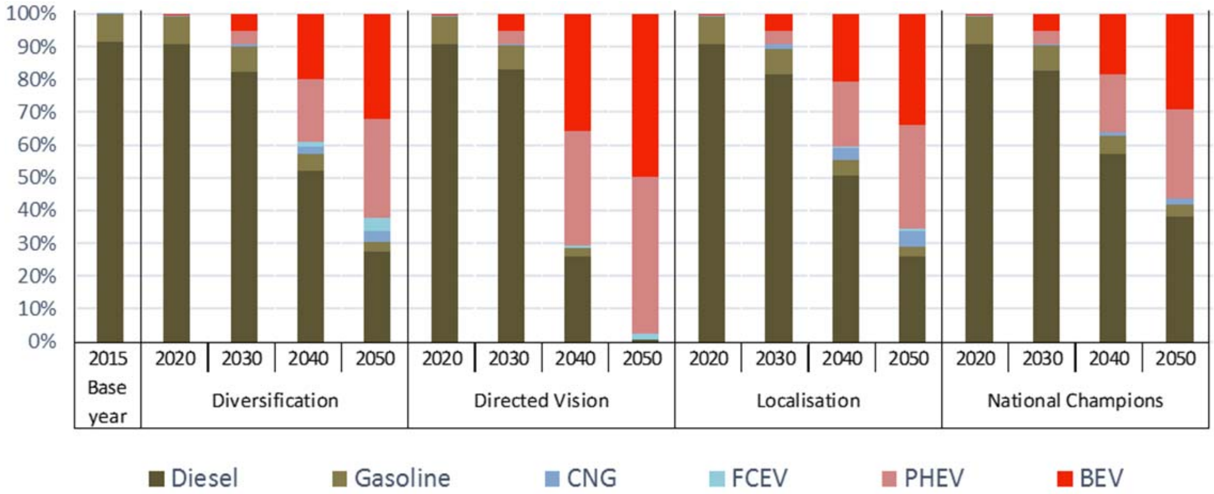


Figure 53: Light Duty Vehicle (LDV) fleet composition by technologies in EU28 until 2050

For the truck fleet, the technology diffusion over time is illustrated in Figure 54. In the Directed Vision pathway, the diffusion of hybrid trolley trucks for the heaviest truck weight class becomes obvious. As the trolley truck overhead cable infrastructure is assumed to be deployed as of 2020, trolley technology starts diffusing from this time onwards for the road tractors and long-distance trucks. This is also the case in some countries in the pathways Diversification and National Champions for which the respective infrastructure deployment was assumed based on current pilot studies. The Diversification scenario results with the lowest diesel share in 2050 of all pathways. Technologies in the vehicle stock are diverse including a certain penetration of hydrogen trucks. The diffusion of fuel cell electric trucks starts later and depends on the weight class due to challenges related to the technology, the hydrogen production and its distribution to refuelling stations. Except for the Directed Vision pathways, CNG and LNG trucks also diffuse notably. However, their CO_2 reduction potential is relatively low and requires higher shares of biomethane to contribute to the reduction target. BEV and PHEV trucks diffuse to a certain extent in all pathways for the lowest weight class.

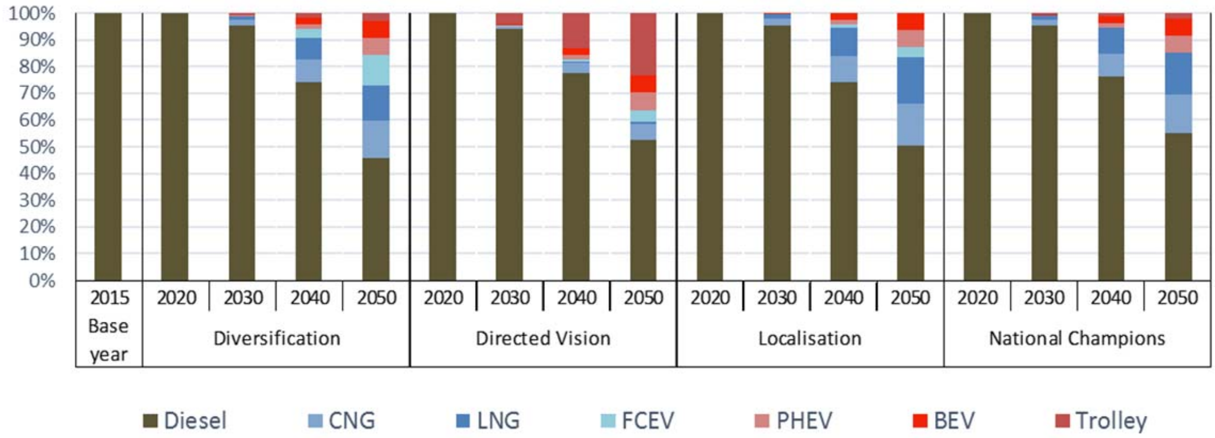


Figure 54: Truck fleet composition by technologies in EU28 until 2050

Figure 55 visualizes the bus fleet composition. The fleet comprises urban buses and coaches. Depending on the infrastructure deployment, learning effects between road modes and decisions on a phase-out of urban diesel and CNG buses, low-emission technologies diffuse in the pathways to a different extent. For urban buses, BEV, FCEV and CNG buses are the most visible alternatives chosen. The number of urban trolley buses increases assuming infrastructure extensions and their suitability for bus lines with high demand. However, their share in the urban bus fleet stays minor compared to other technologies due to lower acceptance of the required infrastructure within the cities. Diesel plays still a major role for coaches except for countries in which LNG and hydrogen is promoted for trucks. With a deployment of overhead power lines on motorways for hybrid trolley trucks, trolleys might become also an option for coaches. As this option has only recently been discussed and due to low modal share of long-distance coach transport, this technology option has not been implemented in the model yet and could not be considered in the pathway simulation.

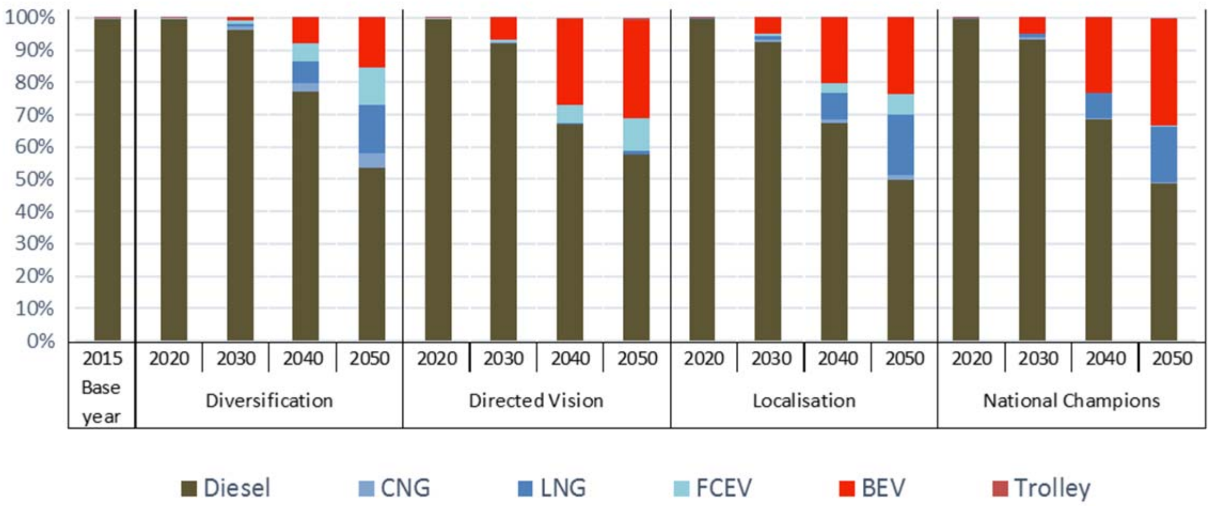


Figure 55: Bus fleet composition by technologies in EU28 until 2050

5.3.3 Development of transport performance and modal split

As already described above, transport demand is assumed to increase over time, mainly caused by economic and population growth expected in the future decades. However, in all pathways, kilometres driven by cars will grow less strongly compared to total passenger transport performance due to policies and measures that encourage to use public transport or to choose walking or cycling for local distances instead of using the car (see Figure 56).

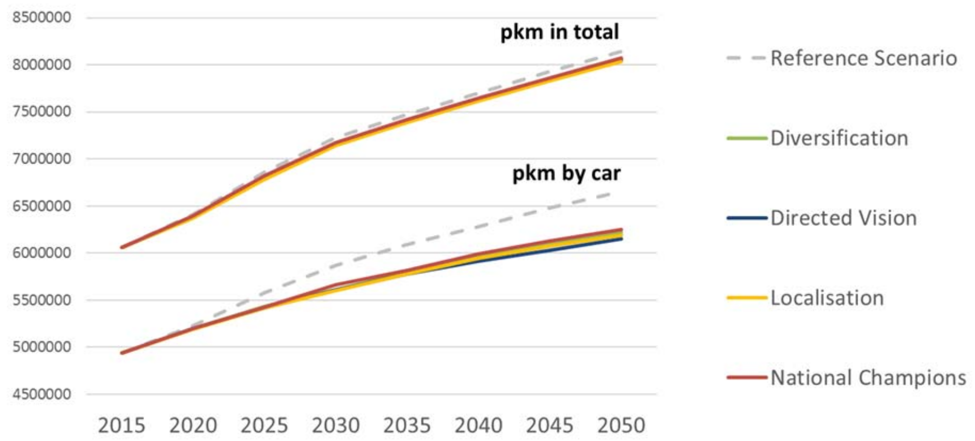


Figure 56: Passenger Land Transport EU28 in Mio. passenger kilometres (pkm)

This impact is also visible when looking at the modal split for passenger total transport demand (see Figure 57). The modal share of cars in the pathways is estimated to decrease by ~6% in 2050 compared to 2015. The highest gains of modal share for public transport (trains and buses) are achieved in the Directed Vision Pathway (+4% in 2050 compared to 2015), followed by the Localisation (+3,5%) and the Diversification Pathway (+3,3%).

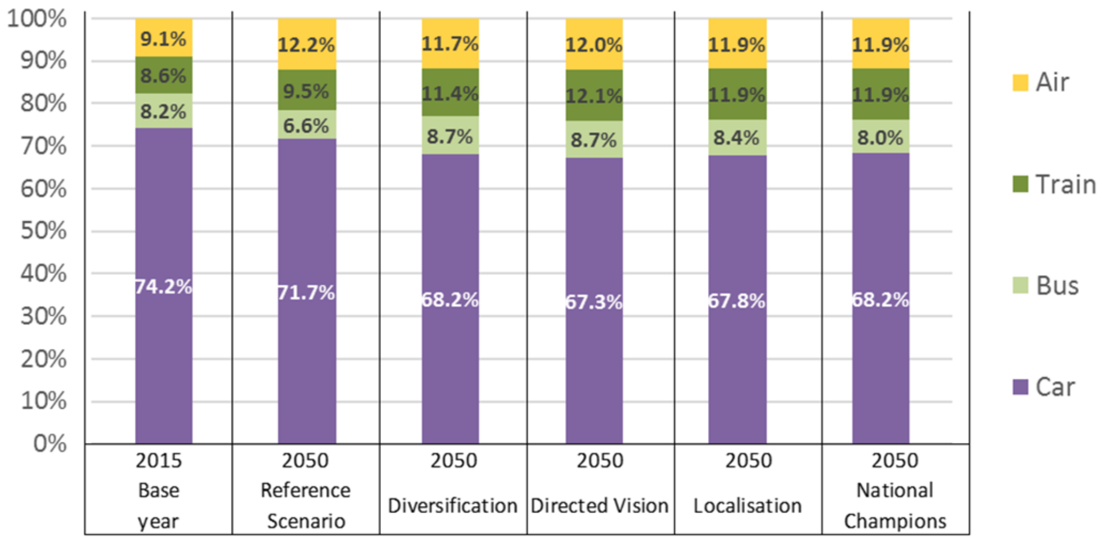


Figure 57: Passenger Transport EU28 - Modal split (based on pkm origin country)

While cars remain the main option for long-distance transport despite a slightly reduced role, more sustainable modes gain modal share in short distances for local transport. These include besides public transport services (bus, train, etc.) innovative mobility solutions (e.g. e-bikes) as well as active modes (walking and cycling).

For the freight sector, road transport will remain the central mode in all pathways. Until 2030, the modal share of trucks decreases slightly but regains share in the modal split towards 2050. This rebound effect results from measures like improved fuel efficiency, emission standards and deployment of refuelling infrastructure for alternative fuels that make road freight transport relatively clean and in addition economically attractive over time. Moreover, prices of low-emission technologies like PHEV, BEV, FCEV and trolley trucks decline due to economies of scale and learning. The smallest rebound effect could be observed in the Directed Vision pathway for which the biggest improvement of railway infrastructure was assumed.

5.3.4 Final energy demand

Figure 58 visualizes the development of the final energy demand for the transport sector[7] by energy carrier.[8] For all pathways, the total final energy demand is decreasing over time despite a growing transport activity. The underlying strong improvement of fuel efficiency is achieved through stricter standards for cars, vans, buses and trucks and positive efficiency effects of autonomous driving towards 2050. In addition, the increasing electrification of road transport has a favourable impact as battery electric vehicles and trolley trucks have higher efficiency factors compared to ICE vehicles. Thus, the final energy demand is lowest in the Directed Vision pathway as this pathway has the strongest electrification because pure ICE cars and vans were phased-out and trolley truck infrastructure on highways was deployed.

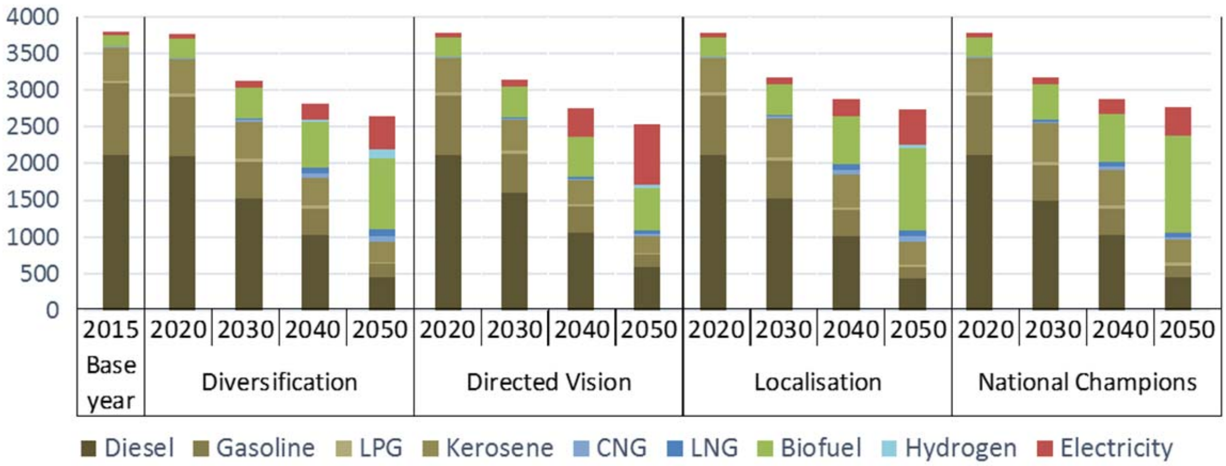


Figure 58: Composition of the final energy demand of the transport sector by energy carrier in TWh in EU28 until 2050

[7] excluding intercontinental shipping

[8] Final energy demand on country level is provided in the Annex in Table 23.

The electricity consumption by the transport sector increases noticeably in all pathways (see Figure 59). The consumption is highest in the Directed Vision pathway with more than 800 TWh in 2050 representing a third of the final energy demand of the transport sector and lowest in the National Champions pathway with about 400 TWh. While trains consume more than 99% of the electricity from transport in 2015, cars will dominate the electricity demand by 2050 in all pathways due to the diffusion of battery electric vehicles.

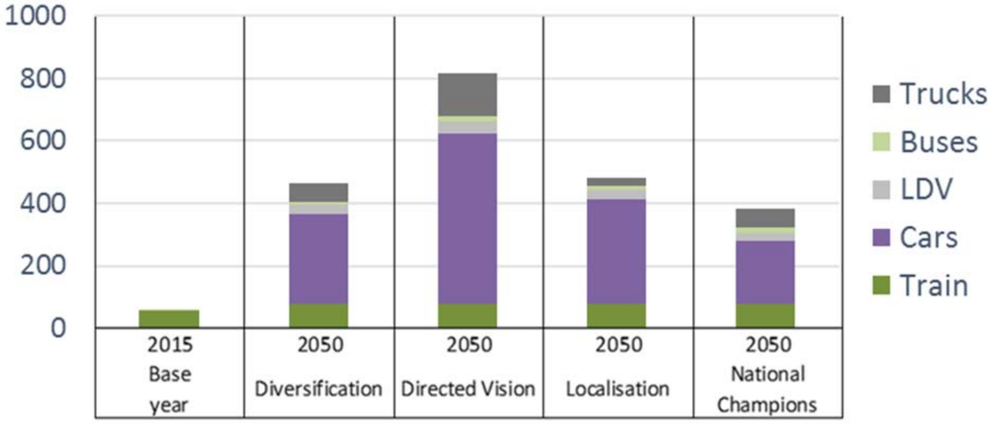


Figure 59: Final electricity demand in TWh in EU28 in 2050 by scenario and mode

Figure 60 shows the development of hydrogen consumption by pathway in 2050. While hydrogen consumption is only marginal in the National Champions pathway, the other three pathways show a certain diffusion of FCEV with respective quantities of hydrogen consumption in particular by trucks but also by cars and buses. The highest amount of hydrogen with more than 110 TWh in 2050 is consumed in the Diversification pathway where heterogeneous actors and experimentation lead to a higher diffusion of FCEV technology.

