European Climate Foundation

Modelling the socioeconomic impacts of zero carbon housing in Europe

cambridge econometrics
clarity from complexity

Technical Report

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Executive Summary

This report assesses the socio-economic costs and benefits of different potential pathways for decarbonising the residential building sector in Europe. A scenario approach has been developed to envisage different potential levels of heat demand and combinations of technologies to meet that demand, and then economic modelling has been applied to assess impacts.

This technical report sets out the findings from our analysis. It uses a housing stock model to set out the required expenditure on both up-front technology (and energy efficiency measure) costs and ongoing fuel/electricity costs by households, and a macroeconomic model (E3ME) to assess the socioeconomic impacts of this transition.

The study shows that there are social, economic and environmental benefits associated with decarbonising residential buildings in Europe. A key driver of these results is the deployment of greater energy efficiency measures in buildings, which reduces energy demand from the housing stock in the long term, leading to major benefits for the European economy as it shifts consumption away from imported fossil fuel energy and towards other goods and services with greater European domestic content. In addition, changing heating technologies can further reduce demand for fossil fuels, and increase demand for electricity (which is generated almost entirely within Europe) or hydrogen (which can be sourced either from Europe or further afield).

The modelling results suggests that:

- A renovation wave is expected to boost employment and GDP growth in the short-term due to the large investment stimulus and have a net beneficial impact for the economy. Renovating the EU building stock could cost upward of 300 billion euros per year from 2035 onward, assuming a 3.5% weighted energy renovation rate. This will result in a 50% reduction of the *energy need for heating* by 2050, compared to 2022. A shift towards greater uptake of heat pumps can further reduce the annual *final energy demand for heating* by 74% by 2050, compared to 2022.
- Renovating the European housing stock and electrifying the heat supply will lower the energy bills that households face. Low- and medium-income households will benefit the most as they proportionally spend more on energy. Savings on energy will help to boost Europe's economy as spending flows into sectors with a higher domestic production content.
- Decarbonising the housing stock would cut Europe's energy import dependence, mainly through reducing gas imports. Europe could cut its annual spending on gas imports by 15 billion in 2030 and 43 billion in 2050 by increasing the energy renovation rate and electrifying heat supply. Relying on hydrogen imports for domestic heating would not improve Europe's overall energy trade balance, and therefore has more muted economic benefits.
- The EU economy will be strengthened. In most of the scenarios explored, the transition to a net-zero building stock leads to an increase in GDP. Electrifying the heat supply and lowering the need for heating through renovations shows the most favourable GDP impacts, leading to a 0.7% increase in annual GDP in 2030 and a 1% increase by 2050.

- Renovating Europe's building stock and electrifying the heating supply will help create 1.2 million net additional jobs by 2050; a 0.5% increase from baseline. Most jobs are created in the construction sector (475 thousand) and the power sector (300 thousand). Due to the decarbonisation, 240 thousand jobs will be lost in fossil fuel related industries.
- For the consumer, heat pumps and solar thermal are cost competitive options due to reduced energy spending, while hydrogen boilers are a more expensive technology due to higher energy bills. The total cost of ownership of heat pumps is likely to converge towards that of condensing gas boilers by 2028. Implementation of an emission trading scheme for households will lead to heat pump ownership becoming cost competitive immediately.
- A transition to hydrogen-based heating is not projected to lead to similar wider socioeconomic benefits as households will face higher energy bills. Ultimately, the report therefore finds that renovating the dwellings stock will have a net beneficial impact, however, the choice of heating technology will also play a crucial role in determining the economic impact.

The modelling does not consider how such transitions could be brought about; a key challenge for policymakers is to identify which policy mechanisms could be utilised to drive transitions, and in particular to drive low or no-regret outcomes such as improved energy efficiency across the EU's residential building stock.

1 Introduction

1.1 Objectives and scope

Decarbonising the building stock is a key challenge on the way to Europe becoming the first climate-neutral continent by 2050. At present, buildings account for 40% of the EU's energy consumption, with the population stabilising and household sizes shrinking, the energy consumption of buildings is likely to continue growing unless immediate action is taken. In response to the growing demand for heating, the European Commission has launched a 'renovation wave' which aims to put emphasis on upgrading the existing building stock.

This study assesses the core impacts of potential decarbonisation pathways for the residential housing stock, through modelling the techno- and socio-economic impact of changes in the energy performance of dwellings as well as the main technologies used for heating. Commercial buildings are out of the scope of this study. The purpose of the study is to consider a series of illustrative but plausible scenarios. These are not intended to be forecasts of the most likely outcomes and are deliberately differentiated to show the potential differences in European-wide impacts under different transition pathways. Similarly, this study does not look at system dynamics that may arise between – for example – hydrogen demand and hydrogen supply.

The report is designed to show key trends, and consequently emphasis is placed on the European-wide results. We primarily focus on operational effects resulting from changes to the housing stock and heat supply. The modelling was conducted on a country-by-country basis and aggregated by climatic zones and further to the EU (including UK) level. Graphs showing the breakdown by climate zone are available in the appendix, however, the key focus on this study is on the EU-wide effects.

Overall, the findings of the report generally support previous studies of a similar nature. Renovating the EU building stock will likely cost upward of 300 billion euros per year from 2035 onward, assuming a 3.5% weighted renovation rate continues to be targeted once the 'low hanging fruit' has been tackled in earlier years. The accumulated renovations will result in a reduction of energy demand for heating of almost 190 TWh in 2050. Due to the large investment stimulus, the renovation wave is expected to boost employment and GDP growth in the short term. A shift towards greater use of heat pumps for heating can further reduce the annual final energy demand by 40% compared to baseline levels by 2050. Although a move towards hydrogen for heating will result in similar emission reductions, greater investment will also need to be made into the existing gas grid and there will be lower economic gains.

The scenario with a high degree of electrification coupled with an increase in building renovations shows the most promise. GDP and employment effects in this scenario are in-large driven by the large investment stimulus required for renovations. These effects are further reinforced by moving towards heat pumps for heating, which reduces the consumer expenditure on energy for heating in the long-run due to the large efficiency gains from heat pumps. The savings in spending on heat allows resources to be redistributed to other spending categories and sectors of the economy, promoting growth in the long-run. Ultimately, the report finds that renovating the dwellings stock will have a net beneficial impact, however, the choice of heating technology will also play a crucial role in determining the economic impact.

1.2 Method

The analysis is based on a three-stage modelling framework. First, a building stock model estimates the total energy need for heating under different renovation assumptions. Second, the heat supply model allocates heating technologies by country based on the technology uptake in different countries. Lastly, the changes in the energy need for heating, renovation cost, and other infrastructure costs are plugged in to the macroeconomic model, E3ME, which provides the economic impacts.

All three models have been parameterised based on available historical data where possible. Where historical data was not available, parameter estimates from the literature were used. In the few instances where insufficient detail was available in the existing literature, other regions sharing similar characteristics were used as a proxy. The data and assumptions were consolidated with a panel of industry and policy experts through 4 rounds of workshops. In each round, the panel had the opportunity to challenge any of the assumptions or data used, as well as contribute to the scenario design.

1.3 Limitations

As the modelling framework is built on historical data, it has the ability to mimic previously observed patterns. However, due to the data reliance, there are natural discrepancies between regions driven by data availability. Consequently, results are likely to be more accurate for data-rich regions. In addition, there is uncertainty surrounding some input parameters, due to a lack of data and insufficient literature on the topic. This includes, for example, hydrogen prices and infrastructure costs, as well as the cost of reinforcing the electricity grid with higher electricity demand.

For the modelling, heating degree days (HDD) and cooling degree days (CDD) projections were used to proxy the energy need for heating. However, energy need for heating depends on complex interactions between individual preferences as well as prices. Additionally, it has been suggested that the energy need for heating is endogenous to increases in energy efficiency; people living in less efficient homes prefer to put on more layers, or only heat a few rooms rather than heating the whole home, whereas efficient homes allow for more comfort but not necessarily lower energy consumption. Depending on the extent of this trade-off, increases in energy efficiency may therefore result in lower saving in the energy need for heating.

Due to the complex nature of district heating and cooling, some simplifying assumptions were made. Firstly, due to the infrastructure costs of district heating networks being highly city-dependent, painting a comprehensive picture of the infrastructure costs becomes difficult. Additionally, one of the main opportunities of district heating is the utilisation of waste-heat streams from industrial activity. This would require a heating model which is integrated with industrial activity and the power generation sector, something which is far beyond the scope of this project. In the modelling, it is assumed that waste heat flows will remain available, even in a decarbonised power sector. The share of available residual heat streams was informed based on advice from the panel of experts and the Danish Energy Agency.

Furthermore, there are some aspects raised by the panel of experts which are outside of the scope of this project. For example, the impact of land-grabbing for bio-energy production and the knock-on effects on house prices and local ecosystems. Conventional economic indicators are used, in combination with changes in emissions, however, socio-environmental externalities are not considered in the modelling. Reskilling requirements to service heat pumps, conduct renovations, or any other unmet skillset is also not included in the modelling, beyond the general constraints present in the macroeconomic model (labour force, unemployment). Instead, we assume that workers have the available skills to meet the demand for these services.

1.4 Chapters

Chapter two goes over the modelling framework in more detail, describing the building stock, heat supply, and macroeconomic models. This chapter will also highlight the interlinkages between the individual models and how they work in unison. Chapter three provides a detailed overview of the scenario design and some of the key assumptions. Chapter four then provides an overview over the results for the EU-wide model. Lastly, chapter five highlights some of the key take-aways from the report, setting out the conclusions of the study.

2 Modelling framework

2.1 Overview

In this chapter we present our approach to assessing the socioeconomic impacts of achieving a zero-carbon housing stock in Europe. First (section 2.2), the data inputs to and an outline of the Building Stock Model is presented. Second (section 2.3), describes how the output of the Building Stock Model is used to estimate the heat supply in all EU Member States and the UK, building upon exogenous heat supply scenario inputs. Third (section 2.4), a brief description of the macro-econometric model – E3ME – is provided which is used to evaluate the socioeconomic impacts based on the changing housing stock and heat supply. Fourth and finally (section 2.5), the linkages between all steps are summarised, highlighting important feedbacks.

2.2 Building stock model

2.2.1 Housing stock data

The initial dwelling stock is based on data from the European-funded Hotmaps project (Pezzutuo, et al. 2018). The data on the dwelling stock and characteristics is disaggregated by 21 archetypes. For most member states, the data provides detailed data for 2016, however, where 2016 data was not available, the closest year of available data was used. For each EU27 member state and the UK, the data disaggregates the current residential dwelling stock by 3 dwelling types (single-family homes, multi-family homes, and apartments) and 7 age classes. Combined, this creates the 21-archetype classification which the building stock model (BSM) is based on. The data also breaks down each archetype by tenure type, providing information on the share of dwellings which are privately rented, owner occupied, or are social housing. The tenure status has no immediate impacts on the evolution of the dwellings stock (we do not assume that rented or social housing is renovated later, which could be achieved for example by the use of minimum energy performance standards in such buildings), but it is pivotal in determining who is likely to pay for renovating the stock.

Using population forecasts from the United Nations Department of Economic and Social Affairs (2018), the total number of dwellings required to meet the demand for housing is projected out to 2050. The composition of the total dwelling stock changes over time according to urbanisation rates; as the urban population increases, the shares of dwellings start shifting in favour of multi-family homes and apartments. As well as different archetypes having different dwellings sizes, household sizes and dwelling sizes evolve over time in accordance with data from the Building Stock Observatory (BSO) (European Commission 2021).

After the total number of dwellings has been estimated, buildings are demolished in accordance with a set demolition rate and the quantity of new dwellings is derived. The number of new dwellings is the difference between the total dwelling demand and the post-demolition dwelling stock. In cases where a region sees a large population decline, resulting in the forecasted demand for housing being below the post-demolition dwelling stock, it is assumed that dwellings are left unoccupied, and no new dwellings are developed that year. In 2016, the unoccupied stock is assumed to be 0, and once a building becomes unoccupied, it is no longer factored into any further calculations.

2.2.2 Archetypes

The 21 archetypes encapsulate differences in dwelling characteristics based on dwelling type and age. The main differences pertain to the energy efficiency as well as their probability of being demolished or renovated (see Table 1). Older dwellings tend to have higher demolition rates, as well as poorer initial energy efficiency performance. However, they are also most likely to be renovated. Furthermore, based on available data, single-family homes generally have the largest potential for improvements in the energy need for heating, whereas multi-family homes and apartments generally have a lower renovation potential.

Table 1: Archetype classifications and sample energy efficiency values (kWh/m^2)

Age	Apartments	Multi-Family Homes	Single-Family Homes
Greater than 72 Years Old	155	209	262
–72-48 Years Old	141	199	232
–47-38 Years Old	105	145	211
37-28 Years Old	101	132	164
27-18 Years Old	77	85	110
17-7 Years Old	59	81	102
Less than 7 Years Old	46	51	68

Due to lack of more detailed historical data, it is assumed that the dwelling ages within each archetype are uniformly distributed. In other words, if there are 10,000 Single-Family Homes built 27-18 years ago, it is assumed that exactly 1,000 dwellings were built every year over that time period. Consequently, in the modelling, the same fraction of the dwellings within an archetype is moved to the older archetype class each year. Once in one of the oldest archetype classes, dwellings no longer move to other archetypes, hence the within-archetype distribution is no longer relevant. In cases where the demolition rate is relatively low, this can result in an accumulation of the oldest dwelling classes. This is because dwellings will move down through the archetypes while very few dwellings leave the stock.

2.2.3 Demographics

Changing demographics contribute to the total number of dwellings and the specifications of new dwelling types. Urban dwellings are assumed to be more likely to be multi-family homes or apartment buildings. Consequently, as countries become increasingly urban, the composition of the dwelling stock starts to favour smaller multi-family homes and apartments.

Differences in average household size are factored into the model at the national scale. Changes in household size are assumed to follow the trend according to data from the Building Stock Observatory, and a lower bound of 2.0 people per household applied. The average lower bound is used to reflect the stabilisation of the EU population (Kiss, et al. 2020). Household sizes are used in conjunction with population forecasts to determine the total number of dwellings required in each year. Additionally, average household size and dwelling sizes also change in response to changing demographic characteristics.

2.2.4 Demolition & renovation

Although data on country-specific demolition rates was not available, a demolition rate of 0.4% per annum was agreed with the panel of experts. The 0.4% is in alignment with the dwelling demolition rate in the Leipzig-Halle urban region in 2007 (Rink, et al. 2010). This rate was applied across all regions and remains constant over time. A report by Artola et al. (2016) suggest that the demolition rate in eight EU countries may have been as low as 0.1% between 1980 and 2005. However, the continuation of these trends would result in a large accumulation of older dwellings, and stagnation of new builds.

Country-level renovation rates and depths were calibrated according to figures provided by the European Commission (Esser, et al. 2019). The relative renovation rate between archetypes was then derived based on individual level property data from the UK ministry of housing (Department for Levelling Up, Housing & Communities 2021). There was insufficient data for other countries to break down the renovation rate by archetypes, hence the distribution of renovations from the UK was applied consistently for all member states. The general trend is that the oldest dwellings are more likely to get renovated first, and single-family homes are about twice as likely to get renovated compared to multi-family homes or apartments. It is further assumed that the relative number of renovations between archetypes is time-invariant. This means that the older archetypes will continuously see higher renovation rates.

After the renovations and demolitions have been allocated according to each archetype, renovation costs and improvements in energy efficiency are calculated. The renovation cost curves are fitted based on the EU Reference Scenario 2020 (European Commission 2021). Shallow renovations range between 20 to 100 euros per square metre, and deep renovations range between 180 to 490 euros per square metre. Shallow renovations are renovations which result in less than 5% reduction in the energy need for heating, and deep renovations are renovations which result in a greater than 70% reduction in the energy need for heating.

The cost curves are assumed to be equal across archetypes, however, vary across the 4 regional classifications provided by the EU Reference Scenario. The impact of this is that Eastern Europe generally faces the lowest renovation costs, and Central/Western Europe as well as Northern Europe face the highest renovation costs. This assumption was made due to lack of adequate data to differentiate renovation costs by archetypes and having a country-level renovation cost disaggregation.

2.2.5 Heating & cooling demand

The heating and cooling demand is calculated based on the current energy efficiency of dwellings and regional forecasts of heating degree days (HDD) and cooling degree days (CDD) from Spinioni et al. (2018) (see figure 1 for projections). Based on available data from 2016, the energy need for heating is decomposed by HDD and dwelling efficiency (kWh/m^2). As old buildings are renovated or demolished and new buildings are built, the average energy efficiency by archetype changes. Once the renovations have taken place, the average efficiency within the archetype will then become the baseline efficiency level in the next period. Because the efficiency values are aggregated, the model does not differentiate between dwellings which have been previously renovated, and those which have not.

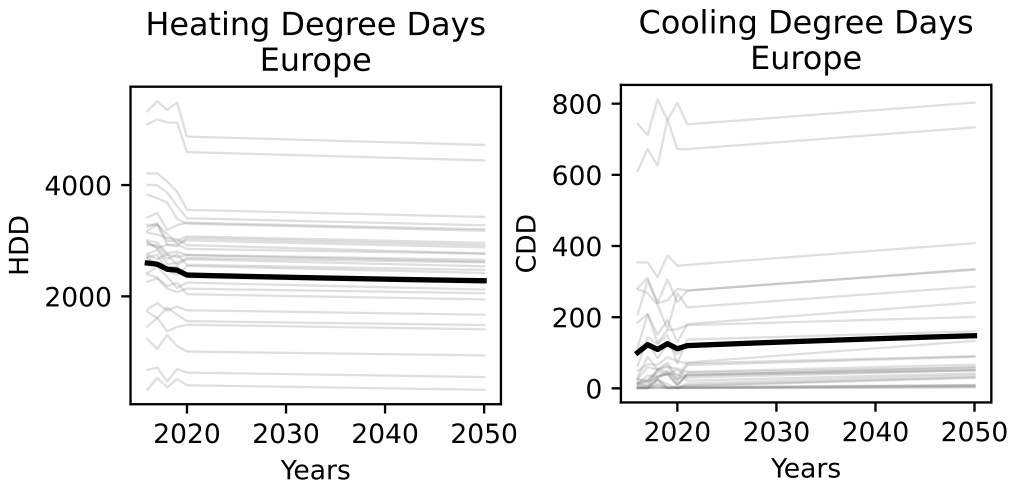

Figure 1: Heating and cooling degree days, EU average

The model takes in a target EU-wide weighted renovation rate and iterates through each year to ensure that the target rate is achieved. We use a definition of the weighted renovation rate which is slightly different from the official definition provided by the European Commission. The Commission defines the weighted renovation rates as, "*…the annual reduction of primary energy consumption, within the total stock of buildings (residential or non-residential respectively), for heating, ventilation, domestic hot water, lighting (only non-residential buildings) and auxiliary energy, achieved through the sum of energy renovations of all depths*" (Esser, et al. 2019, p.15). However, basing the weighted renovation rate on primary energy demand means that quantity of buildings requiring renovation would be endogenous to the heat-supply scenarios, obscuring the renovation impacts. Consequently, from this point onward, when referring to the weighted renovation rate, we refer to reductions in the energy need for heating for the whole dwelling stock. In contrast to primary energy demand, the energy need for heating only considers the amount of heat delivered to a home after any efficiency losses from the heating technologies, and hence represents the heat which is delivered to the dwelling rather than the energy which is delivered.

To achieve the target EU-wide weighted renovation rates, the model solves iteratively and scales up renovation rates where necessary to achieve the target. Renovations are assumed to have equal impacts on the energy need for heating as well as the energy need for cooling, while having no impact on the energy need for hot water. The model also does not consider a comfort trade-off, where the preferred ambient household temperature increases with energy efficiency There is an empirical literature suggesting a comfort trade-off, however, it is uncertain whether this impact is consistent across regions (Gram-Hanssen and Hansen 2016, Majcen, Itard and Visscher 2013, van den Brom, Meijer and Visscher 2017, Weber and Wolff 2018).

The energy efficiency calculations in the model can be summarised in 7 steps:

1. Old buildings are demolished, and new buildings are built

2. Calculate the energy need for heating

3. Conduct renovations and update the energy efficiency by archetype

4. Recalculate the energy need for heating

5. Based on steps 2 & 4, calculate the weighted renovation rates

6. Rescale non-weighted renovation rates based on the difference between the target weighted renovation rate and the rate calculated in step 5.

7. Repeat steps 1 through 6 until convergence between the target rate and the rate calculated in step 5.

Once the efficiencies per HDD have been calculated for each archetype, the total energy need for heating can be derived based on the projected annual HDDs and the total floor area within an archetype. We break down the main dynamics of the heat demand in to four components; first, changes in energy efficiency, second, changes in the number of HDD; third, the number of dwellings of each archetype; and lastly, the total floor area of each archetype.

The treatment for cooling demand follows an identical process, but using CDD projections instead of HDD.

2.3 Heating & cooling supply

2.3.1 Heating & cooling technologies

In the modelling we make a distinction between thirteen individual heating technologies and district heating/cooling (DH/C). Heat pumps (HPs) and DH/C can supply both the demand for heating and cooling, and on top of that there is a generic cooling technology category called air-conditioning (see Table 2). Within DH/C we include seven configuration options. The configuration of the heating/cooling networks can change depending on external considerations, such as assumptions on the potential for residual heat streams from industrial processes to heating networks, the amount of thermal power generation that can produce co-generated heat and need for diurnal and seasonal storage to cover demand-supply mismatches. The DH/C configuration options are summarised in Table 3.

Table 2: Overview of heating and cooling technologies included in this study.

Heating technologies	Cooling technologies
Non-condensing Oil boiler	
Condensing Oil boiler	
Non-condensing Gas boiler	
Condensing Gas boiler	
Wood stove	
Wood boiler	
Coal stove	
District heating	District cooling
Electric heating	
Heat-pump Ground	Heat-pump Ground
Heat-pump Air-Water	Heat-pump Air-Water
Heat-pump Air-Air	Heat-pump Air-Air
Solar Thermal	
Hydrogen boiler	
	Air-conditioning (generic)

Table 3: DH/C configurational options included in this study.

District heating configuration	Comment
Residual heat flows from industry	Industrial processes generate waste heat streams that can be utilised to heat homes
Co-generation	Combined heat and power thermal (non-nuclear) power generation can provide heat flexibly to homes
Geothermal	Large-scale HP that can operate near to baseload.
Air-source HP	Large-scale HP that can operate flexibly (disregarding electricity price profiles)
Solar thermal	Delivers low temperature heat and operates variably
Peak boilers	During peak hours of heat demand, peak boilers kick in to supply the requested heating demand. Depending on the configuration of the rest of the DH/C network, peak boilers can be gas-based, hydrogen-based, or electricity-based.
Thermal storage	Required to back up demand-supply mismatches, which may arise due to lack of baseload and a preference to not run HPs during peak electricity prices

2.3.2 Technology allocation routine

The BSM provides the energy need for heating and cooling for every archetype and region over time, given the inputs for renovation and demolition rates. Technologies are then allocated to fill demand using the technology allocation routine, depending on exogenous scenario inputs for EU-wide technology uptake trajectories. The starting point for the projections is 2022. Technology shares by heat energy delivered between 2016 and 2022 are provided by a baseline scenario run using FTT:Heat (Knobloch, et al. 2017). After 2022, the scenario inputs alter the technology shares. The allocation of technologies to meet heat demand occurs in two rounds.

First, year-on-year European-wide technology changes are disaggregated to a country-by-country level by taking into account pre-existing technology deployment and changes to energy efficiency levels. In addition, this first round allocation adjusts several technology-specific deployment trajectories by following the rules below:

- Hydrogen boilers are favourably deployed in regions with extensive gas grid networks. Historical market shares of gas boilers are used as a proxy.
- District heating is also favourably deployed in regions with extensive gas grid networks. Historical market shares of gas boilers are used as a proxy. This is combined with pre-existing district heating networks. Due to the former rule, there is direct competition between district heating and hydrogen boilers.
- Direct electric heating is favourably deployed in warmer climates where it is more likely to be used to cover peak hot water demand given that there’s often no central heating installed.
- Solar thermal is favourably deployed in sunnier regions.

- Heat pumps are favourably deployed in regions with established or growing heat pump markets. The scope thereof consists of the Scandinavian countries plus the United Kingdom, the Netherlands, Germany, Austria, and France.

A second round of allocation further disaggregates the regional allocation into an allocation by archetype, by following certain rules and by accounting for changes in energy demand for heat, which follows directly from the BSM. Data from Hotmaps (Pezzutuo, et al. 2018) provides us with a normative indication of the relative prevalence of a certain technology for each archetype. These are translated to numbers. Expert judgement was used to allocate older technology types to older archetypes (e.g., it is more likely that an older home is equipped with a non-condensing boiler rather than a condensing boiler). For newer technologies such as solar thermal and heat pumps, a rule was set up to favour newer single-family homes.

This builds on the estimated pre-existing market shares by technology and archetype. On top of that the following allocation rules were applied:

- Heat pumps and solar thermal are favourably deployed in new single-family homes due to space constraints in other dwelling types.
- Bio-based heating technologies are favourably deployed in single-family homes due to a more likely prevalence of fireplaces in such dwelling types
- Direct electric heating is favourably deployed in multi-family family homes and apartments.
- District heating is favourably deployed in multi-family homes and apartments.

The approach for allocating cooling technologies to meet the energy demand for cooling follows from the heating technology allocation. Certain technologies can supply both heating and cooling, such as heat pumps and district heating and cooling. Regarding the latter, it is assumed that district heating and cooling networks allow for greater cooling capabilities over time with a regional rule system: in warmer regions, district cooling has a bigger role to play than in cooler regions. This is reflected by faster uptake of cooling capabilities.

Heat pump and district heating shares of energy demand for heating reflect how many households of a certain archetype utilise said technologies. These households are assumed to apply those technologies to satisfy their cooling demand. If under-capacity of cooling supply still exists, then the rest of the energy demand for cooling is assumed to be supplied by air conditioning.

2.3.3 Technology cost assumptions

A different technology uptake trajectory can have significant micro- and macro-economic effects relating to the changing heating system. It also matters where certain technologies are taken up due to interactions with ambient temperatures and domestic heat demand profiles. The former affects primarily the performance of heat pumps, while the latter affects the capacity required to cover peak heat demand. In Table 4, some of the primary components and their regional variations are summarised. In ‘Appendix A: Technology data sheets’ a more comprehensive data sheet can be found by country, which includes region-specific estimations of HP performance and capacity factors. These components were obtained from Knobloch et al. (2017).

Coefficients describing assumed learning-by-doing effects are also provided in ‘Appendix A: Technology data sheets’ and these were obtained from the EU Reference Scenario 2020. Estimating future upfront costs of relatively novel technologies such as HPs is not without issue as it requires an estimation of learning-by-doing and economies of scale effects. The investment projections used in the EU Reference Scenario 2020 are modest compared to what is assumed in Knobloch et al. (2017), who uses a 35% learning rate. This translates to a 35% reduction of the upfront investments for every time the accumulated installations of HPs double. In a Net-Zero setting with increased uptake of HPs this could lead to cost reductions ranging between 50 to 70% by 2050. Here, we follow the estimations provided within the EU Reference Scenario 2020, which indicates cost reductions ranging between 8 and 15%. The numbers used within the study can therefore be considered to be on the conservative side.

Table 4: Cost components for heating technologies. Ranges relate to regional differences.

Heating technologies	Equipment and installation cost (€/kW)	Maintenance (€/kW)	Lifetime (Years)	Efficiency (%)
Non-condensing Oil boiler	231.17 – 760.73	9.25 – 30.43	18	75
Condensing Oil boiler	231.17 – 760.73	9.25 – 30.43	18	86
Non-condensing Gas boiler	195.95 – 644.84	3.92 – 12.90	18	75
Condensing Gas boiler	195.95 – 644.84	3.92 – 19.90	18	90
Wood stove	198.66 – 653.75	0.05 – 0.16	20	70
Wood boiler	236.14 – 777.08	0.94 – 3.11	20	85
Coal stove	111.52 – 366.99	2.23 – 7.34	20	75
District heating	N.A.	N.A.	25	N.A.
Electric heating	242.91 – 799.36	0.24 – 0.80	20	99
Heat-pump Ground	632.10 – 2080.12	6.32 – 20.80	18	350
Heat-pump Air-Water	338.63 – 1114.35	6.77 – 22.29	18	250 - 270
Heat-pump Air-Air	230.27 – 757.76	10.47 – 34.44	18	250 - 270
Solar Thermal	349.01 – 1148.53	3.49 – 11.49	20	100
Hydrogen boiler	235.141 – 773.81	3.92 – 12.90	18	90

Table 5: Cost components for the configuration options of DH/C.

District heating configuration	Equipment and installation cost (€/kW)	Equipment and installation cost By 2050 (€/kW)	Maintenance (€/kW)	Efficiency (%)
Residual heat flows from industry	1140	1083	21	350
Co-generation	1500	1425	21	350
Geothermal	1500	1350	77.8	460
Air-source HP	2000	1800	21	310
Solar thermal	700	630	10	100
Peak boilers	150	142.5	1.2	90
Thermal storage	125	118.75	97.2	80

2.3.4 Infrastructure requirements

This research evaluates different large-scale transitions of the European housing stock and heating systems. To accommodate such a transition, infrastructure changes are required. Depending on the technologies being deployed, additional investments are required to accommodate hydrogen demand for heating, additional electricity demand due to electrification of the heating systems and electricity required to produce green hydrogen, or additional DH/C infrastructure. However, large uncertainties exist around the investments required to sustain certain transitions. Any scenario involving hydrogen-based heating (either through individual boilers or through DH/C) will need to account for pipeline networks capable of transporting hydrogen reliably. According to ACER (2021), it is possible to repurpose existing natural gas grids, but not without issues and therefore additional costs. Repurposing is also more effective than laying down new hydrogen pipelines. In the report produced by ACER, they highlight some studies trying to estimate the cost of hydrogen infrastructure and note that there are various estimates. Here, we assume that natural gas pipelines are not repurposed, but rather new hydrogen pipelines are built. The EU Reference scenario 2020 provides costs estimates for placing such (new) hydrogen networks.

Estimating the reinforcement costs of the power grid is also challenging. First, there are many factors to consider: the change in demand of electricity; the hourly load-demand profile; and densities of consumption sources. In our modelling, we quantitatively address the first factor, but the others we address qualitatively. Second, sources on power grid reinforcement – specifically due to electrification of household heat supply – are scarce. In this analysis, we used a report commissioned by the CCC (2014). It lays out several scenarios of required grid expansion and related costs under several decarbonisation scenarios in the United Kingdom. We used the difference between the total upgrade costs (consisting of low and high voltage cables, distribution transformers, and substations) of their no climate action scenario and their core decarbonisation scenario to form a static factor by comparing it to a scenario with the greatest increase of household electricity demand compared to 2020 levels in the UK. This factor is then applied to other countries as well. A simple parameter as presented in Table 6 neglects certain considerations. The configuration of power grids differs a lot between countries, and electrification of the heat supply may affect hourly heat demand profiles differently in different regions.

Transitioning to DH/C as the main mode for heating homes also requires additional infrastructure investments. Pipeline networks are required to be laid out, the cost of which depends heavily on site-specific considerations, such as the length of the pipeline networks, distances between supply sites and demand sites (dwellings), density of the dwellings, etc. The UK Department for Business, Energy & Industrial Strategy (BEIS) published a report on planned DH/C projects in the UK with some cost estimates of pipe networks. Numbers from these projects were used to estimate DH/C infrastructure costs (BEIS 2021).

The infrastructure cost assumptions are listed in Table 6.

Table 6: Infrastructure investment cost.

	Investment factor	Unit	Comment
Hydrogen production capacity	1600 (200)	m€/GW	Applied to positive changes in hydrogen demand. Value in brackets is the assumed investment factor in 2050
Hydrogen pipelines	0.2	m€/GWh	Applied to positive changes in hydrogen demand
Power grid reinforcement	0.18	m€/GWh	Applied to changes in residential electricity demand above 2020 levels
DH/C pipelines	0.15	m€/GW	Applied to changes in DH/C capacity

2.3.5 Emissions

Present-day household heating in Europe mostly involves natural gas boilers that burn methane to produce heat, and because of the combustion process these emit CO_2 and other pollutants such as NO_x. While the former negatively impacts radiative forcing, the latter negatively impacts public health. Decarbonising the residential heat supply will certainly address the first, but it may not necessarily address emissions of other pollutants. Combustion of hydrogen in open air will lead to NO_x emissions. The extent to which these emissions occur depends on the specific hydrogen technology, but according to a review study carried out by BEIS (2019), hydrogen-ready boilers can emit up to six times more NO_x than natural gas boilers. However, the Ecodesign[1] limit for boilers with gaseous inputs is 56 mg NO_x / kWh_{input} (15.5 g NO_x / GJ_{input}). We assume that new hydrogen boilers will abide by this regulatory measure. In this study, we do not monetise the adverse health effects due to residential emissions of non-CO_2 pollutants, primarily because there are large uncertainties around such monetisation efforts, but it does not mean that such potential negative or positive effects on air quality should be disregarded altogether.

The emission factors of several pollutants, by technology, used in our modelling, are summarised in Table 7. CO_2 emission factors depend on the emission factors of the specific energy carrier used in each technology. The emission factors for other pollutants were obtained from the heating technology catalogue provided by the Danish Energy Agency (2021).

[1] See COMMISSION REGULATION (EU) No 813/2013: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32013R0813&from=HU

Table 7: Emission factors of six pollutants due to energy inputs for each heating technology.

Heating technologies	CO_2 (kg / GJ input)	SO_2 (g / GJ input)	CH_4 (g / GJ input)	N_2O (g / GJ input)	NO_x (g / GJ input)	$PM_{2.5}$ (g / GJ input)
Non-condensing Oil boiler	74.1	6.7	0	0	52	5
Condensing Oil boiler	74.1	6.7	0	0	52	5
Non-condensing Gas boiler	56.1	0.43	1	1	20.4	0.1
Condensing Gas boiler	56.1	0.43	1	1	20.4	0.1
Wood stove	0	25	125	4	90	29
Wood boiler	0	25	2	4	70	14
Coal stove	98.3	25	125	4	90	29
District heating	*	*	*	*	*	*
Electric heating	0	0	0	0	0	0
Heat-pump Ground	0	0	0	0	0	0
Heat-pump Air-Water	0	0	0	0	0	0
Heat-pump Air-Air	0	0	0	0	0	0
Solar Thermal	0	0	0	0	0	0
Hydrogen boiler	0	0	0	0	15.5	0

Note(s): only CO_2 emissions factors are in kg / GJ input; others are in g / GJ input.
***: Emission factors for district heating/cooling depend on the configuration of the supply to the heating/cooling networks. It includes emissions from co-generation but not from residual heat streams.**

2.4 Macro-economic modelling with E3ME

The outcomes of the BSM and heat supply allocation are linked with the macro-econometric E3ME model, a comprehensive simulation model developed and maintained by Cambridge Econometrics. It follows a school of thought that does not per se involve economies operating at an optimal equilibrium, and this translates to sub-optimal behaviour of economic agents, imperfect foresight, heterogenous agents with different perceptions and valuation of the future, and spare capacity in terms of production and labour which may be utilised (Mercure, Knobloch, et al. 2019).

The model covers economy, environment, and energy domains with feedbacks back and forth and important indicators are solved through 28 econometric relationships across all domains (e.g. employment, industry prices, consumer expenditure, industrial investment, etc.). The power sector is solved by a bottom-up technology model, called FTT:Power, which builds on the evolutionary economic school of thought (Mercure 2012). The geographical coverage is global. All EU member states, the UK and major economies are represented individually, while the rest of world is combined into several different regional aggregates, summing up to a total of 70 regions.

E3ME is a demand-led model, meaning supply responds to effective demand within constraints. Supply and demand are mediated through the framework of national accounts. Effective demand is a sum of products exported, changes in inventories, fixed investment in new capital, final consumption by government, final household consumption, and intermediate demand (reflecting value-chains) (see Figure 2). Total domestic demand minus imports provides the domestic supply (=gross output).

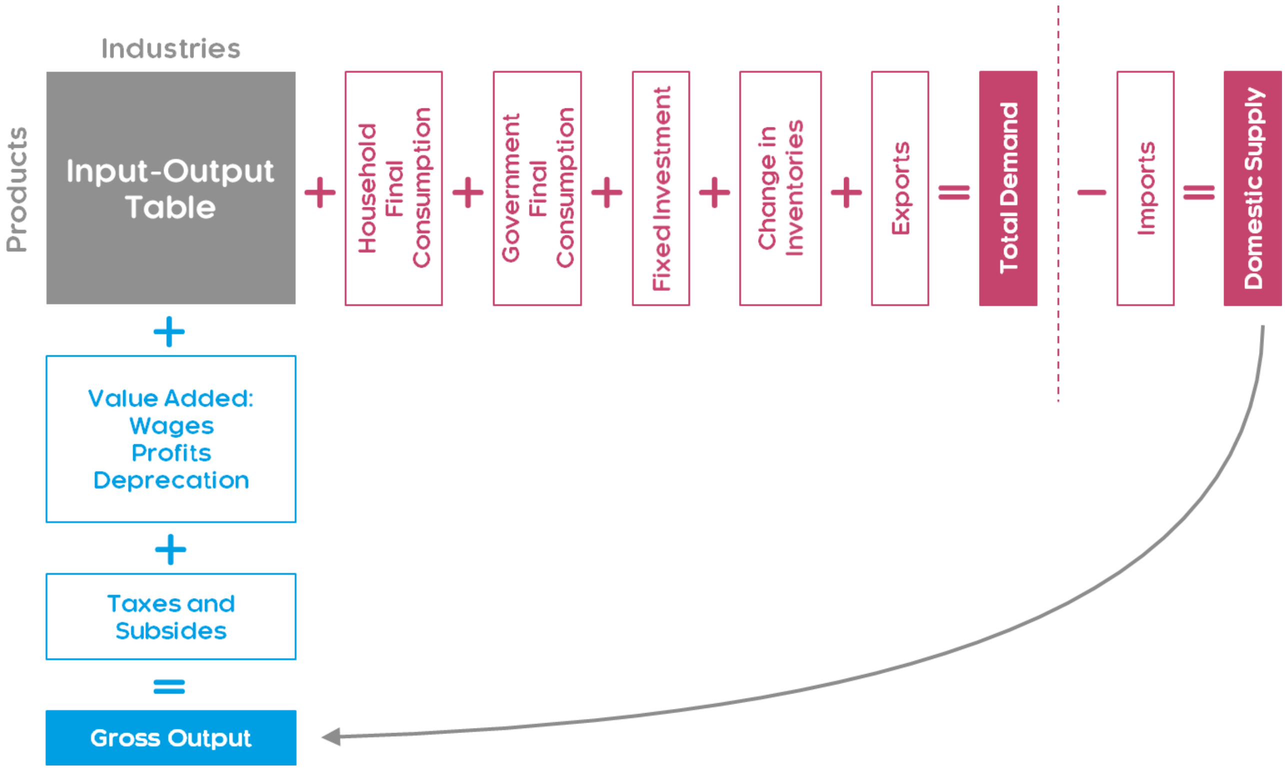

Figure 2: Framework of national accounts.

Gross output is a measure of economic activity by sector, which is an important driver for employment. A unique characteristic of E3ME is the treatment of employment which considers both voluntary and involuntary unemployment. It also includes technological progress which adversely affects the demand for labour. E3ME does not include measures of skills demand and supply explicitly. This is a limitation in scenarios involving large-scale economic restructuring. Employment, together with wages, are the main inputs to determine disposable income, which in turn is an explanatory variable for household consumption.

Estimating household consumption is a two-stage process. Total consumer spending by region is derived using functions estimated from time-series data.

These equations relate consumption to regional personal disposable income, a measure of wealth for the personal sector, inflation and interest rates. Share equations for each of the detailed consumption categories are then estimated. Similar inputs are used to solve consumer demand by category, with the main difference being the exchange of inflation for product specific price levels. Among the household consumer categories are those that are relevant for studying the socioeconomic impacts of decarbonising the European housing stock:

- Spending on different energy carriers;
- Household appliances (such as heating and cooling systems);
- Household maintenance (including on heating and cooling systems);
- Rent payments;
- General maintenance & repair (including renovating dwellings)

Consumer prices are determined by combining domestic and imported industry prices, and relevant changes to fiscal policies. This affects all of the consumer categories listed above. Fiscal policies may change if the government is bearing the costs of policies or if the government generates additional revenues from taxation. We assume net-neutrality of government budgets. In reality, it is possible that governments may accrue debt and correct for that with a time delay. There are also numerous other avenues governments could go down to rebalance policy income or cost. Here, it is assumed to be divided in equal parts to affect VAT rates, income tax, and employer’s contribution to social security. VAT rates affect prices faced by consumers, income tax affect disposable income, and employer’s contribution to social security affects the cost of employment.

A more detailed description of the E3ME model can be found on www.e3me.com. In the next section, a more detailed description of relevant model linkages is provided that evolve from the BSM and the heat supply module.