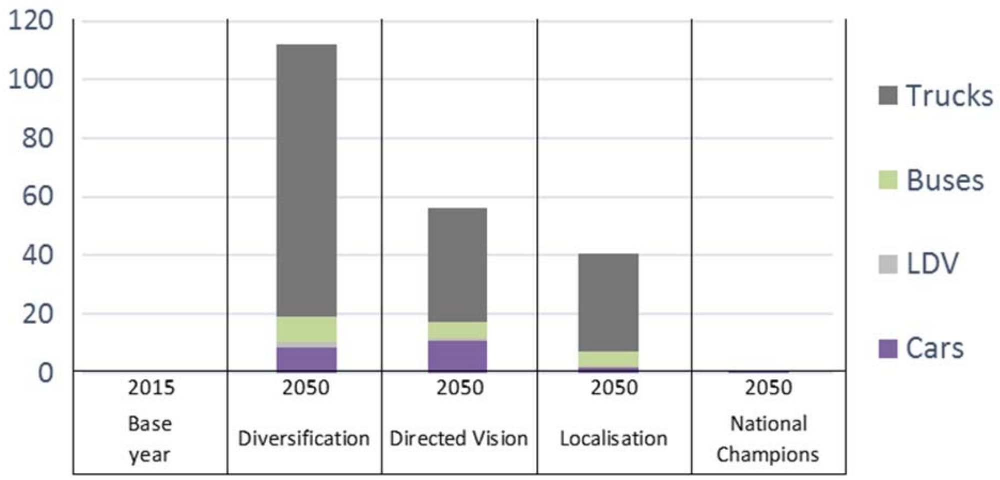


Figure 60: Hydrogen demand in TWh in EU28 in 2050 by scenario and mode

The development of biofuel demand is shown in Figure 61. As technological alternatives with higher efficiency are not available for aircrafts, biokerosene plays an important role in all pathways in order to achieve the GHG emission reduction targets. Biodiesel, bioethanol and biomethane are used for road transport and for ships. The lowest amount of biofuels is consumed in the Directed Vision pathway where the strategy lies on the electrification of road transport while biofuels are mainly intended for non-road modes. The highest amount of biofuels is required in the National Champions pathway where biofuels are also seen as a solution for reducing emissions of road transport.

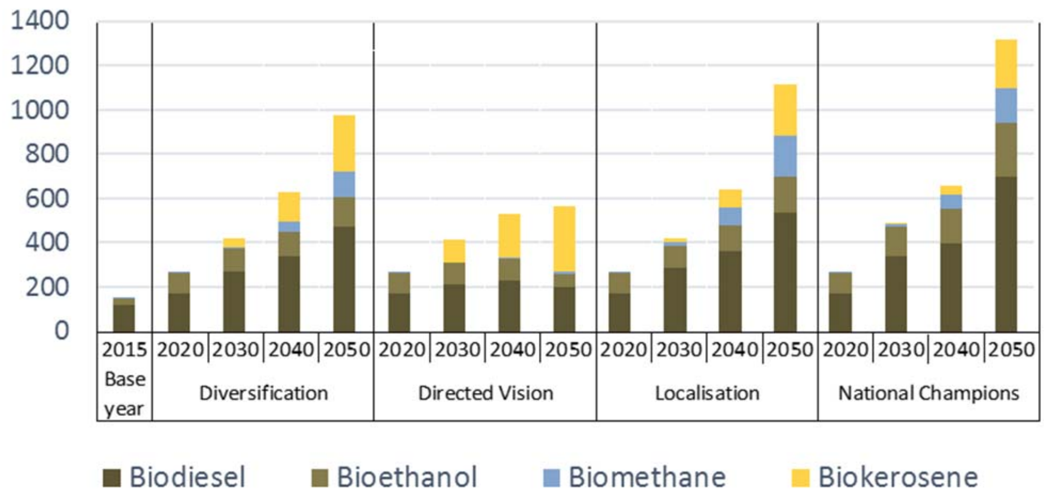


Figure 61: Biofuel demand of the transport sector by type in TWh in EU28 until 2050

The higher the amount of biofuel consumption the more attention has to be paid that sustainable biomass is available in sufficient quantity. Therefore, availability of bioenergy feedstock potential has been checked based on the EC study Biosustain (DG ENER, 2017) in which biomass potential was allocated to different sectors including a certain share for the transport sector. In order to calculate the quantity of bio-based fuels that can be produced with this allocated biomass, the biomass utilization efficiency (BUE) for bio-based fuels was taken from Iffland et al. (2015; cf. table 2 on page 5). Based on these assumptions, European biomass is sufficiently available for the production of the consumed biofuels in all pathways. This development implies learning effects for biofuel production and advanced waste-based biofuels. While the pathways do not include PtX-fuels, these synthetic fuels could be further investigated as substitute for biofuels.

5.4 Related investments and expenditures

Infrastructure investments

The diffusion of technologies as simulated in the case study scenarios and the pathways requires diverse investments in infrastructure (refuelling/charging stations and their supply with alternative fuels, pipelines for hydrogen transport as one distribution option, overhead-cable infrastructure on motorways for trolley trucks) and in production capacities for hydrogen and biofuels. The infrastructure deployment does not develop endogenously in the ASTRA model; instead, the extent of infrastructure deployment is set exogenously as an input for the scenario simulation. The required investments will depend strongly on the chosen configuration of the infrastructure. How the infrastructure should be configured for a most cost-efficient deployment is still part of on-going studies. In the following, selected general insights from technology-specific studies are described to provide a first indication on required investments for infrastructure and to give an idea about alternative realization options under study.

- Investments for setting up a sufficient hydrogen filling station infrastructure with a hydrogen distribution network depend on various factors. The level of investment will depend on the number and scale of the single stations and on the decision whether hydrogen is produced in larger production sites and transported via pipelines and trailers or if hydrogen will be produced on-site directly at the filling stations. Different strategies on combining various scales of filling stations during ramp-up and for the final set-up are discussed as well. According to experts, investment costs for a small-scale hydrogen filling station would be around 1 million Euros. Due to the different tank capacities of passenger cars and long-haul trucks, hydrogen filling stations for trucks need to be large-scale, requiring investments of 10 up to 36 million Euros per filling station. Kluschke et al. (2019) suggest a set-up for Germany consisting of mainly large XXL size hydrogen fuelling stations with a daily capacity of up to 30 t of hydrogen. A hydrogen filling station of this scale is estimated to cost around 36 million Euro per station with additional investments of 111 million Euros for an electrolyzer if hydrogen is produced on-site. Varying numbers and sizes of filling stations, the deployment of a European network of 900 up to 5.000 hydrogen filling stations could lead to infrastructure investments of around 50 billion Euros.
- A study for deploying motorways in Germany with trolley infrastructure concludes that a sufficient and cost-efficient deployment is achieved when a third of all motorways is covered with overhead cables (Wietschel et al. 2017). Routes should be selected in a way that they represent the most highly frequented and thus towards two thirds of the distances driven on motorways by the trucks. Assuming a required infrastructure investment of 2 million Euros per kilometre, total investments would add up to 51 billion Euros for EU28.
- Prices for battery electric vehicles decline fast, making them soon an attractive option from a cost perspective. However, range anxiety is currently one of the biggest barriers to the purchase of battery electric vehicles. Increasing the size of battery capacities is one solution, improving the availability of fast charging stations an alternative. Funke et al. (2019) conclude in their study that sufficient charging infrastructure for fast charging is key to ensure that users of BEV can complete all their trips and from a cost perspective favourable compared with increasing battery capacities.

For the pathways, investments for the filling stations and catenary system were calculated using assumptions based on the studies described above. Figure 62 shows the resulting investments for filling and charging station infrastructure and for the deployment of a catenary system as defined for the individual pathways in the respective years. These investments do neither include electrolyzers for the production of hydrogen nor pipelines for the distribution of centrally produced hydrogen from larger plants to the filling stations. Thus, overall investments that are required for the deployment of a hydrogen filling infrastructure including hydrogen production and distribution will be significantly higher. Large amounts for filling stations in 2035 and 2040 relate to the deployment of LNG and hydrogen filling stations for trucks.

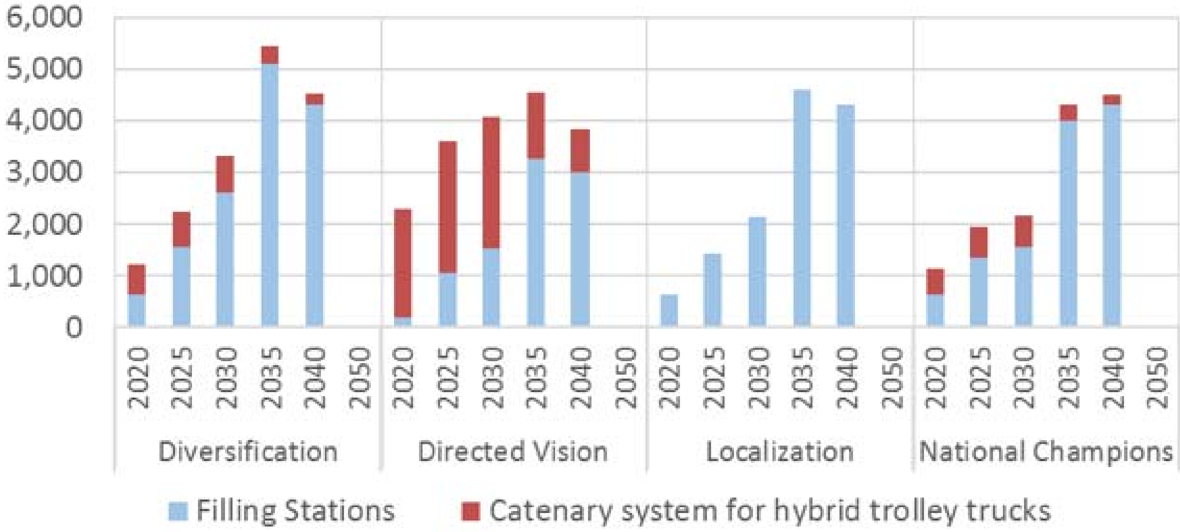


Figure 62: Infrastructure investments for new drive technologies in EU28 by pathway in million EUR

In relation to all infrastructure investments that are required for maintaining and extending the transport infrastructure, the yearly investments for setting-up a catenary system for hybrid trolley trucks and for deploying fueling and charging infrastructure for alternative drive technologies are comparatively low, being in an order of below 5% of yearly total investments. Figure 63 visualizes this proportion. Transport networks investments comprise the TEN-T investments intended for the development of a Europe-wide network of roads, railway lines, inland waterways, maritime shipping routes, ports, airports and rail-road terminals. Investments for biofuel production, hydrogen production and pipelines are not included.

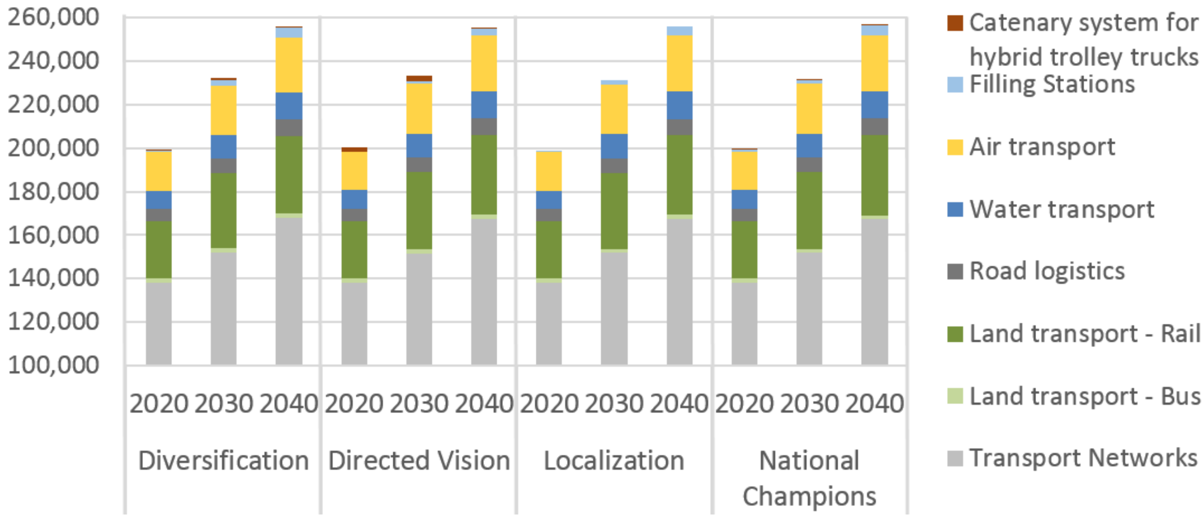


Figure 63: Infrastructure investments in EU28 by pathway in million EUR

A mix of governmental and private investments seems necessary for funding the infrastructure and alternative financing solutions have to be discussed including private-public partnerships. Investments by the private sector might be preferable, only supported by governmental subsidies where needed.

Decisions and regulations on national and European level towards a specific technology and infrastructure would reduce investment risks and could therefore support private investments.

Investments and expenditures of private households

Figure 64 shows the development of investments and expenditures by private households for land transport in the different scenarios. While total spending increases steadily until 2050 in the Reference Scenario and the National Champions pathway, they increase first, but decrease again towards 2050 in the other three pathways due to the diffusion of electric vehicles and an increase in the use of transport services. The Diversification pathway results in 2050 in the lowest investment in vehicles and related expenditures for fuel, maintenance and insurance and the highest spending for transport services as car ownership rates decrease and the popularity of "mobility as a service" solutions with shared rides and vehicles increases in this scenario. Altogether, this leads to total spending for land transport by private households being lowest in the Diversification pathway.

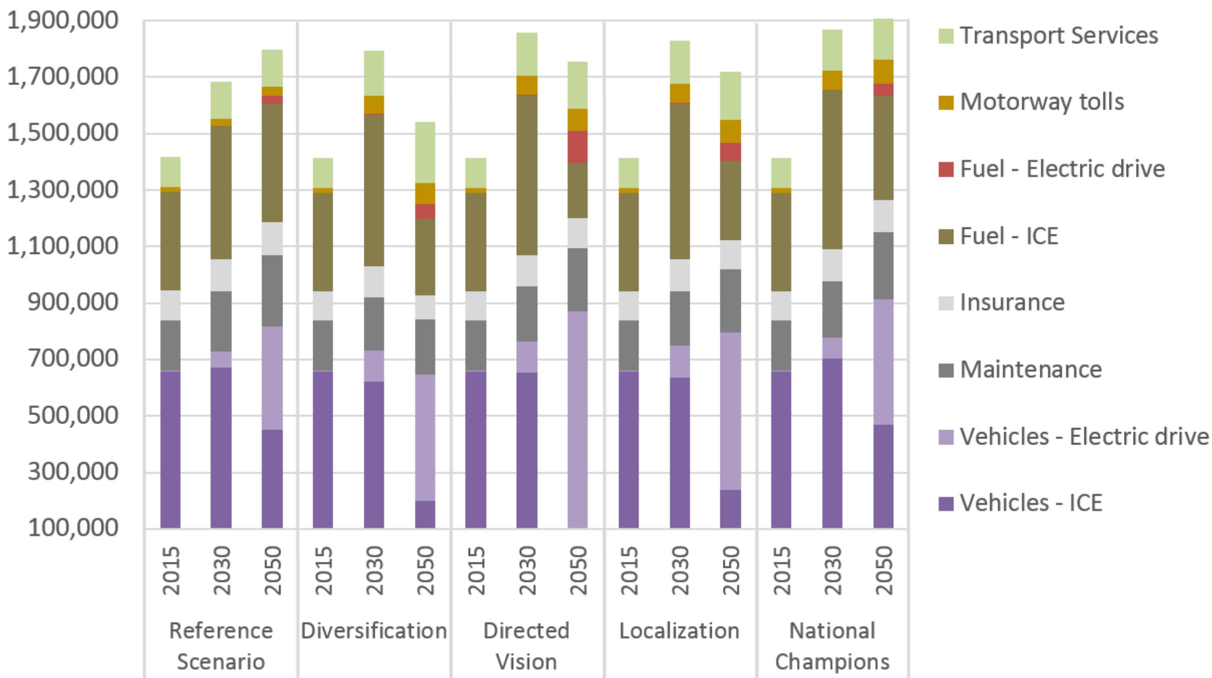


Figure 64: Investments and expenditures for land transport by private households in EU28 in milion EUR

5.5 Conclusions and policy recommendations

A combination of measures is required to accelerate the transition towards a decarbonized transport system. The diffusion of low and zero-emission technologies depends on several factors, in particular vehicle prices and running costs, sufficient filling and charging infrastructure, convenience and the variety of available vehicle models. Measures to push sales of electric vehicles include stricter fuel efficiency or CO_2 standards that put pressure on the automotive industry to develop and offer more and better electric vehicle alternatives to conventional ICE vehicles, infrastructure deployment to ensure reliability and to reduce range anxieties and measures to reduce costs for new technologies while increasing costs for conventional vehicles (such as fuel taxes and vehicle registration taxes based on the related emissions). Decisions on phasing out pure ICE cars are an effective intervention to accelerate the diffusion of alternative drive technologies and should be taken into consideration. By 2030, the infrastructure required for low-emission technologies should be implemented at least for the core motorway network. This includes depending on the chosen technologies overhead cables for trolley trucks, sufficient filling and fast charging stations including their supply with hydrogen and sustainable biofuels.

Modal shift from cars to the more efficient modes public transport, car sharing, cycling and walking can be achieved by making cars less attractive via urban policies (ban in cities at least for fossil-fuel based cars, parking policies) while promoting and increasing the convenience of more sustainable modes (multi-modal platforms enabling seamless ticketing, reduced waiting times and real-time trip planning; town planning measures to improve infrastructure for active modes).

The diffusion of zero-emission vehicles like battery electric cars, fuel cell electric trucks and hybrid trolley trucks generates an increasing electricity demand by the transport sector. Increasing biofuel shares as blend for fossil fuels leads to a growth of required biomass. Biofuel production capacities need to be built up. In contrast, the consumption of fossil fuels should decrease strongly over time.

The ambitious scenarios and pathways analysed reflect radical changes that need to be achieved within only three decades. Policies need to be in place soon to drive this transition considering the lifetime of vehicles, the required time for fundamental acceptance of new technologies and for changes in behaviour, supply chains and business models.

If there are coordinated joint approaches between countries, prices for new technologies could decrease faster due to learning effects and economies of scale. Intensive discussions are required on the best policy mix on European and national level. Relevant discussion points include the current strategy of technological openness versus a focus on the most cost-efficient technology pathway and most effective and cost-efficient policy measures. Moreover, measures for the transition should ensure affordability and inclusiveness of mobility. More research seems needed to evaluate alternative technologies and strategies for the deployment of new infrastructure. Studies on acceptance, economic, social and ecological impacts and secure supply of scarce resources should be considered when narrowing options down to specific technological solutions.

6 Summary and overall development of energy demand in the SET-Nav pathways

This section provides an overview of the outcomes for all demand sectors that were modelled in the SET-Nav project and the additional energy demand that was not directly modelled by the models applied in the SET-Nav project.

6.1 Consideration of energy demand not modelled by sector models

Additionally to the sector results presented in the previous sections also the energy demand for electric appliances, cooking, agriculture and other uses were added to derive a more complete picture of total final energy demand in EU28. Total energy demand developments for electric appliances, cooking, agriculture and other uses was derived from the Primes EUCO-30 scenario (European Commission 2016g). The energy carrier mix for the status quo for each category was derived from national statistics on energy balances and projected into the future assuming decreasing shares of fossil fuels and increases in electricity shares in line with the average pathway results of the sector analysis. Figure 65 illustrates those assumptions which have been held constant in all pathways. The following figures will show the sum of the pathways results from all sector models plus the additional demand developments that have not been directly modelled in the SET-Nav project. The results on electric appliances and cooking are summarized in the buildings sector while energy demand on agriculture and other uses are summarized under the category "others".

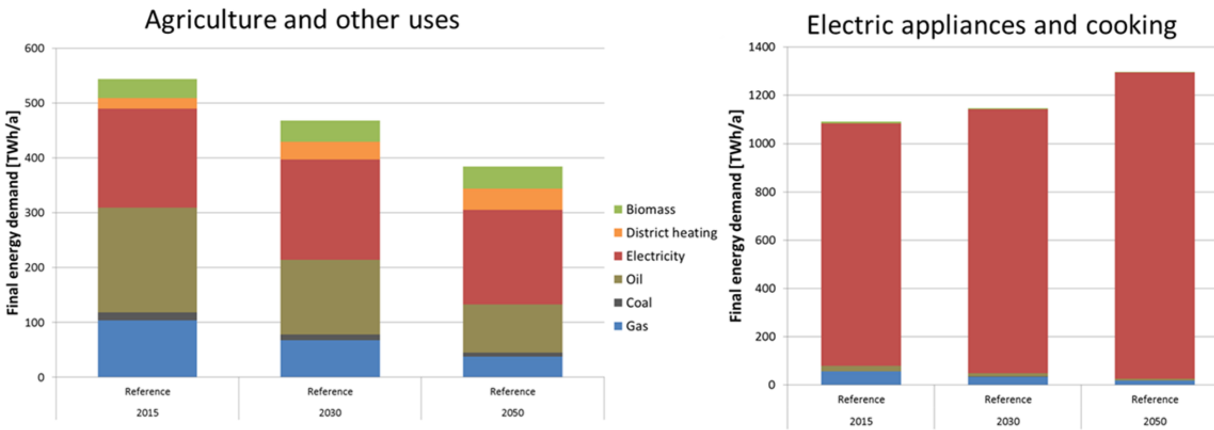


Figure 65: Assumptions on development of energy demand in sectors not modelled by sector models used in the SET-Nav project

6.2 Development of total final energy demand in SET-Nav pathways

Figure 66 and Table 1 show the development of energy demand per sector and the respective shares in all pathways. As already discussed in the previous chapters final energy demand decreases significantly from 2015 to 2050 in all pathways. In total, final energy demand is expected to decrease by -20% to -25% as a result of different efficiency increases in each sector. The reference scenario only results in reductions of -6% until 2050. The share of the building sector is expected to stay at around 36% throughout the simulation period. In the transport sector, the final energy demand decreases to a greater extent compared to the other sectors due to high efficiency increases that stem from a strong improvement of fuel efficiency for all vehicles, positive effects of connected and automated driving and the switch to electric drives. Therefore, the share in total energy demand is lower in 2050 than in 2015. Note that the reference scenario only leads to reduction of -2% in the transport sector while the pathways result in reductions of up to -34% of final energy demand. The reference scenario for the industry sector results in a slight increase of 2%. The pathways where CCS is allowed (Directed vision and National Champions) lead to final energy demand reductions of -11% compared to reductions of -23% in the other pathways. This also indicates that much stronger efficiency measures are needed for strong decarbonisation pathways in the industry sector if CCS is not an option.

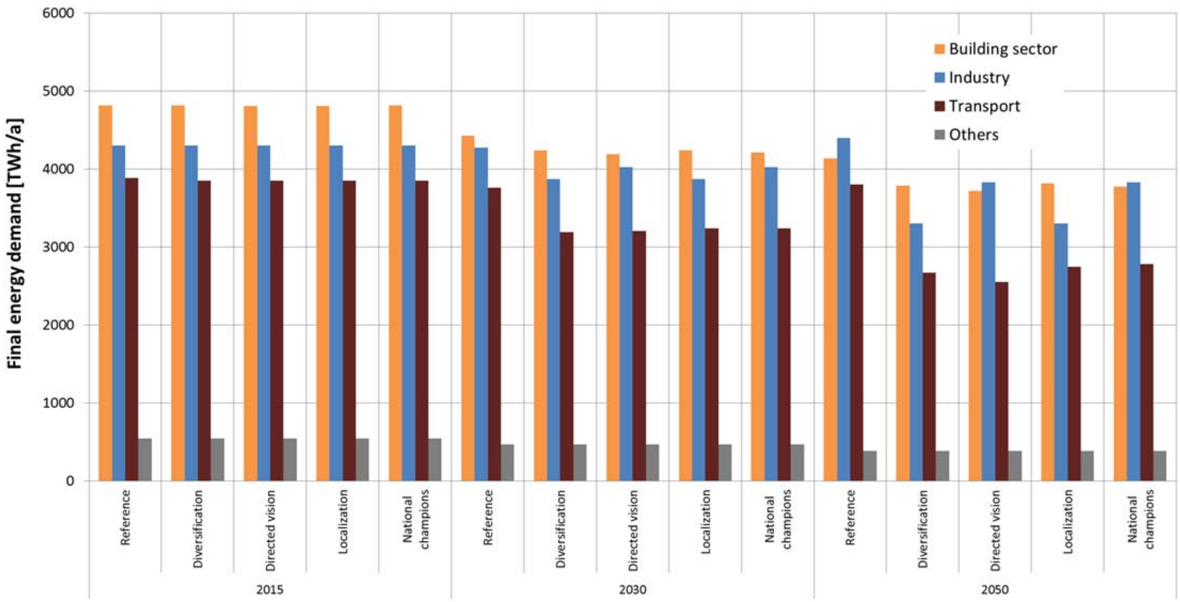


Figure 66: Development of final energy demand per sector in EU28

Table 15: Shares of sectors in final energy demand and change in total final energy demand from 2015 to 2050

		Building sector	Industry	Transport	Others	Total
	Share 2015	36%	32%	29%	4%	100%
Shares 2050	Reference	33%	35%	30%	3%	100%
	Diversification	37%	33%	26%	4%	100%
	Directed vision	35%	37%	24%	4%	100%
	Localization	37%	32%	27%	4%	100%
	National champions	35%	36%	26%	4%	100%
Change	Reference	-14%	2%	-2%	-29%	-6%
	Diversification	-21%	-23%	-31%	-29%	-25%
	Directed vision	-23%	-11%	-34%	-29%	-22%
	Localization	-21%	-23%	-29%	-29%	-24%
	National champions	-22%	-11%	-28%	-29%	-20%

Figure 67 shows the development of final energy demand for all sectors per energy carrier. The phase out of fossil fuels in the pathways in contrast to the reference scenario is clearly visible in this figure. The higher remaining shares of fossil fuels in the Directed Vision and National Champions pathway are a result of the existence of CCS in the industry sector in both pathways and the remaining gas demand for buildings in the National Champions pathway which is added to Gas in this figure. Under this assumption final energy covered by fossil fuels is reduced by -76% in the Diversification and Localisation pathway, -64% in the Directed Vision and -59% in the National Champions pathway. The reference scenario leads to a reduction of only -20%. Total gas demand is reduced dramatically in all pathways until 2050 with reductions between -49% in the National Champions and -75% in the Diversification and Localization pathway. Demand for oil is drastically reduced to -76% in the Diversification and Localization pathway and around -65% in the Directed Vision and National Champions pathway. The main share of remaining oil demand in 2050 can be attributed to the use of Diesel and Gasoline in the transport sector.

Electricity demand increases significantly in all scenarios with increases of more than +50% in the Diversification and Localization pathway. Also final energy demand for biomass related energy carriers (biomass, biofuel, biogas) increases strongly ranging from +69% in the Directed Vision to +138% in the National Champions pathway.

With shares of 5% (National Champions) to 8% (Localization) ambient heat utilized through installations of heat pumps in the building and industry sector makes up for a significant share of final energy demand. While the share of district heating in total final energy supply for the year 2050 increases in all pathways, absolute final energy demand for district heating in 2050 compared to 2015 only increases in the Directed Vision pathway. Despite a strong uptake of solar thermal systems in the building sector energy delivered from solar thermal systems only makes up for relatively low shares in an overall demand perspective. Note that electricity delivered from rooftop PV systems is included in total electricity demand within this figure.

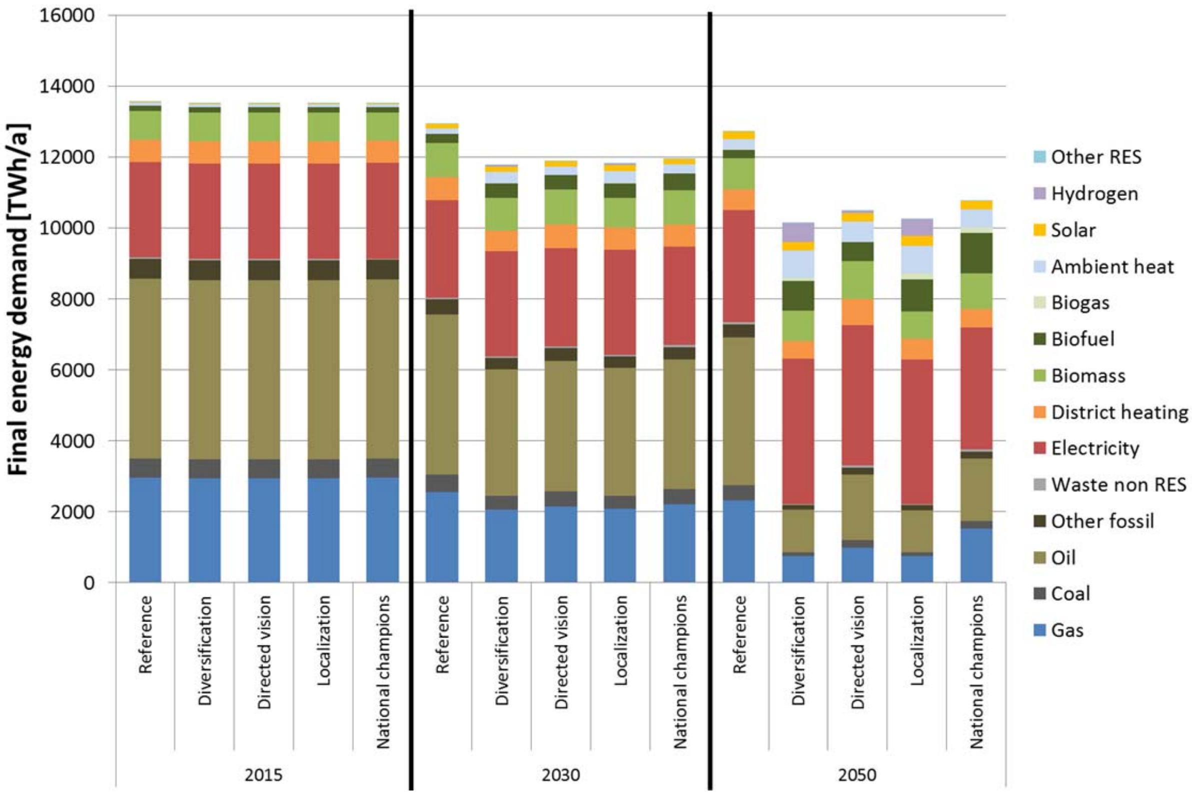


Figure 67: Overall final energy demand per energy carrier for EU-28 in all pathways

Table 16: Overall final energy demand per energy carrier for EU28 in all pathways in TWh

	Reference	Diversification	Directed vision	Localization	National champions
Gas	2328	750	995	748	1516
Coal	426	101	212	101	229
Oil	4168	1200	1830	1197	1756
Other fossil	352	135	198	135	198
Waste non RES	73	31	66	31	66
Electricity	3154	4096	3950	4088	3430
District heating	591	495	733	571	519
Biomass	870	850	1089	767	1005
Biofuel	249	839	529	904	1141
Biogas	6	104	9	179	139
Ambient heat	276	758	580	784	517
Solar	220	234	233	262	244
Hydrogen	7	554	57	483	2
Other RES	2	0	1	0	1
Total	12721	10148	10482	10249	10765

Figure 68 and Figure 69 illustrate the development of final energy demand for biomass related energy carriers per energy carrier and per sector respectively. The figures show that the main difference between the pathways can be attributed to the difference in demand for biofuels in the transport sector and to a lesser extend to the fuel switch in the industry sector in the National Champions and Directed Vision scenario. The increase in the use of biofuels in the transport sector is directly linked to a lower level of electrification in the National Champions pathway. The differences within the building sector only play a minor role in the overall demand for biomass within the pathways.

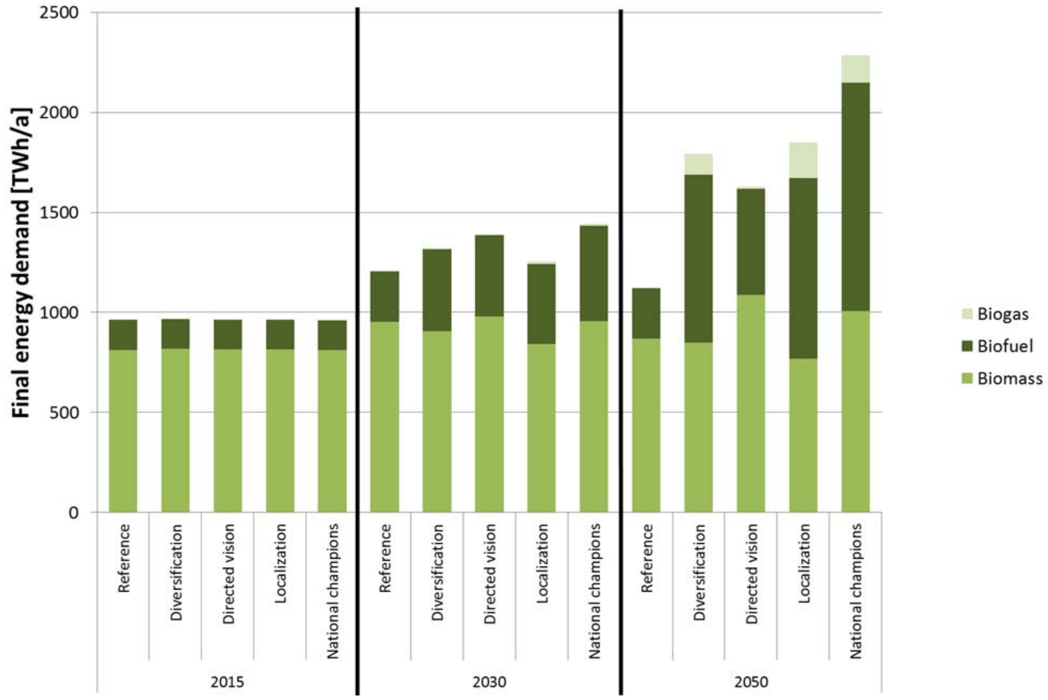


Figure 68: Development of final energy demand for biomass for EU-28 in all pathways

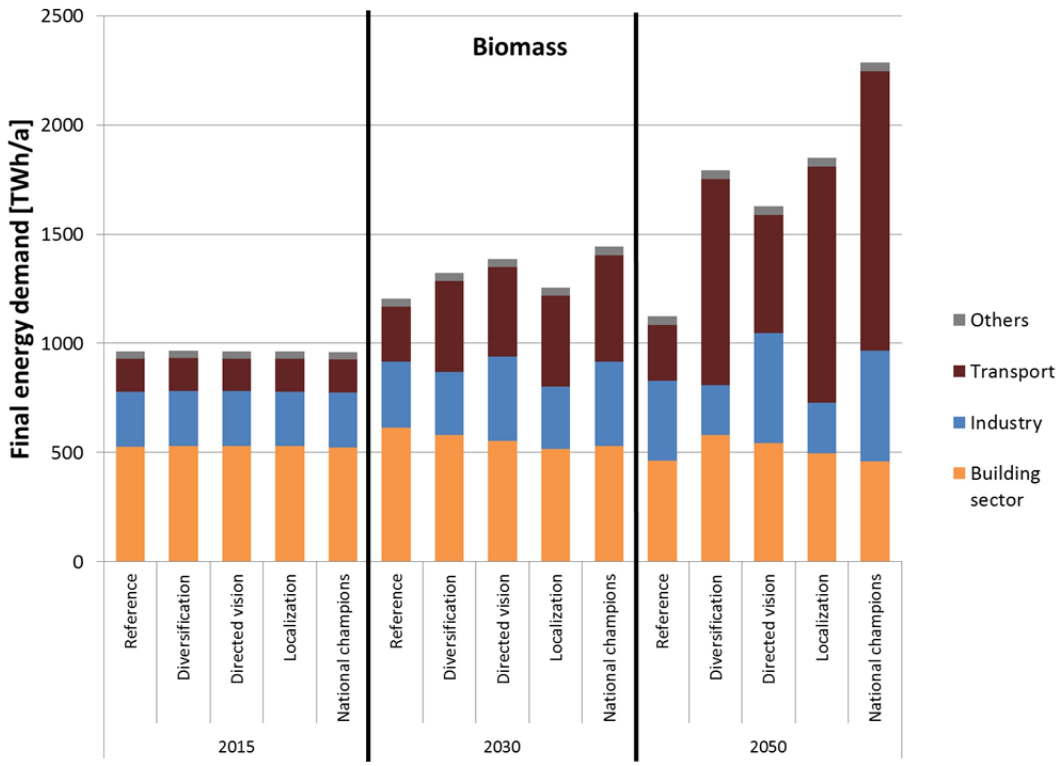


Figure 69: Biomass demand per sector in SET-Nav pathways.