2.5 Model linkages

Evaluating the socioeconomic effects of decarbonising the European housing stock involves a 3-step process. First, the building stock modelling determines the need for heating and cooling. Second, the heat supply allocation routine determines how the need for heating and cooling is satisfied. Third, the outputs from the two preceding steps form the inputs of macroeconomic modelling where E3ME is used to evaluate the socioeconomic effects.

2.5.1 Process steps

The process starts with the projections for the **housing stock**, building on Hotmaps and the Building Stock Observatory. The year of departure is 2016 and projections are made to 2050. With assumptions on changing demographics, renovation rates and depths, demolition rates, and projections of CDD and HDD, we estimate the end-use energy demand intensities for space heating, hot water, and cooling by archetype and region for each year going forward.

The **supply of energy by heating technologies** is then projected to match the sum of space heating and hot water demand. We use exogenously set EU-wide market shares (in terms of energy supplied for heating) and scale this up using the EU-wide energy need for heating, which is then broken down to a regional level and subsequently to an archetypical level. Based on the technologies used for heating and cooling, the associated final energy demand, expenditure on new equipment, expenditure on O&M, emissions (all by technology, archetype, and region), investment infrastructure requirements, and renovation investments (by archetype and region) are derived.

The outputs from step 2, changes in consumer expenditure and investment requirements in particular, serve as inputs to **E3ME for the purpose of assessing the socioeconomic impacts** of a changing residential heating system. Changes to the inputs to E3ME lead to distinctively different macro-economic outcomes throughout the projection period (2022-2050).

Figure 3 illustrates the approach taken in the BSM and heat supply allocation routine (step 1 and 2). Cooling supply is omitted for clarity and – as highlighted in Section 2.3 – it follows the same approach as for the heat supply allocation.

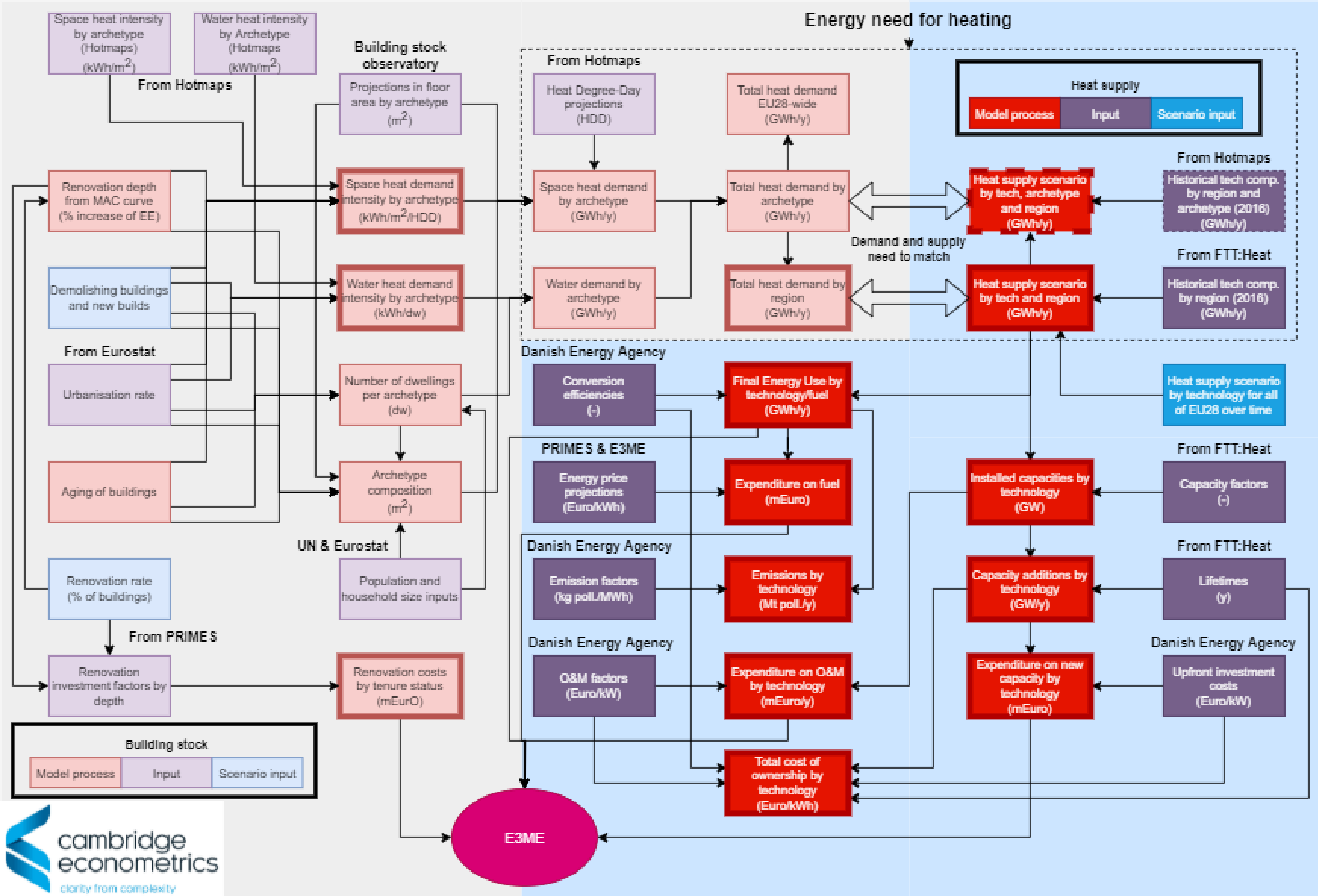

Figure 3: Model structure of the BSM with its linkages to to the heat supply allocation routine.

2.5.2 Inputs to E3ME

Decarbonising the European housing stock will entail changes in consumer expenditure and require investments to be made by different economic actors with distinctly different responses. The main actors involved are different types of households (those living in social housing, owner-occupied homes, or privately rented homes), sectors related to energy supply, sectors related to manufacturing heating and cooling equipment, and governments. To capture the economy-wide effects of the expenditure and investment changes for these economic actors, results from the BSM and heat supply model are use as inputs to the macroeconomic model E3ME. he different inputs to E3ME are outlined below:

Expenditure on heating & cooling equipment:

- Upfront expenditure on new heating & cooling equipment – calculated by the BSM and heating technology supply routine – is added to the consumer category Household appliances in E3ME. The main assumption here is that consumers pay for new equipment through loans, payment schemes, or directly from accumulated wealth and therefore it does not lead to crowding out of consumer expenditure on other spending categories.
- Upfront expenditure on new DH/C networks is added to the investments made by the Gas Supply sector. DH/C networks are usually operated by companies or public bodies, and not directly by consumers.
- O&M expenditure on heating & cooling equipment - calculated by the BSM and heating technology supply routine - is added to the consumer category Household maintenance in E3ME. This leads to crowding out effects of consumer expenditure on other spending categories.

Expenditure on household energy consumption:

Household energy consumption is determined by the BSM and heat supply allocation routine and complemented with energy consumption for other end-uses (e.g., appliances and cooking). Together with the energy prices (which may contain environmental taxation effects), household expenditure on energy is estimated. Expenditure on energy will crowd out other consumption.

Expenditure on infrastructure:

Depending on how the household heating configuration changes, auxiliary investment stimuli may play a role. Hydrogen use requires additional investment in hydrogen infrastructure. If the hydrogen is assumed to be produced domestically, then increased hydrogen consumption leads to investment in the supplying sector. This leads to another round of investment in power generation capacity infrastructure. Expansion of DH/C networks requires additional investment in pipe networks.

- Investment in the hydrogen gas supply sector
- Investment in the hydrogen supply sector
- Investment in reinforcing the power grid
- Investment in additional power generation capacity

Renovation investments:

The investments associated with renovations to improve the energy efficiency of buildings can have several effects depending on the tenure states of dwellings:

- We assume that government absorbs the full costs for renovating social housing and 25% of the expenditure for renovating owned & occupied and privately rented dwellings. In E3ME, government budgets are a given and it is assumed that governments pursue net neutrality of spending and income. Additional government spending leads to increasing VAT, income tax, and employer's contribution to social security, while additional income (e.g. carbon tax revenues) do the opposite.
- The remainder of the 75% of expenditure on renovating owned & occupied dwellings is added to the consumer category Maintenance & repair and this leads to crowding out of consumer expenditure on other categories directly.
- The remainder of the 75% of expenditure on renovating privately rented dwellings is added to the consumer category Maintenance & repair and this does not lead to crowding out directly. It is assumed that landlords can absorb the costs directly from wealth, but we do assume it will lead to higher rental prices faced by households living in such dwellings. This affects the consumer category actual rents and does lead to crowding out.

Figure 4 illustrates how the outputs of the combined BSM and heat technology allocation play a role in E3ME.

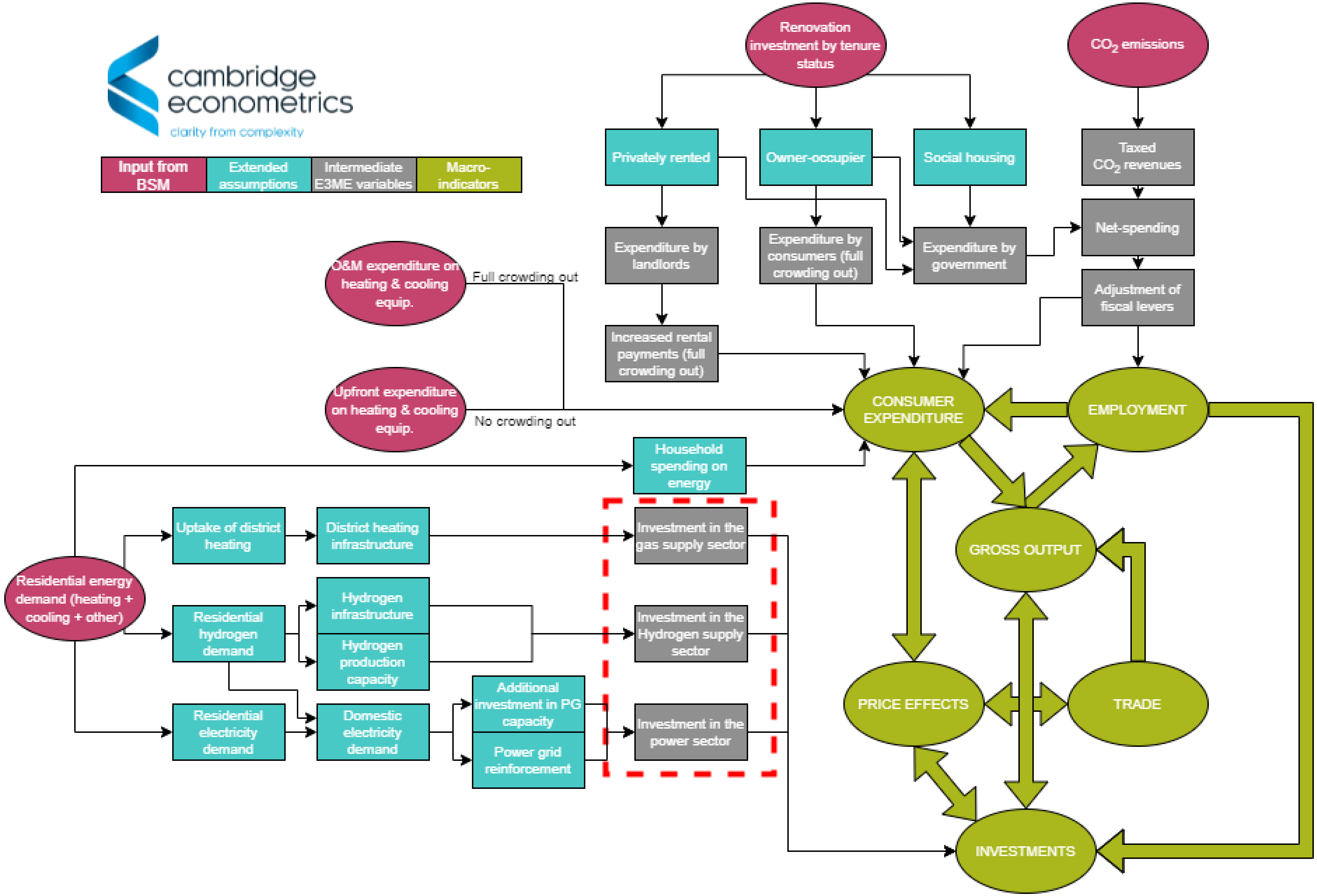

Figure 4: Model linkages between the BSM and heat supply allocation output and E3ME, including internal interactions.

2.5.3 Economy-wide effects

Consumer expenditure or sectoral investment is affected directly by the changes in residential heating, which has economy-wide indirect and induced effects that lead to changes in the E3ME outcome of macro-indicators (green arrows and boxes in Figure 4). The changes in consumer expenditure and investments play a central part but there are many interplays with other macro-economic variables, such as gross output, price levels, employment, and government finances. To summarise:

- **Additional investments** (or capital creation) will initially affect gross output, followed by a debt repayment phase which is characterised by changes in industry prices.
- **Industry prices** – together with tax rates – translate to consumer prices and can alter the spending patterns or lead to crowding out effect. Prices can also shift trade competitiveness and thereby affect imports and exports.
- **Trade** can – in turn – change consumer prices and through the national accounts framework affect gross output. If the European economies become less competitive, imports will increase and GDP will decrease and vice versa.
- **Gross output** is an indicator of sectoral activity, which is determined via the framework of national accounts and involves value-chain effects (though input-output tables)
- The net change in gross output leads to changes in **employment levels**. In turn, employment levels – together with wages – affect total consumer expenditure, while labour costs affect total investment.
- Total **consumer expenditure** is solved as a function of disposable income and price levels. Disposable income relates to income after tax, wealth, and benefits received. Price levels are estimated as average prices by consumer category weighted by consumption volumes.
- Total **expenditure** is subdivided over 43 consumer categories. The spending by category is affected by end-use prices of the corresponding categories and the external inputs coming from the BSM and heat technology allocation (e.g., spending on new heating equipment).
- **Government fiscal policy** also plays a role here through the assumed behaviour of revenue recycling. For example, the renovation investments covered by government are offset by higher tax rates, while environmental taxation leads to lower tax rates. VAT taxes will affect the end-use prices of products. Income tax will affect the disposable income of consumers. Employer's social security contribution will affect the cost of employment and through that the demand for employment.
- In our modelling framework, government budgets are required to remain **net-neutrality**. Policy revenue or costs are rebalanced through fiscal levers.

3 Scenario assumptions

3.1 Scenario overview

The objective of this study is to evaluate the economy-wide effects of different pathways towards decarbonising the European housing stock, rather than to estimate the most likely or cost-optimal pathway to achieve such decarbonisation. To that end, several 'what-if' scenarios were designed to investigate the potential direct and indirect effects of decarbonising the housing stock in various ways. A summary can be found in Table 8.

First, we assume that the archetypical development of the housing stock is invariant of other policy settings, meaning it is fixed between scenarios. The same demolition rate, urbanisation rates, and demographic changes are assumed across all scenarios (see column A).

Second, for all scenarios except the baseline (designated BA–LEE–BA–O) a full decarbonisation of the power sector is achieved to prevent secondary emissions of electricity use by households. This is achieved by implementing a carbon tax on top of other carbon pricing schemes. In the baseline, the power sector develops in line with the EU Reference 2020 scenario (European Commission 2021), while it decarbonises in all other scenarios. It is also assumed that all hydrogen is produced through electrolysis.

Third, we apply two different weighted renovation rates to the building stock model which affects the demand for heating and cooling. The low weighted renovation rate increases to a renovation rate of 1.5%, building upon historical rates. This reflects ongoing endeavours to increase energy efficiency levels of households. The high weighted renovation rate reflects increased efforts to renovate homes even further (3.5% weighted rate pa). The efficiency levels will dictate what the need for heating is of hot water and space heating, together with the need for cooling.

Fourth, on the heat supply side, several distinctively different technology pathways are constructed. In the baseline we assume a constant market share of technologies after 2022. In the High Electrification scenario (HE), we assume a transition that is focussed on heat pumps and electrified DH/C. In the High Gas scenario (HG), we assume a transition to individual hydrogen boilers and hydrogen-based DH/C (where applicable). Lastly, the two preceding scenarios are mixed (MIX), which reflects a more diversified European heating system.

The fifth and last scenario variance relates to the source of hydrogen. In the domestic case (D) we assume that every country satisfies its own demand. In the import case (I) we assume that every country imports all the hydrogen from outside of Europe. All hydrogen is assumed to be green hydrogen. The difference of the two hydrogen source sensitivities affects end-use hydrogen prices and the establishment (or lack thereof) of a domestic hydrogen supply sector.

Table 8: Scenario settings.

Scenario designation	A. Building stock	B. Power sector	C. Renovation rate	D. Heat supply	E. H_2 source
BA–LEE–BA–O Baseline Eff. & Baseline Supply	=	EU Ref	Low	Baseline	N.A.
NZ–LEE–BA–O Baseline Eff. & Baseline Supply	=	Net-zero	Low	Baseline	N.A.
NZ–LEE-HE–O Baseline Eff. & High Electrification Supply	=	Net-zero	Low	HE	N.A.
NZ–LEE–HG–D Baseline Eff. & High Gas Supply	=	Net-zero	Low	HG	Domestic
NZ–LEE–HG–I Baseline Eff. & High Gas Supply	=	Net-zero	Low	HG	Import
NZ–LEE–MIX–D Baseline Eff. & Mixed Supply	=	Net-zero	Low	MIX	Domestic
NZ–LEE–MIX–I Baseline Eff. & Mixed Supply	=	Net-zero	Low	MIX	Import
NZ–HEE–BA–O High Eff. & Baseline Supply	=	Net-zero	High	Baseline	N.A.
NZ–HEE–HE–O High Eff. & High Electrification Supply	=	Net-zero	High	HE	N.A.
NZ–HEE–HG–D High Eff. & High Gas Supply	=	Net-zero	High	HG	Domestic
NZ–HEE–HG–I High Eff. & High Gas Supply	=	Net-zero	High	HG	Import
NZ–HEE–MIX–D High Eff. & Mixed Supply	=	Net-zero	High	MIX	Domestic
NZ–HEE–MIX–I High Eff. & Mixed Supply	=	Net-zero	High	MIX	Import

3.2 Carbon price

The EU and the UK already have an emission trading scheme (ETS) in place for industrial sectors. The ETS price projection was obtained from the EU Reference Scenario 2020 (European Commission 2021). In the EU there is also a proposal to implement an ETS for consumers (ETS2) which would target emissions from private road transport and household activities such as heating and cooling. The ETS2 price projection was received from the European Climate Foundation, obtained from an ongoing study carried out by Vivid Economics for them. Decarbonising the housing stock but neglecting to achieve the same in the power sector would prevent direct emissions and would be replaced by indirect emissions. To that end, an additional carbon tax is applied to decarbonise the power sector. The additional carbon tax increases to add 40% on top of the ETS price in 2050.

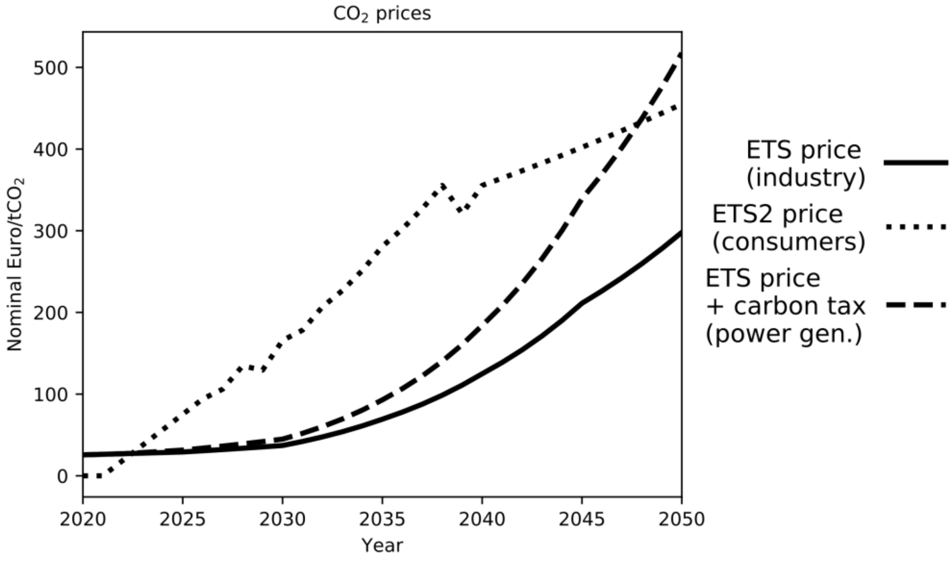

Figure 5: Three different carbon pricing schemes with different scopes are included in the scenario setup.

The ETS for industry is applied to all scenarios including the baseline. The ETS2 for consumers is applied to all scenarios except the baseline. Finally, the carbon tax is applied to all scenarios where the power sector is required to achieve net-zero emissions. See Figure 5 for an overview of the various pricing schemes.

3.3 Power sector

The power sector plays a pivotal role in any decarbonisation pathway. More so for scenarios where the demand for electricity is expected to increase. The High Electrification scenarios do that directly via a transition to efficient electricity-based HPs. The High Gas scenarios do so indirectly through hydrogen demand which may be produced domestically via electrolysis.

The baseline projection of installed capacities by technology is in line with the EU Reference Scenario 2020 (European Commission 2021) and shows an increased role for renewables in the European power generation system (top panel on the left-hand side of Figure 6), which is reflected in lower emissions in 2050 compared to 2022 (top panel on the right-hand side).

Decarbonisation of the power sector is achieved by applying an additional carbon tax which incentivizes greater take up of low-carbon and renewable alternatives (bottom panel on the left-hand side). As a result, emissions go to zero or beyond by 2050 (bottom panel on the right-hand side). Note that the electricity demand levels vary from scenario to scenario depending on the development of the heating and cooling systems. Overall, the system mix remains the same.

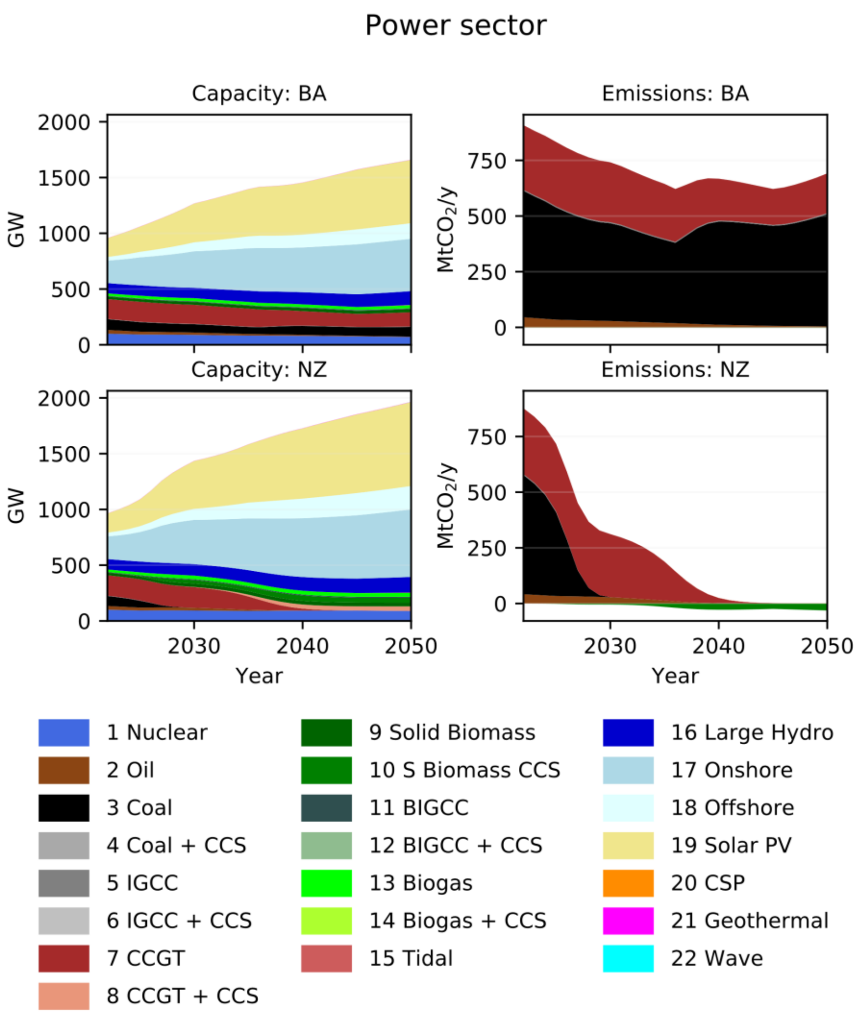

Figure 6: Developments in the power sector under different conditions. On the left-hand side, the deployment of power generation capacities is shown over time under baseline assumptions (in line with the EU Reference Scenario 2020) and a net-zero scenario. The right-hand side shows the timeline of emissions.

3.4 Building stock

As section 2.2 points out, many inputs are required to simulate changes of the European building stock. Demographics, demolition rates, urbanisation rates, area per dwelling projections, HDD and CDD projections all remain the same across scenarios. Only the weighted renovation rate changes as an input, providing the low (or baseline) energy efficiency and high energy efficiency variants. The building stock in terms of archetypical development remains the same across scenarios.

Figure 7 illustrates the development of archetypes across all of Europe. Due to the urbanisation rate, it is expected that the number of multi-family houses and apartments grows (due to urbanisation), while single-family houses remain approximately constant over time. Generally, the share of older archetypes increases which is a function of demolition rates and demographics.

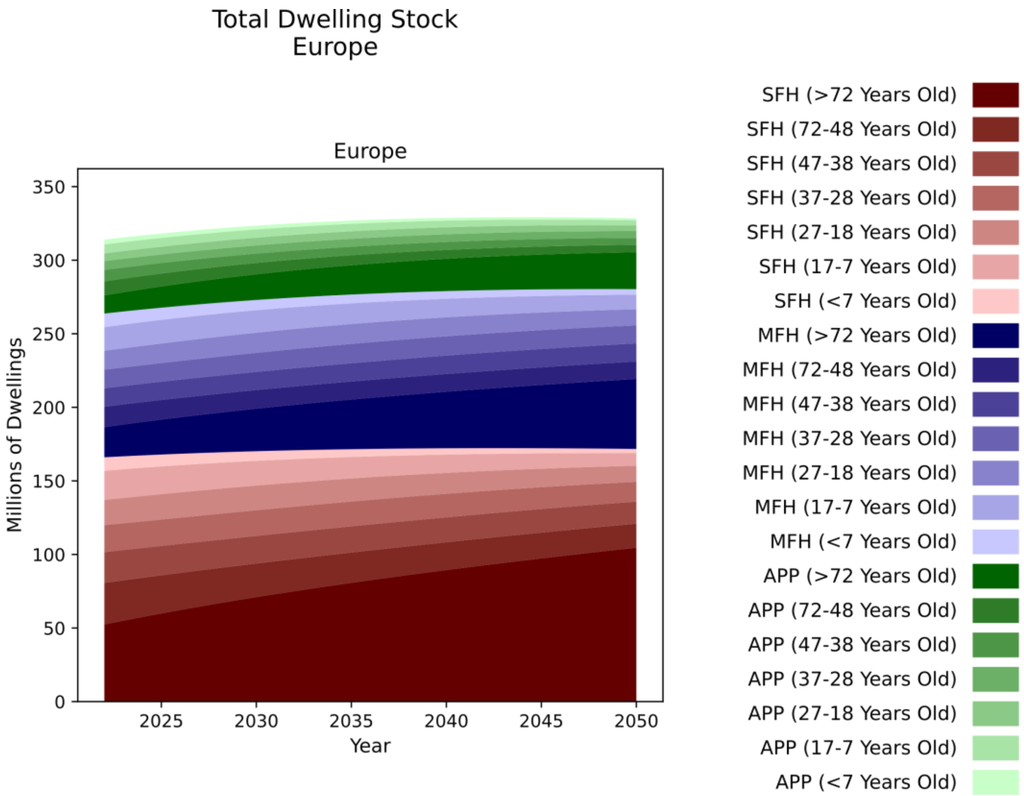

Figure 7: European building stock development by archetype.

3.5 Energy efficiency

Different renovations rates can be applied to the fixed building stock composition. To represent the baseline demand for heating and cooling, a weighted renovation rate of 1.5% pa was used. It grows to that level by 2030 from an historical weighted renovation rate of approximately 1% pa. In the high efficiency scenarios, the weighted renovation rate grows to 3.5% (see Figure 8).

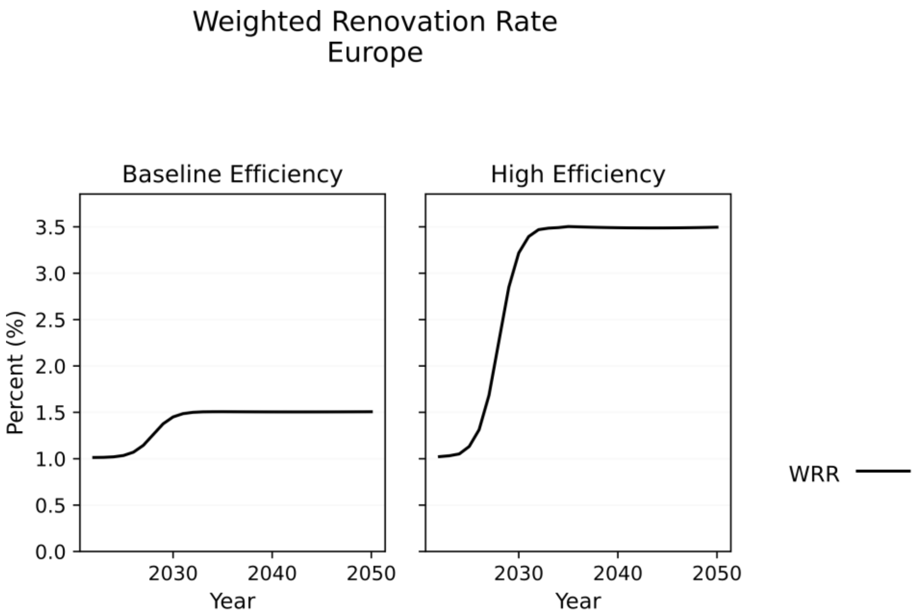

Figure 8: Weighted renovation rate across all archetypes in Europe.

The more renovations are performed on the European housing stock the lower its energy intensity becomes, thereby lowering the energy need for heating and cooling. Recalling section 2.2, energy needs are not only a function of renovation rates, but also demolition, demographics, size of dwellings, urbanisation, and HDD/CDD projections. HDD projections generally decline, but CDD increases over time. All the other effects cancel out the greater need for cooling. Figure 9 shows the development of the energy need for heating and cooling by archetype over time.

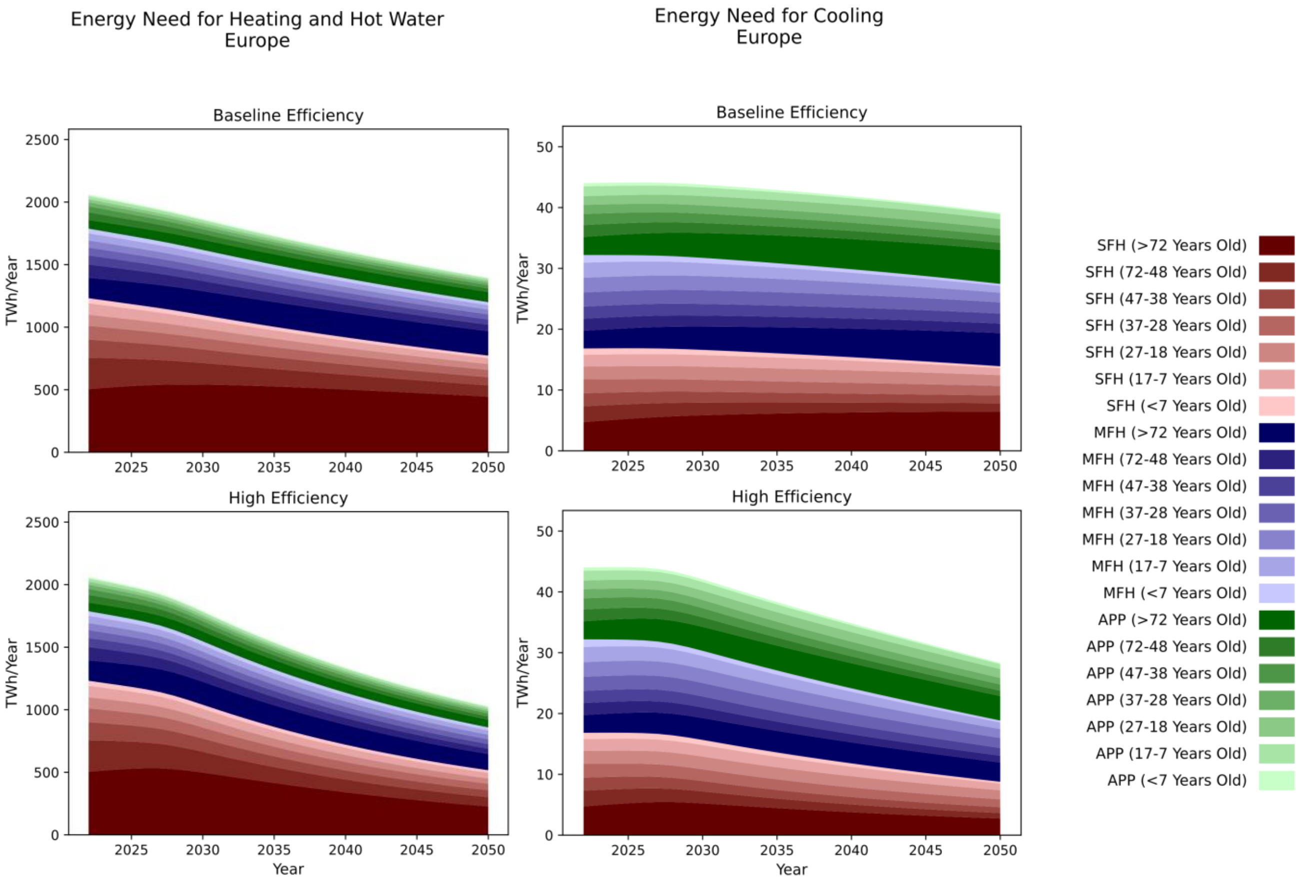

Figure 9: Energy need for heating (left) and cooling (right) by archetype.

3.6 Technology pathways

One of the main inputs for the scenarios listed in Table 8 are the technology pathways. Four distinctively different heat supply scenarios have been formulated, displayed in Figure 10 (left-hand side). In the baseline heat supply scenario, market shares by technology remain constant over time from 2022 onwards, with the exception of replacing non-condensing boilers with their condensing counterparts. DH/C networks play a more prominent role in each of the other three scenarios, where it grows to a market share of 35%, but in each case the configuration is different (see right-hand side of Figure 10). The High Electrification scenarios display a greater uptake of HPs and electrified DH/C networks. The High Gas scenarios display a greater uptake of hydrogen boilers and hydrogen-based DH/C networks (where applicable).

The DH/C configuration changes in the decarbonisation scenarios because

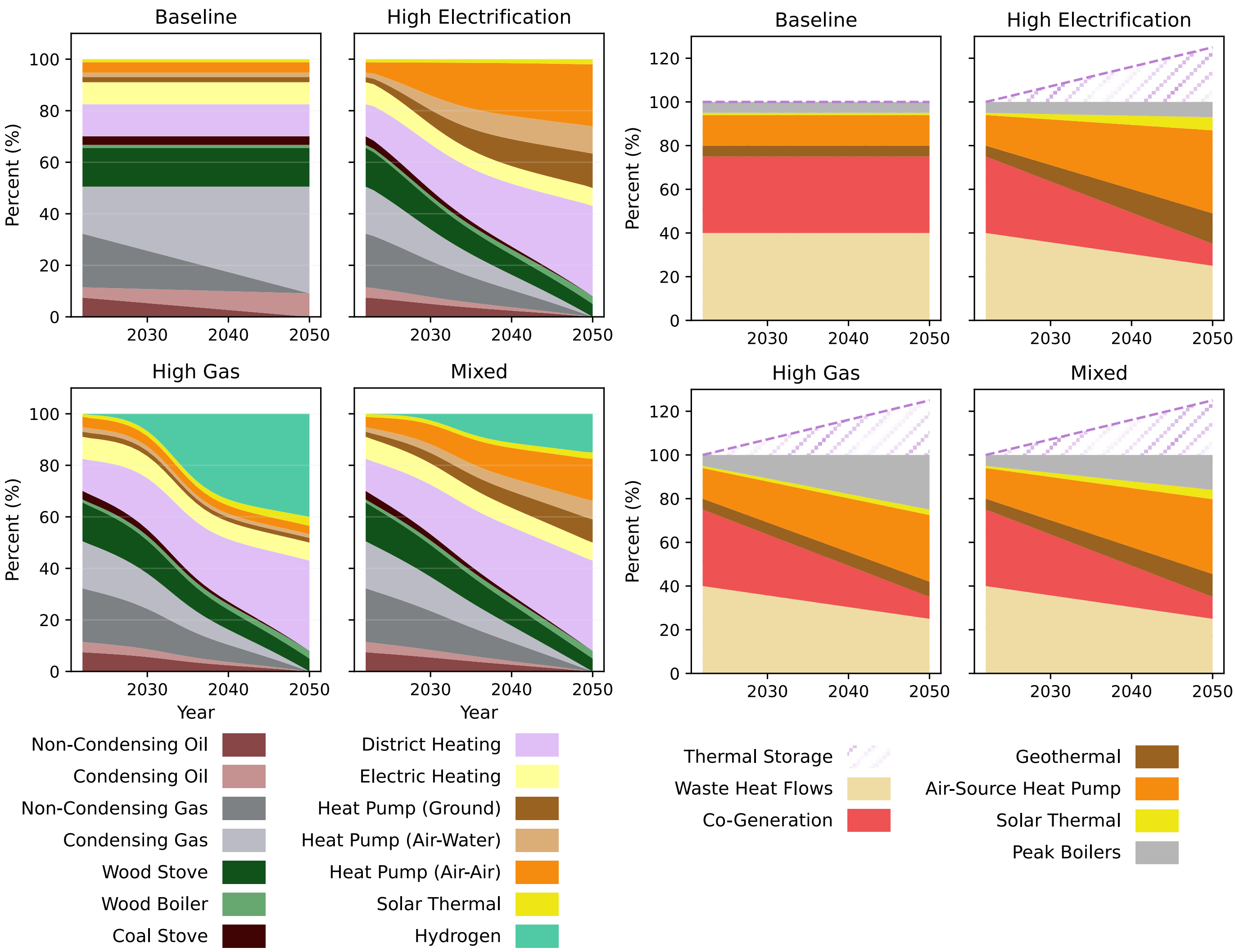

Figure 10: Uptake trajectories by technology (left-hand-side) and changing DH/C configuration (right-hand side).

there is less potential for co-generation and waste heat flows from industry in a net-zero setting. First, the power sector (see Figure 6) transitions primarily to non-thermal power generation which reduces the potential for co-generation of power and heat. Second, in a net-zero setting, it is likely that industrial processes will be electrified and that will likely reduce the potential for utilising waste heat flows. Other configurational options have to cover for the gap and thermal storage is added to cover for peak-demand.

3.7 Hydrogen production

Hydrogen is a potential zero-carbon energy carrier that can help the transition away from fossil fuels. In recent years, many use cases have been proposed for hydrogen, such as in heavy industry, mobility, and also in the heating of buildings (IEA 2019), with the latter the subject of much debate. This study does not seek to address the feasibility of heating systems dominated by hydrogen. Instead, it seeks to elucidate the macro-economic effect of a potential trajectory in which hydrogen dominates. Whether hydrogen for heating will be feasible in the future depends on technological and economic considerations. The hydrogen prices faced by end-users is the most prominent economic consideration.

Expectations on future hydrogen prices are shrouded in uncertainty. Especially so if we only consider green hydrogen. Uncertainties arise due to expectations on the rate of declining capital costs due to technological progress, development of future electricity prices, and to what degree hydrogen will be taxed. Since hydrogen plays a prominent role in some of the scenarios presented in Table 8, a reliable projection for end-use prices must be established. The prices used in this study build upon four components:

- Capital cost component (from EU Reference Scenario 2020), which is estimated to start at a level of 1600 €/kW and declines to 200 €/kW due to assumed learning-by-doing effects.
- Operation and maintenance cost component (EU Reference Scenario 2020), which is estimated to start at a level of 49 €/kW and declines to 10 €/kW due to assumed learning-by-doing effects.
- Electricity costs, which are determined using an endogenous industrial electricity price multiplied by the conversion ratio of hydrogen production via electrolysis. The former is determined by FTT:Power, the latter is taken from the EU Reference Scenario 2020, and starts at 1.39 and declines to 1.17 due to assumed learning-by-doing effects.
- End-use tax bracket for hydrogen. How hydrogen will or should be taxed is open to discussion, but it is evident that can have a big impact on the end-use prices faced by consumers. In this study we assume a tax of 20% is levied on top of the combined capital and electricity costs.