Figure 70 illustrates the development of electricity demand per sector. It can be seen that the overall electricity demand increase in the Diversification and Localization (+52%) pathway is strongly driven by the increased electrification in the industry sector. The option of CCS in the industry sector reduces the stress on the electricity system in the Directed Vision and National Champions pathway. In the Directed

Vision pathway the strong electrification of the transport sector leads to an increase of total electricity demand (+47%) which is in the range of the Diversification and Localisation pathway. The National Champions pathway leads to the lowest increase of electricity demand (+27% compared to 2015). This is due to the existence of CCS in the industry sector, allowance of higher shares gas in the building sector and the substantial increase in the use of biofuels in the transport sector.

The strong increase in electricity demand in all pathways highlights the importance of a parallel decarbonisation of the electricity system to reach ambitious overall CO_2 reduction targets. For an analysis on the impact on the electricity system please see the WP7 summary report of the SET-Nav project where the electricity supply mix has been simulated for each pathway with the electricity system model Enertile©.

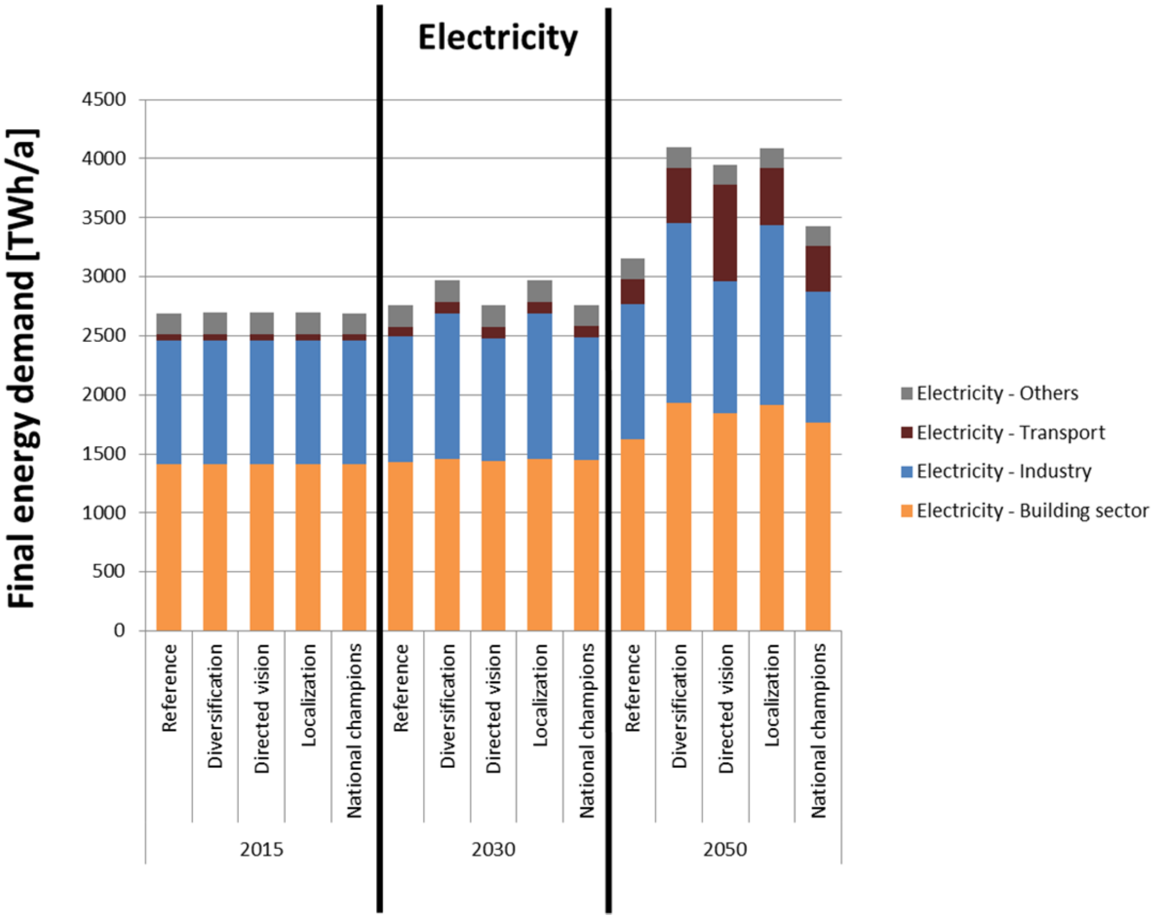


Figure 70: Electricity demand per sector in SET-Nav pathways

6.3 CO_2 emissions

Finally the direct CO_2 emissions resulting from the final energy demand of fossil fuels in the SET-Nav pathways are summarized. Note that these figures do not include CO_2 emissions of the secondary energy carriers electricity and district heating. Table 17 shows the conversion factors assumed to estimate the emissions based on the resulting overall final energy demand.

Table 17: Conversion factors to estimate CO_2 emissions from final energy demand

	Emission factor [$kgCO_2/kWh$ primary]
Coal	0.342
Fuel oil	0.288
Natural gas	0.198
Other fossil fuels	0.288
Waste non-RES	0.36

Figure 71 illustrates the development of CO_2 emissions, process emissions and captured emissions (CCS) in all demand sectors. Table 18 shows direct emissions from fossil fuels and Table 19 shows all total emissions including process emissions and captured emissions. In all pathways direct CO_2 emissions from fossil fuels are decreased substantially compared to the reference scenario which only leads to a reduction of -20%. The Diversification and Localization lead to the highest direct emission reductions of -76% until 2050. Note that these figures include the emissions that are subsequently stored in CCS facilities in the industry sector which is why the Directed Vision and National Champions pathway result in only -64% and -60% respectively. The lower reductions in the National Champions pathway are a result of the higher remaining gas demand in the building sector which has been added to the natural gas demand to show the effects if this remaining gas demand is not substituted by some form of non-fossil gas. Overall, the strongest reductions compared to the reference scenario stems from the reduction of CO_2 emissions from oil due to the substitution of conventional drives for transport.

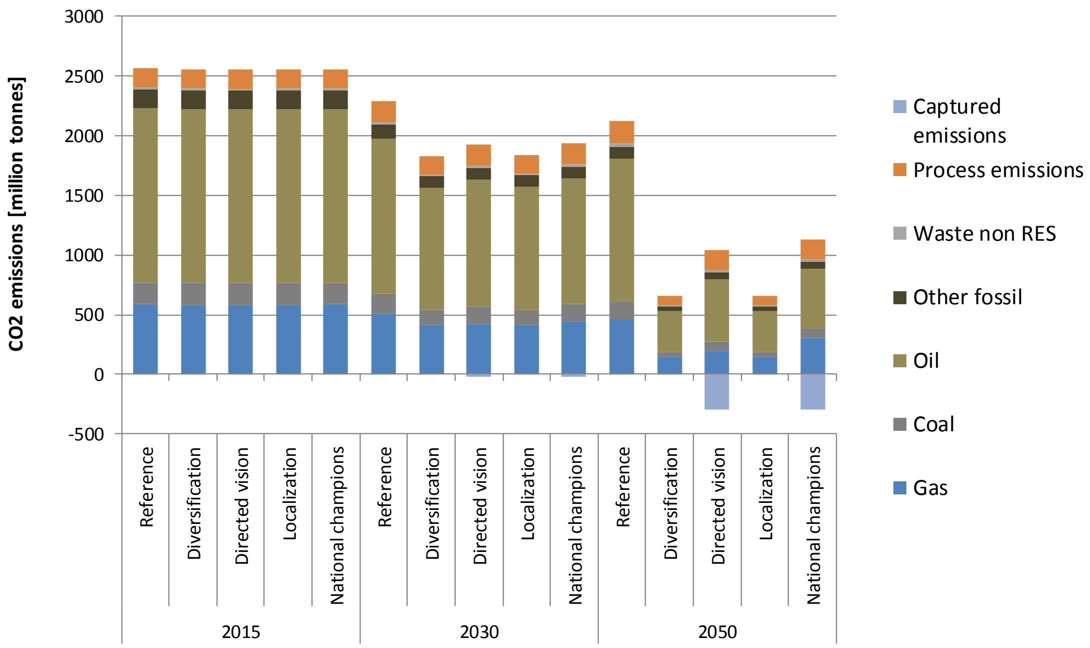


Figure 71: Development CO_2 emissions in demand sectors in SET-Nav pathways (emissions from electricity and district heating are not included in this figure)

Table 18: Direct CO_2 emissions from fossil fuels in demand sectors for EU28 in SET-Nav pathways in million tonnes CO_2

Year	Pathway	Gas	Coal	Oil	Other fossil	Waste non RES	Total	Change
2015	Reference	585	184	1464	160	13	2407	
2030	Reference	506	172	1296	123	16	2112	-12%
	Diversification	410	127	1029	94	14	1673	-30%
	Directed vision	426	143	1062	101	20	1752	-27%
	Localization	411	126	1040	94	14	1685	-30%
	National champions	437	150	1051	101	20	1759	-27%
2050	Reference	461	146	1200	101	26	1934	-20%
	Diversification	149	35	346	39	11	579	-76%
	Directed vision	197	73	527	57	24	877	-64%
	Localization	148	34	345	39	11	577	-76%
	National champions	300	78	506	57	24	965	-60%

Table 19 shows total CO_2 emissions including process emissions in the industry sector as well as captured emissions in CCS facilities in the industry sector in all pathways. The captured emissions lead to reductions of -71% in the Directed vision and -67% in the National Champions pathway. Including process emissions in industry the Diversification and Localization pathway result in net emission reductions of -74%.

Table 19: Total CO_2 emissions in demand sectors for EU28 in SET-Nav pathways in million tonnes CO_2

		Fossil emissions	Process emissions	Total emissions	Captured emissions	Net emissions	Change
2015	Reference	2407	163	2570	0	2570	
2030	Reference	2112	180	2293	0	2293	-11%
	Diversification	1673	152	1825	0	1825	-29%
	Directed vision	1752	173	1925	-18	1907	-26%
	Localization	1685	152	1837	0	1837	-29%
	National champions	1759	173	1932	-18	1914	-26%
2050	Reference	1934	185	2119	0	2119	-18%
	Diversification	579	80	659	0	659	-74%
	Directed vision	877	168	1045	-292	753	-71%
	Localization	577	80	657	0	657	-74%
	National champions	965	168	1133	-292	840	-67%

The results on CO_2 emission reduction of up to -74% until 2050 do not mean that the overall target of more than 85% reductions of CO_2 emissions are not achieved in the overall SET-Nav pathways. The strong decarbonisation of the electricity system and heat supply in heat grids of around -95% in all pathways (see WP7 summary report) leads to total reductions that are in the range of the overall targets which have been set for the SET-Nav pathways. However, if these supply sectors cannot be decarbonized to such extend even more reductions would have to be achieved in the transport, industry and building sector.

Overall, the pathway calculations on the demand side in SET-Nav show that deep carbonization until 2050 is possible. However, the analysis and model runs in each sector show that the necessary changes would be very hard to achieve. Each pathway implies huge challenges and significant transitions in each sector. The comparison with case study results show that the main challenges arise for very ambitious targets compared to moderate emission reduction targets that allow at least part of the energy system to be operated in a conventional way. In all pathways strong policy interventions in some form are needed as early as possible to set the path for all actors in each sector. It is the hope of the authors that the presented pathways provide a quantitative basis to shape the vision of potential low carbon energy system in the future.

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8 Annex

Table 20: Final energy demand in buildings for all EU28 countries in SET-Nav pathways in GWh

	gas	fuel oil	coal	District heating	Electricity	biomass	ambient heat	solar thermal	Total
AT									
2015									
reference	16156	13466	408	16813	6978	18913	1872	2004	76611
diversification	16160	13525	407	16787	6976	18966	1847	1989	76656
directed_vision	16154	13477	409	16732	6992	18952	1847	1992	76554
localization	16182	13609	400	16812	6970	18837	1830	2000	76640
national_champions	16162	13525	403	16784	6981	18954	1844	1994	76647
2030									
reference	13973	7541	82	15731	4381	15511	3138	3754	64112
diversification	13881	7619	84	15877	4323	15529	2878	3271	63462
directed_vision	12976	7502	80	16506	4051	13864	2310	3270	60558
localization	13177	7793	74	16388	4375	13408	3133	3322	61670
national_champions	13186	7883	81	15908	4380	14104	3036	3239	61817
2050									
reference	9216	2862	7	10479	3546	13757	4406	6394	50666
diversification	4318	1204	2	11623	3543	16547	4080	4892	46209
directed_vision	3663	1196	1	14884	2664	12574	2375	4456	41814
localization	3899	1439	1	13714	3653	13136	4399	4629	44872
national_champions	3747	1202	2	12777	3563	12665	4356	4465	42777
BE									
2015									
reference	52352	36097	962	3422	8482	9714	528	215	111772
diversification	52009	35841	969	3265	8549	10604	666	220	112123
directed_vision	51963	35792	967	3245	8538	10713	638	215	112070
localization	51951	35801	966	3256	8549	10615	665	217	112021
national_champions	52487	35956	962	3321	8514	10145	592	214	112191
2030									
reference	37863	23015	465	8867	6333	11931	2835	1053	92362
diversification	37276	21581	433	4074	7131	10075	4912	1883	87364
directed_vision	34539	20337	423	7345	6682	9866	4264	1899	85354
localization	35768	20985	432	5030	7196	9915	5380	2215	86922
national_champions	38499	22147	417	4167	6843	9274	4490	1870	87707
2050									
reference	29526	13831	49	9298	5617	6348	7262	1934	73865
diversification	6533	4123	50	6373	14065	6441	22673	2629	62886
directed_vision	5764	3729	53	13411	10636	6642	16890	2592	59717
localization	6016	3945	56	8061	13341	6794	22457	3343	64014
national_champions	26729	4326	41	3704	8480	5369	11874	3330	63853

	gas	fuel oil	coal	District heating	Electricity	biomass	ambient heat	solar thermal	Total
BG									
2015									
reference	1451	468	2387	5392	5205	8789	1506	171	25368
diversification	1420	464	2384	5350	5222	8770	1507	171	25287
directed_vision	1422	461	2382	5353	5219	8774	1504	174	25289
localization	1424	463	2389	5353	5222	8754	1510	172	25286
national_champions	1428	462	2387	5346	5221	8763	1511	172	25290
2030									
reference	1911	205	685	5325	4756	8211	1827	512	23432
diversification	1399	273	637	4581	4701	6850	1632	678	20752
directed_vision	1007	178	621	4702	4388	7013	1350	671	19931
localization	1281	242	621	4438	5050	5585	2425	708	20350
national_champions	1039	160	646	4714	4656	7252	1835	643	20945
2050									
reference	1674	174	3	4310	4477	8535	1734	823	21730
diversification	284	35	4	2531	4455	6290	986	1326	15911
directed_vision	170	16	4	3133	4412	4677	905	1179	14497
localization	243	27	4	1695	5140	3514	3448	1116	15187
national_champions	202	12	3	2142	4923	5434	2479	991	16185
CY									
2015									
reference	0	1305	9	8	1036	87	173	752	3370
diversification	1	1303	9	8	1040	75	175	751	3362
directed_vision	0	1300	8	8	1040	75	176	751	3359
localization	0	1302	9	8	1040	75	176	751	3360
national_champions	0	1304	9	7	1040	75	176	751	3362
2030									
reference	9	767	5	18	1142	261	328	828	3358
diversification	5	733	5	8	1224	203	313	823	3314
directed_vision	5	723	5	19	1207	194	304	831	3288
localization	5	744	5	12	1199	192	308	843	3309
national_champions	5	747	5	8	1203	204	329	818	3320
2050									
reference	24	367	1	21	1325	454	530	961	3683
diversification	9	131	1	5	1312	314	437	871	3079
directed_vision	10	125	1	12	1236	303	395	897	2979
localization	10	126	1	8	1216	345	433	917	3054
national_champions	10	152	1	5	1235	383	499	843	3128
CZ									
2015									
reference	33948	315	6494	18149	8382	14700	2120	173	84282
diversification	33853	294	6476	18184	8325	14735	2075	164	84105
directed_vision	33602	271	6456	18082	8297	14609	2082	163	83561

	gas	fuel oil	coal	District heating	Electricity	biomass	ambient heat	solar thermal	Total
localization	33757	257	6471	17990	8319	14668	2112	165	83738
national_champions	33847	304	6468	18112	8330	14723	2095	164	84043
2030									
reference	21493	1039	2492	16238	6545	25746	3393	1967	78912
diversification	19482	877	2376	16358	6358	23054	3347	2431	74283
directed_vision	18673	664	2349	18189	5929	19478	2738	2660	70680
localization	19875	727	2402	16428	6430	19040	3624	3328	71853
national_champions	18983	717	2399	17930	6401	20295	3456	2537	72719
2050									
reference	20041	1700	87	12353	6017	16692	4196	4618	65705
diversification	2462	299	83	12502	10349	16518	9918	5090	57222
directed_vision	2136	194	110	14637	6587	18389	4671	5726	52450
localization	2408	235	140	11916	8770	16937	8151	6723	55280
national_champions	2378	230	136	14158	8557	17974	7536	5097	56065
DE									
2015									
reference	348748	186482	7441	69944	38533	75045	8772	7112	742077
diversification	350350	186779	7447	71044	38543	75290	9047	7143	745643
directed_vision	351276	187527	7515	70983	38657	73579	8974	7039	745550
localization	351227	187634	7497	70974	38520	74371	9052	7101	746377
national_champions	358707	183478	7435	67979	37573	73328	9231	6573	744304
2030									
reference	291163	116742	261	58143	30400	89237	9496	19943	615385
diversification	265422	100588	389	57213	32471	78674	10883	16581	562219
directed_vision	269746	99544	258	60592	31275	69217	8477	16213	555321
localization	275702	101878	343	62075	32456	72210	10126	16259	571048
national_champions	267095	104163	312	57458	32477	63594	11700	13233	550031
2050									
reference	214881	48071	2	38648	37380	79304	11295	25035	454616
diversification	7118	1838	2	60800	119350	136059	75914	20162	421241
directed_vision	7965	2171	13	81662	109605	127597	66887	18572	414473
localization	9359	2715	6	70598	131937	116052	83594	19207	433468
national_champions	208000	8306	11	50288	49676	65213	20037	15568	417099
DK									
2015									
reference	8790	4217	10	27394	4891	10299	1300	179	57081
diversification	8721	4204	10	27368	4886	10211	1293	148	56840
directed_vision	8721	4192	10	27218	4886	10118	1296	148	56591
localization	8739	4194	10	27303	4889	10089	1299	145	56668
national_champions	8730	4201	11	27463	4896	10370	1304	145	57120
2030									
reference	5892	1651	4	22283	3250	14441	960	1731	50212
diversification	4965	1570	5	20887	3314	13691	994	2151	47577

	gas	fuel oil	coal	District heating	Electricity	biomass	ambient heat	solar thermal	Total
directed_vision	4599	1553	4	21882	3313	11442	979	2348	46120
localization	5084	1591	4	21399	3333	12160	1072	2607	47250
national_champions	4531	1596	4	22641	3314	13831	1014	1783	48714
2050									
reference	5872	219	0	16116	2488	16200	631	3356	44882
diversification	354	87	0	12067	3095	19016	1204	4828	40652
directed_vision	316	108	0	13684	3073	14506	961	5203	37851
localization	385	153	0	13695	3182	16276	1659	5325	40676
national_champions	328	78	0	15131	3129	18106	1723	3899	42396
EE									
2015									
reference	835	449	116	4867	2305	3939	843	32	13385
diversification	817	449	115	4853	2300	4102	844	32	13512
directed_vision	816	453	115	4844	2297	4100	840	32	13496
localization	815	450	116	4846	2294	4104	838	32	13493
national_champions	821	450	114	4842	2297	4097	840	32	13495
2030									
reference	862	206	45	3418	1068	5027	315	112	11053
diversification	647	196	38	3358	1035	5840	291	114	11519
directed_vision	836	196	42	3774	1076	4779	321	69	11093
localization	770	200	41	3444	1062	5295	325	155	11292
national_champions	764	207	41	3517	1054	5392	314	119	11408
2050									
reference	645	37	0	1453	465	5417	23	187	8228
diversification	120	16	1	1381	514	6228	38	186	8483
directed_vision	174	12	0	1839	533	4941	69	145	7713
localization	139	12	0	1473	520	5824	75	280	8324
national_champions	158	20	0	1603	495	5979	43	192	8490
ES									
2015									
reference	50560	38911	1062	460	33295	39751	2065	2495	168597
diversification	50014	38749	1058	449	33073	41057	2132	2503	169036
directed_vision	49952	38825	1066	440	33068	41059	2102	2506	169017
localization	49993	38767	1034	441	33033	40827	2130	2509	168735
national_champions	50135	38842	1048	455	33052	40741	2187	2518	168980
2030									
reference	32868	18749	252	409	33603	57084	4216	14289	161470
diversification	34970	19475	253	388	32340	51170	4891	12713	156201
directed_vision	34598	19314	214	641	31570	50705	3933	13334	154309
localization	32764	18528	231	383	33744	44177	9180	16132	155140
national_champions	38055	20878	246	378	32145	46805	5954	12630	157091
2050									
reference	30794	11954	105	448	42888	26273	9761	27705	149929

	gas	fuel oil	coal	District heating	Electricity	biomass	ambient heat	solar thermal	Total
diversification	8510	3867	2	2118	51370	22707	22638	21405	132616
directed_vision	8236	3730	1	1497	47141	30105	16571	22411	129691
localization	7781	3589	2	276	45088	28480	24389	26561	136165
national_champions	10085	4618	1	2231	47076	31132	22728	21420	139292
FI									
2015									
reference	346	8501	79	31624	20096	14394	3842	66	78949
diversification	348	8498	77	31605	20108	14330	3906	51	78922
directed_vision	347	8515	80	31613	20075	14357	3875	47	78910
localization	347	8511	78	31641	20093	14296	3891	54	78912
national_champions	347	8499	79	31630	20106	14310	3908	53	78931
2030									
reference	108	4020	30	29066	16422	15539	6411	1495	73091
diversification	131	3949	31	30764	17007	10619	7181	911	70593
directed_vision	143	4129	29	31878	16530	10364	6301	1309	70683
localization	124	4071	29	30279	17622	9709	7497	1476	70807
national_champions	129	4061	28	32498	16343	10605	5985	992	70640
2050									
reference	20	399	0	21725	14820	14472	11338	2931	65704
diversification	20	222	0	22575	14294	11377	11606	1748	61843
directed_vision	20	355	1	24647	13684	9513	10171	2678	61069
localization	18	282	1	22236	15589	8806	12934	2974	62840
national_champions	18	299	0	26038	13251	10217	9613	1967	61402
FR									
2015									
reference	216356	86259	550	24051	90022	87373	18596	921	524128
diversification	213224	85792	530	24099	89967	86779	19940	1015	521347
directed_vision	213665	85813	553	24030	89795	86499	19770	997	521121
localization	213597	85732	538	24104	89861	86362	19896	1002	521090
national_champions	213285	85865	553	23882	90294	85931	19692	985	520487
2030									
reference	176885	47436	138	38246	67361	100167	34897	12335	477464
diversification	152700	43130	123	28681	68549	96350	38498	17207	445238
directed_vision	149342	42933	119	42728	66128	87677	34354	17333	440613
localization	152587	44610	108	34677	69125	83334	38909	21431	444781
national_champions	154817	44456	153	27633	68582	79845	38461	17943	431891
2050									
reference	145103	26167	0	41574	61944	62621	51548	25302	414260
diversification	22360	5443	0	36514	90339	77715	88444	29678	350494
directed_vision	21426	5356	0	74182	76400	66062	65554	28518	337497
localization	21257	5679	0	52718	84537	67365	82062	36359	349976
national_champions	90641	6290	0	19651	72963	48500	62199	34248	334492
GB									

	gas	fuel oil	coal	District heating	Electricity	biomass	ambient heat	solar thermal	Total
2015									
reference	373121	34681	5749	7279	50829	9760	1327	0	482747
diversification	371527	34646	5770	7470	50810	9192	1354	0	480770
directed_vision	371570	34613	5765	7323	50776	8819	1285	1	480150
localization	371526	34740	5750	7411	50892	8686	1515	0	480520
national_champions	375663	34716	5759	7443	50729	8760	1219	0	484289
2030									
reference	301268	25044	1997	50936	35197	19105	5525	9288	448360
diversification	241282	22241	1863	41688	42077	24126	9264	26168	408709
directed_vision	228251	20877	1860	58347	38462	25855	5420	28221	407293
localization	235908	21484	1856	54934	39817	19076	8475	34055	415604
national_champions	254558	22543	1917	37777	43827	26253	10261	17151	414287
2050									
reference	257862	20468	111	94646	31514	14287	8253	17584	444726
diversification	32136	4058	31	90498	113457	24055	62954	33003	360191
directed_vision	30780	3745	73	155637	80826	32696	36966	31116	371839
localization	32678	3937	74	124238	94068	24270	64227	39263	382757
national_champions	121853	5101	64	76514	69947	21459	29622	38061	362620
GR									
2015									
reference	5503	30605	5	406	11032	8014	2384	2510	60459
diversification	5339	30461	5	401	11065	8075	2421	2508	60274
directed_vision	5337	30451	5	398	11054	8072	2407	2509	60232
localization	5347	30414	5	409	11061	8042	2418	2508	60204
national_champions	5335	30431	5	413	11049	8077	2389	2505	60204
2030									
reference	8019	16405	2	456	11398	10092	3280	4386	54037
diversification	5903	16831	2	401	11765	8499	3641	4346	51389
directed_vision	5345	16053	2	478	11369	7890	3229	4454	48820
localization	5417	16584	2	498	11459	7855	3684	4689	50188
national_champions	5984	17266	2	499	11511	8333	3818	4390	51804
2050									
reference	9195	8253	0	412	12064	8670	3827	6664	49085
diversification	757	2697	0	572	15060	8282	8235	6168	41770
directed_vision	621	2763	0	713	13715	6715	6501	6288	37316
localization	668	3081	0	686	13735	7038	8190	6763	40162
national_champions	828	2916	0	842	14191	8035	9744	6071	42628
HR									
2015									
reference	5908	2057	54	2648	3061	5031	10	86	18854
diversification	5912	2060	55	2651	3057	5049	8	86	18878
directed_vision	5904	2060	55	2649	3061	5027	13	86	18853
localization	5906	2059	55	2644	3058	5038	9	86	18855

	gas	fuel oil	coal	District heating	Electricity	biomass	ambient heat	solar thermal	Total
national_champions	5906	2058	55	2645	3058	5035	10	85	18853
2030									
reference	2802	1123	13	4547	3480	5408	578	530	18481
diversification	2503	944	13	3413	3507	5631	798	476	17285
directed_vision	2205	729	9	4307	3315	5479	918	453	17414
localization	2379	832	12	3864	3293	5641	946	520	17487
national_champions	2555	958	9	3422	3516	5394	1051	472	17378
2050									
reference	903	439	1	3580	4123	5597	2333	1081	18057
diversification	342	143	0	1653	4379	5087	3330	858	15792
directed_vision	222	66	0	2432	4112	4375	3025	847	15079
localization	241	87	0	1993	4245	4782	3802	1033	16184
national_champions	362	144	0	1812	4303	5038	3880	864	16403
HU									
2015									
reference	42484	1225	1616	8657	6379	12026	82	75	72544
diversification	41762	1236	1618	8416	6403	13558	74	71	73137
directed_vision	41767	1230	1611	8407	6391	13553	65	72	73096
localization	41716	1224	1615	8425	6398	13586	81	71	73117
national_champions	42451	1231	1612	8590	6389	12833	98	69	73274
2030									
reference	25967	902	629	8697	5835	18726	1215	1268	63239
diversification	24258	908	598	7996	5737	18718	1207	1236	60658
directed_vision	24106	877	597	10184	5404	16425	780	1221	59593
localization	24708	868	593	8906	5662	16538	1325	1384	59984
national_champions	26144	846	610	11236	5257	16235	676	977	61981
2050									
reference	18623	556	31	6862	6098	15157	2462	2305	52093
diversification	3124	165	9	6802	8265	23799	5578	1883	49627
directed_vision	3333	157	32	10354	7000	20322	3608	1816	46621
localization	3401	158	7	9114	8584	19231	6822	2079	49396
national_champions	10061	155	10	9474	4848	15664	1261	1679	43152
IE									
2015									
reference	10844	14345	4650	636	4273	759	469	133	36108
diversification	10887	14252	4658	632	4286	917	530	99	36260
directed_vision	10865	14274	4657	622	4282	921	530	97	36247
localization	10843	14244	4650	633	4290	940	544	100	36245
national_champions	10865	14263	4657	639	4282	924	528	98	36256
2030									
reference	9000	9631	2184	1317	3210	3140	1149	522	30153
diversification	7519	8908	2121	1697	3593	3856	2021	436	30150
directed_vision	6993	8926	2089	2546	3460	3113	1547	604	29276

	gas	fuel oil	coal	District heating	Electricity	biomass	ambient heat	solar thermal	Total
localization	7319	9131	2115	1925	3619	2839	2051	689	29688
national_champions	7578	9255	2116	1629	3610	3183	2105	458	29934
2050									
reference	7742	6557	223	1371	2732	5443	1956	1066	27089
diversification	1080	1463	148	1735	4289	9219	6965	110	25010
directed_vision	832	1275	155	3216	4191	5425	6234	377	21706
localization	911	1508	152	2189	4738	5369	8205	583	23655
national_champions	1059	1540	143	1907	4561	7297	7773	121	24403
IT									
2015									
reference	259156	28963	26	10545	49167	79785	12195	2099	441937
diversification	256436	28934	28	10578	49701	81920	13198	2029	442824
directed_vision	256155	28902	24	10638	49678	81489	13154	2034	442075
localization	256371	28684	25	10584	49616	81808	13094	2073	442256
national_champions	256174	28922	24	10550	49694	81499	13277	2074	442215
2030									
reference	197920	20613	7	9754	49053	68238	12890	23579	382055
diversification	158667	19976	6	9886	54944	69749	17426	36200	366854
directed_vision	154713	17602	7	11827	52873	73370	15513	34212	360117
localization	154992	19180	7	10216	54424	65432	20086	38977	363313
national_champions	159707	19657	5	9665	55106	65867	17977	36389	364374
2050									
reference	172092	17233	0	8449	58772	33898	17712	45709	353864
diversification	6302	4757	0	15211	109428	45867	69164	60830	311558
directed_vision	5323	3554	0	30140	96972	48988	57030	56065	298073
localization	6312	4714	0	21256	102256	41951	70697	61206	308391
national_champions	6006	4625	0	15122	109838	43068	66903	61139	306700
LT									
2015									
reference	1820	489	1187	6841	737	6388	15	100	17578
diversification	1789	489	1189	6850	739	6437	19	104	17615
directed_vision	1774	484	1185	6816	739	6386	19	104	17508
localization	1778	487	1187	6829	738	6402	19	103	17542
national_champions	1783	489	1190	6849	740	6440	21	103	17615
2030									
reference	2857	386	577	4912	944	6118	129	457	16380
diversification	1719	461	540	4614	1074	6104	269	560	15340
directed_vision	1466	481	512	4413	1093	5555	219	539	14278
localization	1471	463	526	4445	1185	5539	369	565	14563
national_champions	1608	515	545	4594	1062	6165	250	553	15290
2050									
reference	4516	129	42	2379	1287	5239	406	796	14796
diversification	277	98	18	2348	1598	6913	655	966	12872

	gas	fuel oil	coal	District heating	Electricity	biomass	ambient heat	solar thermal	Total
directed_vision	207	117	18	2082	1564	5484	471	921	10863
localization	224	115	42	2184	1825	5118	951	965	11424
national_champions	273	133	40	2329	1433	7280	373	959	12821
LU									
2015									
reference	4187	2547	6	859	576	297	43	27	8541
diversification	4169	2543	6	859	580	309	55	27	8549
directed_vision	4167	2540	6	861	582	304	57	27	8545
localization	4170	2540	6	858	582	305	58	27	8545
national_champions	4176	2543	6	858	581	302	54	26	8546
2030									
reference	4028	1116	4	1239	644	810	230	150	8222
diversification	3585	1130	4	1104	647	965	336	161	7932
directed_vision	3194	1067	4	1642	619	932	281	168	7907
localization	3461	1156	3	1282	663	826	400	190	7982
national_champions	3593	1123	3	1141	644	805	330	158	7795
2050									
reference	3719	286	0	1492	923	862	494	269	8044
diversification	736	150	0	1217	1101	2089	1257	226	6774
directed_vision	527	97	0	2458	980	1243	983	207	6495
localization	704	161	0	1538	1173	1574	1493	293	6935
national_champions	2656	145	0	1146	834	756	703	268	6508
LV									
2015									
reference	1660	832	245	5832	847	8485	21	0	17923
diversification	1653	830	243	5818	840	8428	22	0	17835
directed_vision	1641	828	242	5791	839	8406	20	0	17767
localization	1644	830	246	5812	840	8403	21	0	17797
national_champions	1645	835	246	5820	841	8425	20	0	17832
2030									
reference	1540	408	99	4106	599	8966	43	103	15865
diversification	1361	433	101	4211	608	8305	63	86	15167
directed_vision	1372	433	100	4769	583	7274	39	114	14684
localization	1513	441	96	4722	584	7448	60	131	14995
national_champions	1435	448	97	4914	579	7676	53	95	15297
2050									
reference	1653	73	6	2075	491	8578	10	227	13113
diversification	195	46	3	2210	596	8651	120	184	12004
directed_vision	176	44	3	2904	555	7305	39	244	11271
localization	230	50	4	2927	573	7821	149	284	12037
national_champions	227	49	3	3209	534	8400	90	195	12709
MT									
2015									

	gas	fuel oil	coal	District heating	Electricity	biomass	ambient heat	solar thermal	Total
reference	23	170	0	0	536	28	55	309	1122
diversification	23	170	0	0	536	27	55	310	1122
directed_vision	23	169	0	0	535	28	55	310	1121
localization	23	169	0	0	535	27	55	310	1120
national_champions	23	170	0	0	535	28	55	310	1122
2030									
reference	9	62	0	0	375	133	78	214	870
diversification	23	79	0	0	484	119	108	274	1087
directed_vision	24	80	0	0	482	117	105	276	1083
localization	24	81	0	0	483	109	119	276	1093
national_champions	21	82	0	0	476	130	113	274	1096
2050									
reference	12	16	0	0	302	120	127	170	746
diversification	8	11	0	0	499	120	194	259	1090
directed_vision	8	11	0	0	494	115	184	264	1076
localization	8	12	0	0	480	115	224	266	1105
national_champions	8	12	0	0	478	118	246	264	1125
NL									
2015									
reference	132476	2543	120	7377	10693	7349	1667	521	162745
diversification	130485	2543	119	7613	10837	10214	1800	441	164054
directed_vision	130414	2581	120	7597	10831	10196	1784	450	163972
localization	130483	2554	119	7605	10818	10182	1766	440	163966
national_champions	131761	2538	120	7466	10821	8879	1797	427	163809
2030									
reference	92809	3545	85	11574	9472	14781	2026	3022	137314
diversification	85274	3155	82	10176	10427	17767	3287	3963	134131
directed_vision	86460	2560	83	13263	9952	13827	2737	4048	132931
localization	89197	2700	82	10972	10324	13429	3474	4556	134735
national_champions	86083	3435	83	9892	10346	11969	3523	3965	129295
2050									
reference	71672	3519	14	13018	10942	8437	1553	6067	115223
diversification	13392	737	15	12641	29533	12874	27191	6135	102519
directed_vision	13742	464	14	27594	23831	10057	19189	5968	100861
localization	16368	612	13	16918	28778	9590	27406	6738	106422
national_champions	52034	857	14	8359	14772	7272	6501	7859	97666
PL									
2015									
reference	48843	7172	87213	62589	16436	36652	730	441	260077
diversification	50680	7720	86603	62095	16265	32091	691	684	256830
directed_vision	52039	8581	82648	61815	16282	33287	720	744	256115
localization	50508	7738	86554	62035	16270	31852	679	682	256317
national_champions	50651	7936	86609	62120	16236	31751	739	667	256710