Prices of imported hydrogen are calculated similarly, but we assume a much lower industrial electricity price. The rationale behind this is that it only makes sense to import hydrogen. instead of domestically producing it, if the price differential is large enough.

4 Results

4.1 Investment in renovations

Renovating the European housing stock can help accelerate the decarbonisation process. However, renovations come at a cost and the deeper the level of renovations, the higher the costs become. Figure 11 shows the projected investments broken down by archetype required to achieve the energy intensities as displayed in Figure 9 (section 3.5). In the baseline efficiency variants (all scenarios with the “LEE” designation), investment needs increase from 86 bn€ in 2022 to 132 bn€ in 2050 across all archetypes and European countries. When more effort is exerted to increase energy efficiency the investments grow to 362 bn€. Older dwellings require the largest investments, especially single-family homes.

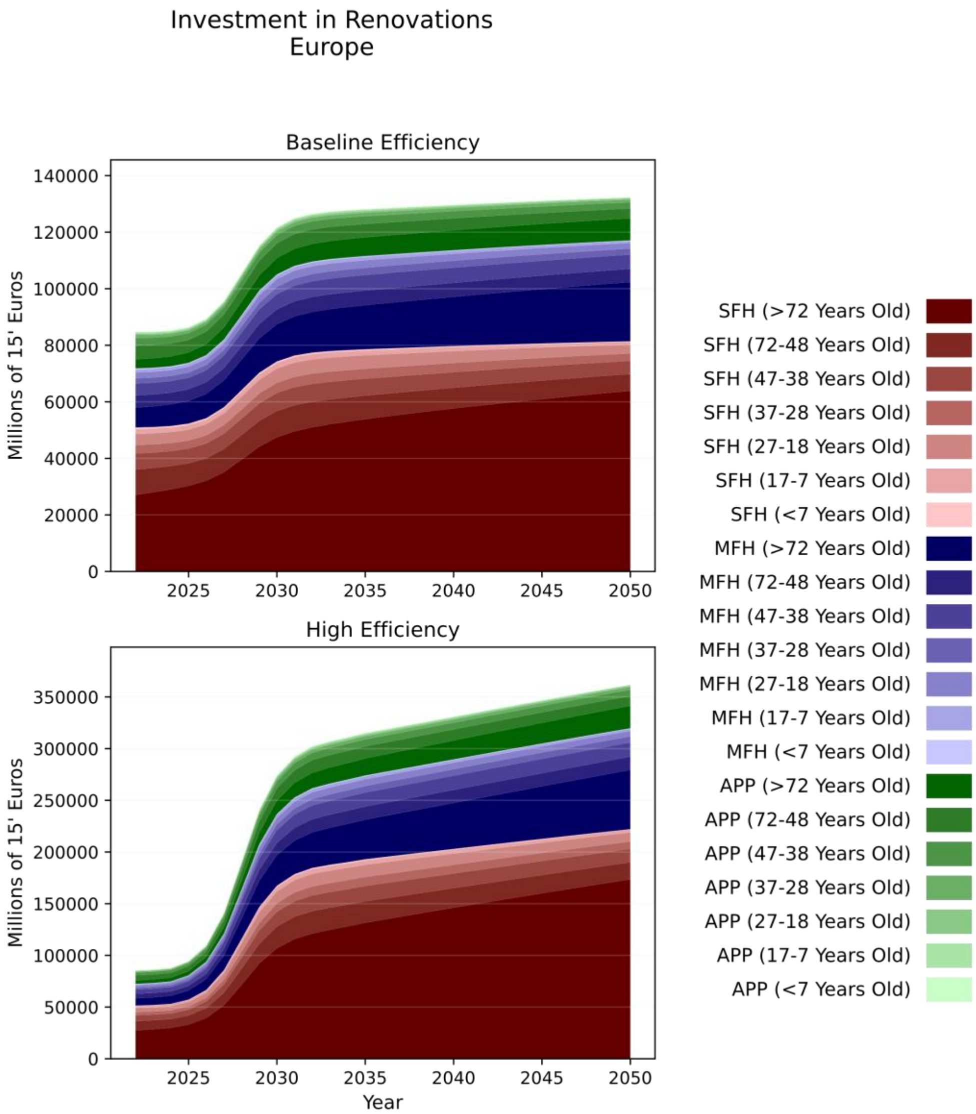

Figure 11: European building stock development by archetype.

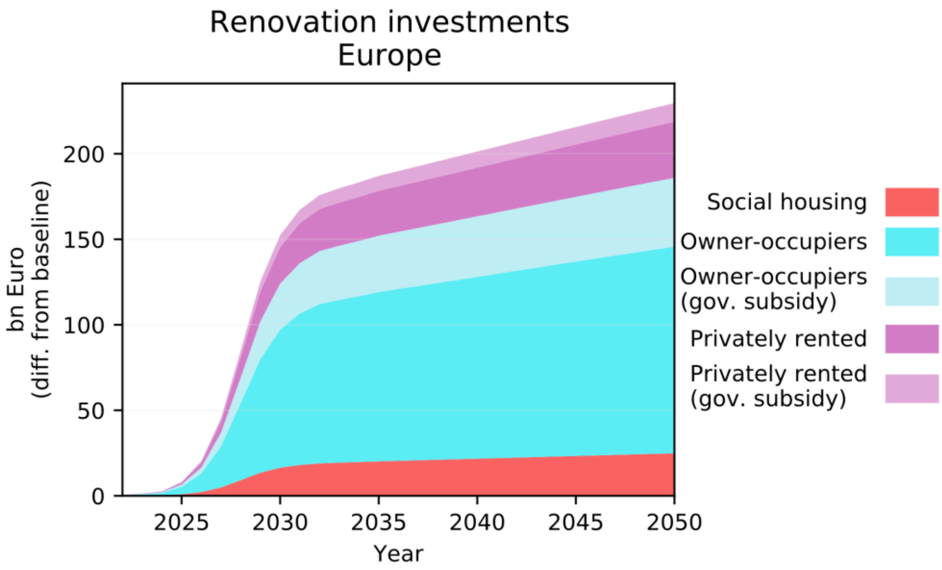

Figure 12: Difference between renovation investment between the high and low energy efficiency scenarios broken down by tenure status.

In our scenarios, renovations are paid for by different stakeholders (see Figure 12). Owner-occupiers face the highest additional investment costs of all tenure types when efforts are taken to increase the energy efficiency of the European housing stock. From a macro-economic perspective this means that such households would need to change their spending patterns to facilitate such levels of renovations. The investments required for privately rented dwellings will come through higher rents. The portion of renovation investments subsidised by governments will have consequences on fiscal tax rates, in order to maintain net-neutrality of government balances. The effect on the tax rates compared to the baseline is summarised in Table 9. There are minor deviations between scenarios due to revenues from environmental taxes.

Table 9: Per cent changes in fiscal tax rates due to government revenue rebalancing in all Net-Zero and High Energy Efficiency scenarios (NZ-HEE) compared to the Baseline (BA-LEE-BA-O).

	2030	2040	2050
VAT	+1.0%	+1.8%	+2.7%
Income tax	+0.8%	+1.6%	+2.7%
Employer's social security contribution	+2.1%	+4.2%	+7.4%

4.2 Final energy demand for heating & cooling

The combined effect of technology pathways and renovations change the energy requirements of the European heating and cooling system substantially. In terms of heating technologies employed (see Figure 13), a decrease in total final energy demand is observed in every scenario. This decrease is due to a reduced need for heating in a warming climate, baseline energy efficiency gains of the housing stock, and more efficient heat delivery by technologies including a phase-out of less efficient non-condensing boilers for their condensing counterparts.

Supply-side efficiency is greatest in the High Electrification scenarios because of the increased uptake of HPs which are also expected to become more efficient over time due to learning-by-doing effects (see Appendix A: Technology data sheets). Combined with increased efforts to renovate homes, the lowest final energy demand levels are found in the High Energy Efficiency & High Electrification scenario variants. Direct use of hydrogen for heating is much less efficient than HPs and therefore shows higher levels of energy demand overall: 832 TWh and 613 TWh by 2050 in the Baseline Efficiency and the High Efficiency scenarios respectively. Compared to the High Electrification counterpart scenarios, it is 3 to 4 times higher.

In addition, electrolysis of hydrogen requires additional electricity to be generated which includes additional conversion efficiency losses. In the NZ-LEE-HG-D scenario, total electricity demand increases by 591 TWh (15%) compared to the Baseline in 2035, whilst it increases by 77 TWh (2%) in the same year for the NZ-LEE-HE-O scenario. By 2050, electricity demand increases by 810 (19%) and 207 TWh (5%) compared to the Baseline for the NZ-LEE-HG-D and NZ-LEE-HE-O scenarios respectively. Such changes affect the power generation profile by technology. See Table 10. In each scenario, there is sufficient power generation through variable renewable energy sources in order to produce hydrogen via electrolysis.

Another consequence of decarbonising the wider European economy is that DH/C becomes less efficient, as co-generation and industrial waste heat flow potentials go down and demand needs to be covered by thermal storage and other configuration options (see Figure 14).

Final energy demand for cooling purposes is much lower than it is for heating. In the High Electrification scenarios, a greater proportion of the cooling demand is satisfied by HPs. Air-to-air HPs are especially used for cooling in warmer regions as the take-up is greater in such regions compared to other HP types (see Appendix B: Results by climate zone). Some DH/C is expected to deliver cooling but given that the take up of DH/C is mostly expected to occur in Northern and Eastern Europe where the demand for cooling is low, DH/C is not expected to play a significant role for cooling on the European scale (see Figure 15).

The take up of various heating technologies and the changing configuration of DH/C leads to a change in the type and quantity of energy carriers consumed (see Figure 16). In 2022, natural gas is the dominant energy carrier used to heat European homes and it remains so for both Baseline Heat Supply scenarios (LEE and HEE) throughout the considered period. By 2050, the rest of heat generated in dwellings occurs through biomass, electricity, residual heat flows (in DH/C), and small quantities of oil and coal. In the other scenarios, residual heat flows and biomass remain important, but the rest gets substituted by electricity (High Electrification scenarios), hydrogen (High Gas scenarios), or a combination of the two (Mixed scenarios).

Table 10: Power generation profile by aggregate technology groups. Numbers are in TWh/y. Bio-based includes carbon capture and storage applications. Other non-renewables includes nuclear power and CCS applications on fossil fuel-based power generation.

Scenario	Type of power generation	2030	2040	2050
BA-LEE-BA-O	Variable renewables	1431	1885	2245
	Bio-based	196	198	205
	Other renewables	330	380	431
	Other non-renewables	1682	1429	1347
NZ-LEE-HE-O	Variable renewables	1736	2507	2932
	Bio-based	227	271	274
	Other renewables	353	418	477
	Other non-renewables	1301	678	536
NZ-HEE-HE-O	Variable renewables	1772	2574	3024
	Bio-based	232	279	284
	Other renewables	355	422	483
	Other non-renewables	1315	684	547
NZ-LEE-HG-D	Variable renewables	1867	3078	3569
	Bio-based	245	337	330
	Other renewables	362	456	523
	Other non-renewables	1377	790	616
NZ-HEE-HG-D	Variable renewables	1860	2965	3381
	Bio-based	244	324	313
	Other renewables	362	447	509
	Other non-renewables	1372	765	589

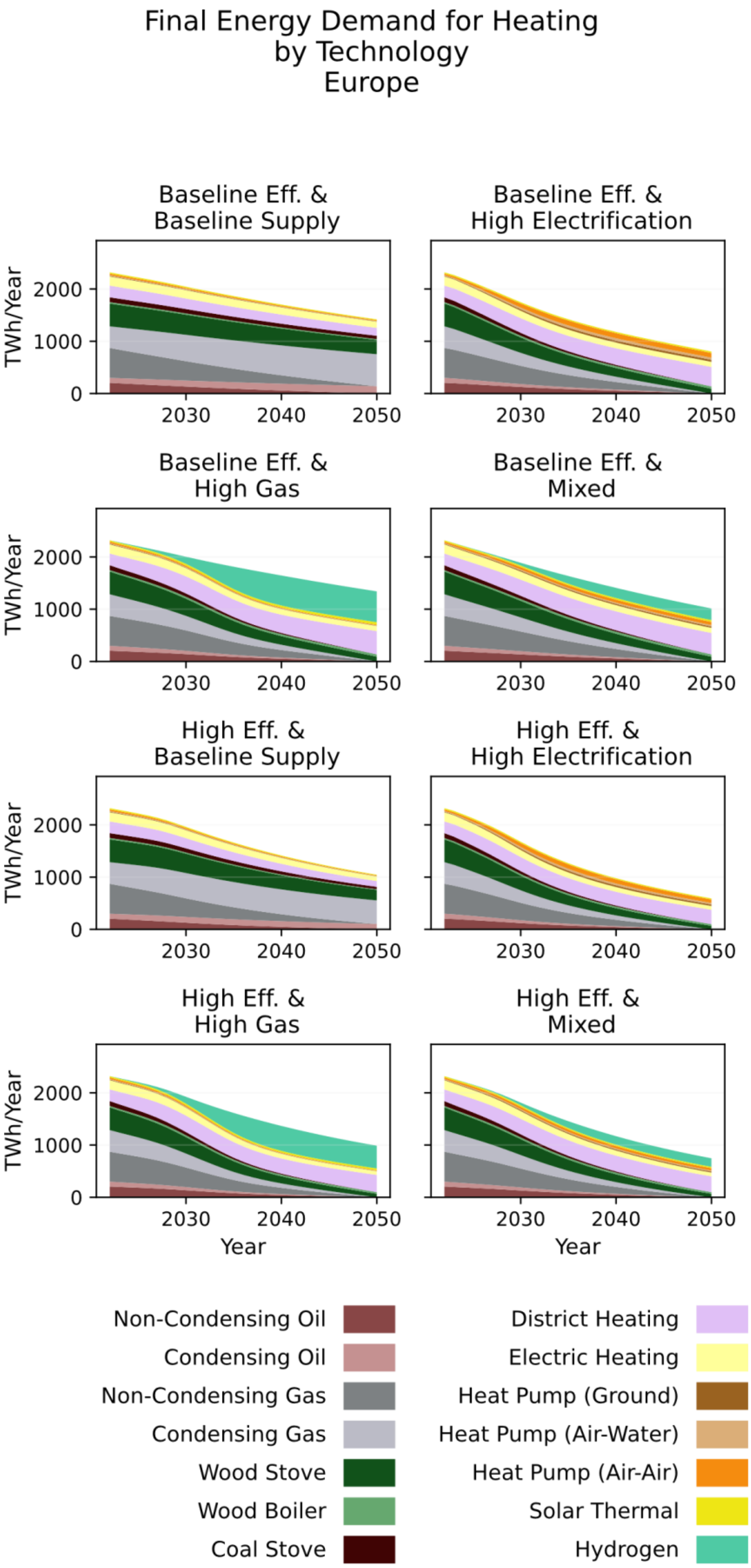

Figure 13: Final energy demand by heating technology.

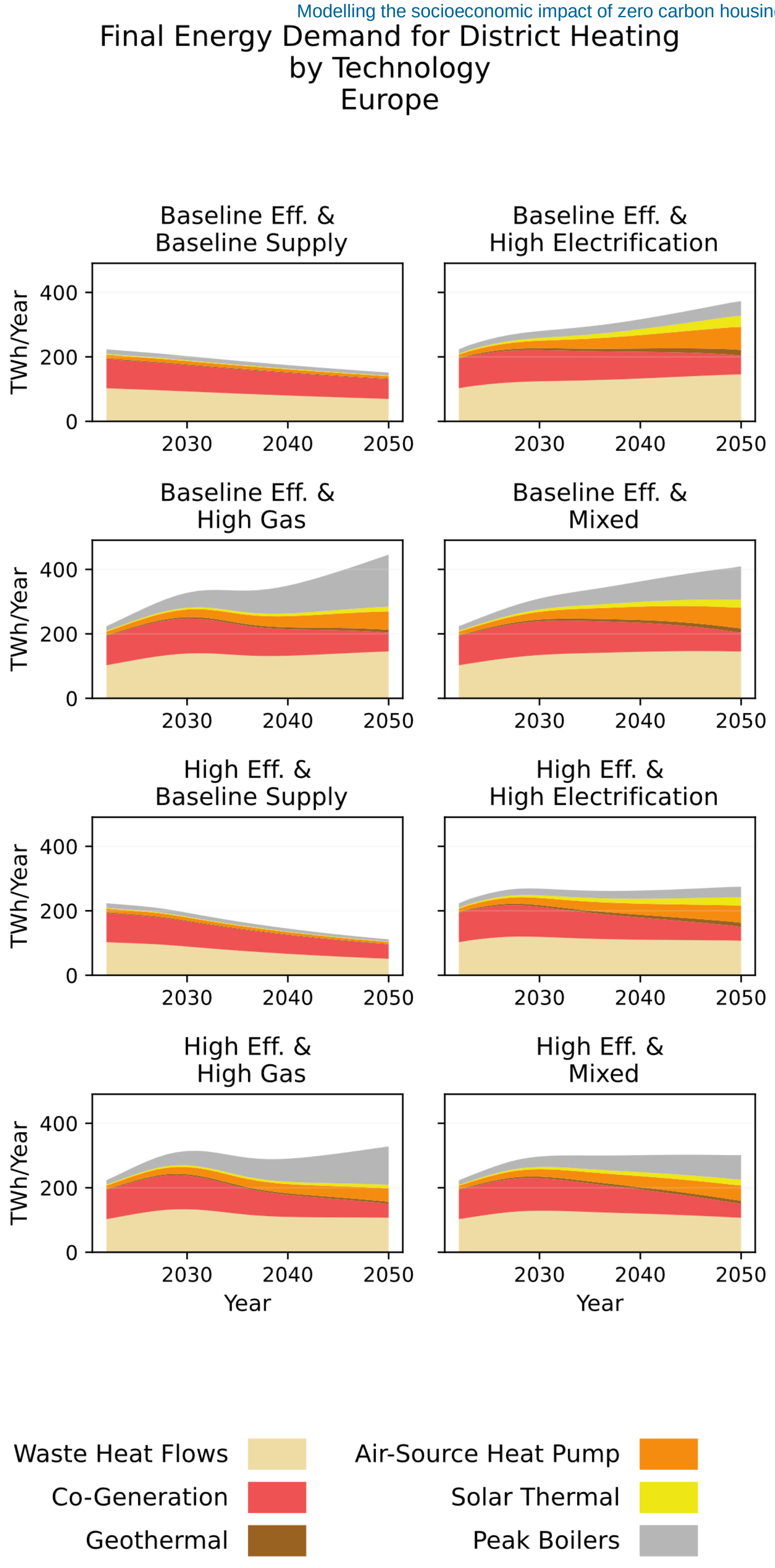

Figure 14: Final energy demand by DH/C configuration option.

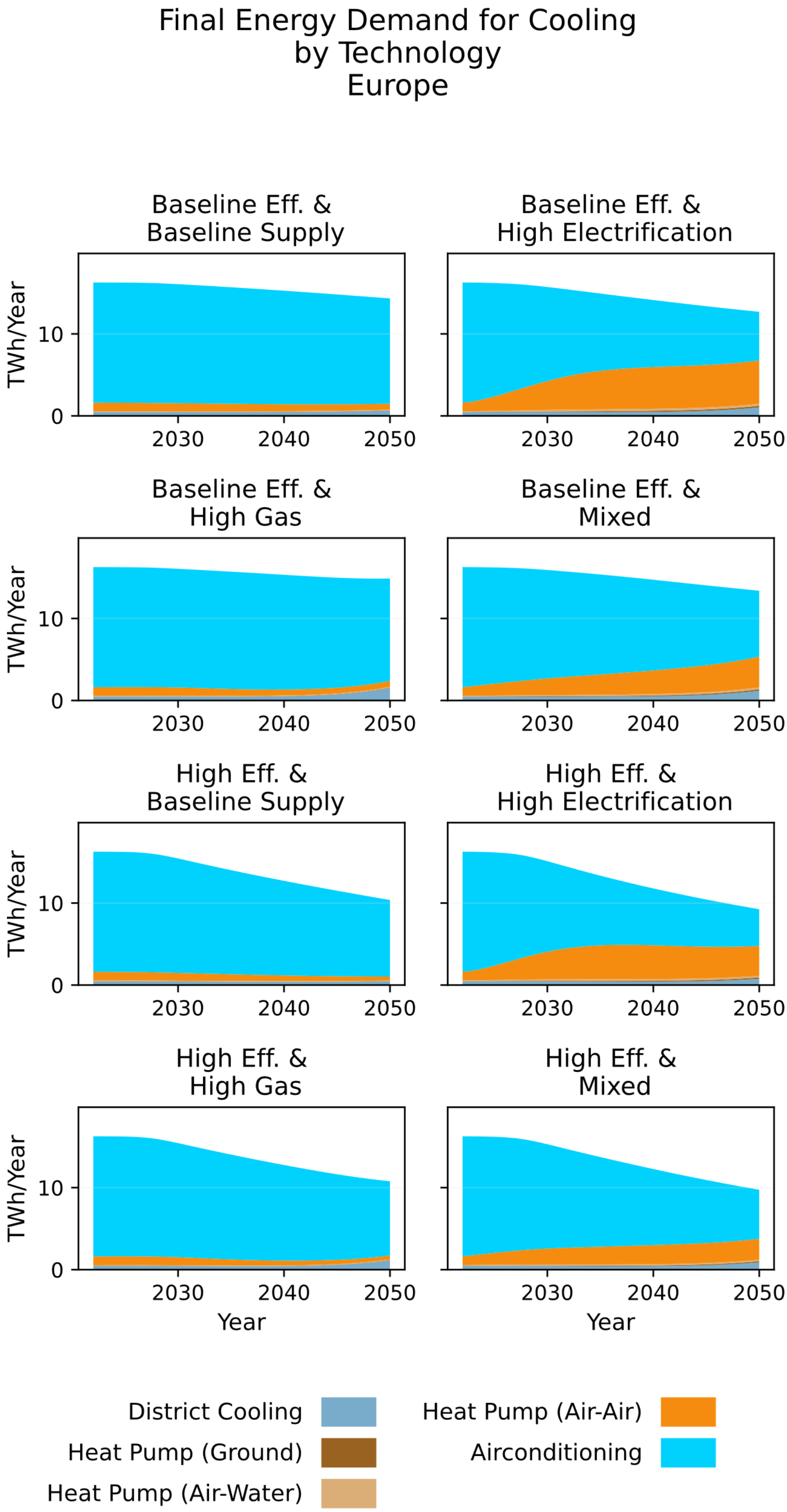

Figure 15: Final energy demand by cooling technology.

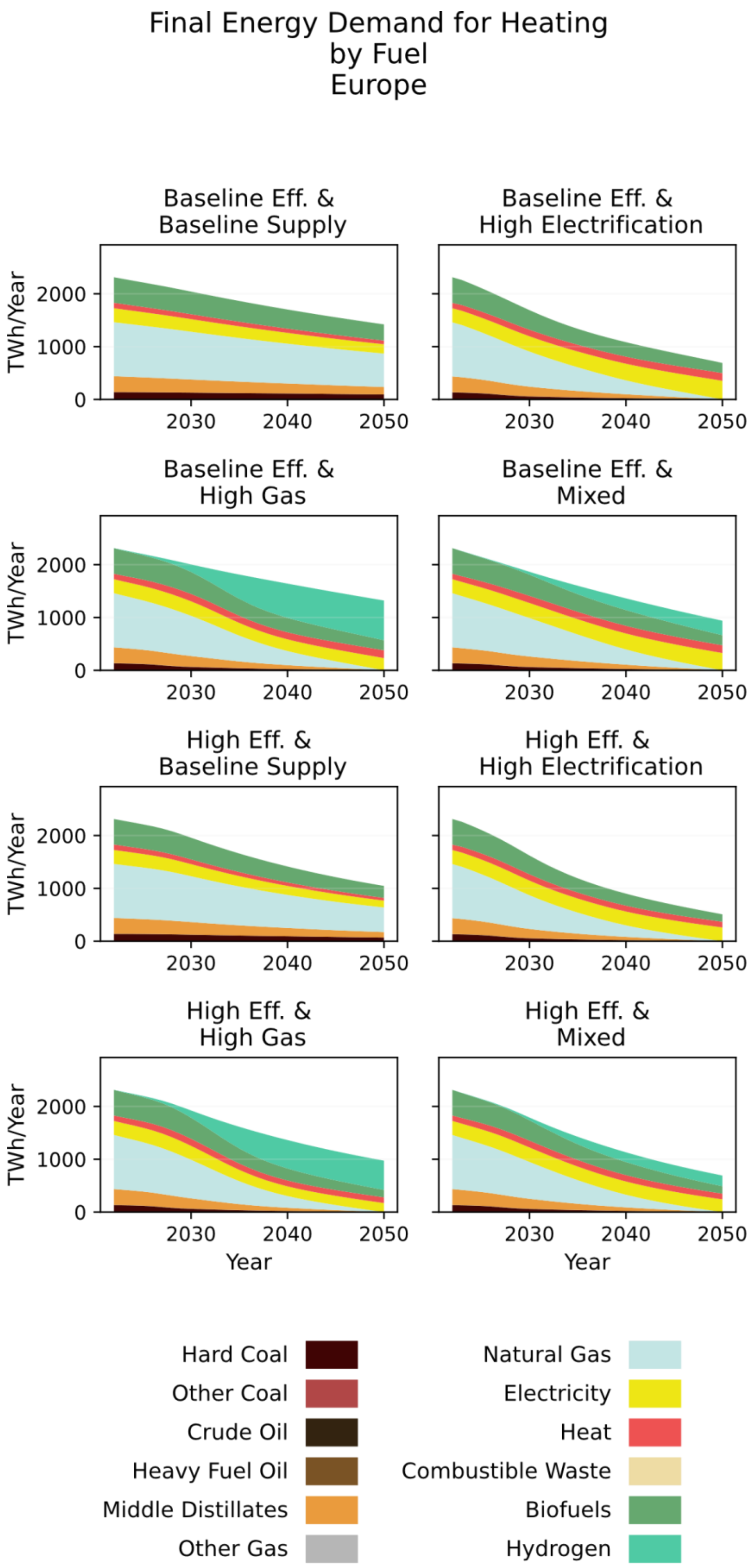

Figure 16: Final energy demand by fuel for heating only.

4.3 Energy trade balance

Decarbonising the housing stock will lower coal, gas, and oil imports. All heat supply scenarios – except the baseline heat supply ones – fully decarbonise. On a European scale, mostly gas imports are prevented, and decarbonisation will also affect domestic gas supply. However, if these fossil fuels are replaced by imported hydrogen, then this would not lead to an improvement in Europe's energy security, as it would in the case of electrification or if the hydrogen were to be produced in Europe. Figure 17 summarises the effects of decarbonising the housing stock on cumulative energy imports and cumulative import value.

Depending on the uptake profile of low-carbon heating equipment, around 50 EJ of cumulative energy imports – without hydrogen imports – can be prevented from the sole effect of decarbonising the European housing stock. When hydrogen is imported, the effects cancel out in units of energy, but in terms of trade value Europe will be worse off because hydrogen is simply a more expensive energy carrier. In this regard, the NZ-LEE-HG-I is the worst scenario as it increases the energy import value by around 300 bn€ over the whole period from 2022 to 2050. This is somewhat mitigated when increased efforts are undertaken to renovate the housing stock (i.e. in the NZ-HEE-HG-I scenario).

In the High Gas scenario with Baseline Efficiency with hydrogen imports (NZ-LEE-HG-I), the net effect of decarbonisation leads to a status quo in terms of fuel imports to the EU. This may still improve the energy security position as hydrogen production can theoretically occur anywhere, while fossil fuel production only occurs in regions with access to such resources. With more efforts to renovate the housing stock, net energy imports will reduce slightly (NZ-HEE-HG-I).

At present, Europe as a whole is dependent on energy imports. This was highlighted by the recent surge in gas prices and therefore electricity prices. Moving away from energy imports means a more secure and controllable energy supply market. Less reliance on energy imports can give governments the opportunity to control prices and prioritise price stability through regulations.

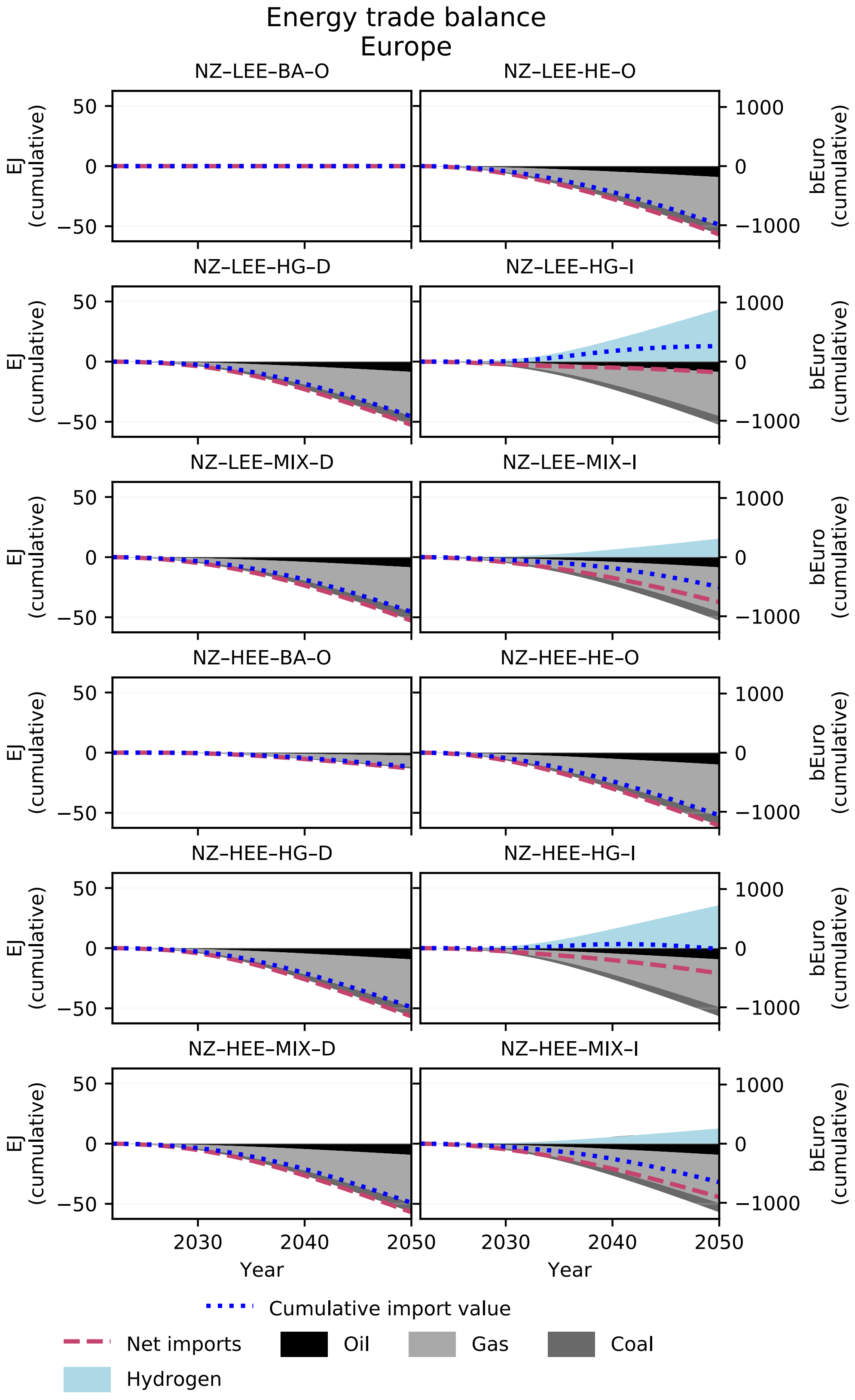

Figure 17: Cumulative energy import change by energy carrier compared to the baseline scenario (BA-LEE-BA-O) in units of energy (left-hand side y-axis and in units of value (right-hand side axis). Negative wedges indicate a reduction of imports, while positive wedges indicate an increase of imports. Negative trade values indicate a decrease in the value of net imports, while positive trade value indicate an increase in the value of net imports.

4.4 Emissions

Technology substitutions change the energy profile of the residential sector, which leads to a changing emission profile. Under baseline conditions (BA-LEE-BA-O), total CO_2 emissions decrease by 40.4% by 2050 compared to 2022. When more efforts are undertaken to renovate homes, a decrease of 56% is achieved over the same period (BA-HEE-BA-O). All other heat supply scenarios achieve full decarbonisation by design, but their rates of decarbonisation differ; the High Electrification scenarios decarbonise quicker than the High Gas and Mixed scenarios. The main reason is that HPs are expected to diffuse into the heating system quicker because an industry around it has already been established. This is not the case for novel hydrogen boilers, which therefore are expected to diffuse into the system at a lower rate initially. Therefore, cumulative operational CO_2 emissions are higher compared to the High Electrification equivalents.

The cumulative CO_2 emissions and annual emission changes are displayed in Table 11. The timelines of annual emissions by heating technology are shown in Figure 18.

Table 11: Cumulative direct CO_2 emissions of the European residential sector and per cent change in annual emissions over selected time periods.

Scenario	Cumulative direct emissions and per cent change Gt CO_2 (% change in annual emissions)			
	2015-2030	2022-2030	2015-2050	2022-2050
Baseline Eff. & Baseline Supply	5.37 (-33.2%)	2.78 (-11.7%)	10.12 (-54.9%)	7.53 (-40.4%)
Baseline Eff. & High Electrification	4.97 (-54.9%)	2.38 (-40.4%)	6.55 (-100%)	3.96 (-100%)
Baseline Eff. & High Gas	5.09 (-49.7%)	2.49 (-33.5%)	6.74 (-100%)	4.15 (-100%)
Baseline Eff. & Mixed	5.03 (-51.4%)	2.44 (-35.7%)	6.75 (-100%)	4.16 (-100%)
High Eff. & Baseline Supply	5.34 (-35.8%)	2.75 (-15.2%)	9.33 (-66.7%)	6.74 (-56.0%)
High Eff. & High Electrification	4.95 (-56.7%)	2.36 (-42.8%)	6.33 (-100%)	3.74 (-100%)
High Eff. & High Gas	5.06 (-51.7%)	2.47 (-36.1%)	6.51 (-100%)	3.92 (-100%)
High Eff. & Mixed	5.01 (-53.3%)	2.42 (-38.2%)	6.51 (-100%)	3.92 (-100%)

Burning fuels will also lead to emissions of other airborne pollutants besides CO_2. While CO_2 emissions make up the bulk of all emissions (see Figure 19), other pollutants can be detrimental to public health at low levels. Decarbonising the European heat supply will lead a decrease in emission levels of all pollutants. However, some NO_x emissions remain in the High Gas and – to a lesser extent – the Mixed scenarios due to the take up of hydrogen boilers in the system. By 2050, 200 kt NO_x is emitted in the Baseline. In the Baseline Efficiency and High Gas scenario NO_x emission levels drop to 70 kt/y NO_x, while in the Baseline Efficiency and High Electrification scenario emission levels of 36 kt/y are observed. The potential adverse health effects of NOx emissions have not been taken into account into the evaluation of the socioeconomic impacts.

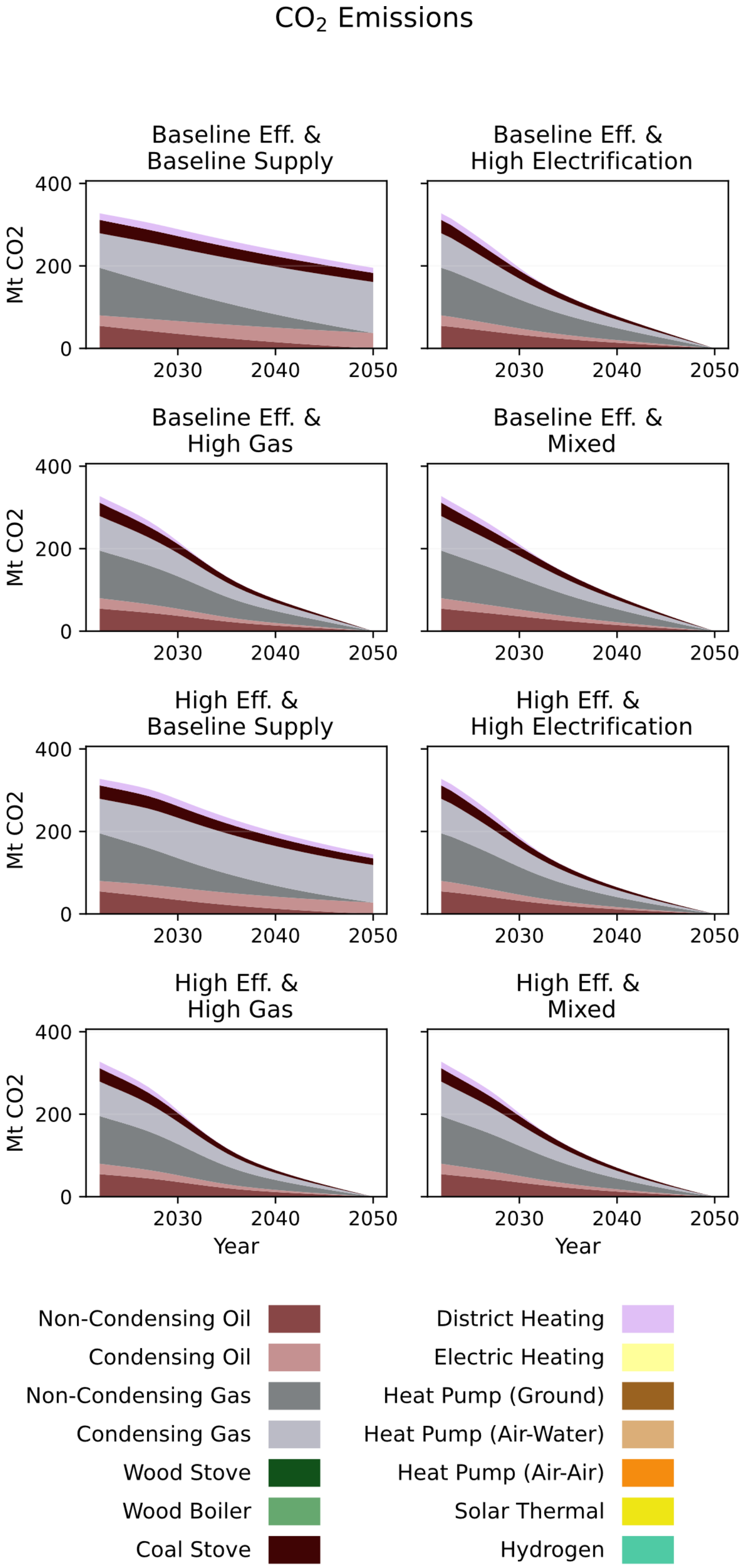

Figure 18: CO_2 emissions by technology.

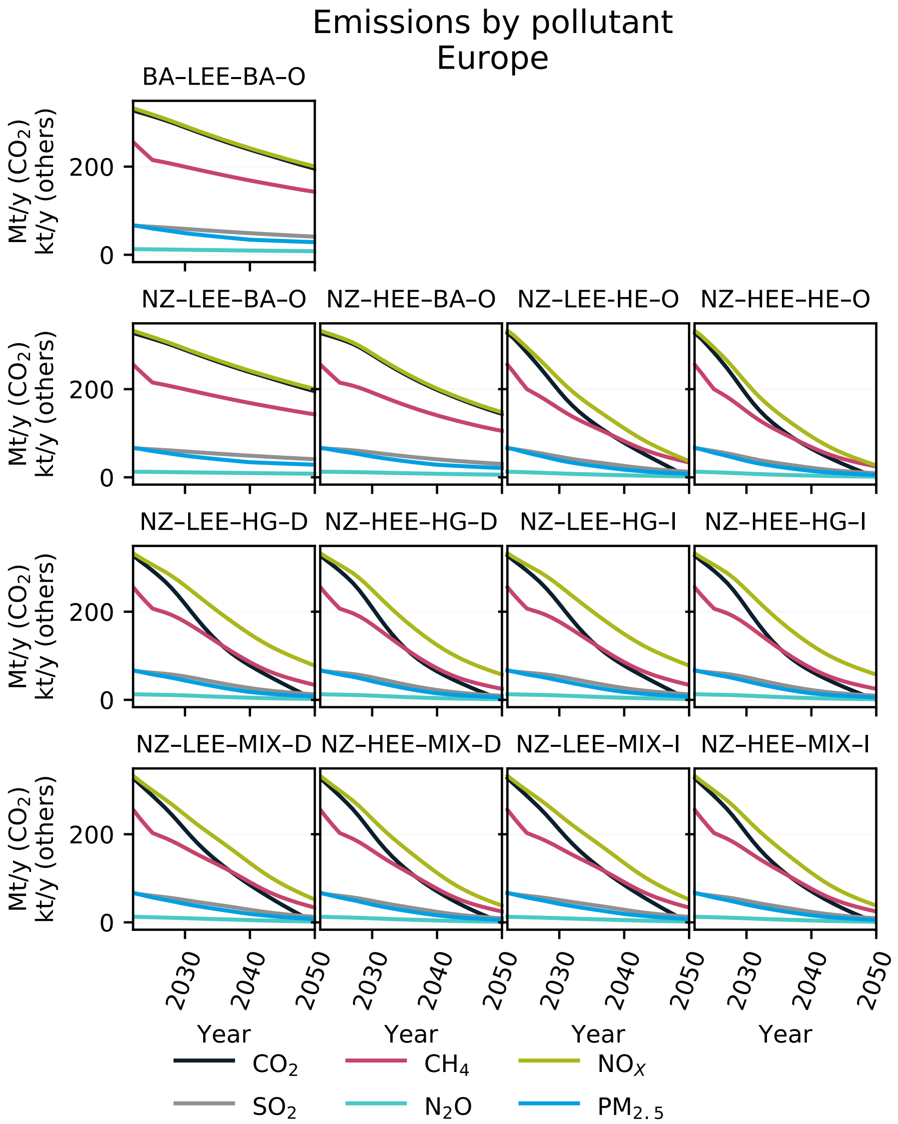

Figure 19: Emissions by pollutant as a sum across technologies.

4.5 Upfront investment on heating & cooling technologies

European households are estimated to face a cumulative upfront cost of maintaining present day's heating system of 719 bn€ between 2022 and 2050. Transitioning to different heating systems will increase the upfront costs because newer systems are often more expensive initially. Switching to a system dominant with HPs and DH/C – without increased efforts to further renovate homes – will add 274 bn€, summing to a total of 993 bn€ over the same time period. The bulk of all investments are due to investments in HPs (more than 50%). Less investments are required to facilitate a transition to hydrogen. Greater efforts to renovate homes will reduce the need for heating, which allows for installation of heating units of lower capacity, which reduce the upfront investments required. Yet, the NZ-HEE-HE-O scenario still requires more investments than the baseline, in which no additional efforts are undertaken to decarbonise the housing stock. See Table 12 for a summary of heating and cooling investments.

The timeliness of upfront investments is different by scenario (see Figure 20) In all cases where the heating system decarbonises, the upfront investment increases initially as the heating system undergoes radical change. The High Electrification scenarios show peaks around 2030 which coincides with the inflexion point of HP uptake. The High Gas scenarios show peaks around 2035. The uptake of hydrogen boilers is slower at first due to its novelty, while by comparison HPs are already commercially available on the market. In the Mixed scenarios, both HPs and hydrogen boilers are taken up in the system, which means that both the 2030 HP peak and the 2035 hydrogen peak are lower and combined, leading to a smoother profile.

Upfront investments in equipment dedicated to cooling are estimated to be much lower. This is exacerbated as DH/C and especially HPs diffuse more rapidly into the European heating system. Investments in those technologies are accounted for in the investment figures for heating equipment. However, following the allocation rules of heating, DH/C mostly ends up in Northern and Eastern European countries where lower needs for cooling prevail. HPs do see a greater uptake in the warmer climate zones of Europe, which therefore reduces the investments required for cooling dedicated equipment, as is evident from Table 12 and Figure 21. In the Baseline Efficiency and High Electrification scenario, upfront investment in cooling dedicated is 1.33 bn€ lower than the baseline. For the High Efficiency equivalents, this amounts to 0.64 bn€.

Table 12: Cumulative upfront investment for DH/C, HP, and hydrogen boiler deployment in each heat supply scenario, and total cumulative investment in heating and cooling equipment. All numbers relate to the period between 2022 and 2050.

Scenario	Cumulative investment in DH/C (bn€)	Cumulative investment in HPs (bn€)	Cumulative investment in hydrogen boilers (bn€)	Total cumulative investment in heating (bn€)	Total cumulative investment in cooling (bn€)
Baseline Eff. & Baseline Supply	74	90	0	719	4.08
Baseline Eff. & High Electrification	139	498	0	993	2.75
Baseline Eff. & High Gas	141	84	233	855	4.03
Baseline Eff. & Mixed	145	303	87	906	3.18
High Eff. & Baseline Supply	73	76	0	608	3.05
High Eff. & High Electrification	124	400	0	860	2.41
High Eff. & High Gas	128	72	183	743	3.03
High Eff. & Mixed	132	240	68	788	2.71

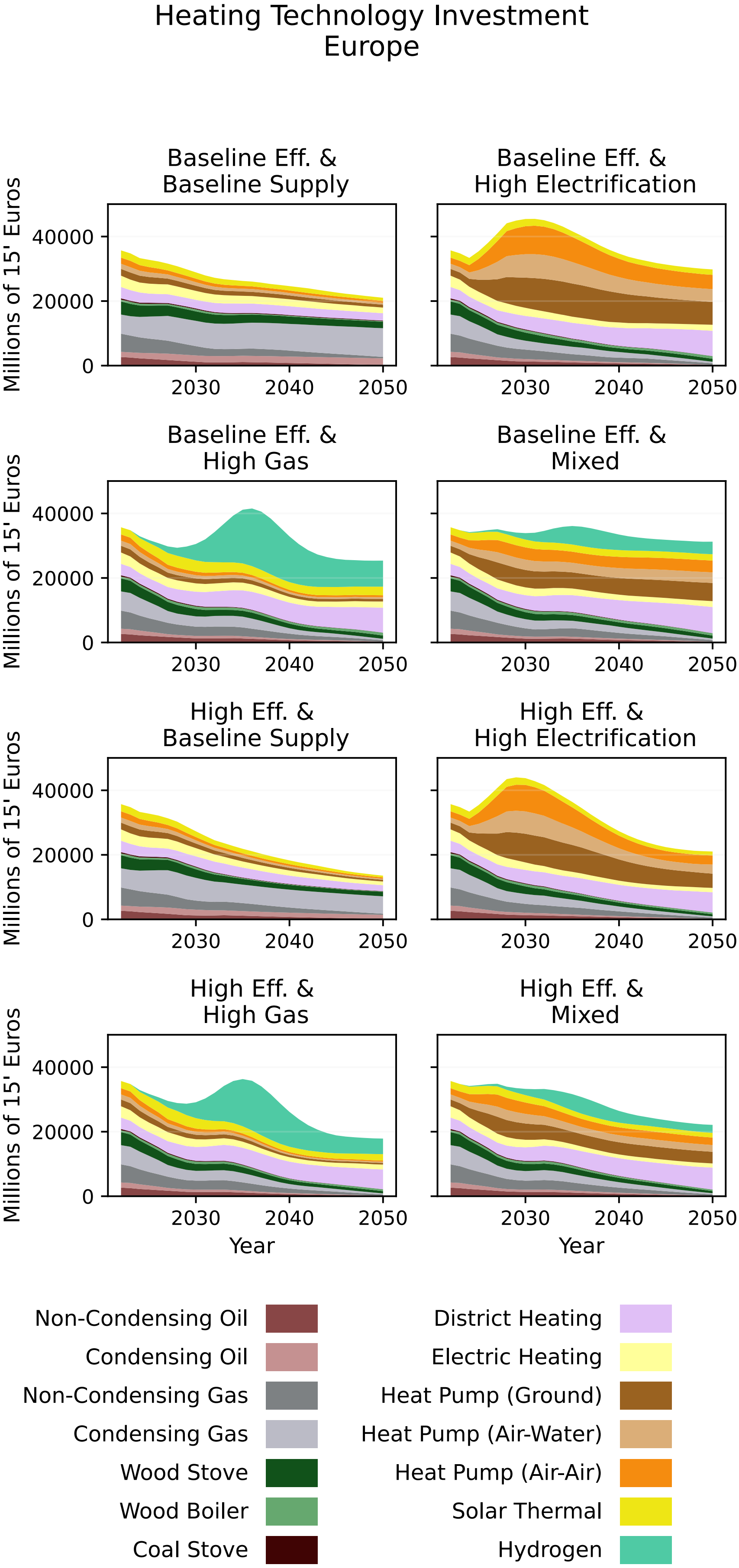

Figure 20: Investment requirements by technology.

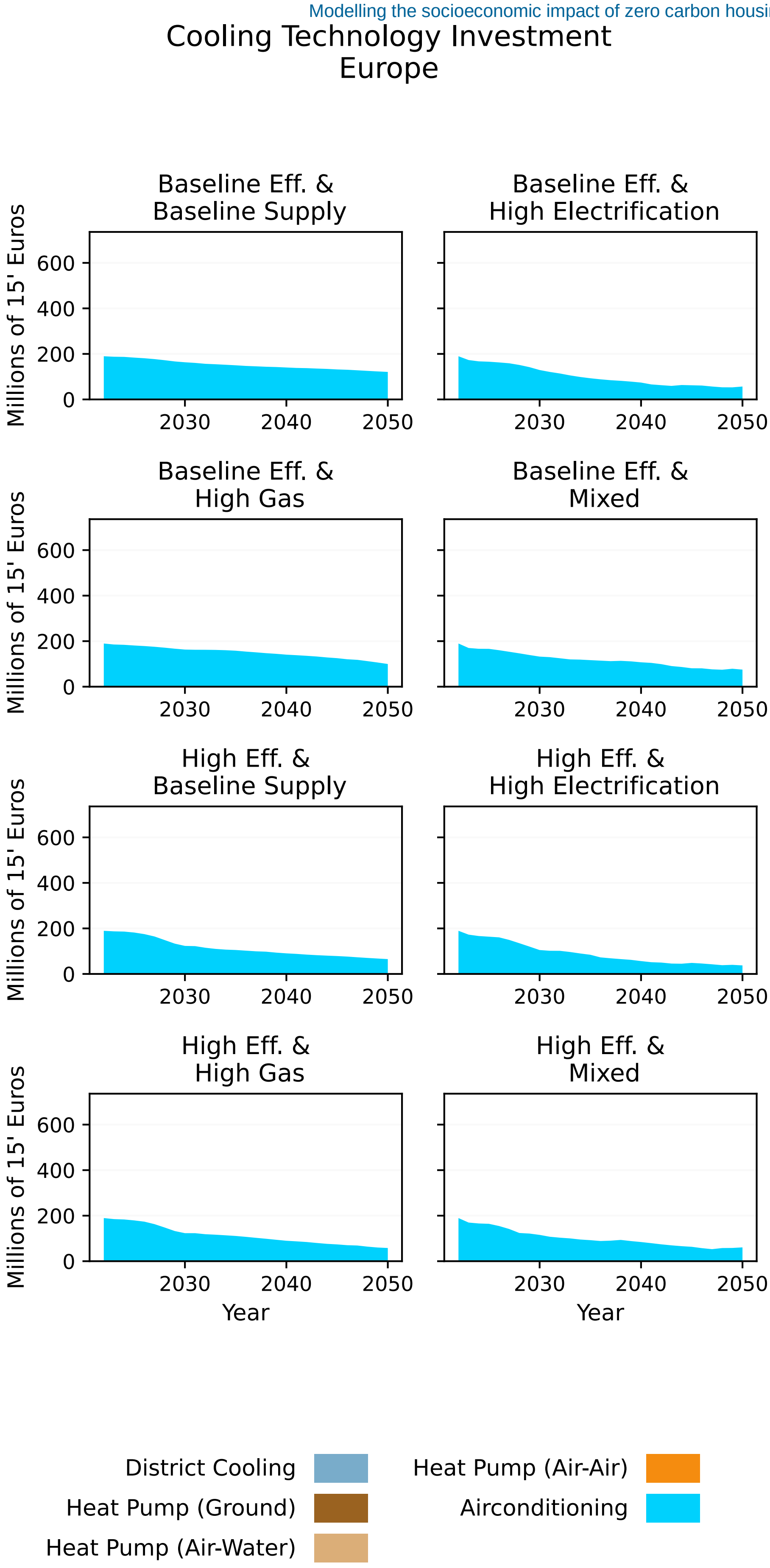

Figure 21: Investment in cooling equipment.

4.6 Infrastructure investments

Large scale deployment of DH/C (35% of heat delivered in non-baseline scenarios), HPs (48% in the High Electrification scenarios), or hydrogen boilers (40% in the High Gas scenarios) will require investments in DH/C pipelines, electricity grid reinforcement, and hydrogen pipelines and production capacity (where applicable) respectively. In addition, green hydrogen produced domestically will also require investment in production facilities.

Using the uncertain and static investment factors for these categories as listed in section 2.3.4, we note that large-scale transitions are paired with high infrastructure investments. Without additional efforts to renovate homes, an estimated cost between 400 and 500 bn€ is required to facilitate the various transitions. These costs are halved to around 200 bn€ in most scenarios when homes are made more efficient, except for the High Gas scenario with onshore hydrogen production. The rate of hydrogen infrastructure investments aligns with the uptake profile of hydrogen boilers, and therefore peaks around 2035. Due to the decreasing need for heat, the rate of infrastructure deployment will slow down, and the investments with it. DH/C networks diffuse more gradually into the European heating system and therefore the associated investment in pipeline networks shows a similar trend. Power grid reinforcement investment relate to changes in electricity demand relative to the base year of 2020. It encompasses electricity use for heating, cooling, and other appliances. Regarding the latter, we assumed that when gas boilers are phased out, gas-fired hobs will follow in favour of electric cooking. In all High Electrification, High Gas, and Mixed scenarios, HPs increase compared to the Baseline and therefore lead to additional investments to reinforce the grid. See Figure 22.

While the infrastructure investments are sizeable, they do not reach the same scale as the investments required to renovate homes (362 bn€ in 2050, see section 4.1). Infrastructure investments for grid reinforcements are therefore only a minor driver for the socioeconomic impacts.

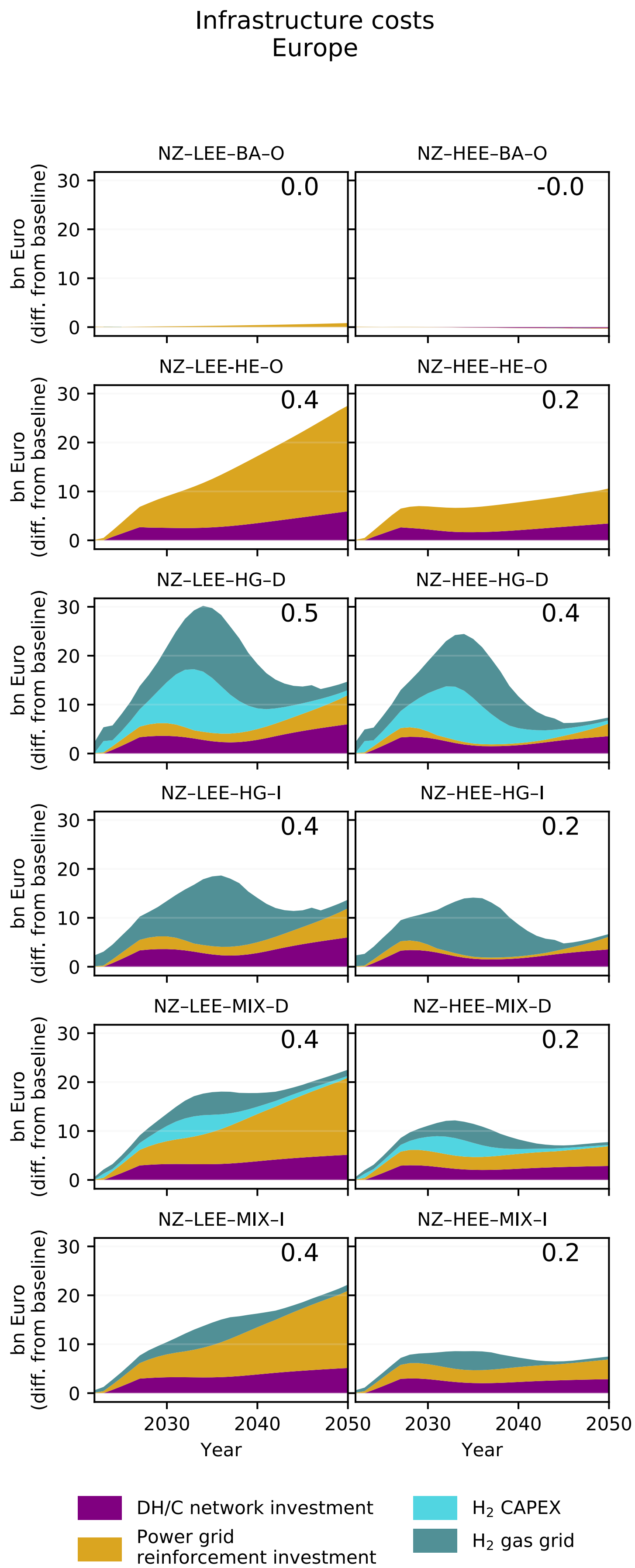

Figure 22: Infrastructure investments required to accommodate the transition of the residential heat supply. The cumulative value of the combined infrastructure requirements is listed in the top right of each panel in trillion Euro.

4.7 Residential energy prices

Households can face vastly different energy bills based on the quantity and type of energy carrier they demand and what the prevailing energy prices are. Energy prices depend on the economic and policy environment. European average electricity prices are projected to remain around the 15 c€/kWh mark. In the scenarios where the power sector decarbonises with an additional carbon taxation, the electricity prices increase only marginally by 3.5% at its peak in 2035. This is due to greater uptake of renewables in the system even in the baseline which builds on the EU Reference Scenario 2020. See Figure 23

Hydrogen – when produced domestically – starts off at the 25 c€/kWh mark but declines to approximately the same price level as electricity due to the assumed learning-by-doing effects. Looking at the High Gas scenarios, one notes that – in the case of onshore production –hydrogen achieves price parity with coal and oil before 2035. The same happens with gas five years later. When hydrogen is produced offshore and imported, then price parity with electricity is achieved around 2025, while all fossil fuels have crossed over before 2033.

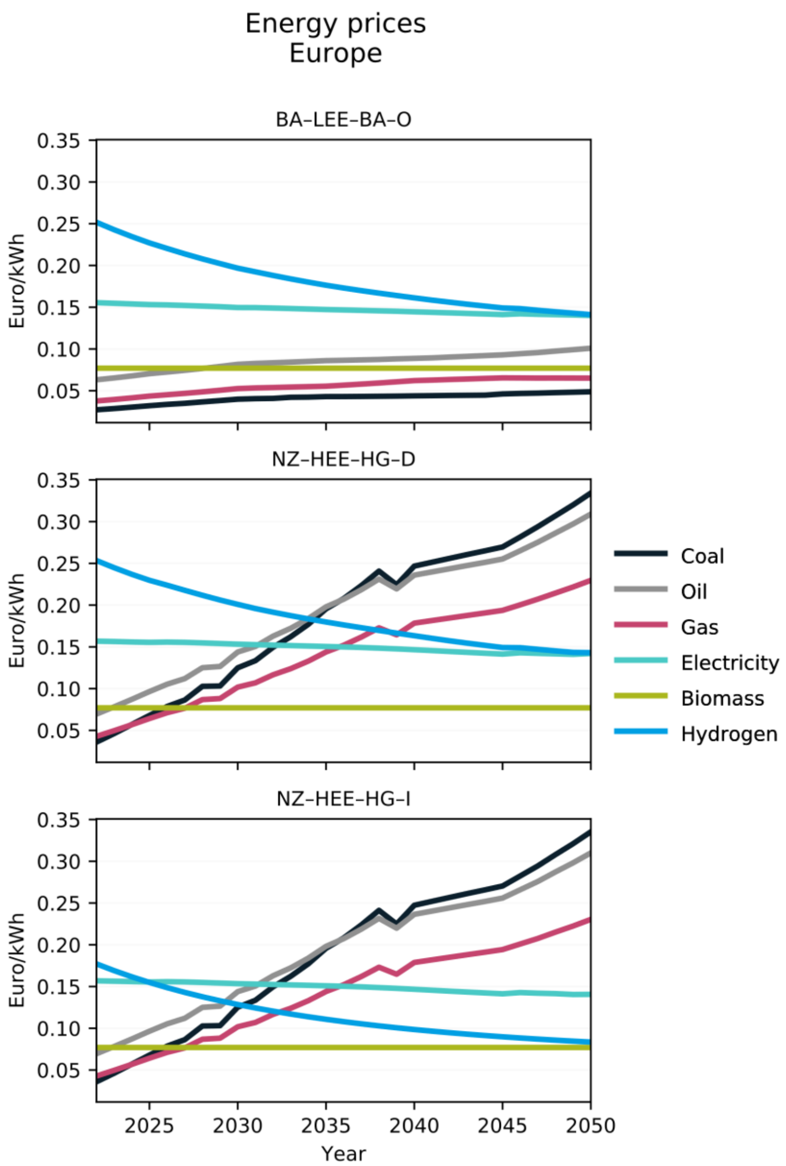

Figure 23: Average end-use energy prices in Europe of selected scenarios. Minor differences exist between scenarios not shown here.

4.8 Total household expenditure on heating & cooling

Households face different types of expenses to satisfy their demand for heating and cooling. Upfront expenditure has been discussed in section 4.5, and on top of that there is spending on maintaining the equipment over its lifetime and spending on energy costs. Energy costs for heating purposes are the largest spending category.

Spending on heating & cooling categories varies between scenarios due to the changing energy system (see Figure 24). Spending on heating makes up the bulk of all heating & cooling related spending. When only the ETS2 price is applied (NZ-LEE-BA-O), households face much higher energy bills because of increasing fossil fuel prices while the fossil fuel technologies remain unmitigated, see Table 13. On average, a household will spend 817 €/y on energy for heating in 2050. That is more than twice as much as in the Baseline. The average energy bill decreases the most by 2050 in the NZ-HEE-HE-O scenario to a level of 144 €/y. The energy bills vary a lot regionally. In general, expenditure on energy is expected to increase for each of the heat supply variants between 2022 and 2039 due to environmental taxation on fossil fuels which are still part of the household energy system.

Under the High Electrification scenarios, heating and cooling related expenditure decreases compared to the baseline (BA-LEE-BA-O) with cross-over points in 2042 in the Baseline Efficiency variant and in 2039 in the High Efficiency variant. This cross-over does not occur in the High Gas scenarios with onshore hydrogen production, in which expensive hydrogen replaces (environmentally taxed) fossil fuels in an inefficient heating system, which means that energy bills do not decrease compared to the Baseline in the High Gas scenario using domestically produced hydrogen. Only when cheaper hydrogen is imported from outside Europe and the building stock is renovated at a higher rate, a cross-over is observed towards the end of the simulation. Three out of the four Mixed scenarios show cross-over points before 2050. NZ-HEE-MIX-D does so in 2045, NZ-LEE-MIX-I in 2049, and NZ-HEE-MIX-I in 2042.

Table 13: Total spending on energy for heating and average heating bills per dwelling for selected scenarios.

	Energy bills for heating	2022	2030	2040	2050
	Total dwellings (mln dw.)	314	324	329	328
BA-LEE-BA-O	Total spending (bn€)	140	142	126	108
	Average spending per dwelling (€/dw)	446	439	385	331
NZ-LEE-BA-O	Total spending (bn€)	149	214	265	268
	Average spending per dwelling (€/dw)	474	662	807	817
NZ-HEE-HE-O	Total spending (bn€)	149	168	117	47
	Average spending per dwelling (€/dw)	474	519	354	144
NZ-HEE-HG-D	Total spending (bn€)	149	208	192	111
	Average spending per dwelling (€/dw)	474	642	585	339

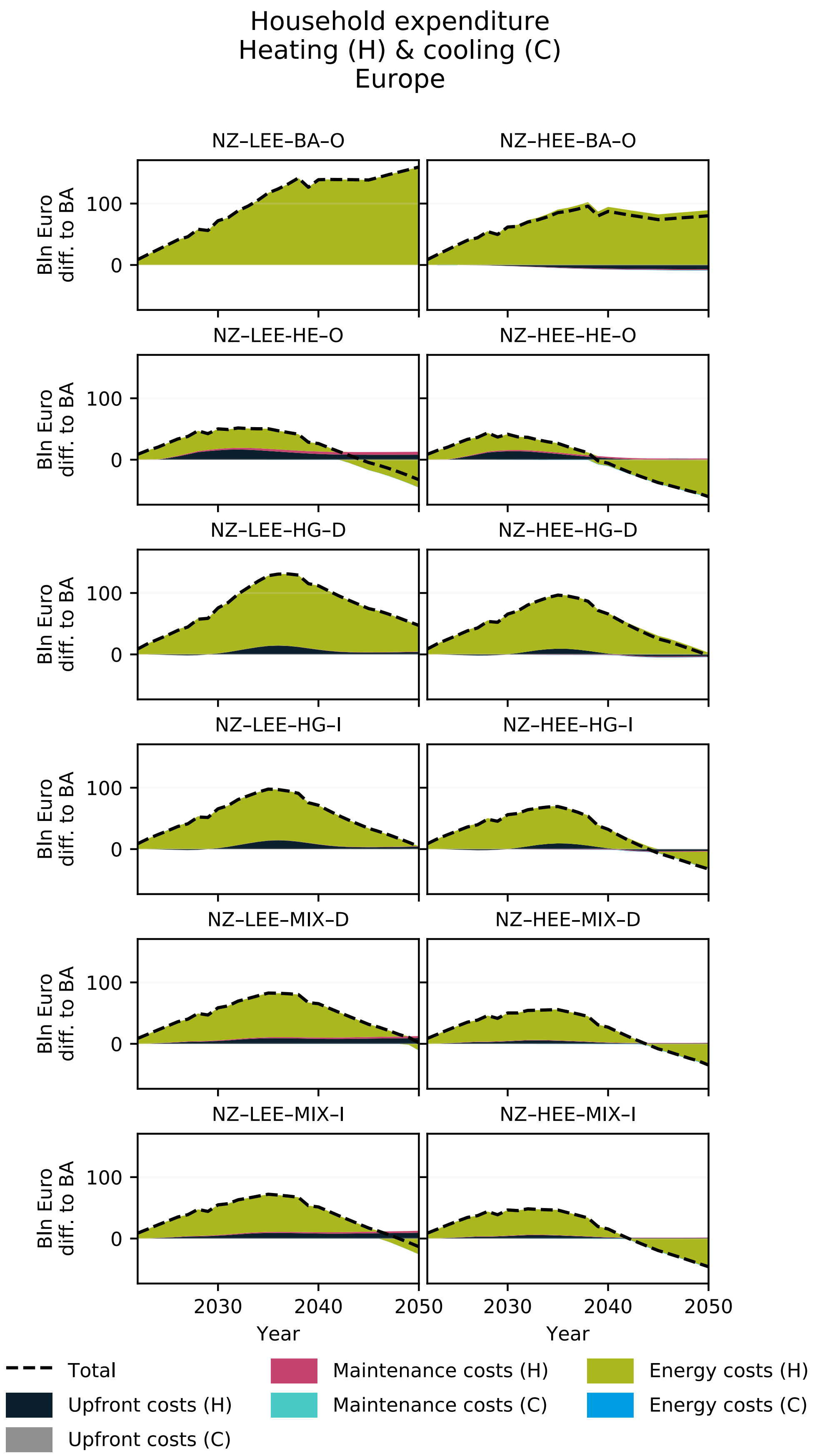

Figure 24: Household expenditure by expenditure category.

4.9 Total cost of ownership

The previous section highlighted the total changes to the baseline in household expenditure on various heating and cooling related aspects. These outcomes arise due to households swapping their existing heating technologies for alternative ones. As highlighted section 2.3.3, the techno-economic parameters by technology are vastly different. HPs, for example, are more costly upfront, but by making use of ambient heat sources they are very efficient and – depending on electricity prices – HPs save on energy costs. Estimates on upfront and running costs are important to evaluate the total cost of ownership (TCO). Here, the TCO is estimated over a 10-year period, using annualised upfront investment costs and no discounting of running costs.

Figure 25 shows the development of TCO estimates over time for selected technologies and scenarios. In every scenario, air-to-air HPs and ground-source HPs reach cost parity with condensing gas boilers by 2028. Air-to-water HPs follow around 2031. When environmental taxes are imposed, all HP types become competitive alternatives to condensing gas boilers before 2022.

Changing the configuration of DH will come at a cost, especially if the focus shifts towards utilising hydrogen. TCO estimates in the High Electrification scenarios will also become slightly more expensive than their Baseline counterparts due to the increased need of thermal storage. Hydrogen boilers never achieve cost parity with neither HPs nor DH, regardless of the DH configuration and regardless of whether hydrogen is imported at a much lower price or whether it is produced domestically.

Figure 26 shows the TCO estimates for all technologies for two periods (2030-2040 and 2040-2050) and four representative scenarios. Without mitigation policies, hydrogen boilers are the most expensive technology, but costs decrease over time due to learning-by-doing effects. Comparatively, hydrogen boilers appear to be a more favourable alternative to condensing gas boilers once the ETS2 prices are applied. Fossil fuelled boilers then quickly become more expensive, especially in the cases where low-cost hydrogen is imported

In the baseline, HPs and solar thermal are already cost competitive options due to lower spending on energy inputs for these technologies. However, they face high upfront costs which can be too high for consumers to bear, especially if the access to finance is limited. This barrier is expected to decrease over time as the HP market becomes more established. and the upfront costs decrease. We reflect on this in Table 13 where the payback periods are calculated for switching from condensing gas boilers to alternative heating modes. Payback periods are calculated as the ratio between the upfront costs of the alternatives divided by the difference in operational costs of the alternative and a condensing gas boiler. Without application of the ETS2 system (i.e. the BA-LEE-BA-O scenario), one would need to own and operate a HP for a period between 13 to 24 years in order to outperform a condensing gas boiler. By 2050, the payback periods are reduced to 7 to 13 years. When the ETS2 is applied, payback periods for HPs reduce even further, which is also the case for DH and hydrogen boilers. While the difference in energy costs of those modes of heating compared to condensing gas boilers is lower than it is for HPs, the upfront costs are also much lower. DH in the High Electrification scenarios is heavier on the upfront costs than DH in the High Gas scenarios.

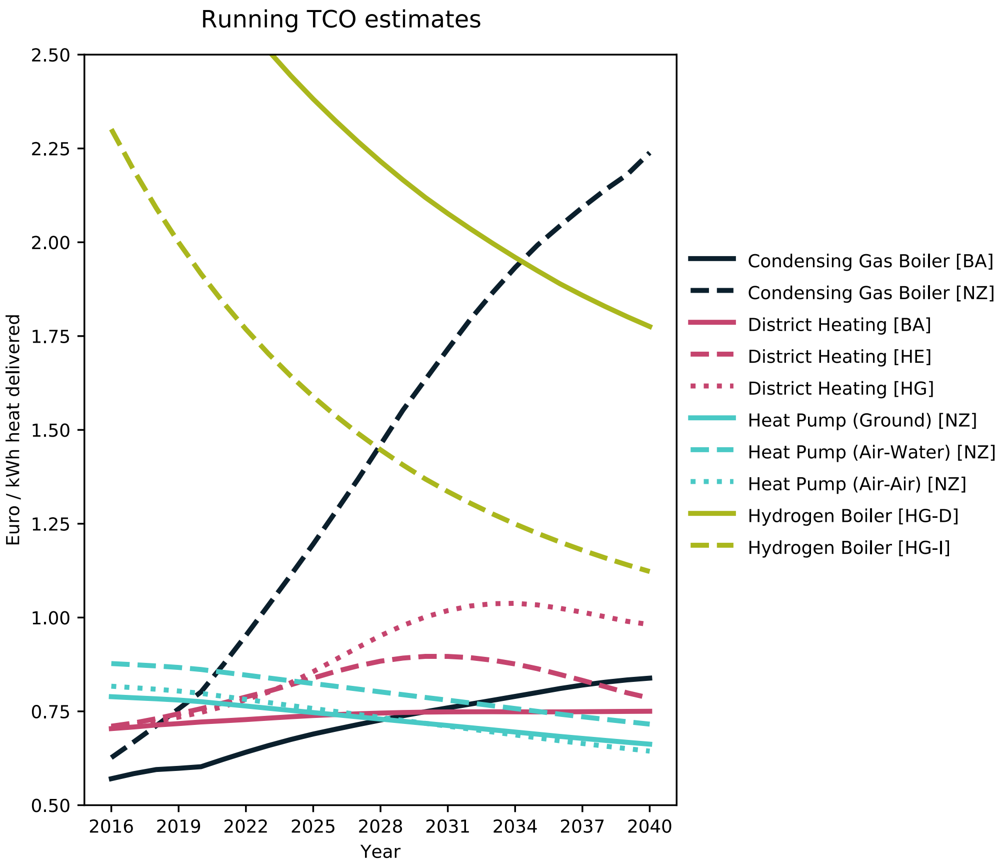

Figure 25: Running TCO estimates of selected technologies and equipment. TCO is undiscounted and runs over a 10-year period, so the value in 2020 represents the ownership of a technology from 2020 to 2029. BA: Baseline; NZ: Any net-zero scenario; HE: Any High Electrification scenario; HG: Any High Gas scenario; HG-D: Any High Gas scenario with domestic production of hydrogen; HG-I: Any High Gas scenario with imported hydrogen.

Table 14: Payback periods of switching from a condensing gas boiler to an alternative technology for the cases where the ETS2 is included or excluded.

No. of years required to earn back the upfront cost of alternatives to condensing gas boilers due the savings on energy bills		Including the effect of ETS2 on operational costs of condensing gas boilers					
		No			Yes		
		2030	2040	2050	2030	2040	2050
Switching to…	Heat Pump (Ground)	18	14	13	4	3	3
	Heat Pump (Air-Water)	24	14	13	3	2	2
	Heat Pump (Air-Air)	13	8	7	2	1	1
	District heating (HE)	-	-	17	3	1	<1
	District heating (HG-D)	-	-	-	1	<1	<1
	District heating (HG-I)	-	-	5117	1	<1	<1
	Hydrogen boiler (HG-D)	-	-	-	-	3	2
	Hydrogen boiler (HG-I)	-	-	-	3	2	1

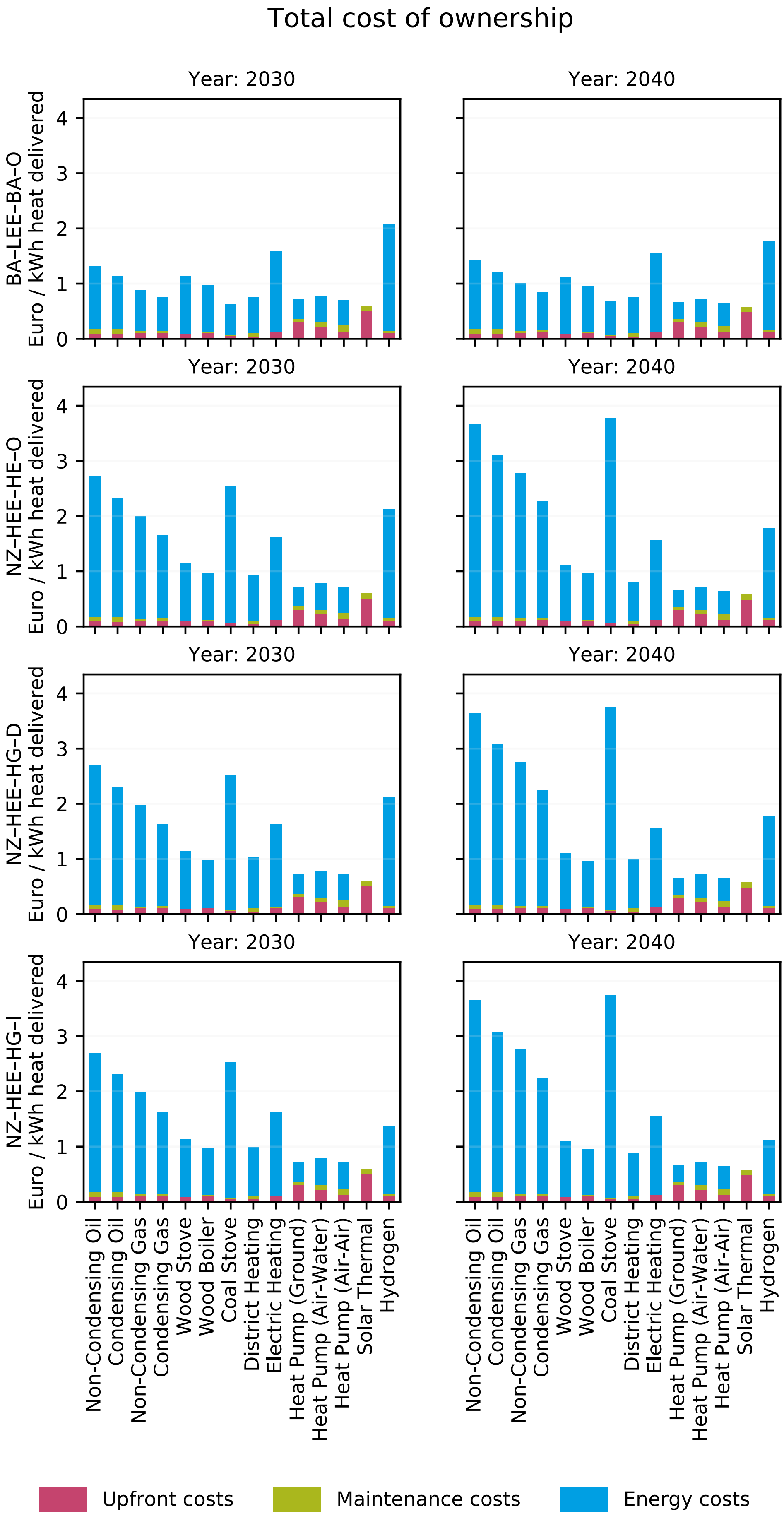

Figure 26: Total cost of ownership by heating technology over a 10-year period in 2030 and 2040. Estimates are undiscounted. Each row represents a scenario, each column represents a year.

4.10 Consumer expenditure

Consumer expenditure is an important driver to evaluate socioeconomic impacts. Household expenditure on heating, cooling, and renovations are important expenditure categories. Unlike industries and governments, the access to capital is limited for households, which means crowding out of spending can occur leading to different spending patterns. Figure 27 shows the changes in total (aggregate) consumer expenditure compared to the baseline. When households spend less on energy it unlocks spending in other goods and services. Generally, this leads to higher domestic production, employment, and lower import dependency overall.

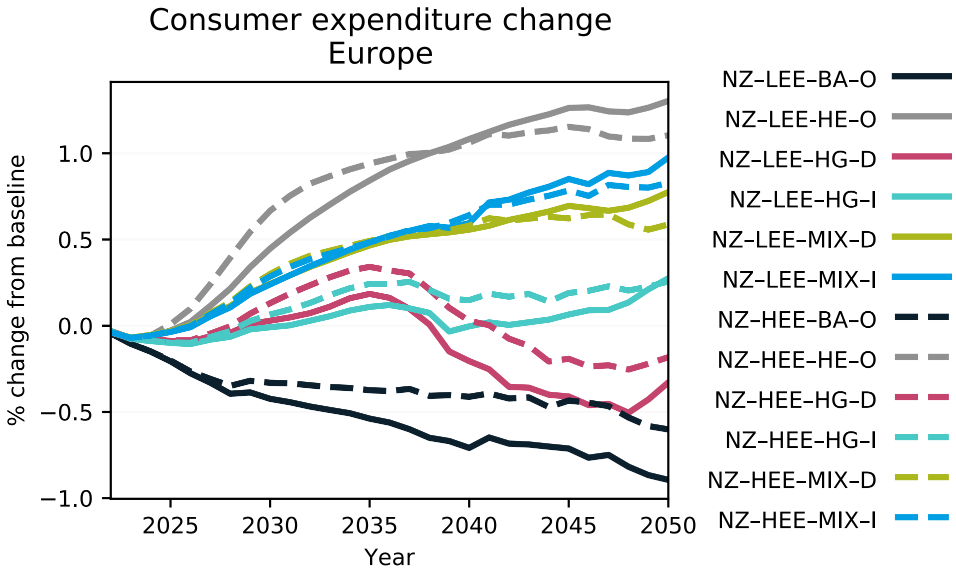

Figure 27: Total consumer expenditure changes relative to the baseline.

Total consumer expenditure decreases in an environmentally taxed environment that leaves the heat supply unmitigated (NZ-LEE-BA-O). Households are then faced with high energy bills and thereby crowding consumption elsewhere. A portion of this can be prevented by increasing the efforts to renovate homes (NZ-HEE-BA-O). On the other hand, in our modelling it is assumed that governments cover some of the renovations through subsidies, which leads to a response in tax rates and a reduction of consumer expenditure.