	gas	fuel oil	coal	District heating	Electricity	biomass	ambient heat	solar thermal	Total
2030									
reference	43637	8007	57489	41459	14809	50455	3861	11103	230820
diversification	42932	9531	54770	39046	16189	35858	7875	8454	214655
directed_vision	46949	15349	34173	38643	17250	41685	9052	10766	213866
localization	41390	9561	54635	39054	17195	32615	9826	8540	212816
national_champions	42161	10784	54918	39120	15739	35751	7121	8209	213804
2050									
reference	49016	10640	23460	17612	16457	50223	8900	22120	198428
diversification	0	1068	19739	15280	31073	40131	40634	12790	160716
directed_vision	0	3094	2338	14471	32283	49060	40400	15995	157640
localization	0	739	19003	14755	32745	31087	43736	13812	155877
national_champions	24905	1417	19653	15158	21420	44035	21415	15152	163154
PT									
2015									
reference	4006	4341	0	234	6077	5418	256	981	21313
diversification	4015	4326	0	236	6058	5476	446	1013	21569
directed_vision	4014	4322	0	238	6054	5479	448	1008	21564
localization	4015	4325	0	237	6054	5481	448	1004	21565
national_champions	4016	4325	0	237	6053	5471	446	1016	21564
2030									
reference	1551	1855	0	146	5903	4879	1681	4002	20017
diversification	1427	1580	0	100	5926	3165	2774	5181	20153
directed_vision	1458	1597	0	107	5997	3385	2617	4922	20083
localization	1425	1631	0	104	5854	2985	2922	5517	20438
national_champions	1464	1675	0	108	5830	3237	3078	5275	20667
2050									
reference	366	1265	0	28	7165	3045	2441	5687	19998
diversification	124	169	0	0	8017	823	4237	6648	20018
directed_vision	125	165	0	0	8235	896	3749	6498	19669
localization	97	197	0	0	7627	916	4731	7257	20826
national_champions	124	213	0	0	7369	1025	5706	6866	21303
RO									
2015									
reference	20517	1503	195	13878	2884	36521	53	1	75551
diversification	20312	1530	199	13655	2906	36898	53	0	75553
directed_vision	20312	1517	212	13637	2904	36890	59	0	75531
localization	20363	1519	201	13677	2902	36852	49	0	75563
national_champions	20367	1515	205	13698	2901	36961	46	0	75693
2030									
reference	16728	551	16	12258	3434	30707	1017	1382	66093
diversification	15544	606	17	10388	3452	32567	418	2146	65137
directed_vision	13908	546	12	11279	3242	30820	831	1853	62492
localization	13642	489	15	12480	3491	30789	1552	1387	63846

	gas	fuel oil	coal	District heating	Electricity	biomass	ambient heat	solar thermal	Total
national_champions	13744	506	25	13105	3157	34066	928	1200	66731
2050									
reference	11564	163	0	5886	4493	24564	2749	3174	52592
diversification	2955	54	0	5576	4662	30204	1238	4440	49130
directed_vision	2279	48	0	7232	4999	20631	3167	4939	43295
localization	2389	26	0	5459	6126	21896	6075	5751	47722
national_champions	2614	34	0	7941	4693	30711	3756	4366	54116
SE									
2015									
reference	2738	4003	0	47576	23464	13458	11961	153	103353
diversification	2599	3983	0	47645	23543	13640	12189	152	103751
directed_vision	2568	3982	0	47573	23517	13653	12194	151	103638
localization	2614	3975	0	47660	23503	13596	12160	151	103659
national_champions	2597	3988	0	47649	23508	13655	12152	152	103701
2030									
reference	6289	1971	0	43597	14461	14592	8067	994	89971
diversification	2661	2039	0	41201	15895	17592	10990	1057	91435
directed_vision	2295	1841	0	43433	15097	17692	9789	1067	91213
localization	2461	1918	0	41057	16510	15569	12689	1365	91569
national_champions	2142	1805	0	42456	15602	17628	10879	1041	91553
2050									
reference	8613	677	0	35807	9240	15074	7035	1908	78355
diversification	354	242	0	28000	12358	23368	13880	2228	80430
directed_vision	288	187	0	32807	11563	18887	12190	2260	78181
localization	320	269	0	28246	13995	17699	17830	2908	81267
national_champions	240	166	0	30046	12341	19787	14742	2245	79566
SI									
2015									
reference	1510	3285	0	1793	1860	5820	137	160	14566
diversification	1455	3278	0	1756	1862	5996	144	151	14642
directed_vision	1454	3272	0	1754	1860	5978	147	149	14615
localization	1458	3272	0	1749	1860	5981	144	151	14617
national_champions	1453	3270	0	1752	1861	5989	144	151	14619
2030									
reference	1323	1323	0	2904	1216	7236	70	347	14419
diversification	1460	1310	0	1929	1313	6720	318	674	13724
directed_vision	1234	1186	0	2486	1295	5538	232	802	12773
localization	1354	1275	0	2230	1279	6132	323	876	13467
national_champions	1285	1243	0	1814	1279	7198	243	652	13714
2050									
reference	922	161	0	3627	1238	7323	53	523	13846
diversification	364	111	0	1600	1726	7108	803	1290	13002
directed_vision	249	107	0	2254	1751	4393	514	1781	11049

	gas	fuel oil	coal	District heating	Electricity	biomass	ambient heat	solar thermal	Total
localization	283	109	0	2164	1730	5640	944	1716	12586
national_champions	315	120	0	1257	1545	7922	379	1236	12773
SK									
2015									
reference	19483	205	1399	14830	2100	890	273	69	39248
diversification	19460	200	1403	14884	2127	1086	324	66	39549
directed_vision	19372	204	1393	14794	2129	1083	313	66	39353
localization	19439	200	1397	14857	2130	1056	323	64	39466
national_champions	19710	198	1400	14870	2115	1001	304	65	39663
2030									
reference	15883	123	527	10911	2018	2175	560	723	32919
diversification	12406	117	517	11891	2572	5097	1494	780	34874
directed_vision	12014	114	494	12264	2356	4104	1095	800	33241
localization	12468	133	527	11975	2597	3951	1700	1096	34447
national_champions	13348	123	532	13001	2310	4042	1182	745	35283
2050									
reference	13592	52	6	5873	2417	2266	766	1279	26251
diversification	1720	11	18	7761	4718	10419	4246	1290	30182
directed_vision	1405	8	7	9106	3873	7968	2956	1375	26698
localization	1703	15	16	8057	4985	7737	5102	1808	29421
national_champions	4972	14	4	10010	3582	7429	3088	1193	30291

Table 21: Final energy demand in industry for all EU28 countries in SET-Nav pathways in TWh

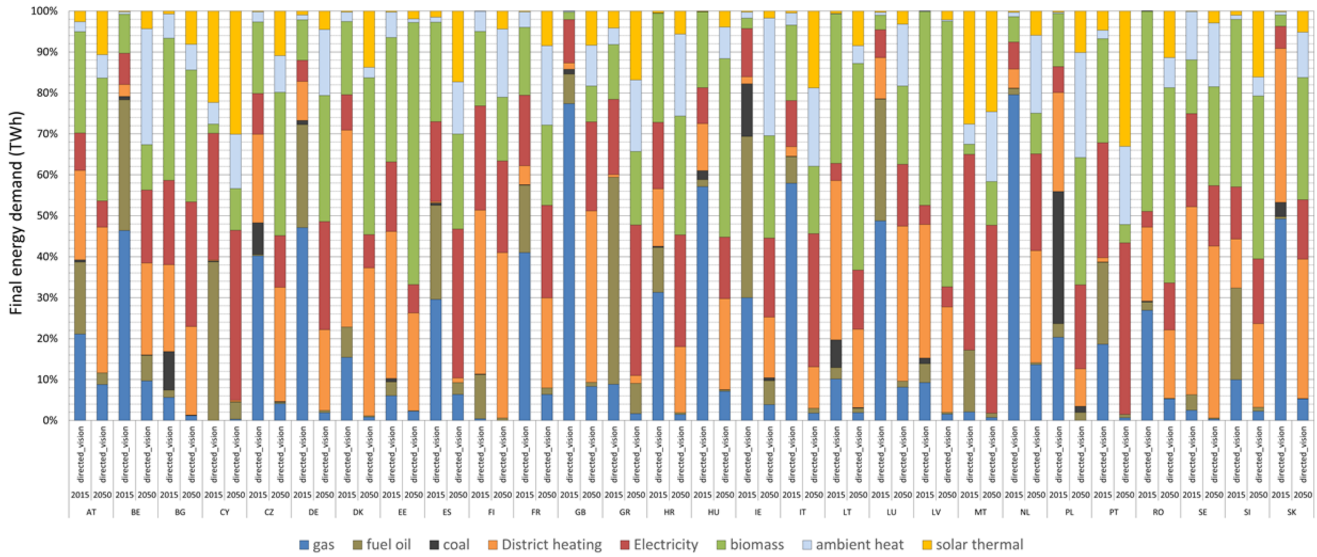

Figure 72: Share of energy carriers in building sector for all countries in 2015 and 2050 in Directed Vision pathway

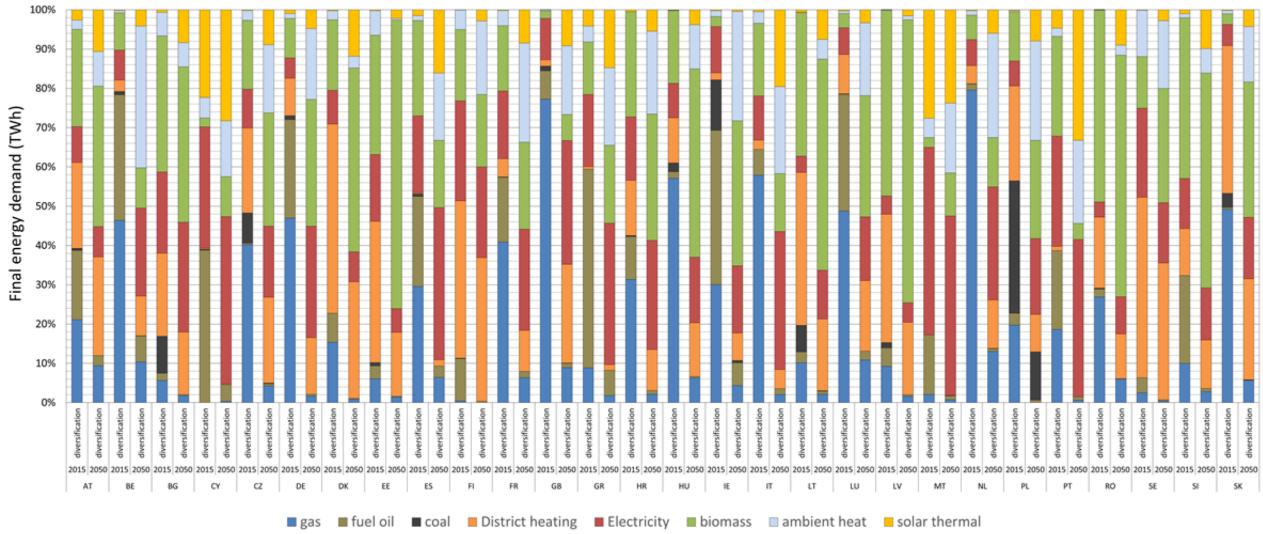

Figure 73: Share of energy carriers in building sector for all countries in 2015 and 2050 in Diversification pathway

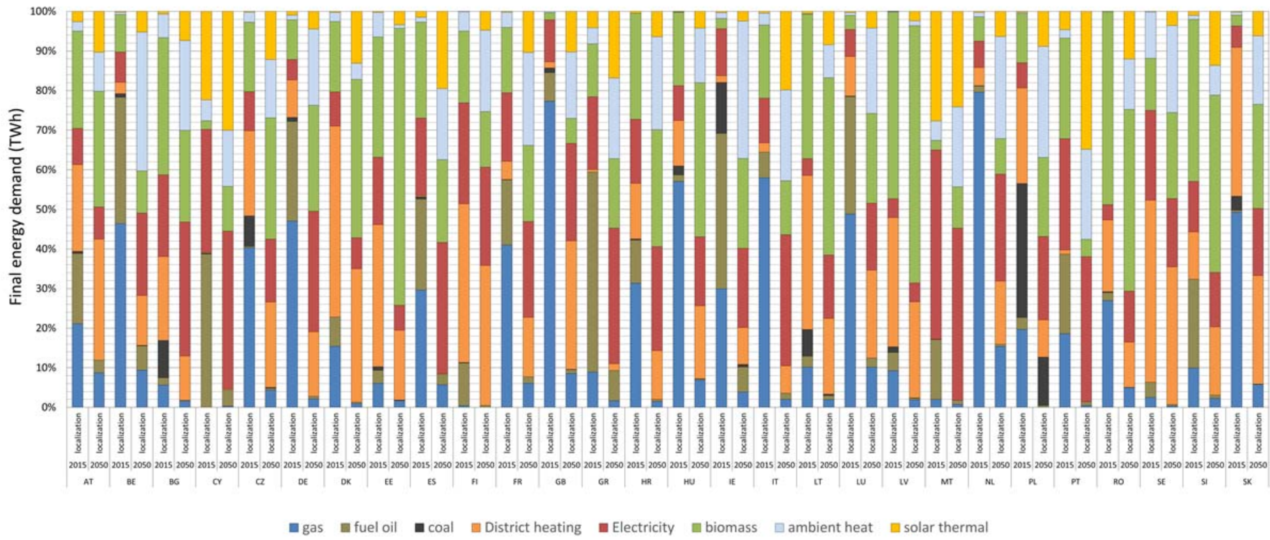

Figure 74: Share of energy carriers in building sector for all countries in 2015 and 2050 in Localization pathway

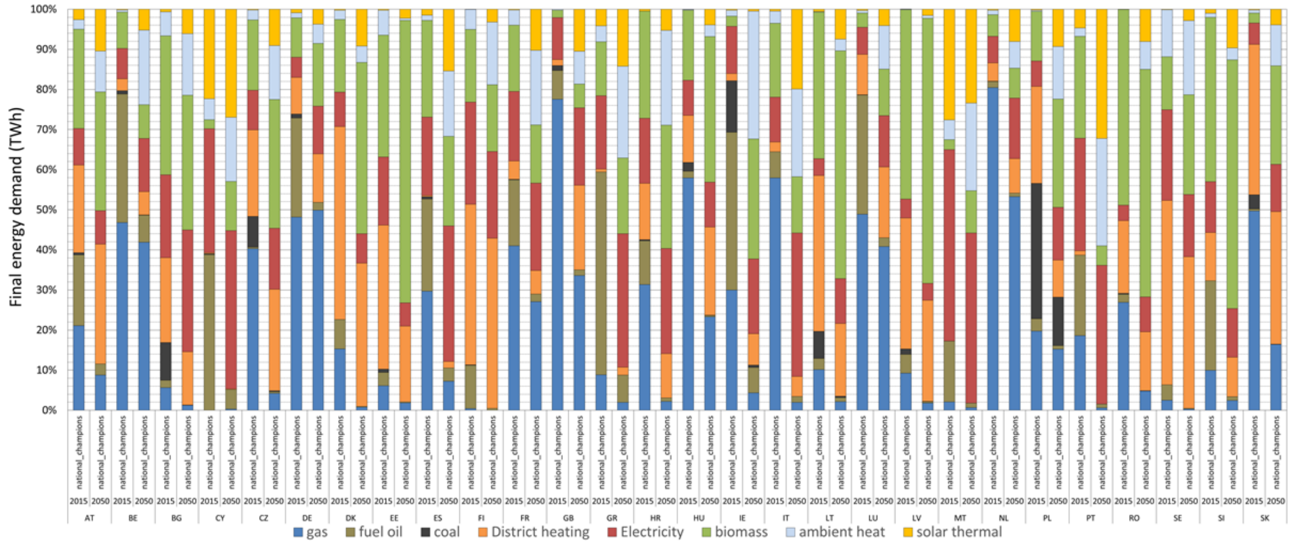

Figure 75: Share of energy carriers in building sector for all countries in 2015 and 2050 in National Champions pathway