Increased tax rates will decrease consumer spending. There is a delicate interplay between the impact of tax due to renovations and reduced energy bills through renovations and changing the heat supply. In some scenarios, the High Energy Efficiency variant outperforms the Baseline Energy Efficiency variant, because the energy savings differential is greater. This is true for the High Gas scenarios, but not for the Mixed and High Electrification scenarios. In those scenarios the energy savings are already substantial in the Baseline Energy Efficiency variant. The additional effect of increased efforts to renovate homes does not offset the tax impact and therefore – towards the end of the time horizon – the High Efficiency scenarios show slightly lower consumer expenditure. Compared to the baseline, the High Electrification scenarios followed by the Mixed scenarios, show the most favourable results (i.e. total consumer expenditure shows highest increase). In the High Gas scenarios with domestic production of hydrogen, aggregate consumer expenditure underperforms compared to the Baseline (BA-LEE-BA-O).

4.11 Gross output

The transition in the heating and cooling supply of households will lead to a change in the economic structure. Decarbonisation will decline the fossil fuel supplying industries, and it can boost others such as electricity supply, other utilities (DH/C and hydrogen), construction (renovations), and manufacturing (new heating equipment). As the previous section pointed out: where household spending patterns move away from energy, more spending occurs in other goods and services produced and provided domestically. Due to value-chain effects, other sectors benefit as well. Figure 28 summarises the effects on gross output of sectors due to the changing spending patterns.

The High Electrification scenarios show a steady growth in gross output across all sectors, while the onshore hydrogen production scenarios (NZ-LEE/HEE-HG/MIX-D) show peaks in gross output of sectors related to hydrogen production and power generation. This overlaps with the uptake profile of hydrogen boilers, which is accommodated by upfront investment in equipment and infrastructure. When hydrogen is imported (NZ-LEE/HEE-HG/MIX-I), the positive initial gains of gross output in those sectors disappear. Yet, the total gross output change compared to the baseline by 2050 is similar between the onshore and offshore hydrogen production variants. This is due to lower hydrogen prices in the offshore hydrogen variant, leading to lower spending on energy by consumers compared to the onshore hydrogen variant. The High Electrification scenarios exhibit a greater increase of total gross output by 2050 due to further reductions in spending on energy.

The High Efficiency variants show an additional increase of gross output in the construction sector due to the additional renovation investments which is a trend found in all HEE scenarios. The construction sector will require more equipment to fulfil the renovation needs, which leads to increased economic activity in the engineering and basic manufacturing sectors.

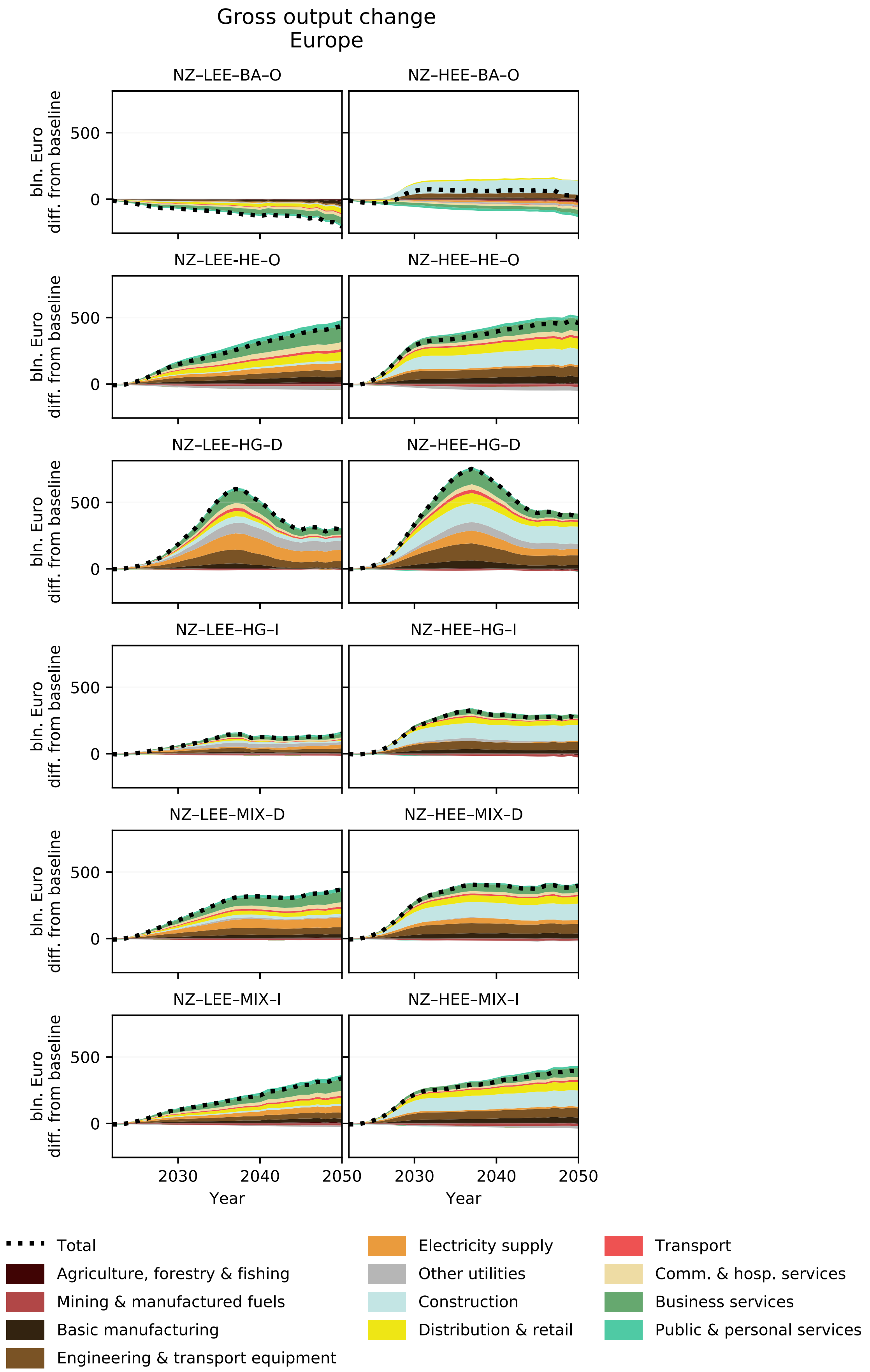

Figure 28: Gross output change by sector as a difference from the baseline (BA-LEE-BA-O).

4.12 Employment

Employment results are ultimately driven by gross output and therefore show similarities. See Figure 29. Generally, investment stimuli lead to an initial increase of gross output and employment, but this effect slows down in the long-term due to the debt repayment phase. This becomes particularly clear in the scenarios involving High Gas with onshore hydrogen production (NZ-LEE/HEE-HG-D). Due to the infrastructure investments, an employment boost is noted around 2035, but after peak hydrogen boiler uptake (and therefore peak infrastructure investment) has occurred, the investments go down while consumers are still faced with high hydrogen prices.

When hydrogen is imported instead (NZ-LEE/HEE-HG-I), European industries miss out on establishing a hydrogen supply sector, but consumers are assumed to face lower end-use prices, reversing the effects of the onshore production variants: lower initial investment and lower long-term price levels. These scenarios do not see the employment peaks around 2035 and generally remain stable over the projected period. By 2050, total employment differences to the baseline are similar for both the onshore and offshore hydrogen production scenarios.

The High Electrification scenarios (NZ-LEE/HEE-HE-O) do not show the same kind of investment stimulus feedback to employment. The uptake of HPs starts earlier and is spread out over a longer period, as is the investment profile. There are also less investments required to update the infrastructure. Unlike the High Gas or Mixed scenarios, household face much lower energy bills in the High Electrification scenarios, which unlocks spending elsewhere with higher multiplier effects (recall section 4.10). Therefore, domestic demand increases which is satisfied through a combination of domestic production and imports (recall section 4.11). Increasing domestic production will lead to increases in employment.

Comparing the Low Energy Efficiency scenario variants to the High Efficiency scenario variants shows that the latter always outperforms the former. Greater efforts taken to renovate the European housing stock require more jobs in construction and other sectors to achieve this.

More employed people will also have a greater ability to spend, further boosting employment when the additional spending leads to domestic production. However, in section 4.10 we have seen that in some cases the High Efficiency scenario leads to slightly lower consumption than the Baseline Energy Efficiency one, while we generally do note higher employment in the High Efficiency scenarios. In such cases, the employment boost is negated by increased tax rates.

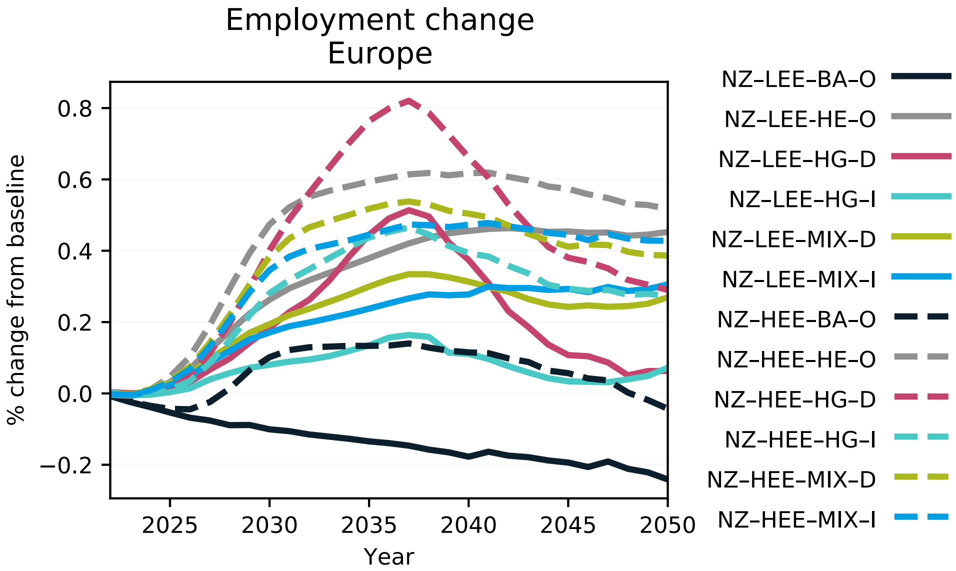

Figure 29: European employment by scenario. Presented as a difference from the baseline (BA-LEE-BA-O).

With respect to differences between sectors, a few observations stand out:

- Decarbonising the power sector will lead to more employment in that sector. In the scenarios, the decarbonisation is achieved primarily through the additional carbon tax applied to power generation, of which the costs of are passed on to industrial and household consumers. However, investments in RES offset the potential losses of employment from more expensive fossil fuels.
- Greater investments in renovating the housing stock create additional demand for the construction sector and therefore creates jobs.
- When the heat supply achieves decarbonisation through electrification, the only sector that loses jobs over the 2022-2050 period is the mining & manufactured fuels sector, due to dwindling demand for fossil fuels. However, the lower energy bills faced by consumers create demand for most of the other sectors – especially services – which leads to higher employment overall. In the High Efficiency scenario, an additional boost in cumulative employment is noted due to construction impacts.
- In the High Gas and Mixed with onshore hydrogen production scenarios, the power sector requires more jobs due to increased electricity demand to produce the hydrogen.

Figure 30 presents the projected differences in job-years by scenario. Jobs-years represent the creation and retention of jobs over the whole time period.

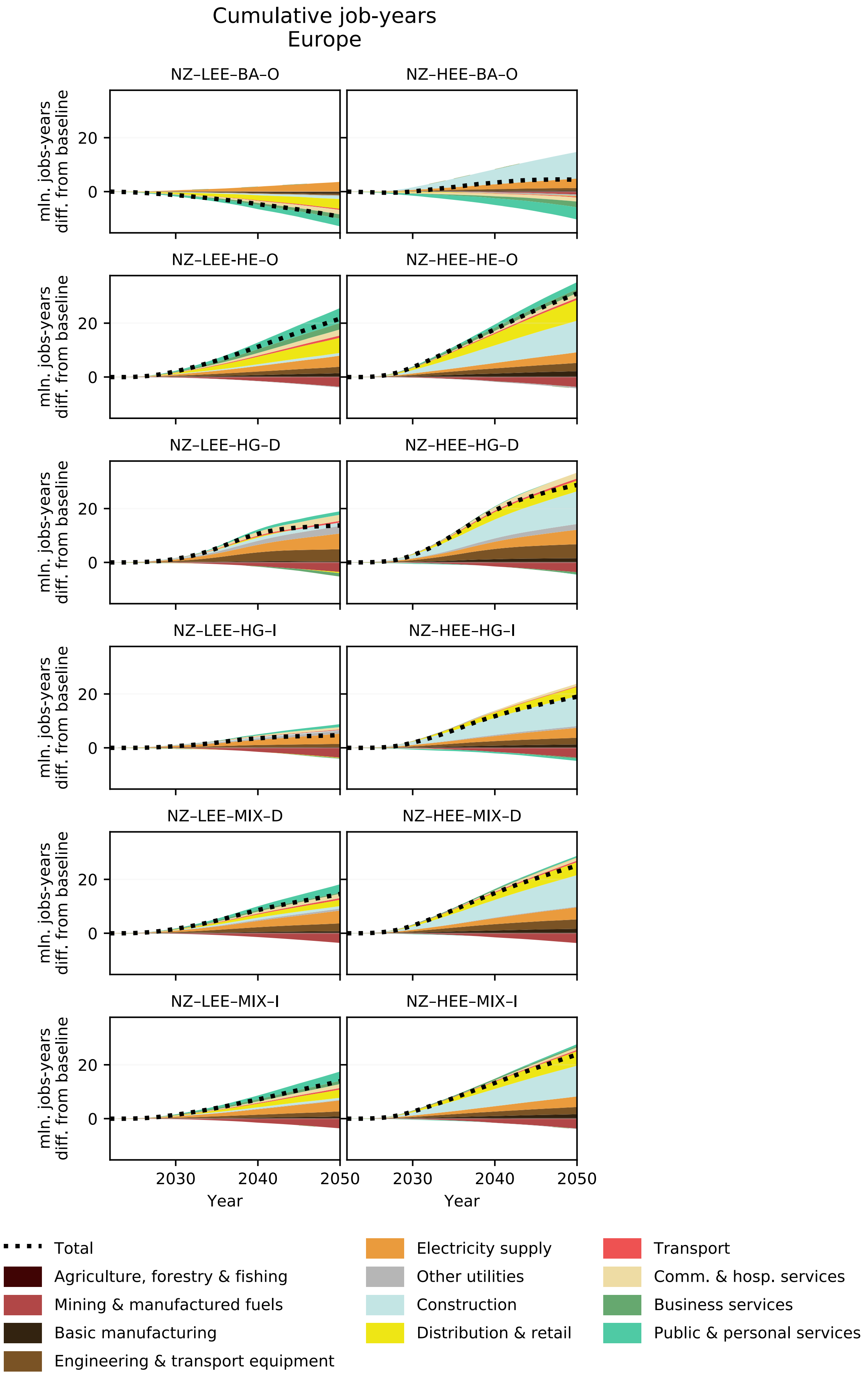

Figure 30: Cumulative job-years change by sector compared to the baseline scenario (BA-LEE-BA-O).

4.13 Distributional effects

The different transitions of the heating & cooling systems lead to different spending levels and patterns of the whole population and will also lead to different spending capabilities by different income groups. See Figure 31.

All in all, there is a delicate interplay of end-use prices (of products, services, and energy – including tax effects), employment (due to changes in economic activity as a result of decreasing or increasing energy bills), and renovation investments:

- Lower income households spend a greater proportion of their income on energy. Lowering the energy expenses of low-income households will therefore unlock more consumption of other goods & services. Where the additional demand for goods & and services has a higher domestic content, this can create more jobs and an increase in aggregate income.
- Renovations require huge investments, which will somewhat reduce the positive effect on household spending but lead most likely to job creation in the construction sector, which is dominated by lower-skilled workers.
- The portion of renovations paid for by governments also cause an increase of VAT, income tax, and employer’s contribution to social security (recall Table 9). VAT will increase price levels and – when corrected for this – reduces disposable income in real terms. Higher income taxes will directly affect disposable incomes of households, and due to progressive tax rates, mostly higher income groups. When employers are mandated to contribute more towards social security, this will increase the cost of employment. Thus, all these tax changes can alter the distribution of income across household groups.
- The portion of renovations paid for by property owners will lead to higher rents and effectively increases price levels for lower income groups who are more likely to rent instead of own and occupy their homes.
- Switching to heating systems that are dominated by electricity or domestically produced hydrogen will create a more favourable energy trade balance. The onshoring effect of energy supply will lead to more jobs from which the lower income groups benefit the most.

This interplay is also visible from the scenario results.

- Lower income groups stand to gain in both High Electrification scenarios and some Mixed scenarios. Their disposable income is least affected by renovation investments due to higher employment offsetting higher price levels.
- Higher incomes groups stand to gain most – or lose least – of additional real disposable income in the Baseline Efficiency scenarios, while they lose out most in the High Efficiency counterparts.
- In the High Gas scenarios with onshore hydrogen production, all income groups lose disposable income in both energy efficiency scenarios, due to the increased energy costs. Importing the hydrogen at lower prices reduces the negative impact somewhat, for all quintiles. This suggests that decarbonisation pathways with a reliance on higher energy costs are more likely have regressive effects.

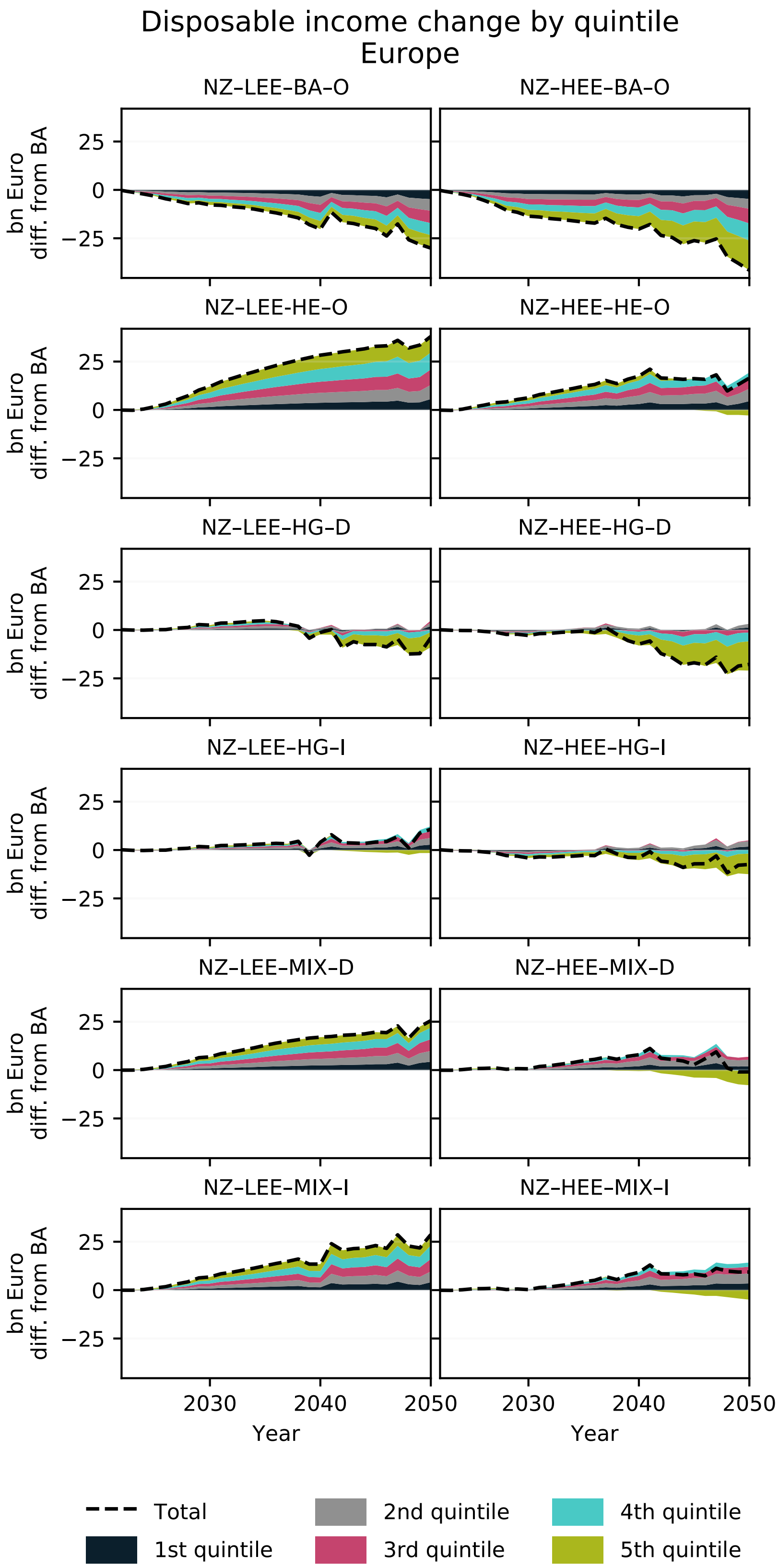

Figure 31: Disposable income change by quintile compared to the baseline scenario (BA-LEE-BA-O).

4.14 Gross domestic product

Drastically changing the residential heating system in Europe will lead to lower emissions, different expenditure patterns on purchasing and running heating and cooling equipment and is associated with additional investment requirements. This translates to changing consumption patterns, economic activity of sectors, and employment. All of these affect high-level economic indicators such as gross domestic product (GDP).

Figure 32 illustrates the effects on GDP compared to the baseline, for all scenario variants. In a net-zero economy consumers and producers are faced with higher energy prices due to taxation, which negatively affects GDP (solid black line, NZ-LEE-BA-O). However, increasing the energy efficiency of buildings will reduce residential final energy demand and therefore expenditure on energy, but it also leads to consumers spending on renovations. This spending leads to additional economic activity and employment. The net effect of further efforts to increase energy efficiency in a net-zero setting leads to slightly more favourable results compared to the baseline and much more favourable compared to the net-zero scenario without more efforts to renovate the housing stock (see the dashed black line, NZ-HEE-BA-O). This trend is seen throughout: scenarios incorporating further efforts to improve the energy efficiency levels of the housing stock outperform their baseline energy efficiency counterparts.

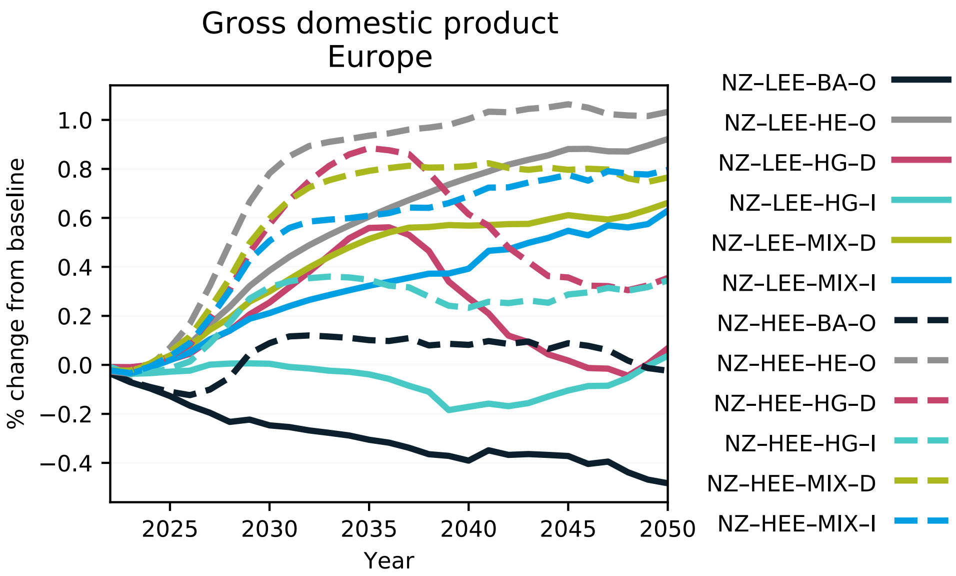

Figure 32: European GDP by scenario. Presented as a difference from the baseline (BA-LEE-BA-O).

When it comes to the scenarios incorporating hydrogen-based heating (HG or MIX), the GDP results show that producing hydrogen domestically (designated by “D”) leads to favourable outcomes initially with a peak around 2035. The same peak can be observed in the final energy demand of hydrogen for heating purposes. European countries will invest in production capacity, which leads to higher employment, but consumers will face higher energy bills, leading to lower consumption. Once the capacity has been established, the initial investment stimulus will be overtaken by a debt repayment phase, as the upfront investments are paid for. Europe misses out on this investment stimulus when hydrogen is imported from outside (designated by “I”). The benefit of importing hydrogen comes through via lower end-use hydrogen prices for consumers. However, importing hydrogen leads to a less favourable energy trade balance. By 2050, the offshore hydrogen scenarios are either on par or perform slightly better than the onshore hydrogen scenarios.

Electrifying the heat supply and lowering the need for heating through renovations shows the most favourable GDP impacts (dashed grey line, NZ-HEE-HE-O). HPs ensure efficiency gains on the supply-side, while the renovations do the same on the demand-side. It lowers consumer expenditure on energy, which allows more consumption other goods and services with a higher domestic content and thereby improving the overall trade balance.

5 Conclusions

This report has presented the projected socioeconomic impacts of decarbonising the housing through a combination of renovation efforts and changing the heat supply. The premise of this study is achieving a zero-carbon housing stock by 2050 in a net-zero setting for the power sector. All scenarios other than the Baseline Heat supply ones achieve complete decarbonisation of residential heating. The heat supply scenarios used in this study are indicative; it is not the purpose of this study to present a likely or optimal residential heating system.

5.1 Summary of analytical findings

In this report we have shown that:

- Increased efforts to renovate homes will come at a high cost to private landlords, owner & occupiers, and governments providing support.
- However, greater efforts to renovate homes will decrease final energy demand for heating and cooling considerably, which has beneficial impacts on the European energy trade balance when reduced fossil fuel imports are not replaced by hydrogen imports.
- Switching away from fossil fuels for heating purposes will lead to a reduction of air-borne pollutants, except if hydrogen boilers are employed (only accounting for operational emissions). In that case, NO_x emissions would decrease compared to the baseline but at a lower rate compared to the High Electrification counterparts.
- Any transition will likely lead to higher upfront costs faced by households, and – in addition – to facilitate such transition higher infrastructure investments are expected as well.
- If households were to keep using fossil fuelled heating equipment in a net-zero setting that includes an emission trading scheme for consumers, then that would lead to much higher running costs as the de-facto fossil fuel prices will rise compared to electricity and hydrogen.
- Despite higher upfront costs, households will face lower costs to meet their heating demand when they electrify their heating system with efficient HPs. Considering all cost components, HPs reach cost parity with condensing gas boilers in 2028 in an unmitigated scenario.
- While increased efforts are exerted to renovate the European housing stock come at a price, it leads to higher consumer expenditure in aggregate, compared to scenarios where no such effort is made. The renovations lead to greater domestic economic activity, and increased employment in the construction sector to facilitate the renovation orders. Electrifying the heat supply enhances the positive impacts as more economic activity is brought onshore.
- Lower income households spend a relatively large proportion of their income on energy. Lowering the spending on energy through higher energy efficiency will allow these households to spend money on other goods & services over time. Direct negative effects on spending from

renovations costs are projected to be offset by positive induced effects from increased employment.

5.2 Implications for policy

Renovating the EU building stock will likely cost upward of 300 billion euros per year from 2035 onward, assuming a 3.5% weighted renovation rate continues to be targeted once the ‘low hanging fruit’ has been tackled in earlier years. Increased efforts to renovate homes will result in a reduction of energy demand for heating of almost 190 TWh in 2050, compared to the Baseline. We find that increased efforts to renovate homes is likely to lead to large costs impacting household budgets directly, either through upfront costs for owner-occupiers or rent payments for households in privately rented dwellings. However, through indirect and induced effects, it leads to greater economic activity. Especially the demand for the construction industry is expected to grow in order to perform the renovations, which leads to higher employment and subsequently higher disposable income. Conversely, government support of renovating homes is expected to lead to higher tax rates to maintain budget neutrality, which is simulated as such, and adversely impacts household budgets.

A change in the technologies used for residential heating can have various outcomes depending on the dominant technology. A shift towards greater use of heat pumps for heating and cooling can further reduce the annual final energy demand by 40% compared to baseline levels by 2050. The use of highly efficient HPs will lower household expenditure on energy, which makes up the largest cost burden related to heating & cooling. This unlocks household’s budgets for spending on other goods and services with a higher domestic content, leading to more economic output and higher employment. The poorest households are expected to benefit from electrifying the heat supply. The benefit is reduced slightly when High Electrification is combined with High Efficiency efforts.

However, while the High Electrification scenarios present the best results across several indicators, there are barriers to heat pump deployment that require consideration. While large-scale uptake of heat pumps may reduce the energy bills faced by households, the large upfront cost is the first and foremost barrier to be addressed. Without access to finance, or the right incentives, it is unlikely that lower income households will be able to access the heat pump market. In addition, there may be “perverse incentives” for landlords to choose for the heating technology with the lowest upfront costs, as the running costs are usually the responsibility of the tenants.

Although a move towards hydrogen for heating will result in similar CO_2 emission reductions, greater investment will also need be made to establish a hydrogen gas grid and there will be lower economic gains. Households will also face higher energy costs compared to electrification of the heat supply.

Ultimately, this study finds that renovating the dwellings stock will have a net beneficial impact, if only through the additional economic activity created by renovations. By additionally moving towards heat pumps for heating, the positive economic effects are reinforced. If the transition moves in the direction of using predominantly hydrogen for heating, the modelling suggests that households will face higher energy bills than is the case with heat pumps, thereby diminishing the positive impacts the transition could bring.

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Appendices

Appendix A: Technology data sheets

Cost parameters

In the next pages you can find a detailed list of parameters used to determine several expenditure categories. The parameters were taken from Knobloch et al. (2017) and updated where appropriate. Knobloch et al. obtained these parameters from a variety of sources which have listed as well. See Table A.1.1

Table A.1.1: Cost parameters.

Sources					
	Danish Energy Agency (2021)	Danish Energy Agency (2021)	(Kenma, et al. 2019)	Danish Energy Agency (2021)	EC (2013a)
	Fleiter et al. (2016)	Fleiter et al. (2016)		Fleiter et al. (2016)	EC (2013b)
	IEA ETSAP (2012b)			IEA ETSAP (2012a)	
				EC (2013)	

BE	Investment	Maintenance	Lifetime	Efficiency	Capacity factor, mean
	€/kW	€/kW	y	-	MWh/kW
Non-condensing Oil boiler	505.97	20.24	18	0.75	2.07
Condensing Oil boiler	505.97	20.24	18	0.86	2.07
Non-condensing Gas boiler	428.89	8.58	18	0.75	2.07
Condensing Gas boiler	428.89	8.58	18	0.9	2.07
Wood stove	434.82	0.11	20	0.7	2.07
Wood boiler	516.85	2.07	20	0.85	2.07
Coal stove	244.09	4.88	20	0.75	2.07
District heating	N.A.	N.A.	25	N.A.	2.07
Electric heating	531.67	0.53	20	0.99	2.07
Heat-pump Ground	1383.53	13.84	18	3.5	2.07
Heat-pump Air-Water	741.17	14.82	18	2.6	1.64
Heat-pump Air-Air	504.00	22.91	18	2.6	1.77
Solar Thermal	763.90	7.64	20	1	0.57
Hydrogen boiler	514.67	8.58	18	0.9	2.07
DK	**Investment**	**Maintenance**	**Lifetime**	**Efficiency**	**Capacity factor, mean**
	€/kW	€/kW	y	-	MWh/kW
Non-condensing Oil boiler	760.73	30.43	18	0.75	2.47
Condensing Oil boiler	760.73	30.43	18	0.86	2.47
Non-condensing Gas boiler	644.84	12.90	18	0.75	2.47
Condensing Gas boiler	644.84	12.90	18	0.9	2.47

Wood stove	653.75	0.16	20	0.7	2.47
Wood boiler	777.08	3.11	20	0.85	2.47
Coal stove	366.99	7.34	20	0.75	2.47
District heating	N.A.	N.A.	25	N.A.	2.47
Electric heating	799.36	0.80	20	1	2.47
Heat-pump Ground	2080.13	20.80	18	3.5	2.47
Heat-pump Air-Water	1114.35	22.29	18	2.5	1.71
Heat-pump Air-Air	757.76	34.44	18	2.5	1.97
Solar Thermal	1148.53	11.49	20	1	0.60
Hydrogen boiler	773.81	12.90	18	0.9	2.47

	Investment	Maintenance	Lifetime	Efficiency	Capacity factor, mean
DE	€/kW	€/kW	y	-	MWh/kW
Non-condensing Oil boiler	615.66	24.63	18	0.75	2.47
Condensing Oil boiler	615.66	24.63	18	0.86	2.47
Non-condensing Gas boiler	521.87	10.44	18	0.75	2.47
Condensing Gas boiler	521.87	10.44	18	0.9	2.47
Wood stove	529.08	0.13	20	0.7	2.47
Wood boiler	628.89	2.52	20	0.85	2.47
Coal stove	297.01	5.94	20	0.75	2.47
District heating	N.A.	N.A.	25	N.A.	2.47
Electric heating	646.93	0.65	20	1	2.47
Heat-pump Ground	1683.45	16.83	18	3.5	2.47
Heat-pump Air-Water	901.85	18.04	18	2.5	1.71
Heat-pump Air-Air	613.26	27.88	18	2.5	1.97
Solar Thermal	929.50	9.30	20	1	0.58
Hydrogen boiler	626.24	10.44	18	0.9	2.47

	Investment	Maintenance	Lifetime	Efficiency	Capacity factor, mean
EL	€/kW	€/kW	y	-	MWh/kW
Non-condensing Oil boiler	371.52	14.86	18	0.75	1.34
Condensing Oil boiler	371.52	14.86	18	0.86	1.34

Non-condensing Gas boiler	314.92	6.30	18	0.75	1.34
Condensing Gas boiler	314.92	6.30	18	0.9	1.34
Wood stove	319.28	0.08	20	0.7	1.34
Wood boiler	379.50	1.52	20	0.85	1.34
Coal stove	179.23	3.58	20	0.75	1.34
District heating	N.A.	N.A.	25	N.A.	1.34
Electric heating	390.39	0.39	20	1	1.34
Heat-pump Ground	1015.88	10.16	18	3.5	1.34
Heat-pump Air-Water	544.22	10.88	18	2.7	1.17
Heat-pump Air-Air	370.07	16.82	18	2.7	1.2
Solar Thermal	560.91	5.61	20	1	1.00
Hydrogen boiler	377.91	6.30	18	0.9	1.34
ES	Investment €/kW	Maintenance €/kW	Lifetime y	Efficiency -	Capacity factor, mean MWh/kW
Non-condensing Oil boiler	419.88	16.80	18	0.75	2.07
Condensing Oil boiler	419.88	16.80	18	0.86	2.07
Non-condensing Gas boiler	355.91	7.12	18	0.75	2.07
Condensing Gas boiler	355.91	7.12	18	0.9	2.07
Wood stove	360.83	0.09	20	0.7	2.07
Wood boiler	428.90	1.72	20	0.85	2.07
Coal stove	202.56	4.05	20	0.75	2.07
District heating	N.A.	N.A.	25	N.A.	2.07
Electric heating	441.20	0.44	20	1	2.07
Heat-pump Ground	1148.10	11.48	18	3.5	2.07
Heat-pump Air-Water	615.05	12.30	18	2.6	1.64
Heat-pump Air-Air	418.24	19.01	18	2.6	1.77
Solar Thermal	633.92	6.34	20	1	1.00
Hydrogen boiler	427.09	7.12	18	0.9	2.07
FR	Investment €/kW	Maintenance €/kW	Lifetime y	Efficiency -	Capacity factor, mean MWh/kW

Non-condensing Oil boiler	609.76	24.39	18	0.75	2.07
Condensing Oil boiler	609.76	24.39	18	0.86	2.07
Non-condensing Gas boiler	516.87	10.34	18	0.75	2.07
Condensing Gas boiler	516.87	10.34	18	0.9	2.07
Wood stove	524.02	0.13	20	0.7	2.07
Wood boiler	622.86	2.49	20	0.85	2.07
Coal stove	294.16	5.88	20	0.75	2.07
District heating	N.A.	N.A.	25	N.A.	2.07
Electric heating	640.73	0.64	20	1	2.07
Heat-pump Ground	1667.33	16.67	18	3.5	2.07
Heat-pump Air-Water	893.21	17.86	18	2.6	1.64
Heat-pump Air-Air	607.38	27.61	18	2.6	1.77
Solar Thermal	920.60	9.21	20	1	0.67
Hydrogen boiler	620.24	10.34	18	0.9	2.07

	Investment	Maintenance	Lifetime	Efficiency	Capacity factor, mean
IE	€/kW	€/kW	y	-	MWh/kW
Non-condensing Oil boiler	526.03	21.04	18	0.75	2.07
Condensing Oil boiler	526.03	21.04	18	0.86	2.07
Non-condensing Gas boiler	445.89	8.92	18	0.75	2.07
Condensing Gas boiler	445.89	8.92	18	0.9	2.07
Wood stove	452.05	0.11	20	0.7	2.07
Wood boiler	537.33	2.15	20	0.85	2.07
Coal stove	253.77	5.08	20	0.75	2.07
District heating	N.A.	N.A.	25	N.A.	2.07
Electric heating	552.74	0.55	20	1	2.07
Heat-pump Ground	1438.35	14.38	18	3.5	2.07
Heat-pump Air-Water	770.54	15.41	18	2.6	1.64
Heat-pump Air-Air	523.97	23.82	18	2.6	1.77
Solar Thermal	794.17	7.94	20	1	0.60
Hydrogen boiler	535.07	8.92	18	0.9	2.07

IT	Investment €/kW	Maintenance €/kW	Lifetime y	Efficiency -	Capacity factor, mean MWh/kW
Non-condensing Oil boiler	404.54	16.18	18	0.75	1.34
Condensing Oil boiler	404.54	16.18	18	0.86	2.07
Non-condensing Gas boiler	342.91	6.86	18	0.75	2.07
Condensing Gas boiler	342.91	6.86	18	0.9	2.07
Wood stove	347.66	0.09	20	0.7	2.07
Wood boiler	413.24	1.65	20	0.85	2.07
Coal stove	195.16	3.90	20	0.75	2.07
District heating	N.A.	N.A.	25	N.A.	2.07
Electric heating	425.09	0.43	20	1	2.07
Heat-pump Ground	1106.18	11.06	18	3.5	2.07
Heat-pump Air-Water	592.59	11.85	18	2.6	1.64
Heat-pump Air-Air	402.96	18.32	18	2.6	1.77
Solar Thermal	610.77	6.11	20	1	0.87
Hydrogen boiler	411.50	6.86	18	0.9	2.07
LX	Investment €/kW	Maintenance €/kW	Lifetime y	Efficiency -	Capacity factor, mean MWh/kW
Non-condensing Oil boiler	524.85	20.99	18	0.75	2.47
Condensing Oil boiler	524.85	20.99	18	0.86	2.47
Non-condensing Gas boiler	444.89	8.90	18	0.75	2.47
Condensing Gas boiler	444.89	8.90	18	0.9	2.47
Wood stove	451.04	0.11	20	0.7	2.47
Wood boiler	536.12	2.14	20	0.85	2.47
Coal stove	253.20	5.06	20	0.75	2.47
District heating	N.A.	N.A.	25	N.A.	2.47
Electric heating	551.50	0.55	20	1	2.47
Heat-pump Ground	1435.13	14.35	18	3.5	2.47
Heat-pump Air-Water	768.82	15.38	18	2.5	1.71
Heat-pump Air-Air	522.80	23.76	18	2.5	1.97

Solar Thermal	792.39	7.92	20	1	0.61
Hydrogen boiler	533.87	8.90	18	0.9	2.47
NL	Investment €/kW	Maintenance €/kW	Lifetime y	Efficiency -	Capacity factor, mean MWh/kW
Non-condensing Oil boiler	659.30	26.37	18	0.75	2.07
Condensing Oil boiler	659.30	26.37	18	0.86	2.07
Non-condensing Gas boiler	558.86	11.18	18	0.75	2.07
Condensing Gas boiler	558.86	11.18	18	0.9	2.07
Wood stove	566.59	0.14	20	0.7	2.07
Wood boiler	673.47	2.69	20	0.85	2.07
Coal stove	318.06	6.36	20	0.75	2.07
District heating	N.A.	N.A.	25	N.A.	2.07
Electric heating	692.78	0.69	20	1	2.07
Heat-pump Ground	1802.78	18.03	18	3.5	2.07
Heat-pump Air-Water	965.77	19.32	18	2.6	1.64
Heat-pump Air-Air	656.73	29.85	18	2.6	1.77
Solar Thermal	995.39	9.95	20	1	0.57
Hydrogen boiler	670.63	11.18	18	0.9	2.07
AT	Investment €/kW	Maintenance €/kW	Lifetime y	Efficiency -	Capacity factor, mean MWh/kW
Non-condensing Oil boiler	621.56	24.86	18	0.75	2.47
Condensing Oil boiler	621.56	24.86	18	0.86	2.47
Non-condensing Gas boiler	526.87	10.54	18	0.75	2.47
Condensing Gas boiler	526.87	10.54	18	0.9	2.47
Wood stove	534.15	0.13	20	0.7	2.47
Wood boiler	634.91	2.54	20	0.85	2.47
Coal stove	299.85	6.00	20	0.75	2.47
District heating	N.A.	N.A.	25	N.A.	2.47
Electric heating	653.12	0.65	20	1	2.47
Heat-pump Ground	1699.58	17.00	18	3.5	2.47

Heat-pump Air-Water	910.49	18.21	18	2.5	1.71
Heat-pump Air-Air	619.13	28.14	18	2.5	1.97
Solar Thermal	938.41	9.38	20	1	0.58
Hydrogen boiler	632.24	10.54	18	0.9	2.47

PT	Investment €/kW	Maintenance €/kW	Lifetime y	Efficiency -	Capacity factor, mean MWh/kW
Non-condensing Oil boiler	303.11	12.12	18	0.75	1.34
Condensing Oil boiler	303.11	12.12	18	0.86	1.34
Non-condensing Gas boiler	256.94	5.14	18	0.75	1.34
Condensing Gas boiler	256.94	5.14	18	0.9	1.34
Wood stove	260.49	0.07	20	0.7	1.34
Wood boiler	309.63	1.24	20	0.85	1.34
Coal stove	146.23	2.92	20	0.75	1.34
District heating	N.A.	N.A.	25	N.A.	1.34
Electric heating	318.51	0.32	20	1	1.34
Heat-pump Ground	828.83	8.29	18	3.5	1.34
Heat-pump Air-Water	444.01	8.88	18	2.7	1.17
Heat-pump Air-Air	301.93	13.72	18	2.7	1.2
Solar Thermal	457.63	4.58	20	1	1.11
Hydrogen boiler	308.32	5.14	18	0.9	1.34

FI	Investment €/kW	Maintenance €/kW	Lifetime y	Efficiency -	Capacity factor, mean MWh/kW
Non-condensing Oil boiler	557.87	22.31	18	0.75	2.47
Condensing Oil boiler	557.87	22.31	18	0.86	2.47
Non-condensing Gas boiler	472.88	9.46	18	0.75	2.47
Condensing Gas boiler	472.88	9.46	18	0.9	2.47
Wood stove	479.42	0.12	20	0.7	2.47
Wood boiler	569.86	2.28	20	0.85	2.47
Coal stove	269.13	5.38	20	0.75	2.47
District heating	N.A.	N.A.	25	N.A.	2.47

Electric heating	586.20	0.59	20	1	2.47
Heat-pump Ground	1525.43	15.25	18	3.5	2.47
Heat-pump Air-Water	817.19	16.34	18	2.5	1.71
Heat-pump Air-Air	555.69	25.26	18	2.5	1.97
Solar Thermal	842.25	8.42	20	1	0.59
Hydrogen boiler	567.46	9.46	18	0.9	2.47

SW	Investment €/kW	Maintenance €/kW	Lifetime y	Efficiency -	Capacity factor, mean MWh/kW
Non-condensing Oil boiler	741.86	29.67	18	0.75	2.47
Condensing Oil boiler	741.86	29.67	18	0.86	2.47
Non-condensing Gas boiler	628.84	12.58	18	0.75	2.47
Condensing Gas boiler	628.84	12.58	18	0.9	2.47
Wood stove	637.54	0.16	20	0.7	2.47
Wood boiler	757.80	3.03	20	0.85	2.47
Coal stove	357.89	7.16	20	0.75	2.47
District heating	N.A.	N.A.	25	N.A.	2.47
Electric heating	779.53	0.78	20	1	2.47
Heat-pump Ground	2028.53	20.29	18	3.5	2.47
Heat-pump Air-Water	1086.71	21.73	18	2.5	1.71
Heat-pump Air-Air	738.96	33.59	18	2.5	1.97
Solar Thermal	1120.04	11.20	20	1	0.52
Hydrogen boiler	754.61	12.58	18	0.9	2.47

UK	Investment €/kW	Maintenance €/kW	Lifetime y	Efficiency -	Capacity factor, mean MWh/kW
Non-condensing Oil boiler	595.61	23.82	18	0.75	2.47
Condensing Oil boiler	595.61	23.82	18	0.86	2.47
Non-condensing Gas boiler	504.87	10.10	18	0.75	2.47
Condensing Gas boiler	504.87	10.10	18	0.9	2.47
Wood stove	511.85	0.13	20	0.7	2.47
Wood boiler	608.41	2.43	20	0.85	2.47

Coal stove	287.34	5.75	20	0.75	2.47
District heating	N.A.	N.A.	25	N.A.	2.47
Electric heating	625.86	0.63	20	1	2.47
Heat-pump Ground	1628.63	16.29	18	3.5	2.47
Heat-pump Air-Water	872.48	17.45	18	2.5	1.71
Heat-pump Air-Air	593.28	26.97	18	2.5	1.97
Solar Thermal	899.23	8.99	20	1	0.56
Hydrogen boiler	605.85	10.10	18	0.9	2.47
	Investment	Maintenance	Lifetime	Efficiency	Capacity factor, mean
CZ	€/kW	€/kW	y	-	MWh/kW
Non-condensing Oil boiler	337.32	13.49	18	0.75	2.47
Condensing Oil boiler	337.32	13.49	18	0.86	2.47
Non-condensing Gas boiler	285.93	5.72	18	0.75	2.47
Condensing Gas boiler	285.93	5.72	18	0.9	2.47
Wood stove	289.88	0.07	20	0.7	2.47
Wood boiler	344.56	1.38	20	0.85	2.47
Coal stove	162.73	3.25	20	0.75	2.47
District heating	N.A.	N.A.	25	N.A.	2.47
Electric heating	354.45	0.35	20	1	2.47
Heat-pump Ground	922.35	9.22	18	3.5	2.47
Heat-pump Air-Water	494.12	9.88	18	2.5	1.71
Heat-pump Air-Air	336.00	15.27	18	2.5	1.97
Solar Thermal	509.27	5.09	20	1	0.48
Hydrogen boiler	343.11	5.72	18	0.9	2.47
	Investment	Maintenance	Lifetime	Efficiency	Capacity factor, mean
EN	€/kW	€/kW	y	-	MWh/kW
Non-condensing Oil boiler	364.44	14.58	18	0.75	2.47
Condensing Oil boiler	364.44	14.58	18	0.86	2.47
Non-condensing Gas boiler	308.92	6.18	18	0.75	2.47
Condensing Gas boiler	308.92	6.18	18	0.9	2.47

Wood stove	313.19	0.08	20	0.7	2.47
Wood boiler	372.27	1.49	20	0.85	2.47
Coal stove	175.82	3.52	20	0.75	2.47
District heating	N.A.	N.A.	25	N.A.	2.47
Electric heating	382.95	0.38	20	1	2.47
Heat-pump Ground	996.53	9.97	18	3.5	2.47
Heat-pump Air-Water	533.85	10.68	18	2.5	1.71
Heat-pump Air-Air	363.02	16.50	18	2.5	1.97
Solar Thermal	550.22	5.50	20	1	0.57
Hydrogen boiler	370.71	6.18	18	0.9	2.47
CY	Investment	Maintenance	Lifetime	Efficiency	Capacity factor, mean
	€/kW	€/kW	y	-	MWh/kW
Non-condensing Oil boiler	382.13	15.29	18	0.75	1.34
Condensing Oil boiler	382.13	15.29	18	0.86	1.34
Non-condensing Gas boiler	323.92	6.48	18	0.75	1.34
Condensing Gas boiler	323.92	6.48	18	0.9	1.34
Wood stove	328.40	0.08	20	0.7	1.34
Wood boiler	390.34	1.56	20	0.85	1.34
Coal stove	184.35	3.69	20	0.75	1.34
District heating	N.A.	N.A.	25	N.A.	1.34
Electric heating	401.54	0.40	20	1	1.34
Heat-pump Ground	1044.90	10.45	18	3.5	1.34
Heat-pump Air-Water	559.77	11.20	18	2.7	1.17
Heat-pump Air-Air	380.64	17.30	18	2.7	1.2
Solar Thermal	576.93	5.77	20	1	1.27
Hydrogen boiler	388.70	6.48	18	0.9	1.34
LV	Investment	Maintenance	Lifetime	Efficiency	Capacity factor, mean
	€/kW	€/kW	y	-	MWh/kW
Non-condensing Oil boiler	425.77	17.03	18	0.75	2.47
Condensing Oil boiler	425.77	17.03	18	0.86	2.47

Non-condensing Gas boiler	360.91	7.22	18	0.75	2.47
Condensing Gas boiler	360.91	7.22	18	0.9	2.47
Wood stove	365.90	0.09	20	0.7	2.47
Wood boiler	434.92	1.74	20	0.85	2.47
Coal stove	205.40	4.11	20	0.75	2.47
District heating	N.A.	N.A.	25	N.A.	2.47
Electric heating	447.40	0.45	20	1	2.47
Heat-pump Ground	1164.23	11.64	18	3.5	2.47
Heat-pump Air-Water	623.69	12.47	18	2.5	1.71
Heat-pump Air-Air	424.11	19.28	18	2.5	1.97
Solar Thermal	642.82	6.43	20	1	0.67
Hydrogen boiler	433.09	7.22	18	0.9	2.47
	Investment	Maintenance	Lifetime	Efficiency	Capacity factor, mean
LT	€/kW	€/kW	y	-	MWh/kW
Non-condensing Oil boiler	378.60	15.14	18	0.75	2.47
Condensing Oil boiler	378.60	15.14	18	0.86	2.47
Non-condensing Gas boiler	320.92	6.42	18	0.75	2.47
Condensing Gas boiler	320.92	6.42	18	0.9	2.47
Wood stove	325.36	0.08	20	0.7	2.47
Wood boiler	386.73	1.55	20	0.85	2.47
Coal stove	182.64	3.65	20	0.75	2.47
District heating	N.A.	N.A.	25	N.A.	2.47
Electric heating	397.82	0.40	20	1	2.47
Heat-pump Ground	1035.23	10.35	18	3.5	2.47
Heat-pump Air-Water	554.58	11.09	18	2.5	1.71
Heat-pump Air-Air	377.12	17.14	18	2.5	1.97
Solar Thermal	571.59	5.72	20	1	0.57
Hydrogen boiler	385.10	6.42	18	0.9	2.47
	Investment	Maintenance	Lifetime	Efficiency	Capacity factor, mean
HU	€/kW	€/kW	y	-	MWh/kW

Non-condensing Oil boiler	317.27	12.69	18	0.75	2.07
Condensing Oil boiler	317.27	12.69	18	0.86	2.07
Non-condensing Gas boiler	268.93	5.38	18	0.75	2.07
Condensing Gas boiler	268.93	5.38	18	0.9	2.07
Wood stove	272.65	0.07	20	0.7	2.07
Wood boiler	324.08	1.30	20	0.85	2.07
Coal stove	153.06	3.06	20	0.75	2.07
District heating	N.A.	N.A.	25	N.A.	2.07
Electric heating	333.38	0.33	20	1	2.07
Heat-pump Ground	867.53	8.68	18	3.5	2.07
Heat-pump Air-Water	464.75	9.29	18	2.6	1.64
Heat-pump Air-Air	316.03	14.36	18	2.6	1.77
Solar Thermal	479.00	4.79	20	1	0.64
Hydrogen boiler	322.72	5.38	18	0.9	2.07

MT	Investment €/kW	Maintenance €/kW	Lifetime y	Efficiency -	Capacity factor, mean MWh/kW
Non-condensing Oil boiler	330.24	13.21	18	0.75	1.34
Condensing Oil boiler	330.24	13.21	18	0.86	1.34
Non-condensing Gas boiler	279.93	5.60	18	0.75	1.34
Condensing Gas boiler	279.93	5.60	18	0.9	1.34
Wood stove	283.80	0.07	20	0.7	1.34
Wood boiler	337.34	1.35	20	0.85	1.34
Coal stove	159.32	3.19	20	0.75	1.34
District heating	N.A.	N.A.	25	N.A.	1.34
Electric heating	347.01	0.35	20	1	1.34
Heat-pump Ground	903.00	9.03	18	3.5	1.34
Heat-pump Air-Water	483.75	9.68	18	2.7	1.17
Heat-pump Air-Air	328.95	14.95	18	2.7	1.2
Solar Thermal	498.59	4.99	20	1	1.14
Hydrogen boiler	335.92	5.60	18	0.9	1.34

PL	Investment €/kW	Maintenance €/kW	Lifetime y	Efficiency -	Capacity factor, mean MWh/kW
Non-condensing Oil boiler	364.44	14.58	18	0.75	2.47
Condensing Oil boiler	364.44	14.58	18	0.86	2.47
Non-condensing Gas boiler	308.92	6.18	18	0.75	2.47
Condensing Gas boiler	308.92	6.18	18	0.9	2.47
Wood stove	313.19	0.08	20	0.7	2.47
Wood boiler	372.27	1.49	20	0.85	2.47
Coal stove	175.82	3.52	20	0.75	2.47
District heating	N.A.	N.A.	25	N.A.	2.47
Electric heating	382.95	0.38	20	1	2.47
Heat-pump Ground	996.53	9.97	18	3.5	2.47
Heat-pump Air-Water	533.85	10.68	18	2.5	1.71
Heat-pump Air-Air	363.02	16.50	18	2.5	1.97
Solar Thermal	550.22	5.50	20	1	0.58
Hydrogen boiler	370.71	6.18	18	0.9	2.47

SI	Investment €/kW	Maintenance €/kW	Lifetime y	Efficiency -	Capacity factor, mean MWh/kW
Non-condensing Oil boiler	389.21	15.57	18	0.75	2.07
Condensing Oil boiler	389.21	15.57	18	0.86	2.07
Non-condensing Gas boiler	329.92	6.60	18	0.75	2.07
Condensing Gas boiler	329.92	6.60	18	0.9	2.07
Wood stove	334.48	0.08	20	0.7	2.07
Wood boiler	397.57	1.59	20	0.85	2.07
Coal stove	187.76	3.76	20	0.75	2.07
District heating	N.A.	N.A.	25	N.A.	2.07
Electric heating	408.98	0.41	20	1	2.07
Heat-pump Ground	1064.25	10.64	18	3.5	2.07
Heat-pump Air-Water	570.13	11.40	18	2.6	1.64
Heat-pump Air-Air	387.69	17.62	18	2.6	1.77

Solar Thermal	587.62	5.88	20	1	0.60
Hydrogen boiler	395.90	6.60	18	0.9	2.07
	Investment	Maintenance	Lifetime	Efficiency	Capacity factor, mean
SK	€/kW	€/kW	y	-	MWh/kW
Non-condensing Oil boiler	356.19	14.25	18	0.75	2.47
Condensing Oil boiler	356.19	14.25	18	0.86	2.47
Non-condensing Gas boiler	301.92	6.04	18	0.75	2.47
Condensing Gas boiler	301.92	6.04	18	0.9	2.47
Wood stove	306.10	0.08	20	0.7	2.47
Wood boiler	363.84	1.46	20	0.85	2.47
Coal stove	171.83	3.44	20	0.75	2.47
District heating	N.A.	N.A.	25	N.A.	2.47
Electric heating	374.28	0.37	20	1	2.47
Heat-pump Ground	973.95	9.74	18	3.5	2.47
Heat-pump Air-Water	521.76	10.44	18	2.5	1.71
Heat-pump Air-Air	354.80	16.13	18	2.5	1.97
Solar Thermal	537.76	5.38	20	1	0.66
Hydrogen boiler	362.31	6.04	18	0.9	2.47
	Investment	Maintenance	Lifetime	Efficiency	Capacity factor, mean
BG	€/kW	€/kW	y	-	MWh/kW
Non-condensing Oil boiler	231.17	9.25	18	0.75	2.07
Condensing Oil boiler	231.17	9.25	18	0.86	2.07
Non-condensing Gas boiler	195.95	3.92	18	0.75	2.07
Condensing Gas boiler	195.95	3.92	18	0.9	2.07
Wood stove	198.66	0.05	20	0.7	2.07
Wood boiler	236.13	0.94	20	0.85	2.07
Coal stove	111.52	2.23	20	0.75	2.07
District heating	N.A.	N.A.	25	N.A.	2.07
Electric heating	242.91	0.24	20	1	2.07
Heat-pump Ground	632.10	6.32	18	3.5	2.07

Heat-pump Air-Water	338.63	6.77	18	2.6	1.64
Heat-pump Air-Air	230.27	10.47	18	2.6	1.77
Solar Thermal	349.01	3.49	20	1	0.70
Hydrogen boiler	235.14	3.92	18	0.9	2.07

RO	Investment	Maintenance	Lifetime	Efficiency	Capacity factor, mean
	€/kW	€/kW	y	-	MWh/kW
Non-condensing Oil boiler	234.71	9.39	18	0.75	2.47
Condensing Oil boiler	234.71	9.39	18	0.86	2.47
Non-condensing Gas boiler	198.95	3.98	18	0.75	2.47
Condensing Gas boiler	198.95	3.98	18	0.9	2.47
Wood stove	201.70	0.05	20	0.7	2.47
Wood boiler	239.75	0.96	20	0.85	2.47
Coal stove	113.23	2.26	20	0.75	2.47
District heating	N.A.	N.A.	25	N.A.	2.47
Electric heating	246.62	0.25	20	1	2.47
Heat-pump Ground	641.78	6.42	18	3.5	2.47
Heat-pump Air-Water	343.81	6.88	18	2.5	1.71
Heat-pump Air-Air	233.79	10.63	18	2.5	1.97
Solar Thermal	354.35	3.54	20	1	0.79
Hydrogen boiler	238.74	3.98	18	0.9	2.47

HR	Investment	Maintenance	Lifetime	Efficiency	Capacity factor, mean
	€/kW	€/kW	y	-	MWh/kW
Non-condensing Oil boiler	336.53	13.46	18	0.75	2.07
Condensing Oil boiler	336.53	13.46	18	0.86	2.07
Non-condensing Gas boiler	285.26	5.71	18	0.75	2.07
Condensing Gas boiler	285.26	5.71	18	0.9	2.07
Wood stove	289.21	0.07	20	0.7	2.07
Wood boiler	343.76	1.38	20	0.85	2.07
Coal stove	162.35	3.25	20	0.75	2.07
District heating	N.A.	N.A.	25	N.A.	2.07

Electric heating	353.62	0.35	20	1	2.07
Heat-pump Ground	920.20	9.20	18	3.5	2.07
Heat-pump Air-Water	492.97	9.86	18	2.6	1.64
Heat-pump Air-Air	335.22	15.24	18	2.6	1.77
Solar Thermal	508.08	5.08	20	1	0.72
Hydrogen boiler	342.32	5.71	18	0.9	2.07

Technological progress coefficients

Table A.2.1: Coefficients indicating technological progress over time

Source	EU Reference Scenario 2020 (PRIMES)
Description	Coefficients are applied to initial conversion efficiencies / initial upfront investment costs to replicate technology improvements.

Conversion efficiency coefficients					
	2016	2022	2030	2040	2050
Non-condensing Oil boiler	1.000	1.000	1.000	1.000	1.000
Condensing Oil boiler	1.000	1.009	1.021	1.035	1.050
Non-condensing Gas boiler	1.000	1.000	1.000	1.000	1.000
Condensing Gas boiler	1.000	1.009	1.021	1.035	1.050
Wood stove	1.000	1.018	1.041	1.071	1.100
Wood boiler	1.000	1.018	1.041	1.071	1.100
Coal stove	1.000	1.000	1.000	1.000	1.000
District heating	n.a.	n.a.	n.a.	n.a.	n.a.
Electric heating	1.000	1.000	1.000	1.000	1.000
Heat-pump Ground	1.000	1.071	1.165	1.282	1.400
Heat-pump Air-Water	1.000	1.071	1.165	1.282	1.400
Heat-pump Air-Air	1.000	1.079	1.185	1.318	1.450
Solar Thermal	1.000	1.000	1.000	1.000	1.000
Hydrogen boiler	1.000	1.009	1.021	1.035	1.050

Upfront investment cost coefficients					
	2016	2022	2030	2040	2050
Non-condensing Oil boiler	1.00	1.01	1.03	1.05	1.08
Condensing Oil boiler	1.00	1.01	1.03	1.05	1.08
Non-condensing Gas boiler	1.00	1.03	1.06	1.11	1.15
Condensing Gas boiler	1.00	1.05	1.11	1.19	1.27
Wood stove	1.00	1.02	1.03	1.06	1.08
Wood boiler	1.00	1.02	1.03	1.06	1.08
Coal stove	1.00	1.02	1.03	1.06	1.08
District heating	n.a.	n.a.	n.a.	n.a.	n.a.
Electric heating	1.00	1.03	1.06	1.11	1.15
Heat-pump Ground	1.00	0.98	0.97	0.95	0.92
Heat-pump Air-Water	1.00	0.98	0.97	0.95	0.92
Heat-pump Air-Air	1.00	0.97	0.93	0.89	0.85
Solar Thermal	1.00	0.97	0.94	0.90	0.86
Hydrogen boiler	1.00	0.97	0.92	0.99	1.06

Appendix B: Results by climate zone

Climate zone: British Isles

The British Isles see a large uptake of hydrogen for heating. This is due to the UK already heating most homes via gas boilers. Due to the large hydrogen uptake, infrastructure investment in the gas network is a large driver of the results. GDP and employment effects dominate in the high gas scenarios, seeing a peak in 2035, in-line with the infrastructure investments. However, in the longer term, GDP in the high gas scenarios fall back towards baseline levels by 2050 due to loan repayments from the gas infrastructure. The lower infrastructure costs for electrification result in a smaller GDP and employment boost in the short term, but in the longer term the reductions in consumer expenditure on energy means that spending increases in other sectors, having a net positive impact. Even for the British Isles, the high electrification scenarios seem to have the best economic outcomes by 2030.

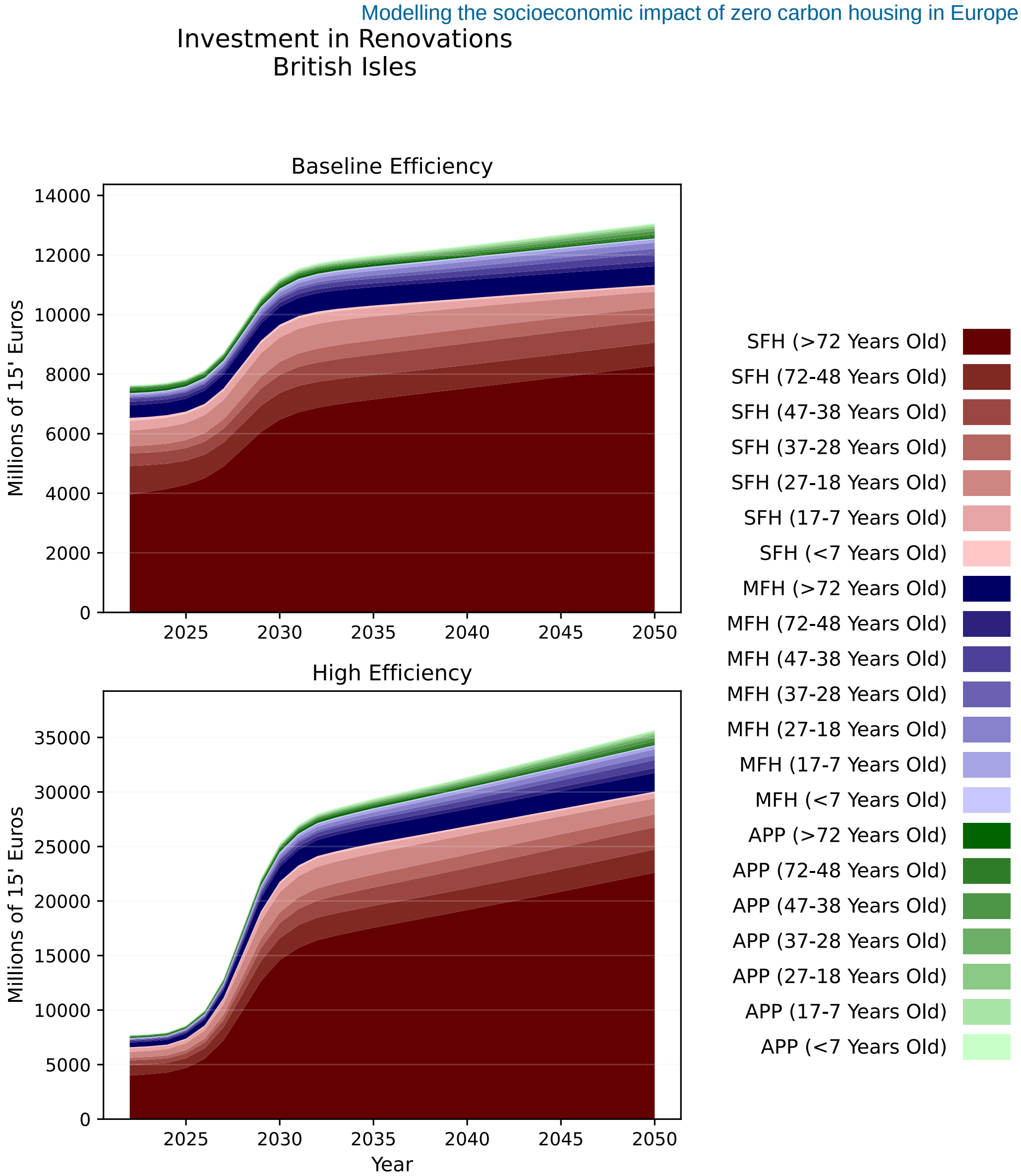

Figure B.1.1: Investments into renovations.

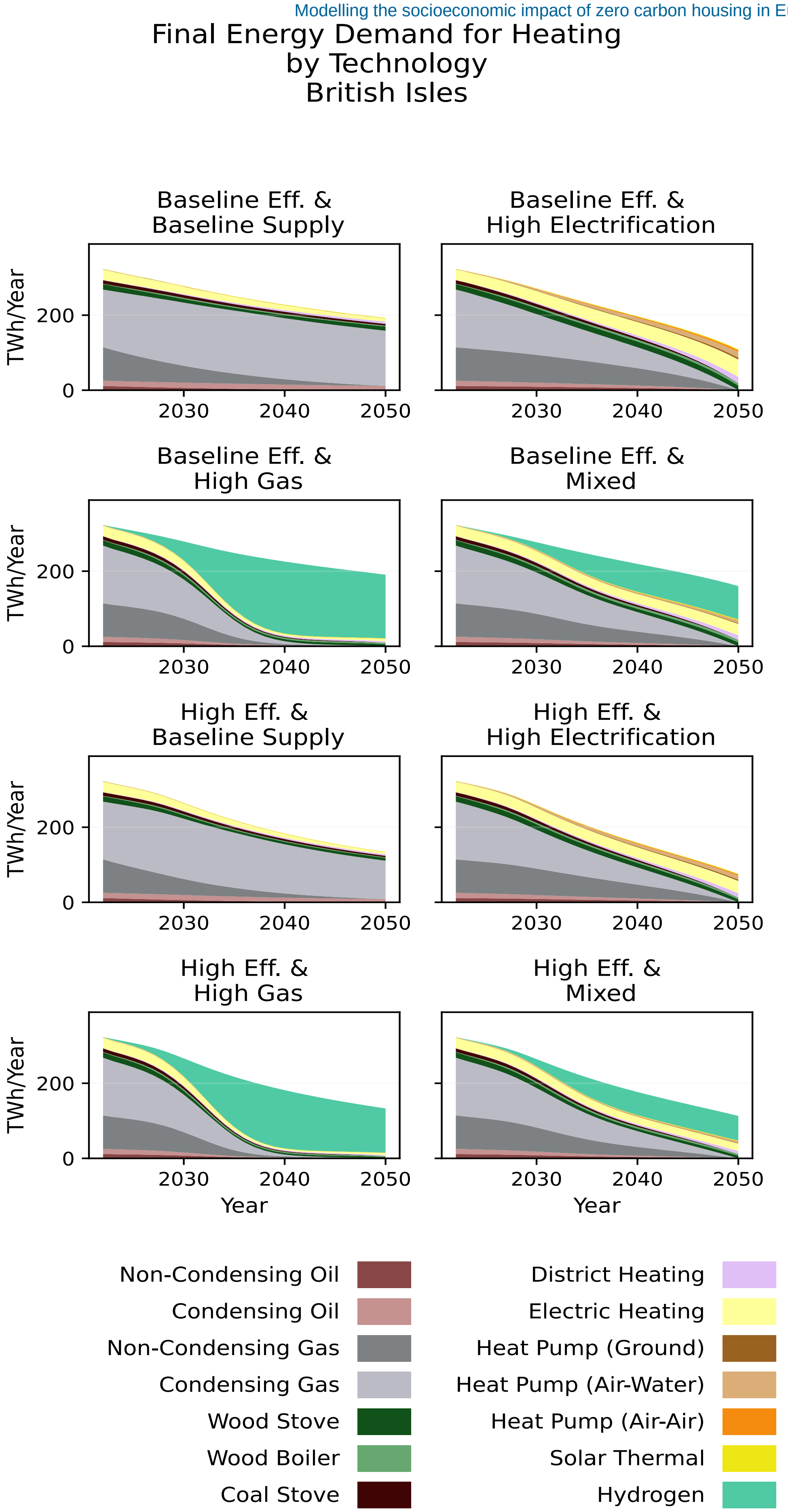

Figure B.1.2: Final energy demand by technology.

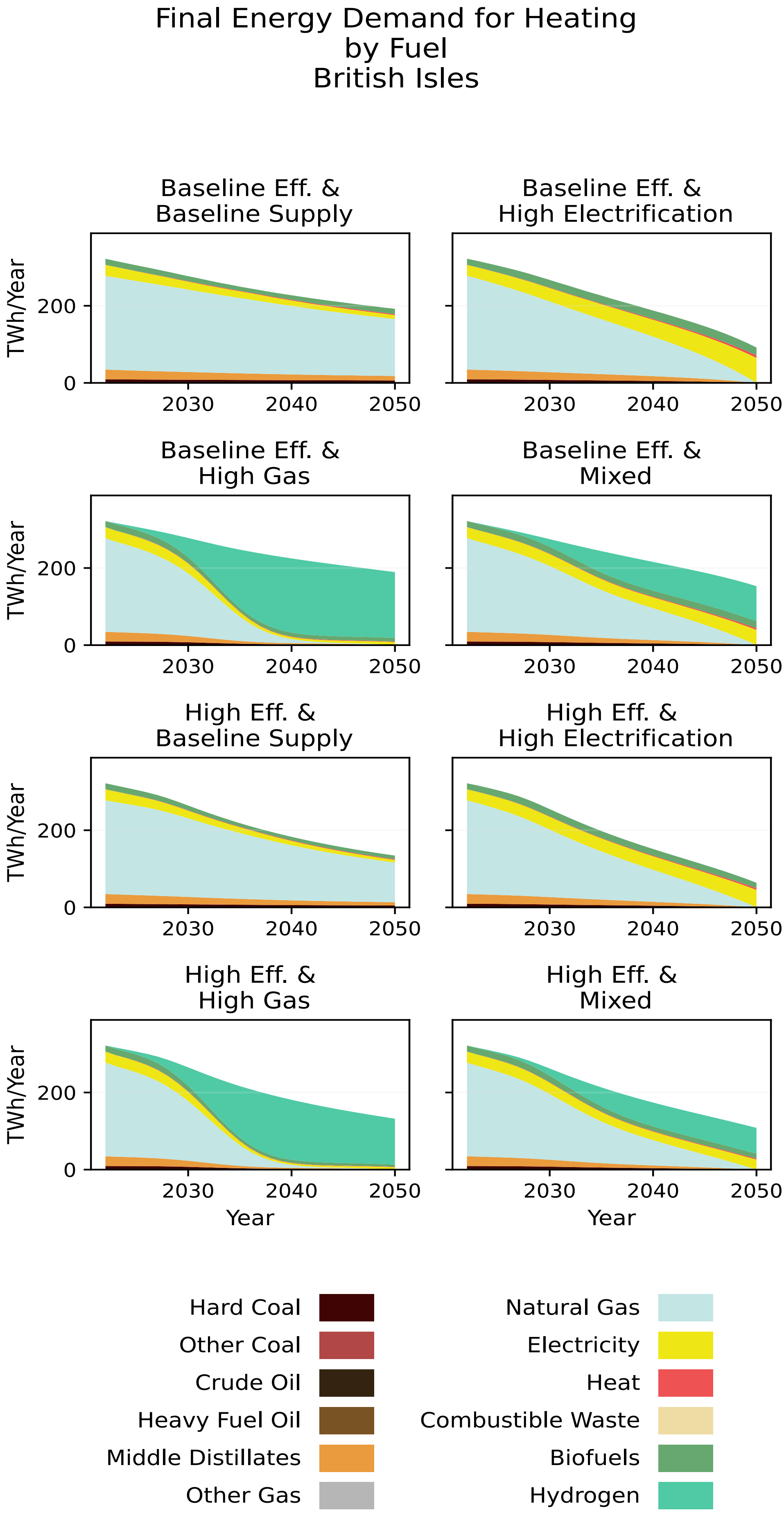

Figure B.1.3: Final energy demand by energy carrier.

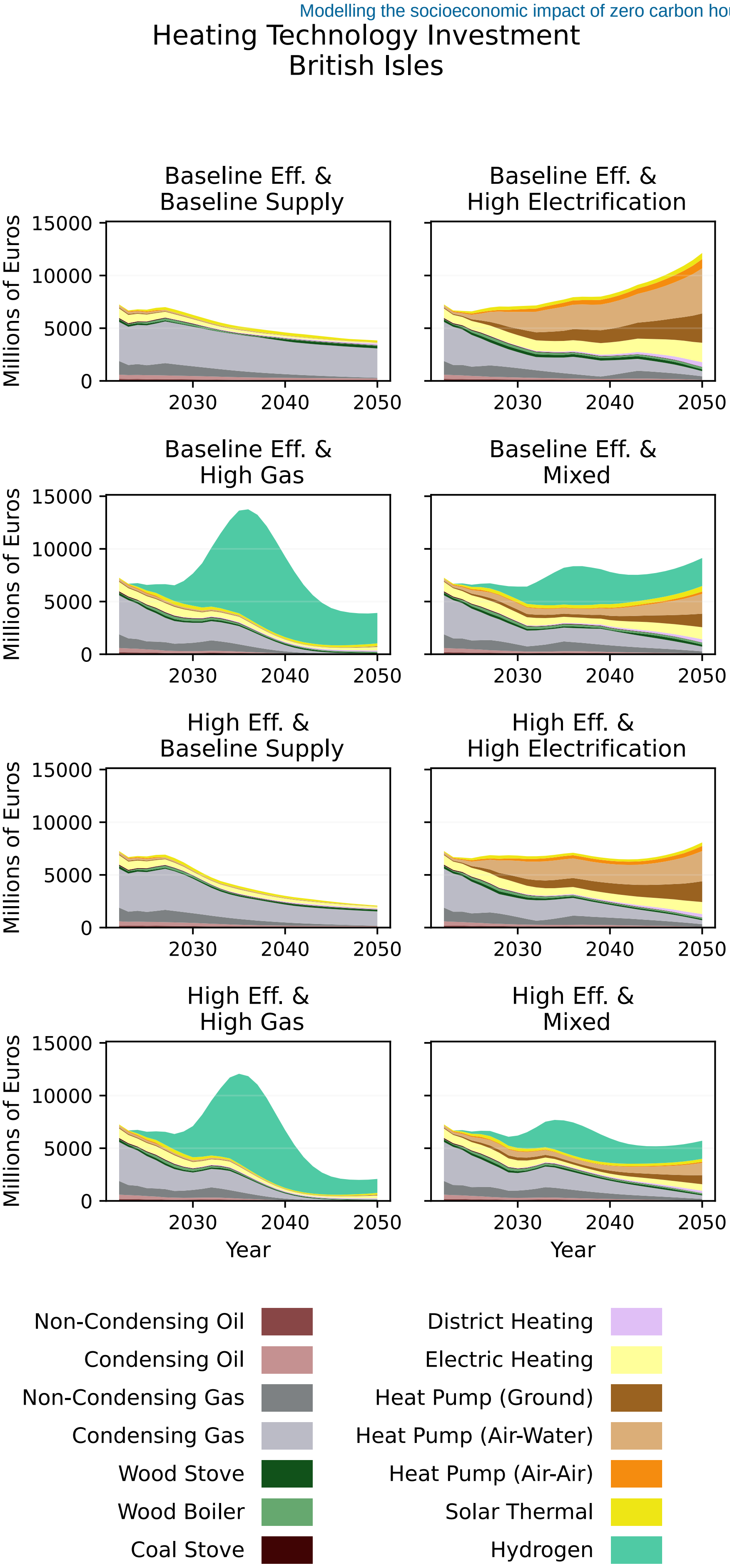

Figure B.1.4: Investment in heating equipment.

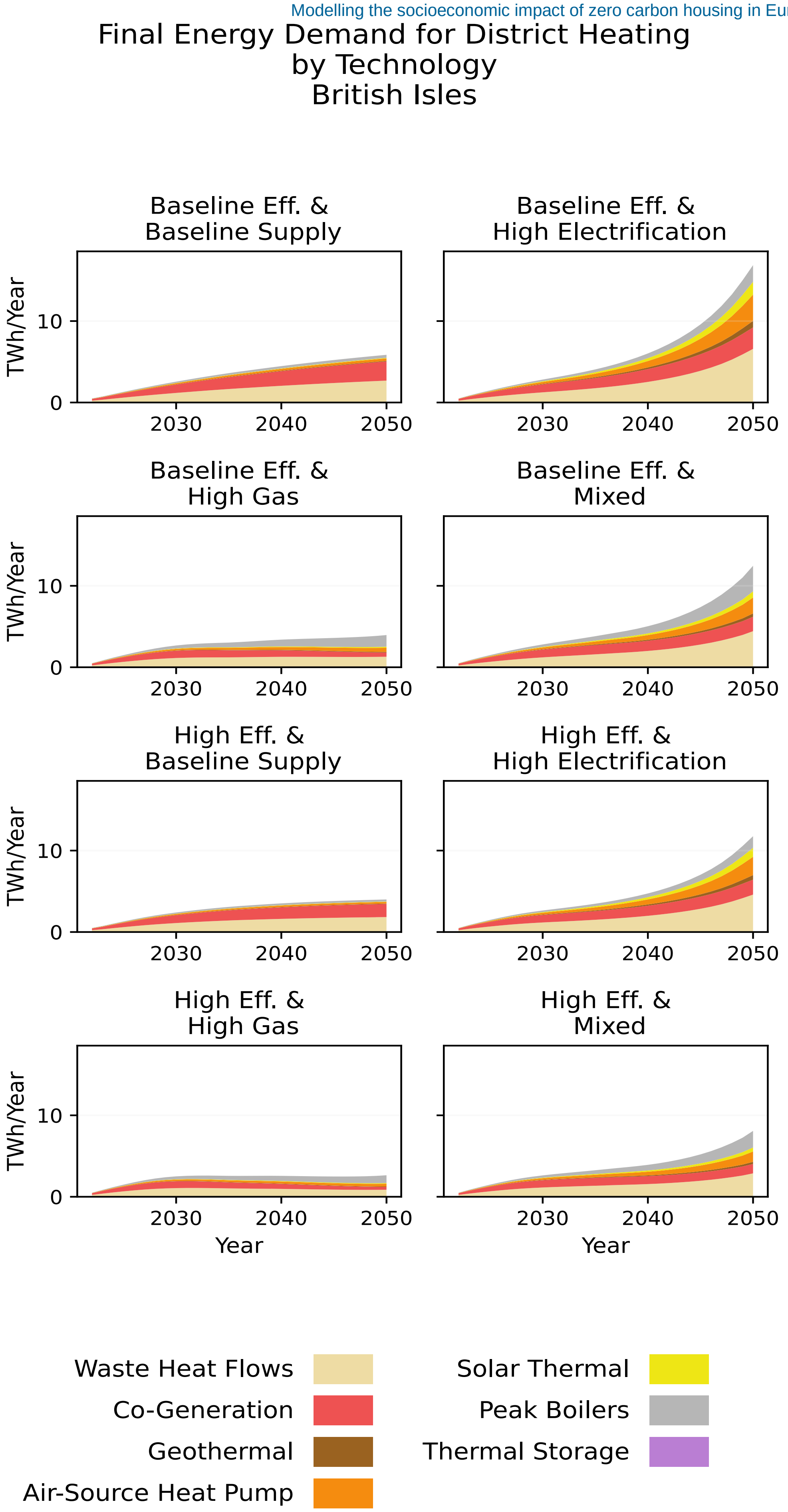

Figure B.1.5: Final energy demand by DH/C configuration option.