Table 22: Energy carrier in industry sector for pathways per country

Scenario	Country	Werte	Energy carrier in TWh Ambient heat	Biomass	Coal	District heating	Electricity	Fuel oil	Natural gas	Other fossil	Solar energy	Waste non-RES	Other RES	Hydrogen	Total
Directed Vision/ National champions	Austria	2015	0	14	16	3	26	8	33	10	0	4	0	0	114
		2030	5	15	16	6	28	3	23	8	0	2	0	0	107
		2040	6	15	13	6	29	3	21	6	0	2	0	0	102
		2050	8	15	10	6	30	3	20	5	0	2	0	0	98
	Belgium	2015	0	8	18	7	39	18	48	21	0	2	0	0	160
		2030	3	10	14	6	37	7	46	23	0	2	0	0	149
		2040	4	13	11	5	39	5	46	20	0	3	0	0	147
		2050	6	18	9	3	42	5	46	18	0	3	0	0	149
	Bulgaria	2015	0	3	2	4	9	1	11	5	0	0	0	0	37
		2030	1	5	2	4	10	1	8	3	0	1	0	0	36
		2040	2	6	1	3	11	1	8	3	0	1	0	0	35
		2050	2	7	1	2	12	1	8	2	0	1	0	0	35
	Croatia	2015	0	0	1	1	4	3	5	4	0	0	0	0	18
		2030	0	2	1	2	4	1	4	2	0	0	0	0	16
		2040	0	2	1	2	4	0	4	2	0	0	0	0	14
		2050	0	2	0	2	4	0	3	1	0	0	0	0	14
	Cyprus	2015	0	0	0	0	0	0	0	1	0	0	0	0	2
		2030	0	0	0	0	0	0	1	0	0	0	0	0	2
		2040	0	0	0	0	0	0	1	0	0	0	0	0	2
		2050	0	1	0	0	1	0	1	0	0	0	0	0	3
	Czech Republic	2015	0	6	17	8	23	1	24	10	0	2	0	0	92
		2030	5	13	11	5	25	1	17	6	0	2	0	0	86
		2040	6	15	8	4	27	1	16	4	0	2	0	0	84
		2050	7	17	5	3	30	1	15	3	0	2	0	0	85
	Denmark	2015	0	2	1	1	9	3	7	6	0	0	0	0	29
		2030	2	3	2	1	9	1	7	3	0	1	0	0	28
		2040	3	3	2	1	10	0	7	2	0	1	0	0	28
		2050	4	4	1	1	12	0	6	1	0	1	0	0	30
	Estonia	2015	0	1	0	0	2	1	1	0	0	0	0	0	6
		2030	0	1	0	0	2	0	1	0	0	0	0	0	6
		2040	1	1	0	0	2	0	1	0	0	0	0	0	6
		2050	1	1	0	0	2	0	1	0	0	0	0	0	6
	Finland	2015	0	41	6	15	39	10	9	16	0	1	0	0	137
		2030	11	33	9	11	41	3	12	7	0	3	0	0	131
		2040	13	27	8	10	42	3	15	5	0	4	0	0	127
		2050	14	23	8	9	44	3	16	4	0	5	0	0	126
	France	2015	0	16	44	13	119	18	132	41	0	0	0	0	383
		2030	13	27	43	15	117	6	85	31	1	5	0	0	342
		2040	21	35	31	12	124	4	72	22	1	7	0	0	330
		2050	31	46	20	11	138	3	64	16	0	7	0	0	337
	Germany	2015	0	30	112	49	231	36	231	90	0	12	0	0	792
		2030	14	65	100	47	211	11	187	50	2	14	0	0	700
		2040	21	79	73	37	206	7	168	35	1	14	0	0	644
		2050	28	96	53	28	205	6	152	26	1	13	0	0	607
	Greece	2015	0	2	3	0	13	10	5	22	0	1	0	0	57
		2030	1	6	2	1	14	3	11	10	0	1	0	0	49
		2040	2	8	2	1	15	1	11	7	0	1	0	0	47
		2050	2	8	1	1	15	1	10	5	0	1	0	0	45
	Hungary	2015	0	1	4	5	16	5	16	8	0	1	0	0	55
		2030	1	8	4	5	17	1	9	4	0	1	0	0	51
		2040	1	10	3	4	17	1	9	3	0	1	0	0	49
		2050	2	12	2	3	18	1	9	2	0	1	0	0	48
	Ireland	2015	0	2	1	0	10	3	9	4	0	1	0	0	29
		2030	1	3	2	1	11	1	6	2	0	1	0	0	27
		2040	2	4	1	1	12	1	6	1	0	1	0	0	28
		2050	3	5	1	1	13	0	6	1	0	1	0	0	30
	Italy	2015	0	5	17	42	118	16	99	57	0	3	0	0	358
		2030	7	20	18	32	110	13	69	30	1	5	0	0	305
		2040	9	28	15	24	108	10	64	20	1	6	0	0	285
		2050	12	37	13	16	111	8	62	15	1	6	0	0	280
	Latvia	2015	0	4	0	0	2	0	1	0	0	1	0	0	9
		2030	1	3	1	1	2	0	2	0	0	0	0	0	9
		2040	1	2	1	1	2	0	2	0	0	0	0	0	9
		2050	1	2	0	1	2	0	2	0	0	0	0	0	9
	Lithuania	2015	0	1	1	2	4	1	3	5	0	0	0	0	18
		2030	1	2	1	2	4	0	4	3	0	0	0	0	15
		2040	1	2	0	1	4	0	3	2	0	0	0	0	13
		2050	1	2	0	1	4	0	3	1	0	0	0	0	12
	Luxembourg	2015	0	0	1	0	3	0	3	0	0	0	0	0	7
		2030	0	1	1	0	3	0	2	0	0	0	0	0	7
		2040	0	1	1	0	3	0	2	0	0	0	0	0	7
		2050	0	1	0	0	3	0	2	0	0	0	0	0	7
	Malta	2015	0	0	0	0	0	0	0	0	0	0	0	0	1
		2030	0	0	0	0	0	0	0	0	0	0	0	0	1
		2040	0	0	0	0	0	0	0	0	0	0	0	0	1
		2050	0	0	0	0	0	0	0	0	0	0	0	0	1
	Netherlands	2015	0	2	18	26	37	5	64	56	0	0	0	0	209
		2030	5	16	20	22	40	1	56	37	0	2	0	0	200
		2040	6	25	15	16	43	1	49	29	0	4	0	0	188
		2050	7	34	12	10	46	1	45	25	0	4	0	0	184
	Poland	2015	0	16	46	8	51	13	45	15	0	6	0	0	199
		2030	6	35	36	11	57	6	28	17	0	5	0	0	202
		2040	8	42	27	11	59	4	25	14	0	5	0	0	196
		2050	9	47	20	11	60	3	23	11	0	4	0	0	190
	Portugal	2015	0	11	0	5	16	5	15	13	0	1	0	0	66
		2030	3	12	2	5	16	2	13	6	0	1	0	0	59
		2040	3	11	2	4	16	1	12	4	0	1	0	0	55
		2050	4	10	2	3	17	1	11	3	0	1	0	0	52
	Romania	2015	0	3	9	4	22	4	28	16	0	1	0	0	86
		2030	4	9	10	4	25	1	19	10	0	1	0	0	83
		2040	4	10	8	4	27	1	16	8	0	1	0	0	80
		2050	5	11	7	3	29	1	15	7	0	1	0	0	78
	Slovakia	2015	0	5	14	2	12	0	10	13	0	2	0	0	58
		2030	2	12	12	2	14	1	8	7	0	1	0	0	57
		2040	3	12	9	2	15	1	7	5	0	0	0	0	54
		2050	3	12	6	2	15	0	6	3	0	0	0	0	49
	Slovenia	2015	0	1	0	1	6	1	5	1	0	0	0	0	14
		2030	1	1	1	1	7	0	3	0	0	0	0	0	15
		2040	1	2	1	1	8	0	3	0	0	0	0	0	15
		2050	1	2	1	1	8	0	3	0	0	0	0	0	15
	Spain	2015	0	16	13	0	79	19	109	76	0	0	0	0	313
		2030	11	34	14	4	86	6	69	52	1	3	0	0	279
		2040	14	37	12	4	92	5	54	40	1	3	0	0	262
		2050	16	38	9	4	97	5	47	32	0	4	0	0	253
	Sweden	2015	0	50	12	6	51	6	5	17	0	0	0	0	147
		2030	8	31	11	5	55	5	14	9	0	2	0	0	138
		2040	10	23	8	4	57	5	15	6	0	3	0	0	132
		2050	13	21	6	3	60	6	15	4	0	4	0	0	132
	United Kingdom	2015	0	10	44	10	98	43	90	48	0	1	0	0	344
		2030	9	22	29	30	92	9	58	29	1	4	0	0	282
		2040	13	28	20	28	95	6	54	18	0	5	0	0	267
		2050	18	33	15	26	100	5	51	12	0	5	0	0	264
Directed Vision/National champions 2015			**0**	**251**	**401**	**212**	**1041**	**233**	**1008**	**556**	**0**	**37**	**0**	**0**	**3739**
Directed Vision/National champions 2030			**115**	**388**	**362**	**222**	**1037**	**82**	**762**	**352**	**8**	**54**	**1**	**1**	**3383**
Directed Vision/National champions 2040			**155**	**442**	**273**	**185**	**1070**	**62**	**692**	**256**	**6**	**64**	**1**	**1**	**3206**
Directed Vision/National champions 2050			**197**	**506**	**202**	**148**	**1117**	**53**	**643**	**198**	**4**	**66**	**1**	**1**	**3137**

Scenario	Country	Values	Energy carrier in TWh Ambient heat	Biomass	Coal	District heating	Electricity	Fuel oil	Natural gas	Other fossil	Solar energy	Waste non-RES	Other RES	Hydrogen	Total
Diversification/ Localisation	Austria	2015	0	14	16	3	26	8	33	10	0	4	0	0	114
		2030	8	12	13	4	35	3	19	7	0	2	0	0	104
		2040	9	9	8	3	40	2	15	5	0	1	0	2	95
		2050	10	8	3	3	43	1	12	3	0	1	0	4	88
	Belgium	2015	0	8	18	7	39	18	48	21	0	2	0	0	160
		2030	5	7	12	6	47	5	39	22	0	1	0	0	143
		2040	7	6	6	4	56	3	32	15	0	1	0	1	131
		2050	8	5	3	2	66	2	22	9	0	1	0	2	121
	Bulgaria	2015	0	3	2	4	9	1	11	5	0	0	0	0	37
		2030	2	4	1	4	12	1	7	3	0	0	0	0	35
		2040	3	3	1	2	14	0	6	2	0	0	0	0	32
		2050	3	3	1	2	15	0	5	2	0	0	0	0	31
	Croatia	2015	0	0	1	1	4	3	5	4	0	0	0	0	18
		2030	0	1	1	2	5	1	4	2	0	0	0	0	15
		2040	0	1	0	2	5	0	3	1	0	0	0	0	14
		2050	1	1	0	1	5	0	2	1	0	0	0	0	12
	Cyprus	2015	0	0	0	0	0	0	0	1	0	0	0	0	2
		2030	0	0	0	0	0	0	1	0	0	0	0	0	2
		2040	0	0	0	0	1	0	1	0	0	0	0	0	2
		2050	0	0	0	0	1	0	1	0	0	0	0	0	2
	Czech Republic	2015	0	6	17	8	23	1	24	10	0	2	0	0	92
		2030	8	8	9	5	32	1	14	6	0	1	0	0	83
		2040	10	7	4	3	38	1	11	3	0	1	0	1	79
		2050	10	6	2	2	43	1	8	2	0	1	0	2	77
	Denmark	2015	0	2	1	1	9	3	7	6	0	0	0	0	29
		2030	2	2	2	1	12	1	6	3	0	0	0	0	27
		2040	3	1	1	0	14	0	5	2	0	0	0	0	27
		2050	3	1	1	0	17	0	4	1	0	0	0	0	28
	Estonia	2015	0	1	0	0	2	1	1	0	0	0	0	0	6
		2030	1	1	0	0	3	0	1	0	0	0	0	0	6
		2040	1	1	0	0	3	0	1	0	0	0	0	0	6
		2050	1	1	0	0	3	0	1	0	0	0	0	0	6
	Finland	2015	0	41	6	15	39	10	9	16	0	1	0	0	137
		2030	14	28	7	8	48	3	10	7	0	2	0	0	125
		2040	16	19	5	6	53	2	10	4	0	2	0	1	117
		2050	16	13	3	5	56	1	9	3	0	2	0	1	109
	France	2015	0	16	44	13	119	18	132	41	0	0	0	0	383
		2030	18	17	32	11	147	4	71	28	0	2	0	1	331
		2040	26	15	15	7	173	2	45	15	0	2	0	3	305
		2050	33	11	5	5	199	2	28	8	0	2	0	5	297
	Germany	2015	0	30	112	49	231	36	231	90	0	12	0	0	792
		2030	28	49	81	40	242	8	167	46	1	10	0	2	675
		2040	39	47	42	27	263	5	122	28	1	8	0	9	591
		2050	48	39	17	17	282	3	80	16	0	6	0	19	526
	Greece	2015	0	2	3	0	13	10	5	22	0	1	0	0	57
		2030	2	4	2	1	17	3	10	10	0	1	0	0	49
		2040	3	4	1	0	19	1	10	6	0	0	0	0	46
		2050	3	4	1	0	21	1	8	4	0	0	0	0	43
	Hungary	2015	0	1	4	5	16	5	16	8	0	1	0	0	55
		2030	2	5	4	4	21	1	9	4	0	1	0	0	51
		2040	3	6	2	3	23	1	7	2	0	0	0	1	48
		2050	3	7	1	2	25	0	5	1	0	0	0	1	45
	Ireland	2015	0	2	1	0	10	3	9	4	0	1	0	0	29
		2030	2	2	1	0	13	1	4	1	0	0	0	0	26
		2040	3	2	1	0	16	0	3	1	0	0	0	0	27
		2050	3	2	0	0	18	0	3	1	0	0	0	0	28
	Italy	2015	0	5	17	42	118	16	99	57	0	3	0	0	358
		2030	12	16	15	30	116	12	61	29	1	4	0	0	297
		2040	17	20	10	20	123	8	47	17	1	4	0	2	269
		2050	22	22	5	12	137	5	35	11	0	3	0	5	257
	Latvia	2015	0	4	0	0	2	0	1	0	0	1	0	0	9
		2030	1	2	1	0	3	0	2	0	0	0	0	0	10
		2040	1	2	0	0	3	0	2	0	0	0	0	0	10
		2050	2	2	0	1	3	0	2	0	0	0	0	0	10
	Lithuania	2015	0	1	1	2	4	1	3	5	0	0	0	0	18
		2030	1	1	1	2	4	0	3	3	0	0	0	0	15
		2040	1	1	0	1	5	0	2	2	0	0	0	0	12
		2050	1	1	0	1	5	0	2	1	0	0	0	0	11
	Luxembourg	2015	0	0	1	0	3	0	3	0	0	0	0	0	7
		2030	0	0	1	0	4	0	2	0	0	0	0	0	7
		2040	0	0	0	0	4	0	1	0	0	0	0	0	7
		2050	0	0	0	0	4	0	1	0	0	0	0	0	7
	Malta	2015	0	0	0	0	0	0	0	0	0	0	0	0	1
		2030	0	0	0	0	0	0	0	0	0	0	0	0	1
		2040	0	0	0	0	0	0	0	0	0	0	0	0	1
		2050	0	0	0	0	0	0	0	0	0	0	0	0	1
	Netherlands	2015	0	2	18	26	37	5	64	56	0	0	0	0	209
		2030	9	9	15	21	57	0	47	33	0	1	0	0	194
		2040	11	11	8	14	70	0	34	22	0	1	0	2	174
		2050	14	10	3	7	80	0	25	15	0	1	0	4	161
	Poland	2015	0	16	46	8	51	13	45	15	0	6	0	0	199
		2030	9	22	31	8	79	6	23	16	0	3	0	0	198
		2040	12	20	19	7	92	4	18	12	0	2	0	1	187
		2050	14	20	11	7	99	2	15	8	0	2	0	3	179
	Portugal	2015	0	11	0	5	16	5	15	13	0	1	0	0	66
		2030	4	9	2	4	20	1	11	6	0	1	0	0	58
		2040	5	7	1	3	22	1	9	4	0	1	0	0	52
		2050	5	5	1	2	23	0	7	2	0	1	0	0	47
	Romania	2015	0	3	9	4	22	4	28	16	0	1	0	0	86
		2030	6	6	8	4	29	1	16	10	0	1	0	0	81
		2040	7	6	5	2	33	1	11	6	0	1	0	2	73
		2050	7	5	2	2	36	0	8	3	0	1	0	3	67
	Slovakia	2015	0	5	14	2	12	0	10	13	0	2	0	0	58
		2030	5	8	10	1	17	1	7	6	0	1	0	0	56
		2040	7	7	5	1	20	0	5	3	0	0	0	2	50
		2050	7	6	1	1	21	0	3	2	0	0	0	3	44
	Slovenia	2015	0	1	0	1	6	1	5	1	0	0	0	0	14
		2030	1	1	1	1	8	0	2	0	0	0	0	0	14
		2040	1	1	0	0	9	0	2	0	0	0	0	0	14
		2050	1	1	0	0	9	0	2	0	0	0	0	0	14
	Spain	2015	0	16	13	0	79	19	109	76	0	0	0	0	313
		2030	16	27	12	3	103	5	58	50	0	2	0	0	275
		2040	19	25	7	2	115	4	38	36	0	2	0	2	250
		2050	20	22	4	2	119	3	28	28	0	2	0	4	232
	Sweden	2015	0	50	12	6	51	6	5	17	0	0	0	0	147
		2030	8	27	8	4	62	4	11	8	0	1	0	0	132
		2040	9	16	4	3	67	4	10	5	0	2	0	0	120
		2050	10	11	2	2	73	3	8	3	0	2	0	1	115
	United Kingdom	2015	0	10	44	10	98	43	90	48	0	1	0	0	344
		2030	15	19	25	25	100	8	52	28	0	3	0	0	277
		2040	22	23	14	21	110	5	40	16	0	4	0	2	257
		2050	26	22	8	18	122	4	31	10	0	4	0	3	247
	EU 28	**2015**	**0**	**251**	**401**	**212**	**1041**	**233**	**1008**	**556**	**0**	**37**	**0**	**0**	**3739**
	EU 28	**2030**	**179**	**287**	**294**	**186**	**1237**	**69**	**655**	**327**	**5**	**38**	**1**	**7**	**3285**
	EU 28	**2040**	**235**	**259**	**162**	**135**	**1392**	**45**	**490**	**209**	**3**	**35**	**1**	**30**	**2995**
	EU 28	**2050**	**270**	**229**	**74**	**95**	**1525**	**32**	**355**	**135**	**2**	**31**	**0**	**58**	**2806**

Table 23: Final energy demand of the transport sector by EU28 country and SET-Nav pathway in GWh

		Year	Oil	Natural Gas	Biofuels	Electricity	Hydrogen	Total
AT	Base year	2015	70,787	0	3,910	1,994	0	76,691
	Reference	2030	68,325	102	6,620	2,539	5	77,592
		2050	67,180	504	6,891	5,464	95	80,134
	Diversification	2030	54,018	194	7,623	3,034	94	64,962
		2050	17,432	1,291	15,578	8,854	10,175	53,330
	Directed Vision	2030	52,025	183	9,263	2,978	0	64,450
		2050	20,711	1,028	9,500	17,916	1	49,157
	Localization	2030	54,282	522	7,638	3,155	5	65,602
		2050	19,354	2,298	23,604	9,758	528	55,542
	National Champions	2030	50,355	397	12,558	2,808	0	66,118
		2050	13,740	1,540	33,239	7,926	1	56,447
BE	Base year	2015	100,611	0	3,077	1,076	0	104,765
	Reference	2030	97,725	2,588	8,718	1,728	16	110,776
		2050	98,171	6,931	9,066	6,088	180	120,436
	Diversification	2030	77,571	2,845	10,461	2,331	202	93,410
		2050	27,173	8,007	23,447	10,008	17,285	85,920
	Directed Vision	2030	74,555	2,829	12,415	2,381	0	92,179
		2050	29,978	8,064	14,534	23,978	3	76,557
	Localization	2030	77,427	3,136	10,652	2,545	20	93,780
		2050	30,207	6,897	36,280	10,947	984	85,315
	National Champions	2030	72,240	2,900	17,259	2,108	0	94,507
		2050	22,577	5,664	48,991	9,487	3	86,722
BG	Base year	2015	32,332	0	1,200	603	0	34,136
	Reference	2030	30,374	635	2,176	565	0	33,750
		2050	29,582	1,590	2,215	1,127	34	34,548
	Diversification	2030	25,852	975	2,651	627	16	30,121
		2050	14,611	2,564	7,000	2,746	533	27,454
	Directed Vision	2030	24,933	760	3,932	638	0	30,262
		2050	11,160	1,909	6,050	6,481	0	25,600
	Localization	2030	26,373	950	2,510	632	2	30,467
		2050	16,088	2,098	6,849	2,997	82	28,113
	National Champions	2030	24,632	712	4,428	622	0	30,393
		2050	11,365	1,402	12,303	2,262	0	27,333
CY	Base year	2015	30,672	0	23	0	0	30,696
	Reference	2030	27,316	10	80	9	0	27,416
		2050	25,735	55	175	85	6	26,055
	Diversification	2030	26,382	11	292	17	6	26,706
		2050	21,866	54	2,211	233	140	24,504
	Directed Vision	2030	21,952	10	4,705	17	5	26,690
		2050	10,930	54	12,498	653	166	24,301
	Localization	2030	26,624	11	120	17	5	26,777
		2050	22,097	57	2,153	243	142	24,691
	National Champions	2030	26,653	8	159	15	0	26,836
		2050	22,445	25	2,131	217	11	24,829