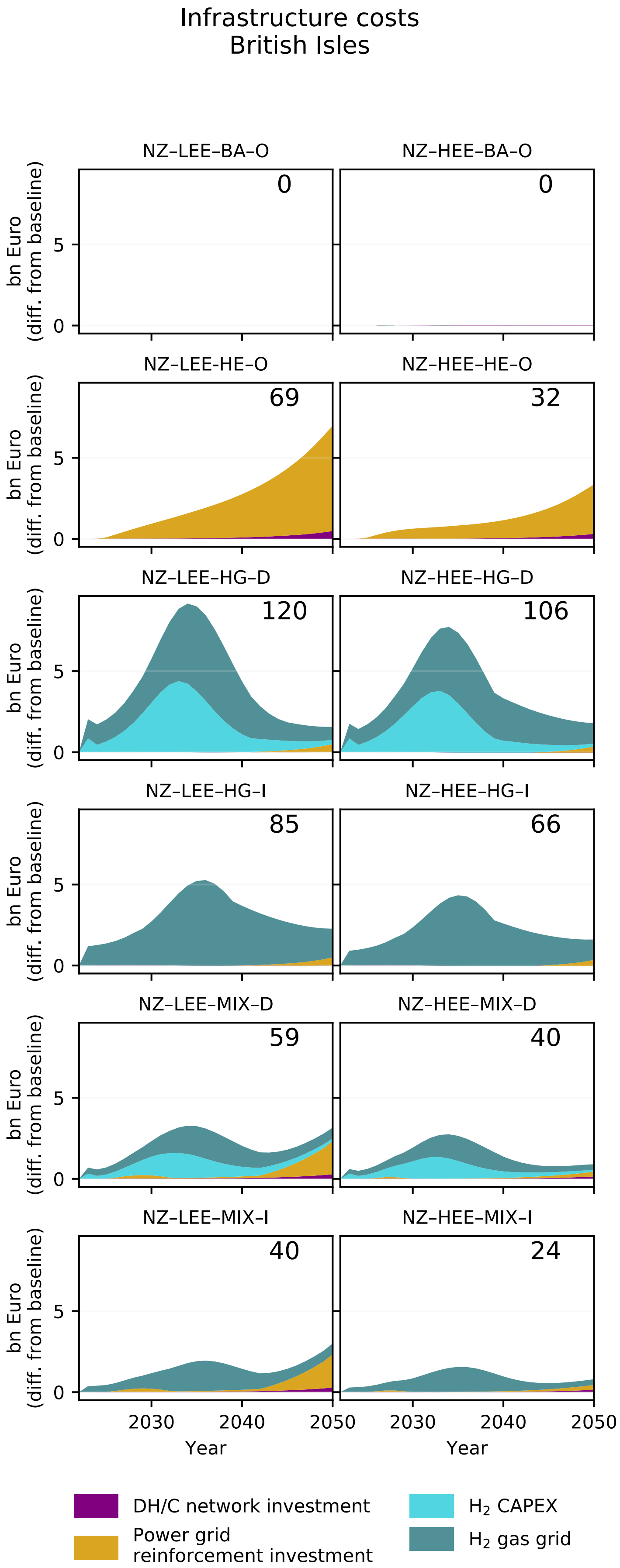

Figure B.1.6: Infrastructure investments. Numbers represent cumulative investment in billion Euro.

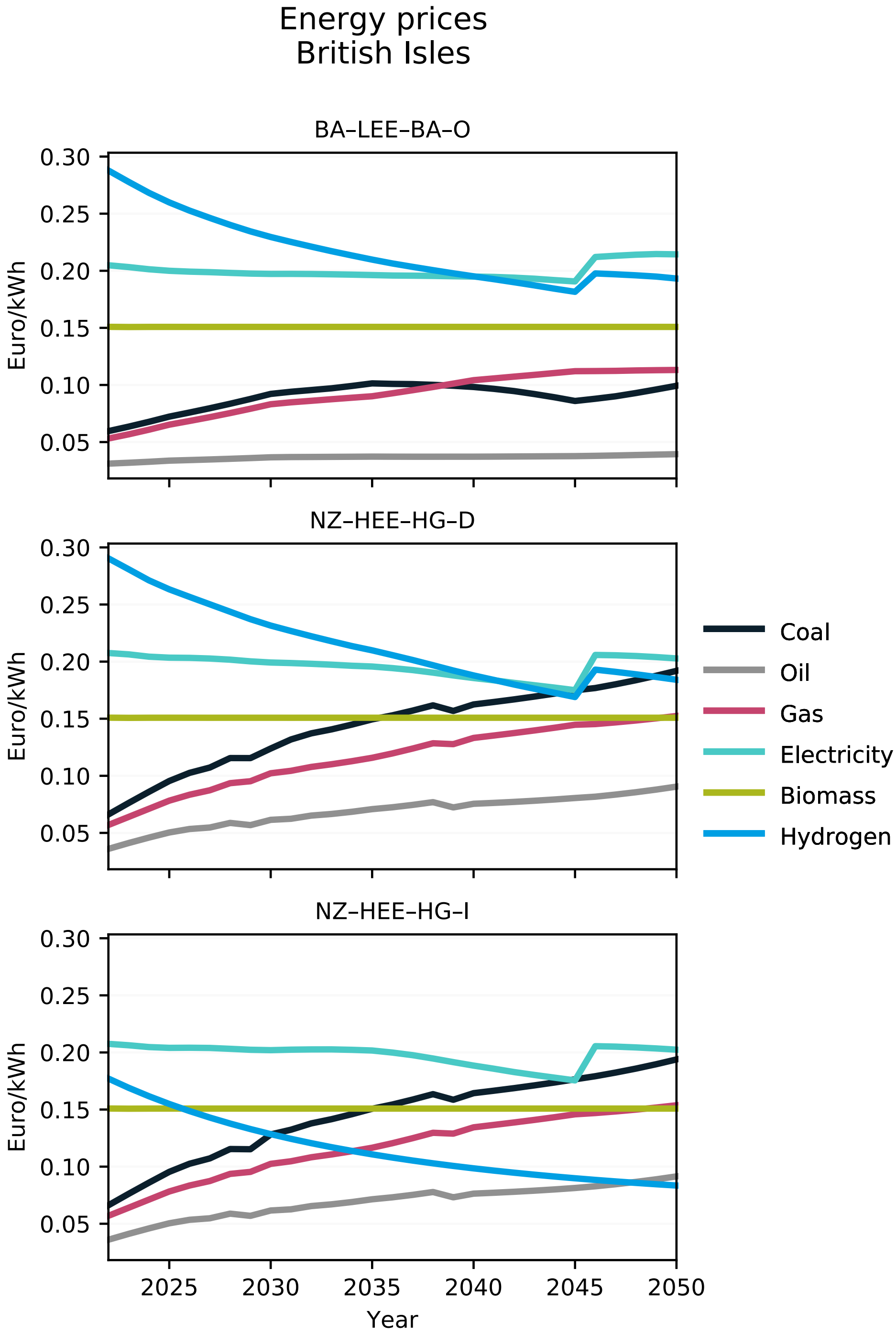

Figure B.1.7: Evolution of energy prices.

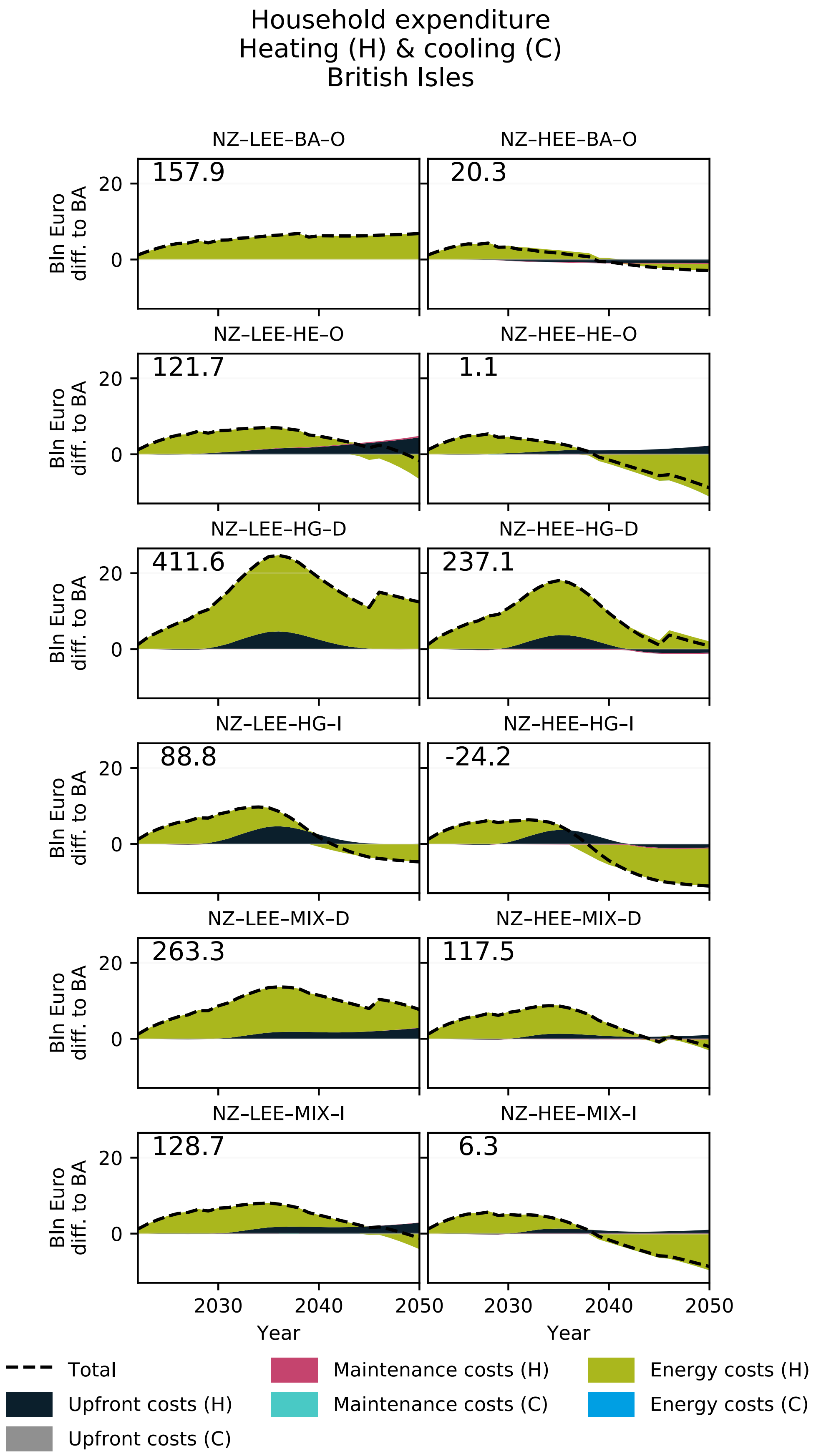

Figure B.1.8: Household expenditure heating and cooling. Numbers represent cumulative total expenditure in billion Euro.

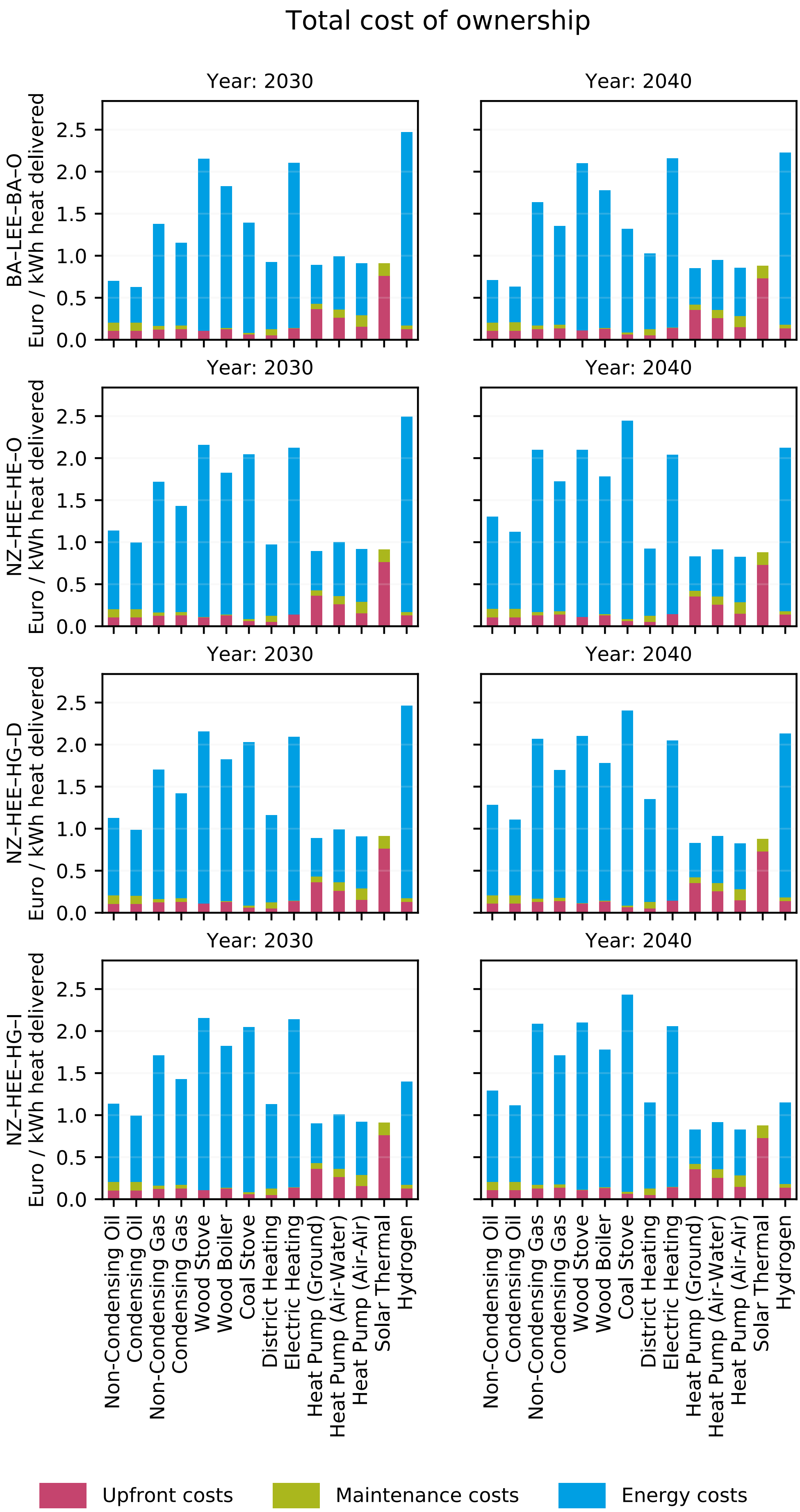

Figure B.1.9: Total cost of ownership by technology.

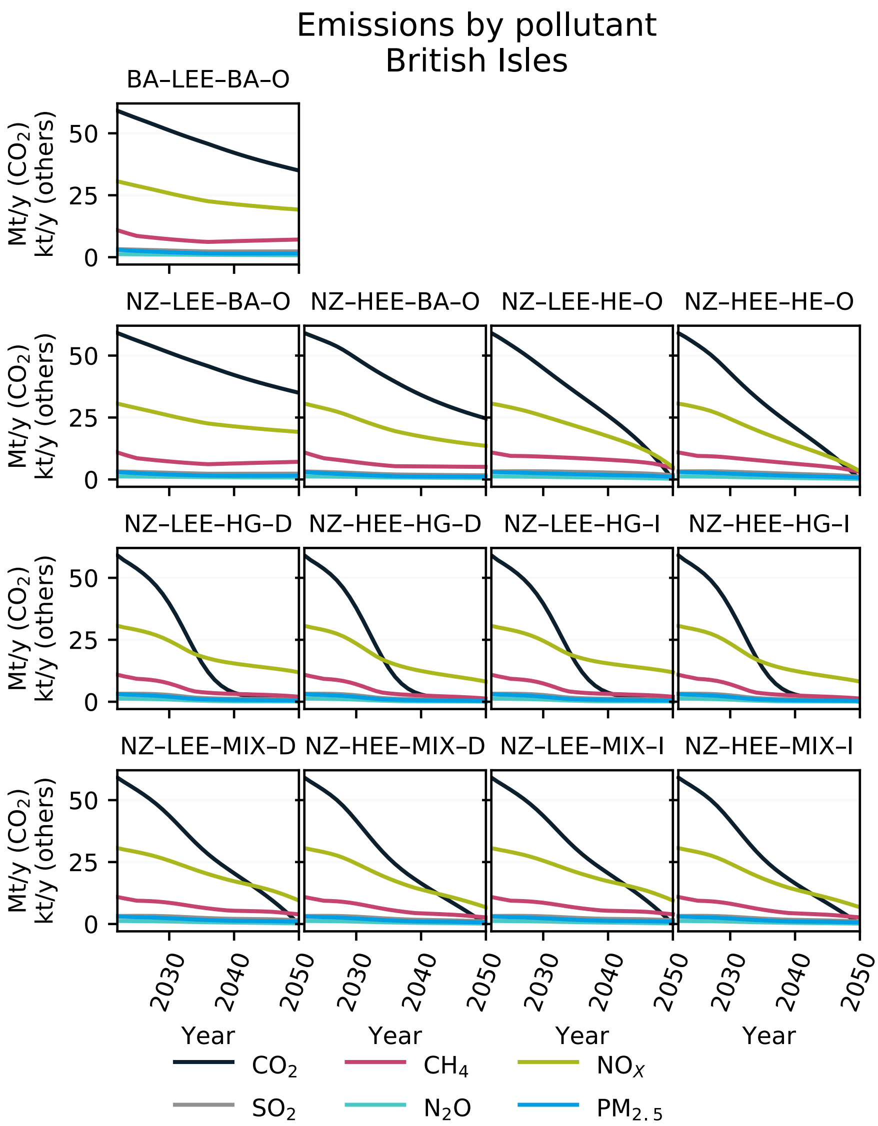

Figure B.1.10: Direct emissions by pollutant.

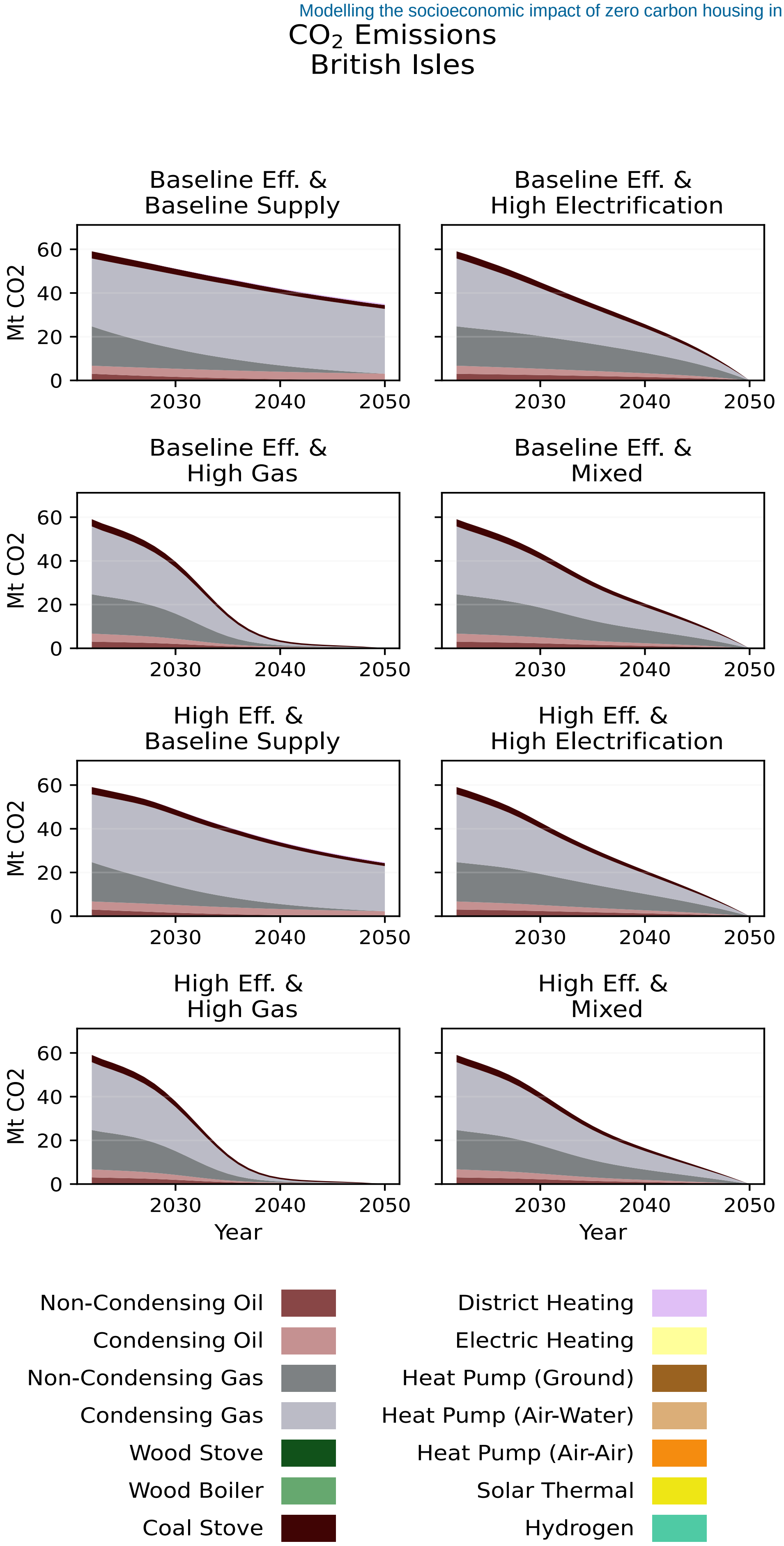

Figure B.1.11: Direct CO_2 emissions by technology.

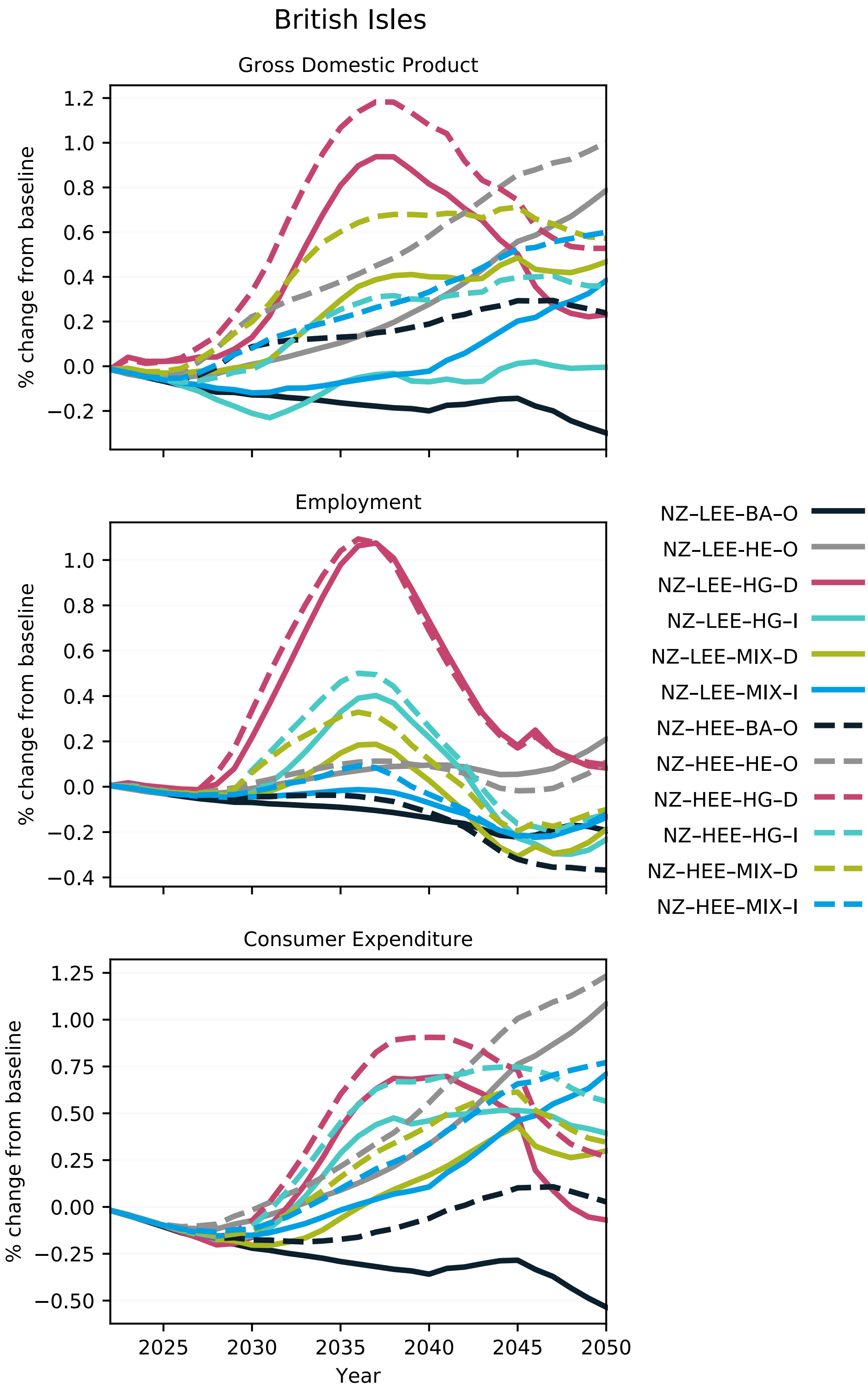

Figure B.1.12: GDP, employment, and consumer expenditure changes.

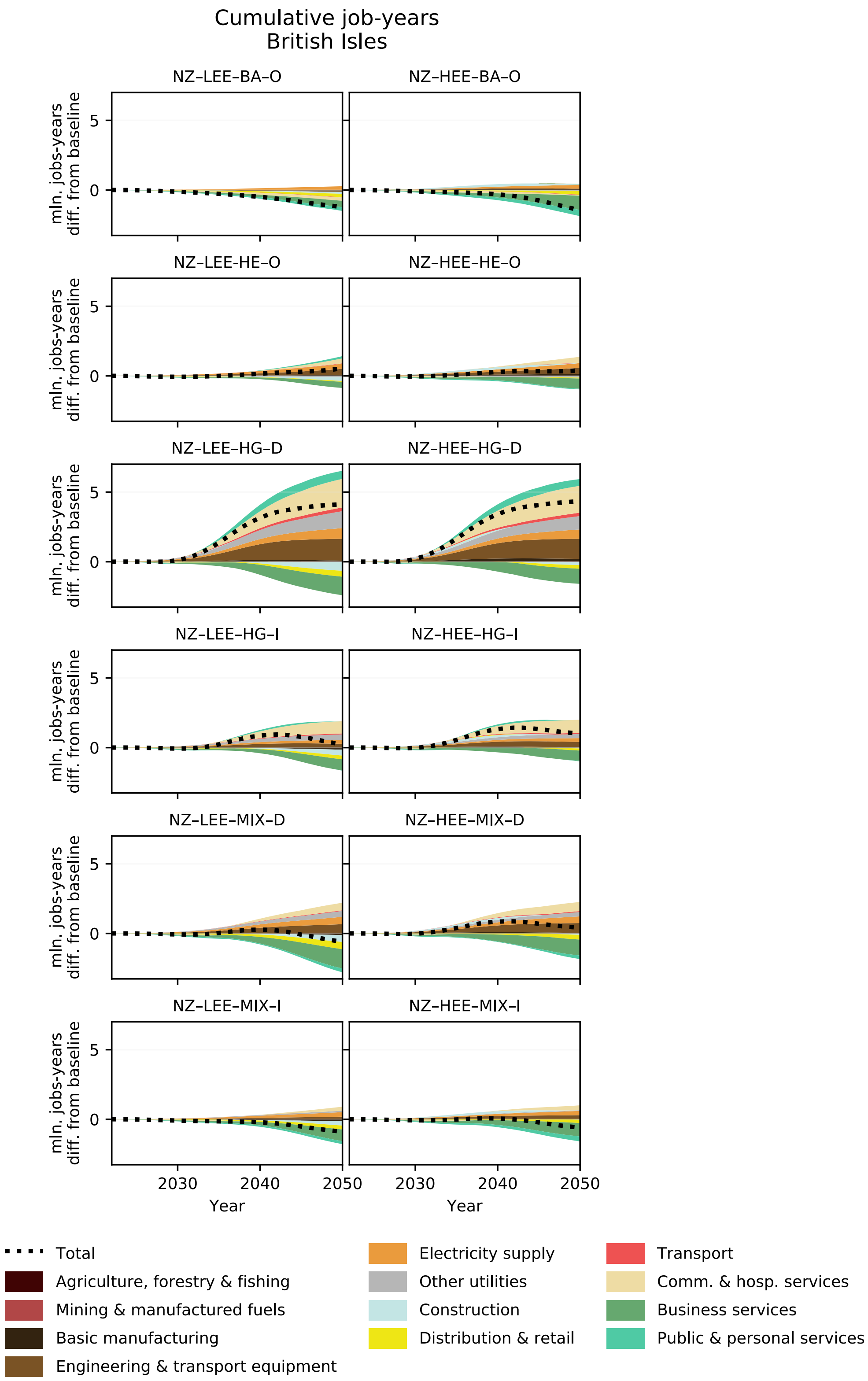

Figure B.1.13: Cumulative job-years by sector.

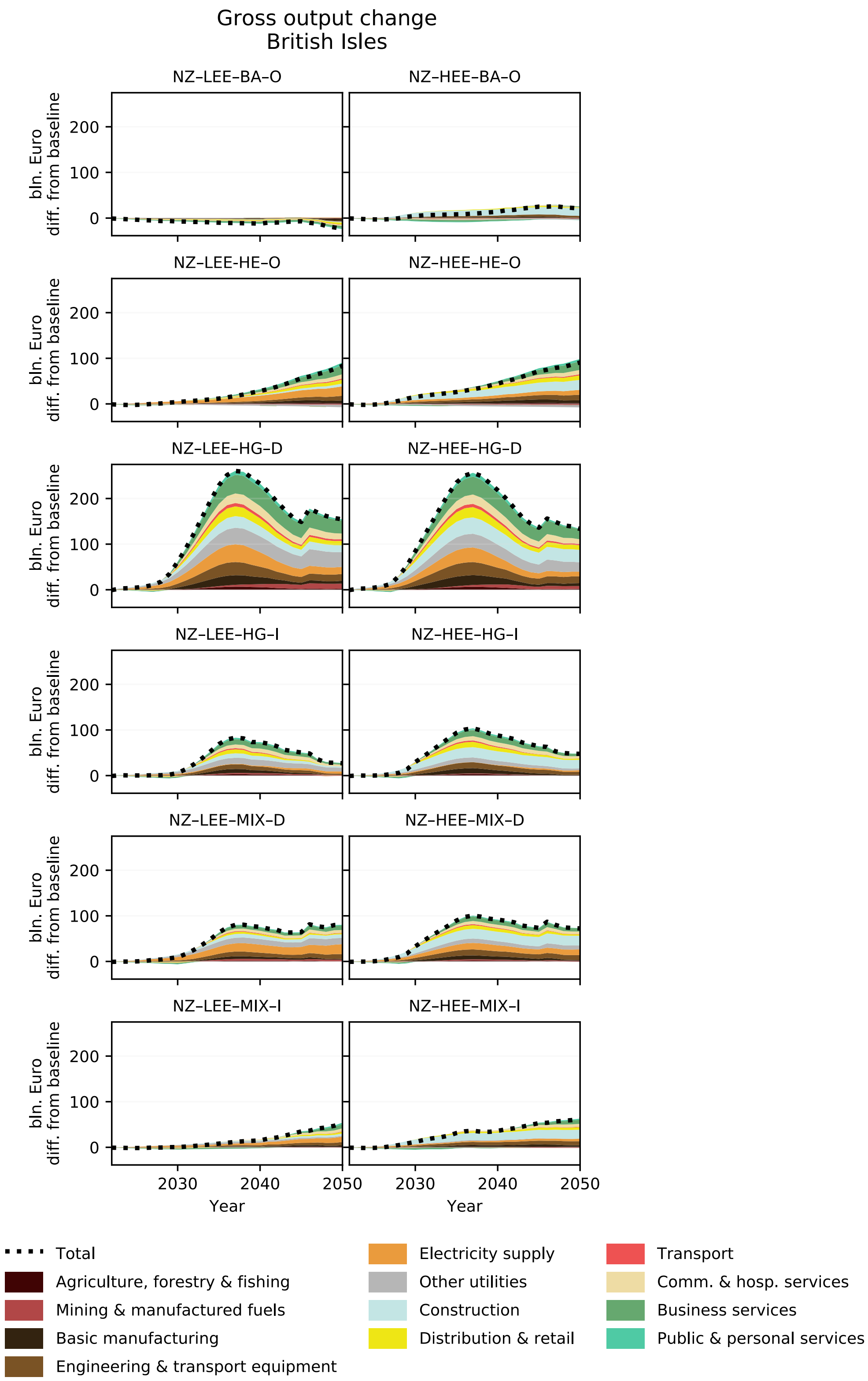

Figure B.1.14: Gross output changes by sector.

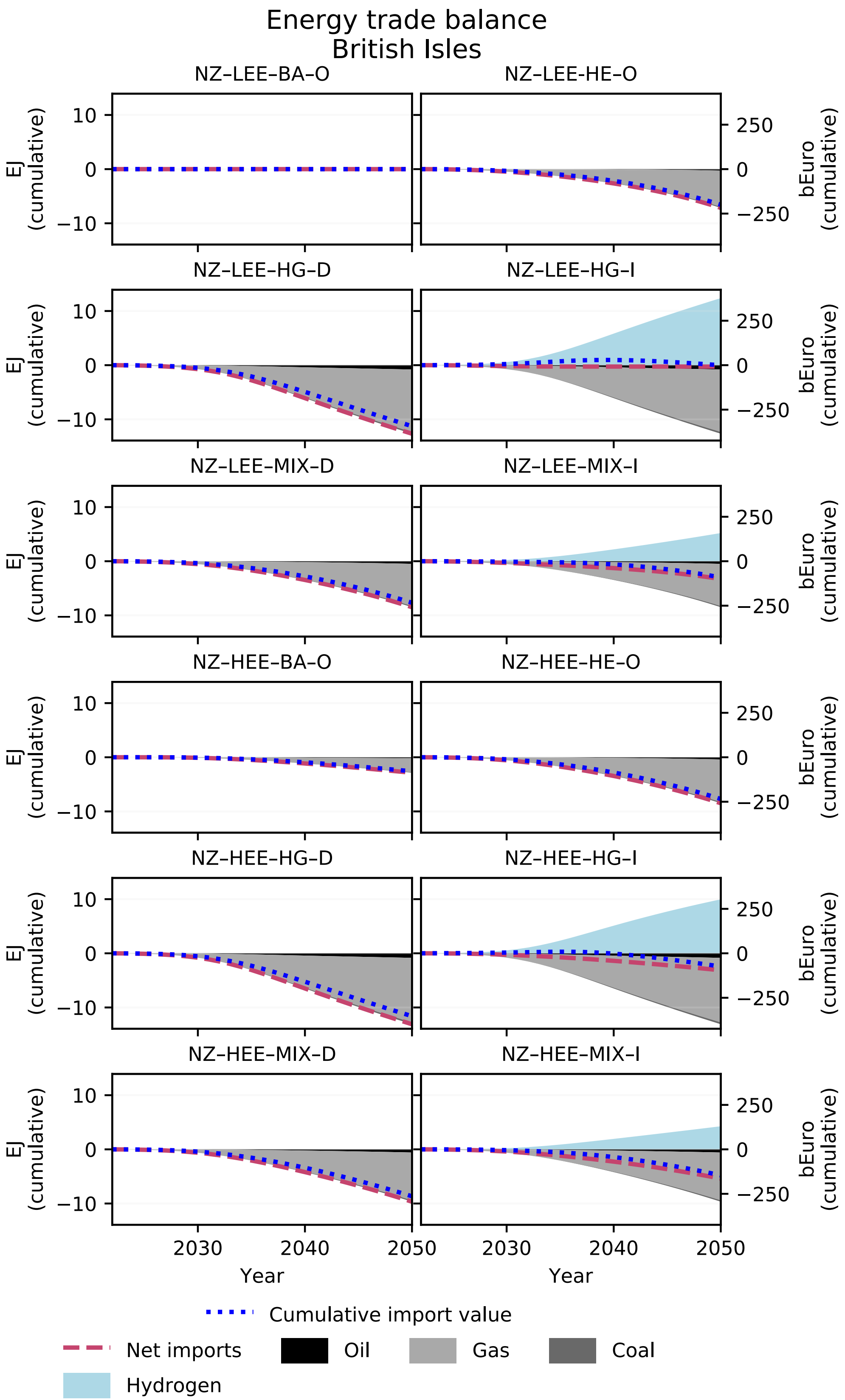

Figure B.1.15: Energy trade balance changes by energy carrier.

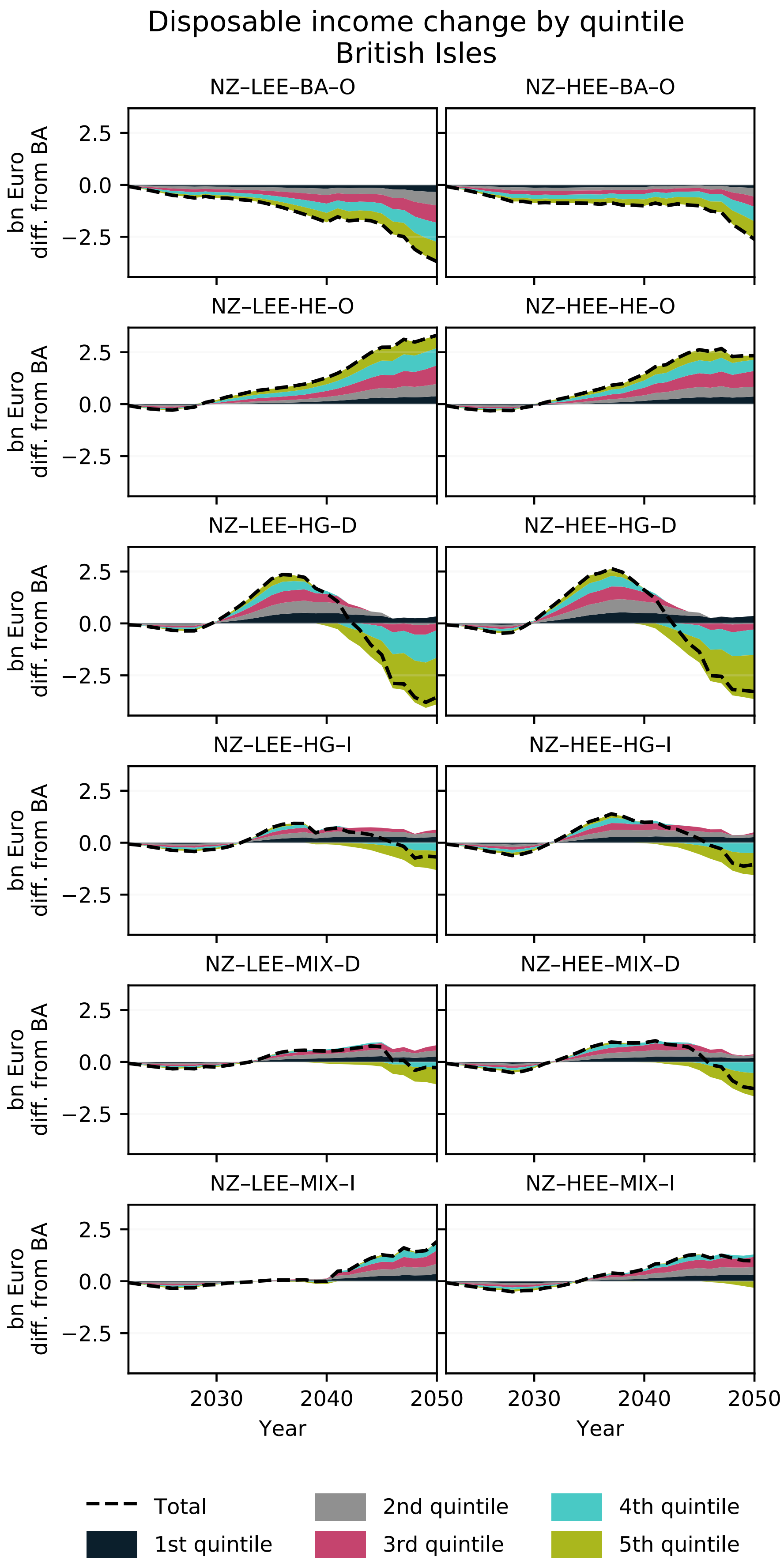

Figure B.1.16: Disposable income changes by income group.