		Year	Oil	Natural Gas	Biofuels	Electricity	Hydrogen	Total
CZ	Base year	2015	57,925	0	2,045	2,456	0	62,427
	Reference	2030	58,927	9	4,841	2,589	1	66,366
		2050	60,562	158	5,305	4,279	89	70,394
	Diversification	2030	47,273	151	4,979	2,785	72	55,262
		2050	29,531	1,063	9,017	6,786	3,058	49,455
	Directed Vision	2030	43,760	146	7,307	2,856	0	54,068
		2050	19,582	912	8,975	15,501	0	44,970
	Localization	2030	48,012	565	4,795	2,818	7	56,197
		2050	31,679	2,049	9,322	7,228	484	50,762
	National Champions	2030	44,230	410	8,869	2,777	0	56,286
		2050	18,309	1,287	23,193	6,767	0	49,556
DE	Base year	2015	633,365	640	32,597	14,209	0	680,811
	Reference	2030	541,677	4,844	36,997	16,607	60	600,184
		2050	498,968	9,327	38,942	41,845	1,425	590,508
	Diversification	2030	394,897	9,340	69,204	22,754	64	496,259
		2050	128,617	17,782	115,466	129,544	2,909	394,318
	Directed Vision	2030	419,484	5,705	54,379	21,982	85	501,634
		2050	172,691	10,596	68,557	143,343	4,227	399,413
	Localization	2030	400,477	10,797	75,517	22,132	293	509,217
		2050	115,400	23,711	147,241	105,208	20,523	412,084
	National Champions	2030	408,940	5,575	66,045	21,617	0	502,177
		2050	161,213	12,997	153,880	90,968	18	419,075
DK	Base year	2015	43,668	0	1,768	460	0	45,897
	Reference	2030	40,593	248	3,254	1,494	3	45,593
		2050	40,428	683	3,457	3,740	60	48,369
	Diversification	2030	33,595	254	4,176	1,597	2	39,624
		2050	13,222	715	11,613	8,935	216	34,701
	Directed Vision	2030	32,259	254	5,799	1,660	3	39,975
		2050	13,180	706	8,672	11,210	235	34,004
	Localization	2030	34,602	376	4,001	1,565	52	40,597
		2050	11,020	731	9,878	8,568	4,976	35,173
	National Champions	2030	31,471	226	6,150	1,648	3	39,498
		2050	10,488	428	14,476	8,999	220	34,610
EE	Base year	2015	11,607	0	87	51	0	11,744
	Reference	2030	10,509	195	192	135	2	11,033
		2050	10,609	435	206	594	20	11,865
	Diversification	2030	9,025	207	443	146	7	9,828
		2050	6,255	527	1,698	906	203	9,590
	Directed Vision	2030	8,872	206	625	163	0	9,866
		2050	4,346	516	2,227	2,021	0	9,111
	Localization	2030	9,076	225	470	147	1	9,920
		2050	6,234	489	2,058	971	33	9,786
	National Champions	2030	9,035	202	597	149	0	9,982
		2050	6,194	398	2,284	851	0	9,727

		Year	Oil	Natural Gas	Biofuels	Electricity	Hydrogen	Total
EL	Base year	2015	86,298	0	2,455	139	0	88,891
	Reference	2030	78,238	278	5,500	172	1	84,188
		2050	75,718	570	5,920	1,451	71	83,730
	Diversification	2030	67,028	281	8,013	380	64	75,766
		2050	29,763	597	22,243	4,874	4,261	61,737
	Directed Vision	2030	63,858	281	11,709	359	0	76,207
		2050	29,286	593	18,445	12,978	0	61,303
	Localization	2030	68,922	283	7,179	423	35	76,842
		2050	33,226	606	24,667	5,354	1,711	65,563
	National Champions	2030	65,115	252	10,993	321	0	76,680
		2050	27,125	416	35,107	3,949	0	66,596
ES	Base year	2015	367,848	19	10,747	1,921	0	380,535
	Reference	2030	364,864	1,354	27,204	3,187	3	396,611
		2050	382,924	4,039	30,265	9,725	314	427,267
	Diversification	2030	279,885	4,255	55,037	3,985	60	343,221
		2050	102,762	23,354	165,912	18,658	2,282	312,967
	Directed Vision	2030	284,611	1,477	51,607	5,203	0	342,898
		2050	130,027	5,317	91,754	63,352	0	290,450
	Localization	2030	285,359	4,541	53,816	4,445	0	348,160
		2050	102,241	18,867	176,846	21,164	0	319,118
	National Champions	2030	288,631	3,891	53,838	4,368	0	350,727
		2050	111,446	14,986	174,095	21,090	0	321,617
FI	Base year	2015	53,439	0	3,499	1,135	0	58,073
	Reference	2030	48,520	332	4,409	1,341	6	54,609
		2050	48,337	834	4,634	3,695	85	57,585
	Diversification	2030	40,062	433	5,789	1,451	5	47,741
		2050	17,126	1,392	16,888	6,632	238	42,276
	Directed Vision	2030	38,860	427	7,245	1,507	6	48,046
		2050	17,201	1,333	9,913	12,584	261	41,293
	Localization	2030	40,705	571	5,783	1,461	5	48,525
		2050	12,718	1,139	15,443	11,557	263	41,119
	National Champions	2030	36,930	354	8,812	1,514	0	47,610
		2050	13,179	570	22,782	6,457	1	42,989
FR	Base year	2015	514,630	0	29,003	8,685	0	552,317
	Reference	2030	490,107	2,395	28,365	12,659	49	533,575
		2050	461,235	7,628	27,825	37,778	774	535,241
	Diversification	2030	368,440	3,472	57,717	14,398	686	444,713
		2050	95,869	12,788	86,604	89,027	62,163	346,451
	Directed Vision	2030	381,745	3,435	42,983	16,219	66	444,448
		2050	129,949	12,426	49,719	142,270	3,512	337,877
	Localization	2030	376,193	6,257	53,940	14,885	66	451,341
		2050	114,895	14,793	126,275	100,569	3,608	360,139
	National Champions	2030	377,037	4,912	54,505	14,980	0	451,434
		2050	166,724	12,342	150,228	58,520	14	387,828

		Year	Oil	Natural Gas	Biofuels	Electricity	Hydrogen	Total
HR	Base year	2015	25,523	0	551	373	0	26,447
	Reference	2030	28,880	525	1,771	420	0	31,597
		2050	31,938	1,410	1,882	716	17	35,963
	Diversification	2030	25,403	518	2,840	464	0	29,226
		2050	18,664	1,131	8,836	1,324	0	29,956
	Directed Vision	2030	24,872	591	3,568	473	0	29,505
		2050	14,960	1,952	8,194	3,975	0	29,081
	Localization	2030	25,717	576	2,769	465	0	29,528
		2050	19,086	1,134	9,012	1,348	0	30,580
	National Champions	2030	24,185	485	4,360	465	0	29,495
		2050	12,338	729	15,600	1,356	0	30,023
HU	Base year	2015	40,521	0	1,467	1,368	0	43,356
	Reference	2030	39,100	158	3,396	1,515	0	44,170
		2050	39,425	571	3,553	2,504	71	46,124
	Diversification	2030	30,423	643	4,021	1,559	7	36,653
		2050	12,288	3,558	10,988	3,688	317	30,838
	Directed Vision	2030	29,602	196	4,818	1,647	0	36,264
		2050	13,013	784	5,061	10,244	0	29,102
	Localization	2030	30,940	712	3,968	1,561	0	37,181
		2050	12,010	3,060	12,665	3,851	0	31,587
	National Champions	2030	29,072	603	6,317	1,587	0	37,579
		2050	9,605	2,376	14,810	4,108	0	30,899
IE	Base year	2015	41,204	0	960	60	0	42,223
	Reference	2030	43,567	155	3,170	137	1	47,028
		2050	39,932	435	3,348	1,006	44	44,764
	Diversification	2030	35,643	159	4,206	214	52	40,274
		2050	15,242	470	13,869	2,302	1,884	33,768
	Directed Vision	2030	33,708	158	6,310	243	55	40,472
		2050	11,970	463	8,533	7,275	2,089	30,331
	Localization	2030	36,772	269	3,867	238	54	41,200
		2050	15,300	1,323	14,019	2,442	1,954	35,038
	National Champions	2030	34,680	133	6,182	244	2	41,241
		2050	11,956	244	20,132	2,369	152	34,852
IT	Base year	2015	427,942	7,097	18,166	5,504	0	458,708
	Reference	2030	365,182	12,616	29,992	6,309	2	414,101
		2050	342,264	14,458	28,042	17,534	526	402,824
	Diversification	2030	288,222	16,517	37,636	7,341	82	349,798
		2050	100,386	55,052	110,374	33,198	1,801	300,811
	Directed Vision	2030	285,967	11,161	43,975	8,615	101	349,820
		2050	95,069	6,784	44,268	100,999	2,648	249,769
	Localization	2030	292,354	15,956	37,976	8,111	0	354,397
		2050	102,892	41,789	126,698	36,919	0	308,298
	National Champions	2030	274,876	12,927	59,949	8,345	0	356,096
		2050	89,274	25,082	145,723	36,388	0	296,467

		Year	Oil	Natural Gas	Biofuels	Electricity	Hydrogen	Total
LT	Base year	2015	18,111	0	165	264	0	18,540
	Reference	2030	15,661	112	224	369	0	16,366
		2050	15,069	340	229	791	25	16,455
	Diversification	2030	13,017	197	416	410	0	14,040
		2050	8,969	701	1,982	1,175	0	12,827
	Directed Vision	2030	12,740	182	745	419	0	14,086
		2050	6,011	771	2,372	3,303	0	12,457
	Localization	2030	13,111	219	427	409	0	14,166
		2050	8,915	685	2,317	1,187	0	13,104
	National Champions	2030	13,100	189	544	408	0	14,240
		2050	8,954	540	2,280	1,256	0	13,030
LU	Base year	2015	6,625	0	399	67	0	7,092
	Reference	2030	6,946	4	678	87	0	7,715
		2050	7,751	16	809	236	11	8,823
	Diversification	2030	5,503	36	783	101	0	6,423
		2050	2,632	193	2,645	477	0	5,947
	Directed Vision	2030	5,359	27	949	122	0	6,457
		2050	2,017	187	789	1,554	0	4,547
	Localization	2030	5,548	41	788	118	0	6,495
		2050	2,343	172	2,987	550	0	6,052
	National Champions	2030	5,060	31	1,295	112	0	6,497
		2050	1,379	111	3,984	529	0	6,003
LV	Base year	2015	20,049	0	254	161	0	20,463
	Reference	2030	23,945	834	406	281	0	25,466
		2050	26,347	1,921	471	504	11	29,254
	Diversification	2030	21,107	829	1,576	309	0	23,820
		2050	15,197	1,888	8,149	826	0	26,061
	Directed Vision	2030	20,787	847	1,952	330	0	23,916
		2050	13,555	2,113	8,023	2,036	0	25,726
	Localization	2030	21,330	920	1,443	310	0	24,002
		2050	15,616	2,724	7,504	849	0	26,693
	National Champions	2030	21,138	766	1,805	317	0	24,026
		2050	15,166	1,536	8,651	873	0	26,227
MT	Base year	2015	6,230	0	12	0	0	6,242
	Reference	2030	5,477	40	20	2	0	5,538
		2050	4,566	68	26	40	3	4,703
	Diversification	2030	5,292	40	92	5	4	5,433
		2050	3,792	72	392	102	69	4,426
	Directed Vision	2030	4,564	40	806	10	4	5,423
		2050	1,865	71	1,911	323	93	4,263
	Localization	2030	5,305	41	77	5	4	5,430
		2050	3,817	74	387	104	69	4,452
	National Champions	2030	5,303	31	95	5	1	5,433
		2050	3,831	23	440	117	12	4,423

		Year	Oil	Natural Gas	Biofuels	Electricity	Hydrogen	Total
NL	Base year	2015	138,527	121	4,021	1,392	0	144,061
	Reference	2030	118,435	5,856	9,429	4,554	13	138,287
		2050	99,842	16,653	8,033	10,946	206	135,681
	Diversification	2030	91,097	5,313	17,792	4,614	9	118,824
		2050	30,478	10,473	38,595	17,984	592	98,124
	Directed Vision	2030	94,558	6,108	15,464	4,719	11	120,861
		2050	37,186	18,929	19,634	26,589	661	102,998
	Localization	2030	91,186	6,282	17,486	4,955	0	119,908
		2050	25,821	10,530	34,255	23,770	2	94,377
	National Champions	2030	91,038	5,924	18,354	4,302	0	119,619
		2050	30,438	9,208	39,787	16,812	2	96,247
PL	Base year	2015	181,969	0	9,066	4,712	0	195,747
	Reference	2030	201,708	485	16,354	5,929	4	224,481
		2050	210,290	1,960	16,892	9,500	222	238,865
	Diversification	2030	160,551	1,967	19,635	6,458	0	188,611
		2050	80,090	8,420	59,882	17,588	0	165,980
	Directed Vision	2030	156,315	1,031	22,810	6,691	0	186,848
		2050	72,211	4,811	29,118	43,880	0	150,020
	Localization	2030	162,235	2,214	19,872	6,529	0	190,850
		2050	76,601	7,527	66,218	18,625	0	168,972
	National Champions	2030	151,471	1,841	31,948	6,445	0	191,704
		2050	62,434	5,394	85,056	16,967	0	169,851
PT	Base year	2015	71,165	0	3,423	422	0	75,010
	Reference	2030	59,666	83	4,768	663	3	65,182
		2050	52,856	396	4,555	3,286	135	61,227
	Diversification	2030	49,075	511	6,192	745	0	56,524
		2050	17,673	2,639	17,183	6,076	1	43,571
	Directed Vision	2030	47,673	201	8,725	744	0	57,342
		2050	17,674	1,296	10,889	12,959	1	42,819
	Localization	2030	50,224	622	5,880	769	0	57,495
		2050	18,438	2,435	18,588	6,268	1	45,730
	National Champions	2030	47,149	203	9,301	737	0	57,390
		2050	15,066	731	25,635	5,099	1	46,532
RO	Base year	2015	55,626	0	1,821	1,512	0	58,959
	Reference	2030	56,567	1,419	4,411	1,947	1	64,346
		2050	61,167	3,726	4,811	3,488	70	73,263
	Diversification	2030	47,466	1,544	4,986	2,181	0	56,178
		2050	31,984	3,566	11,830	6,871	0	54,251
	Directed Vision	2030	45,786	1,450	7,053	2,211	0	56,500
		2050	23,694	3,955	11,435	13,320	0	52,403
	Localization	2030	48,239	1,905	4,754	2,203	0	57,100
		2050	32,393	7,500	10,087	7,626	0	57,607
	National Champions	2030	44,869	1,267	8,649	2,190	0	56,976
		2050	24,231	2,125	24,503	5,736	0	56,595

		Year	Oil	Natural Gas	Biofuels	Electricity	Hydrogen	Total
SE	Base year	2015	90,273	241	5,307	2,156	0	97,976
	Reference	2030	82,746	566	7,540	4,995	7	95,854
		2050	79,971	1,118	7,717	10,977	153	99,935
	Diversification	2030	62,193	1,030	15,791	5,160	54	84,228
		2050	17,912	1,509	26,735	22,434	1,204	69,794
	Directed Vision	2030	66,740	566	12,542	5,152	0	85,000
		2050	27,944	1,005	17,392	24,831	1	71,172
	Localization	2030	63,671	776	13,879	6,631	80	85,035
		2050	15,741	1,015	22,463	24,609	5,321	69,149
	National Champions	2030	63,861	560	14,361	5,165	6	83,954
		2050	21,411	1,755	30,401	19,518	421	73,506
SI	Base year	2015	19,857	0	542	390	0	20,789
	Reference	2030	18,011	30	1,135	453	0	19,629
		2050	18,297	77	1,136	1,004	28	20,542
	Diversification	2030	14,710	109	1,179	492	0	16,490
		2050	10,028	577	1,738	1,965	0	14,308
	Directed Vision	2030	14,555	30	1,537	515	0	16,637
		2050	6,823	81	1,297	4,787	0	12,989
	Localization	2030	14,969	130	1,187	510	0	16,795
		2050	10,189	1,187	1,495	2,089	0	14,961
	National Champions	2030	14,169	27	2,198	488	0	16,882
		2050	7,570	62	5,426	1,841	0	14,899
SK	Base year	2015	25,057	0	1,283	1,144	0	27,484
	Reference	2030	25,930	70	2,551	1,174	0	29,725
		2050	26,801	247	2,603	1,536	22	31,210
	Diversification	2030	21,027	248	2,616	1,209	0	25,100
		2050	14,069	977	4,121	2,546	0	21,714
	Directed Vision	2030	20,309	224	3,489	1,233	0	25,255
		2050	10,145	1,145	3,595	5,513	0	20,398
	Localization	2030	21,324	280	2,630	1,218	0	25,453
		2050	14,180	893	4,607	2,660	0	22,340
	National Champions	2030	18,983	233	4,839	1,226	0	25,281
		2050	7,140	660	11,486	2,425	0	21,711
UK	Base year	2015	502,000	4	13,153	2,570	0	517,726
	Reference	2030	443,242	1,212	38,229	5,706	48	488,436
		2050	394,755	3,629	35,717	29,922	992	465,014
	Diversification	2030	326,945	4,320	69,880	8,619	53	409,817
		2050	88,958	19,364	148,125	59,231	2,616	318,294
	Directed Vision	2030	346,802	1,441	61,325	6,625	624	416,817
		2050	107,408	4,701	64,071	104,631	42,089	322,902
	Localization	2030	331,036	5,286	69,749	9,599	0	415,670
		2050	81,172	18,476	168,953	63,001	15	331,617
	National Champions	2030	334,169	3,973	72,115	6,667	0	416,924
		2050	98,039	12,101	174,297	48,584	15	333,036