Climate zone: Northern Europe

In Northern Europe, district heating plays a large role in the decarbonisation of the dwelling stock, and that remains so in our scenarios. The main difference between the scenarios come in the composition of district heating. In the high gas scenario, peak boilers are being replaced by hydrogen boilers, in contrast to the dominant bio-based CHP, this causes a shift from biomass to hydrogen. Conversely, in the electrification scenarios, the peak boilers move towards heat pumps and electric boilers to satisfy peak demand. The high electrification scenarios generally see the best economic outcomes, with higher GDP and Employment effects. Although the high electrification scenario seems to outperform the other scenarios, regardless of the pathway, net positive effects are likely to persist relative to baseline levels.

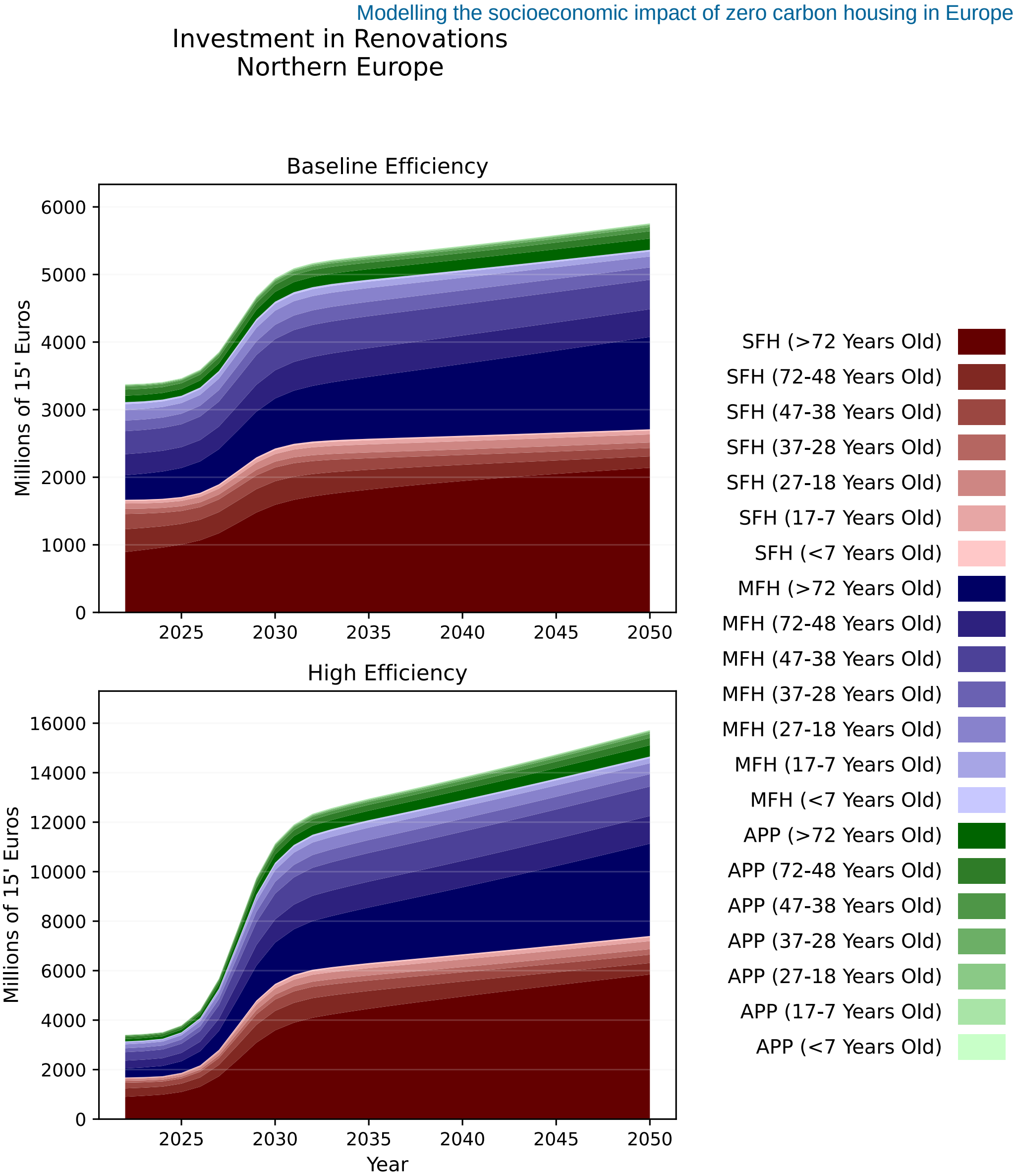

Figure B.2.1: Investments into renovations.

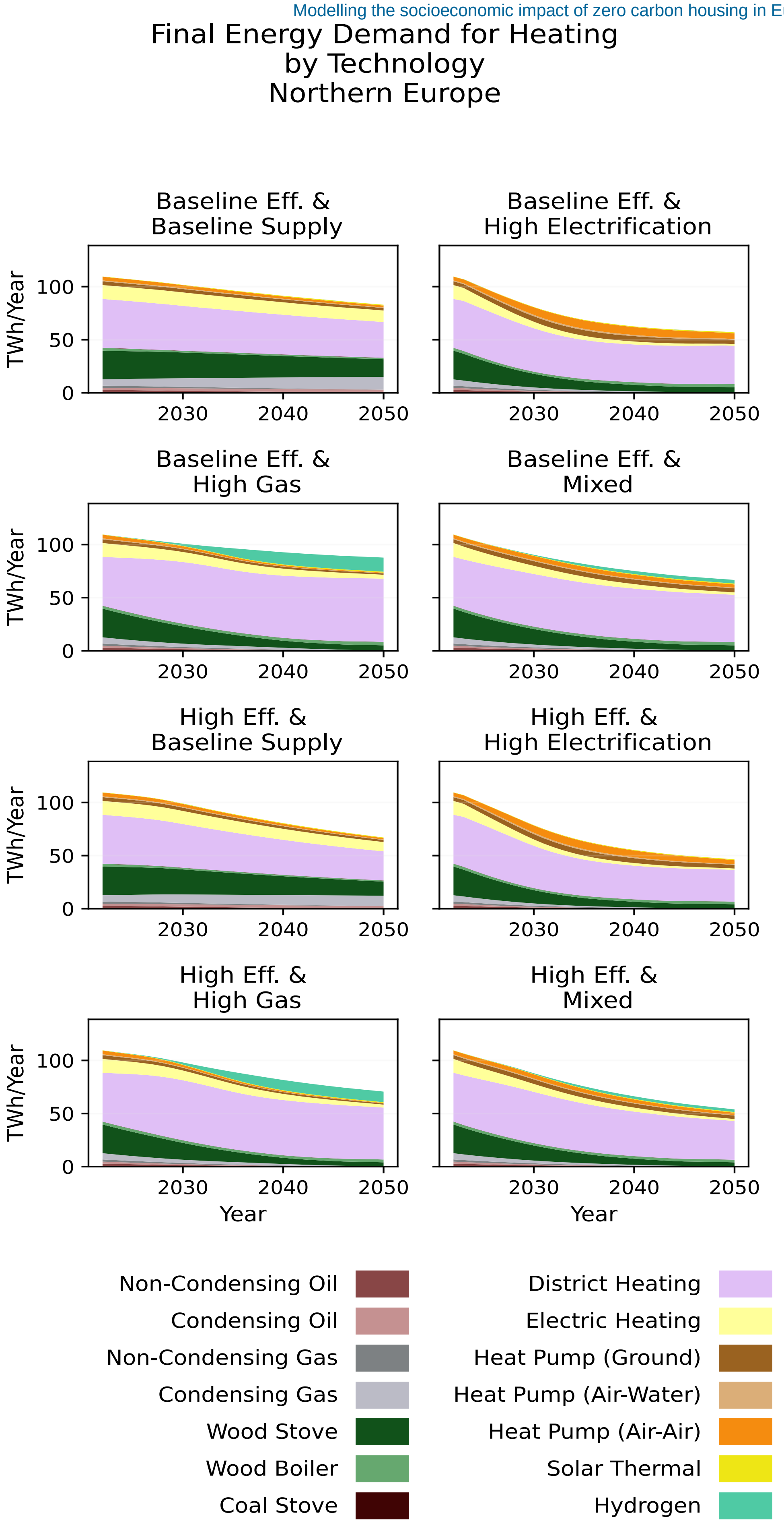

Figure B.2.2: Final energy demand by technology.

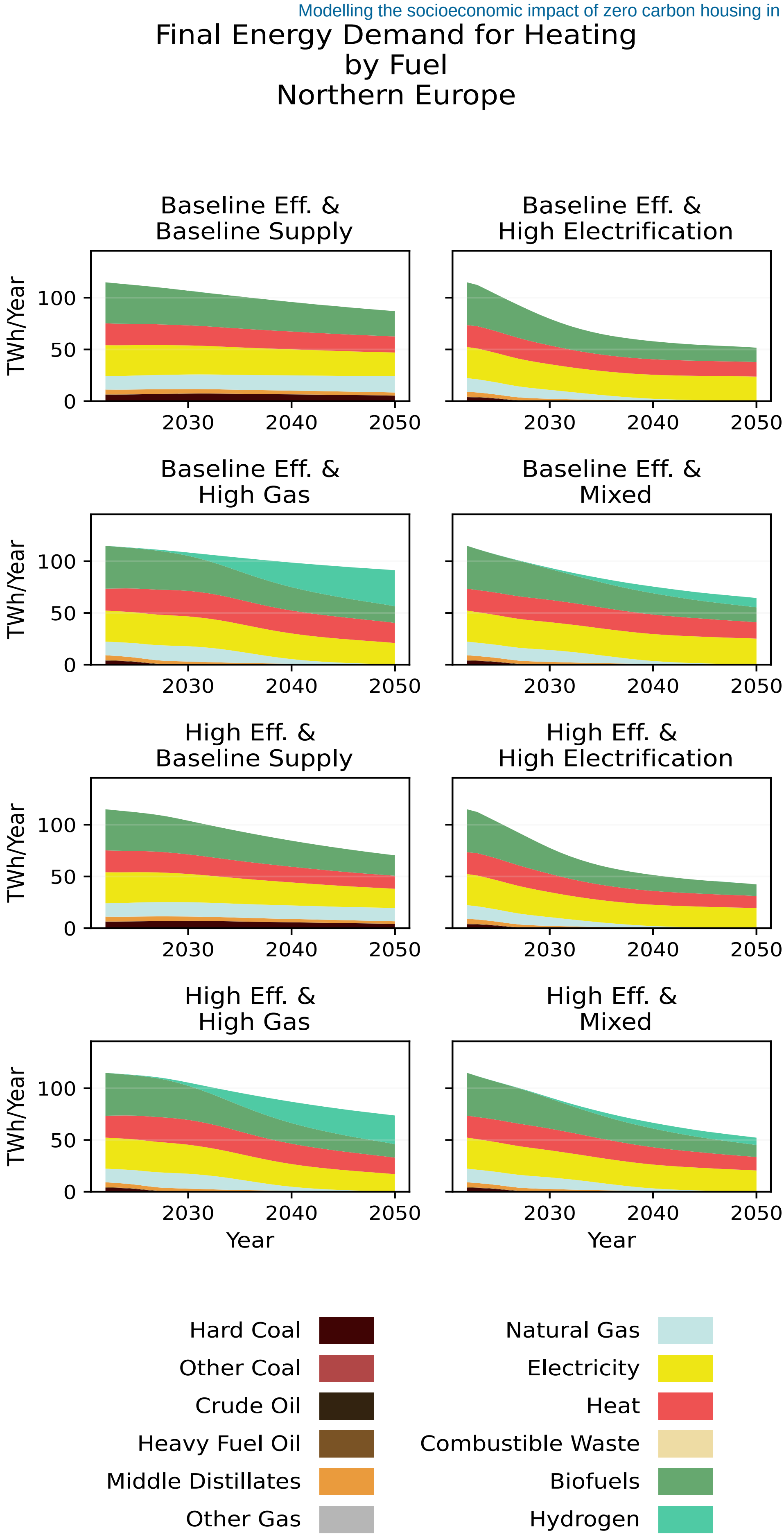

Figure B.2.3: Final energy demand by energy carrier.

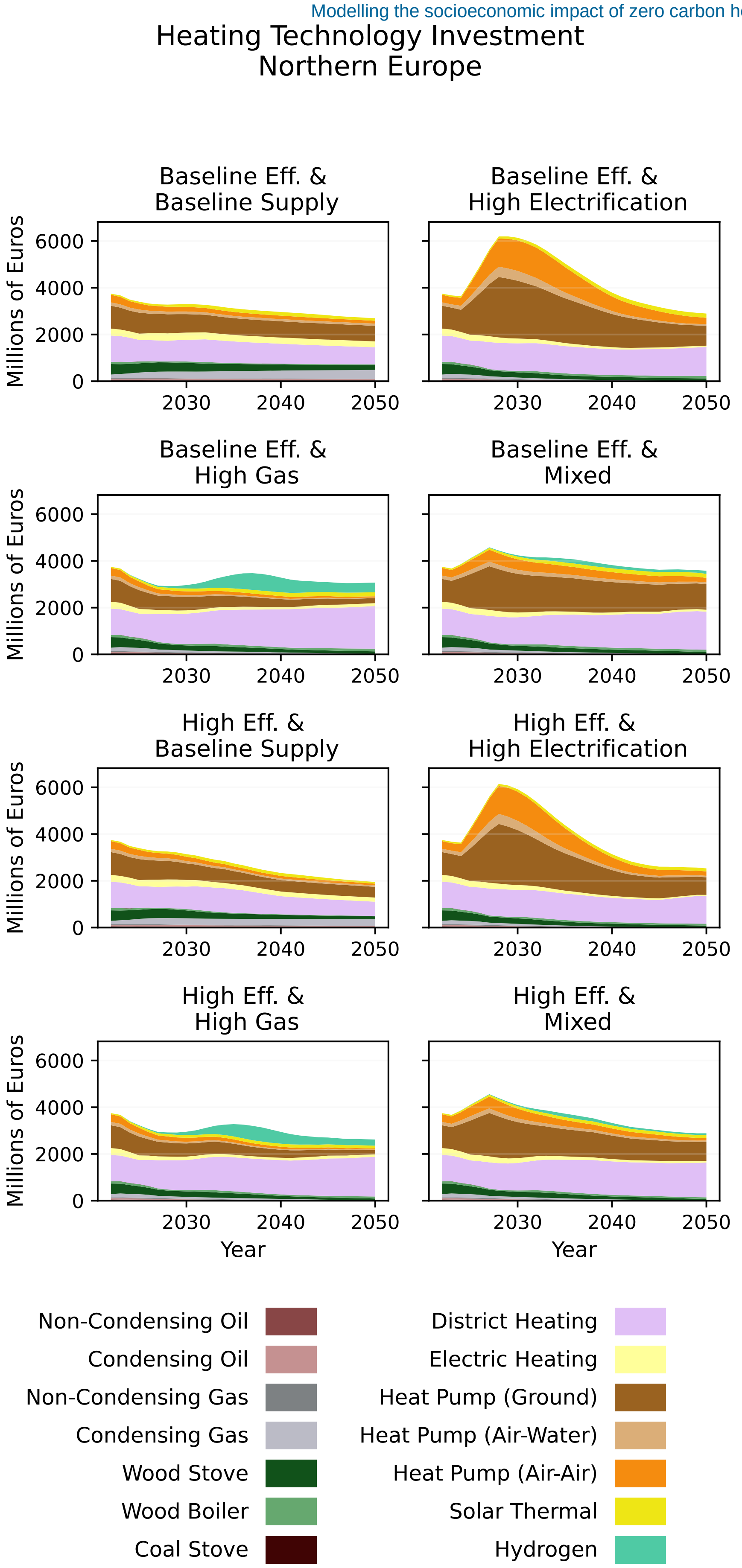

Figure B.2.4: Investment in heating equipment.

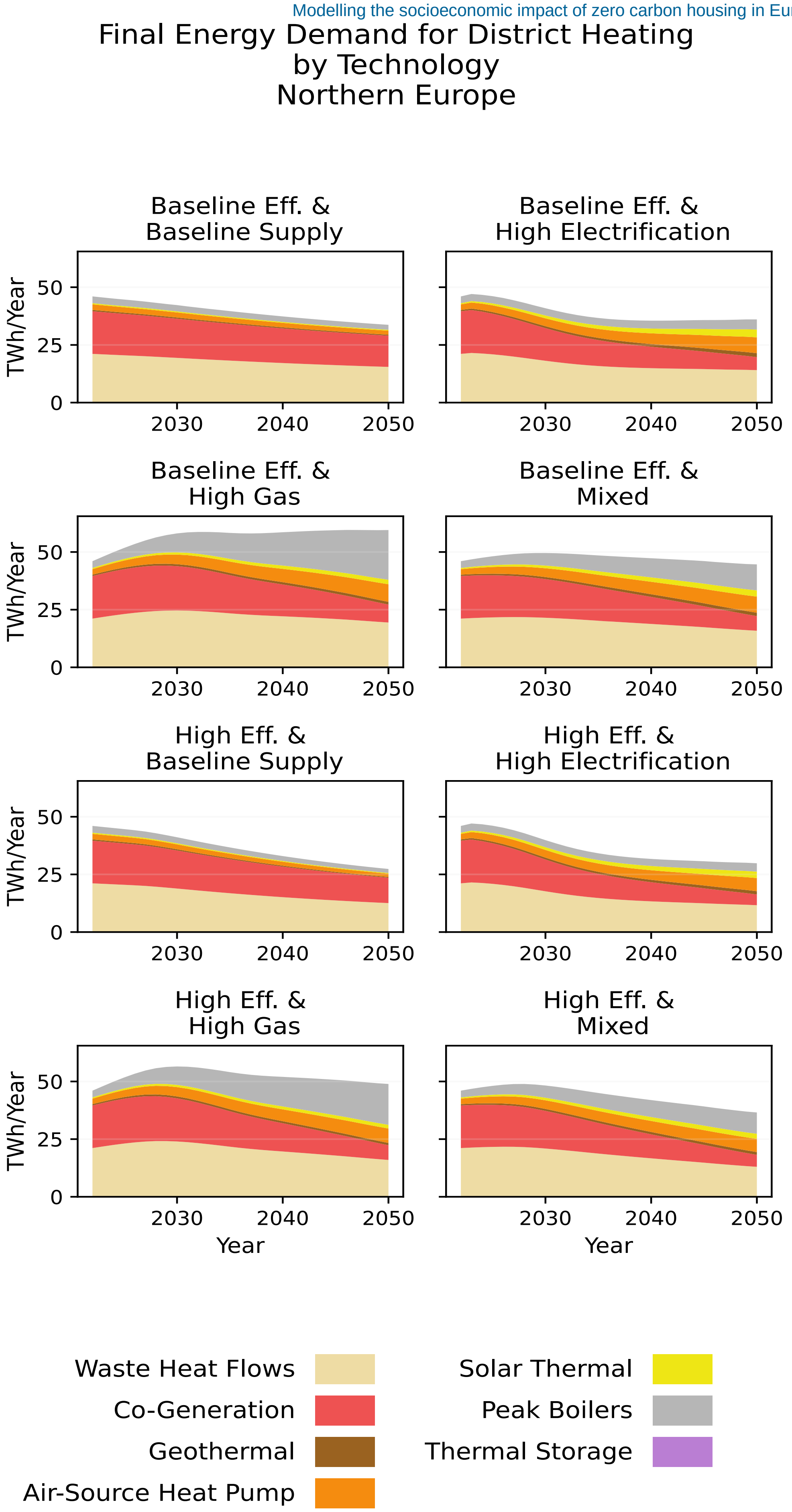

Figure B.2.5: Final energy demand by DH/C configuration option.

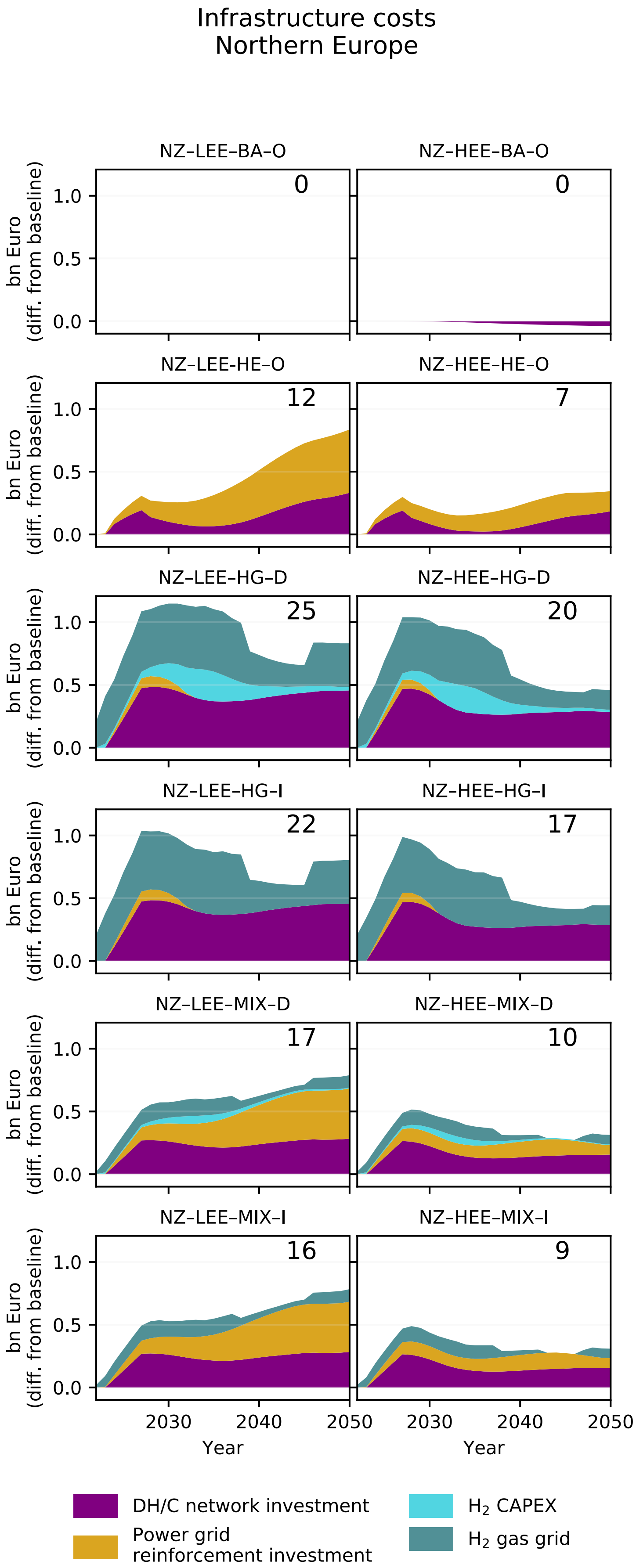

Figure B.2.6: Infrastructure investments. Numbers represent cumulative investment in billion Euro.

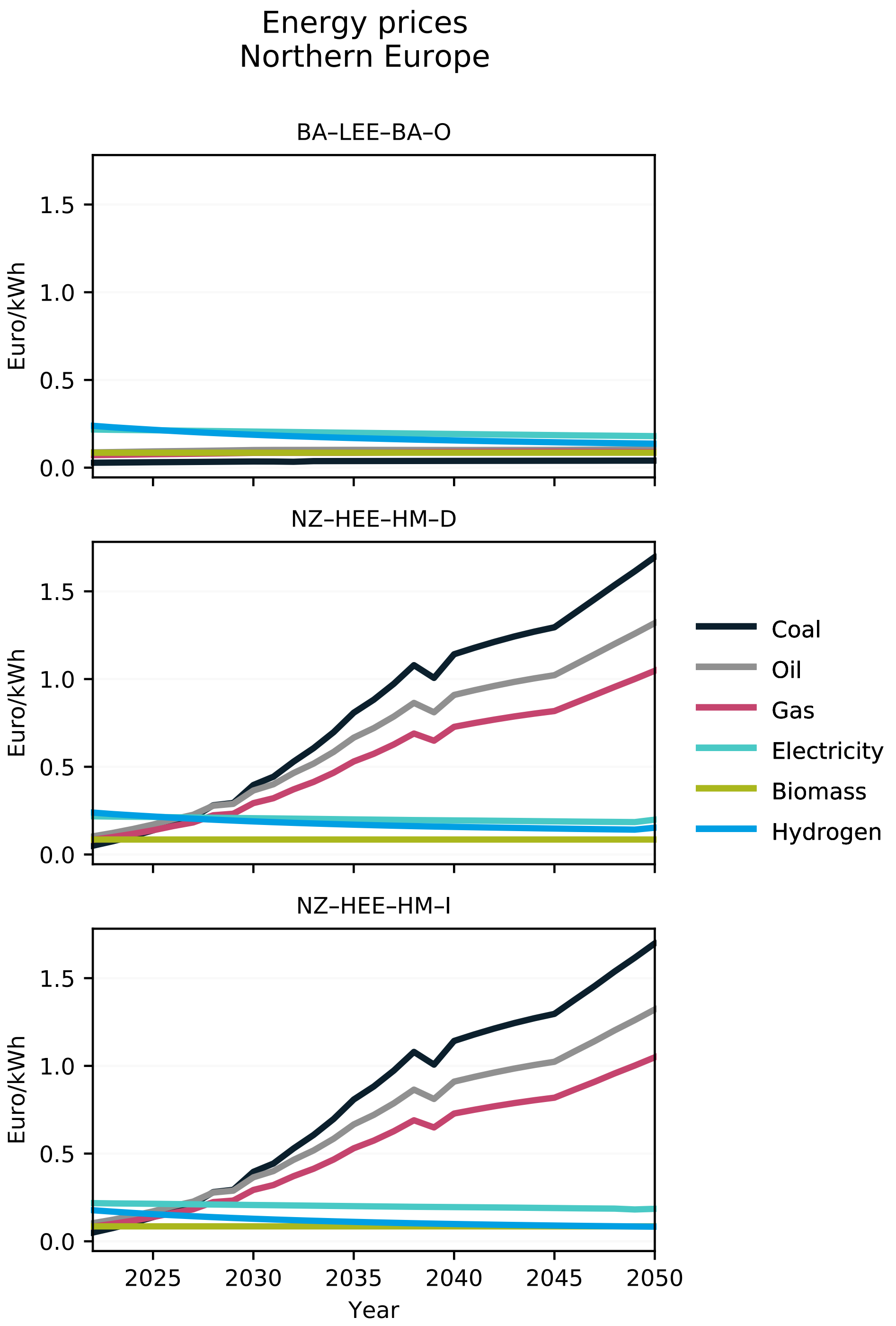

Figure B.2.7: Evolution of energy prices.

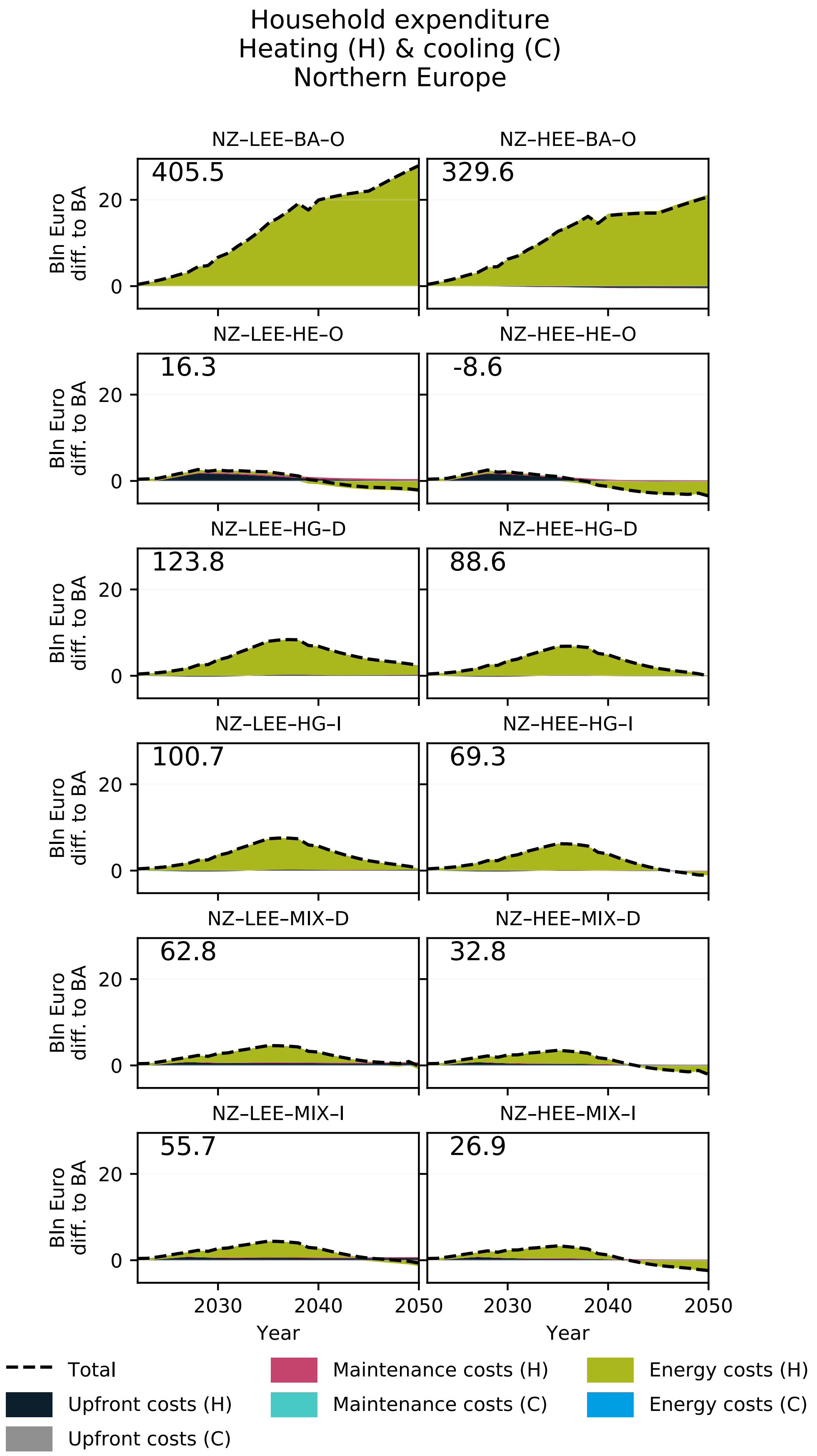

Figure B.2.8: Households expenditure on heating & cooling. Numbers represent cumulative expenditure in billion Euro.

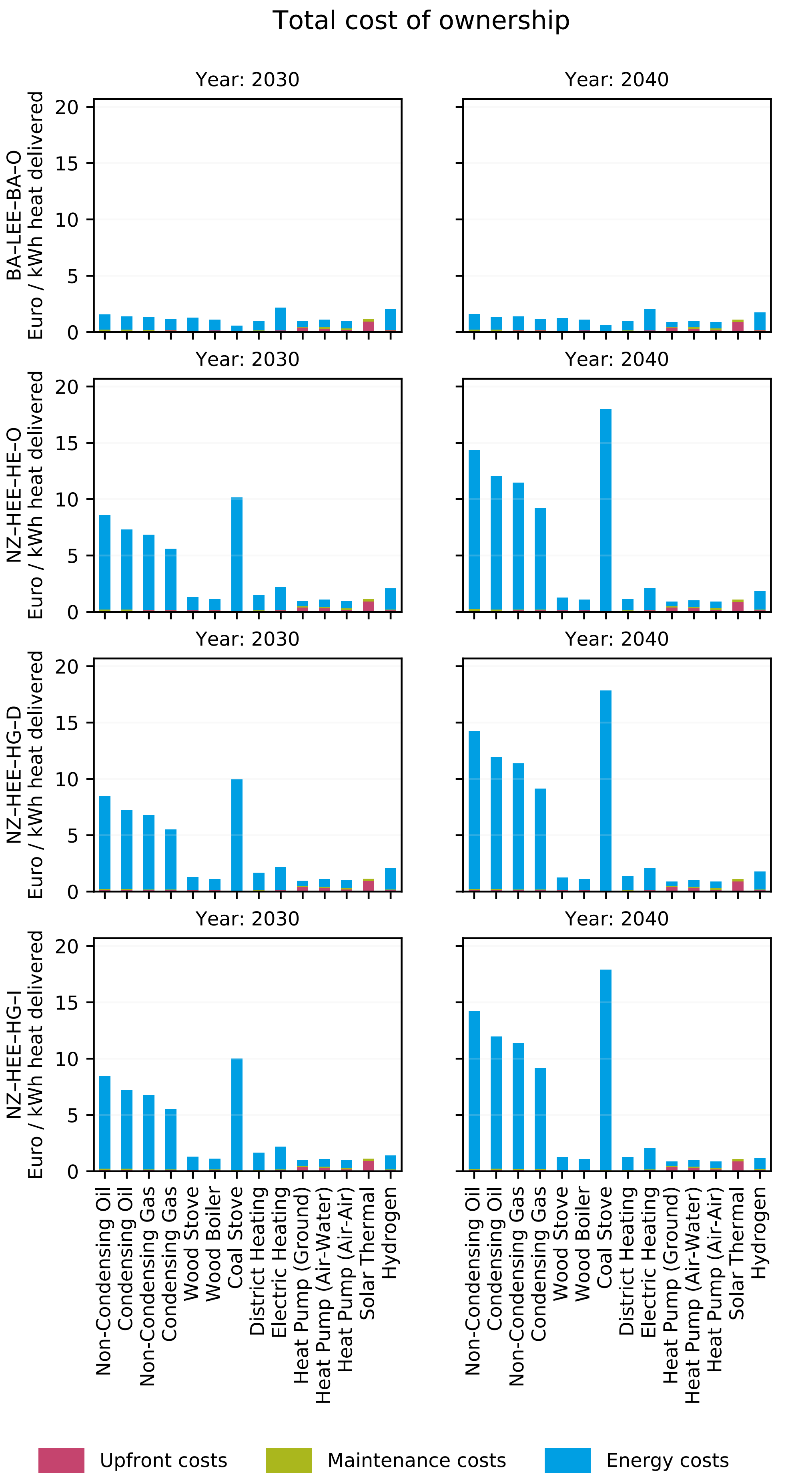

Figure B.2.9: Total cost of ownership by technology.

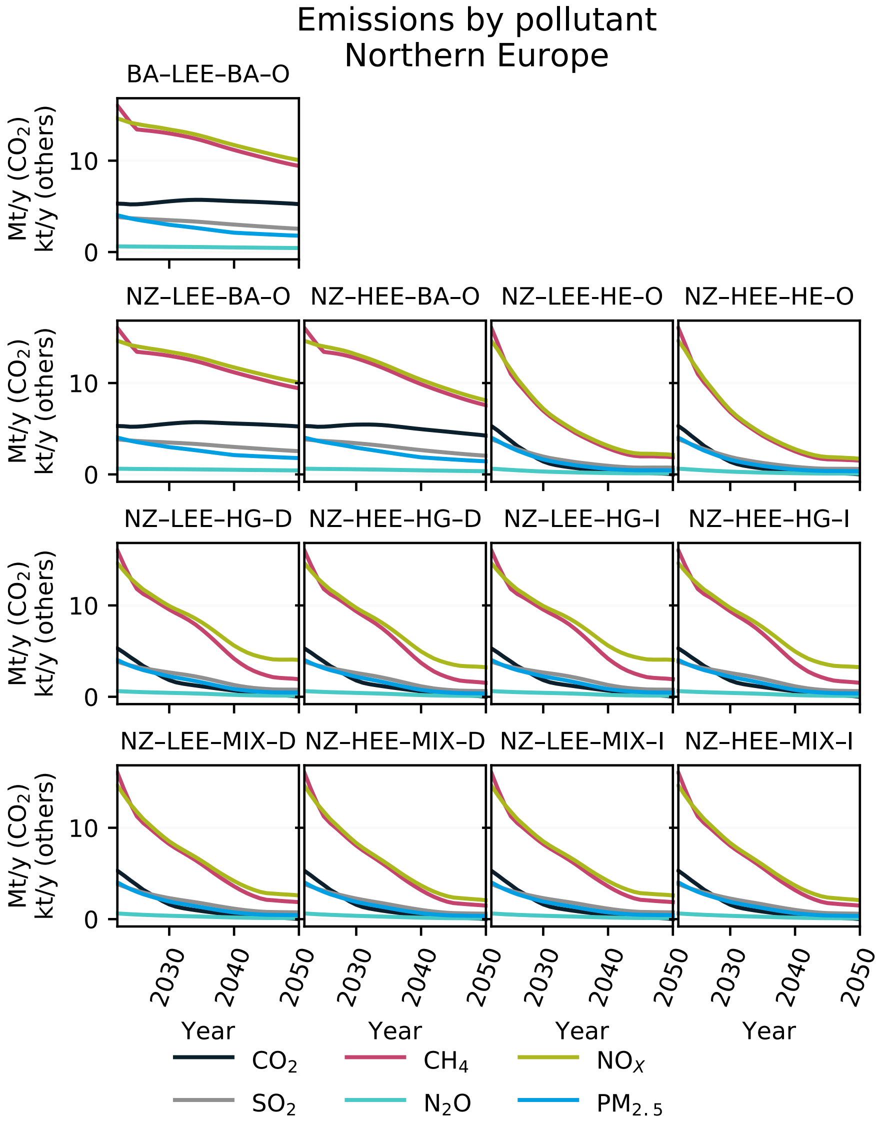

Figure B.2.10: Direct emissions by pollutant.

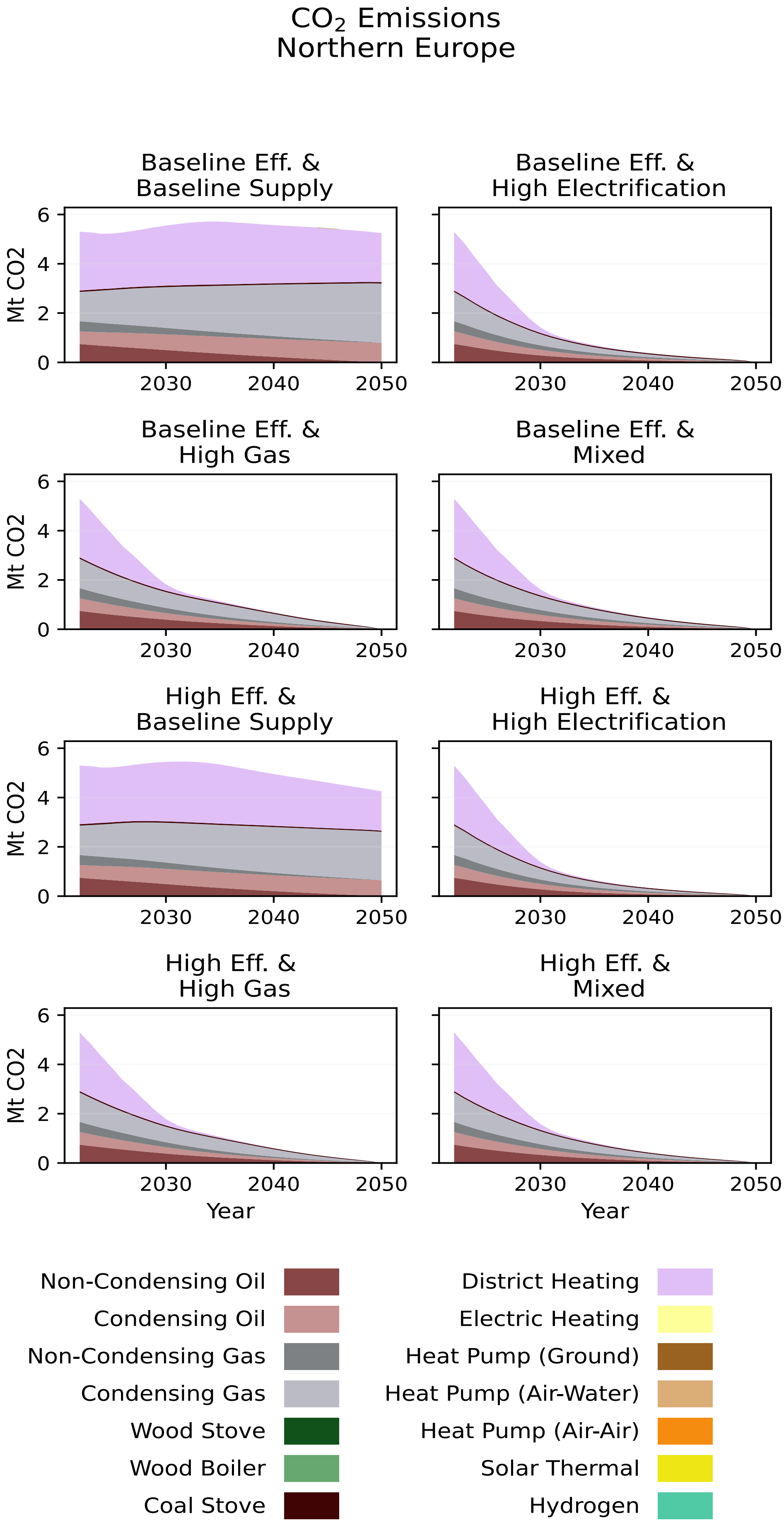

Figure B.2.11: Direct CO_2 emissions by technology.

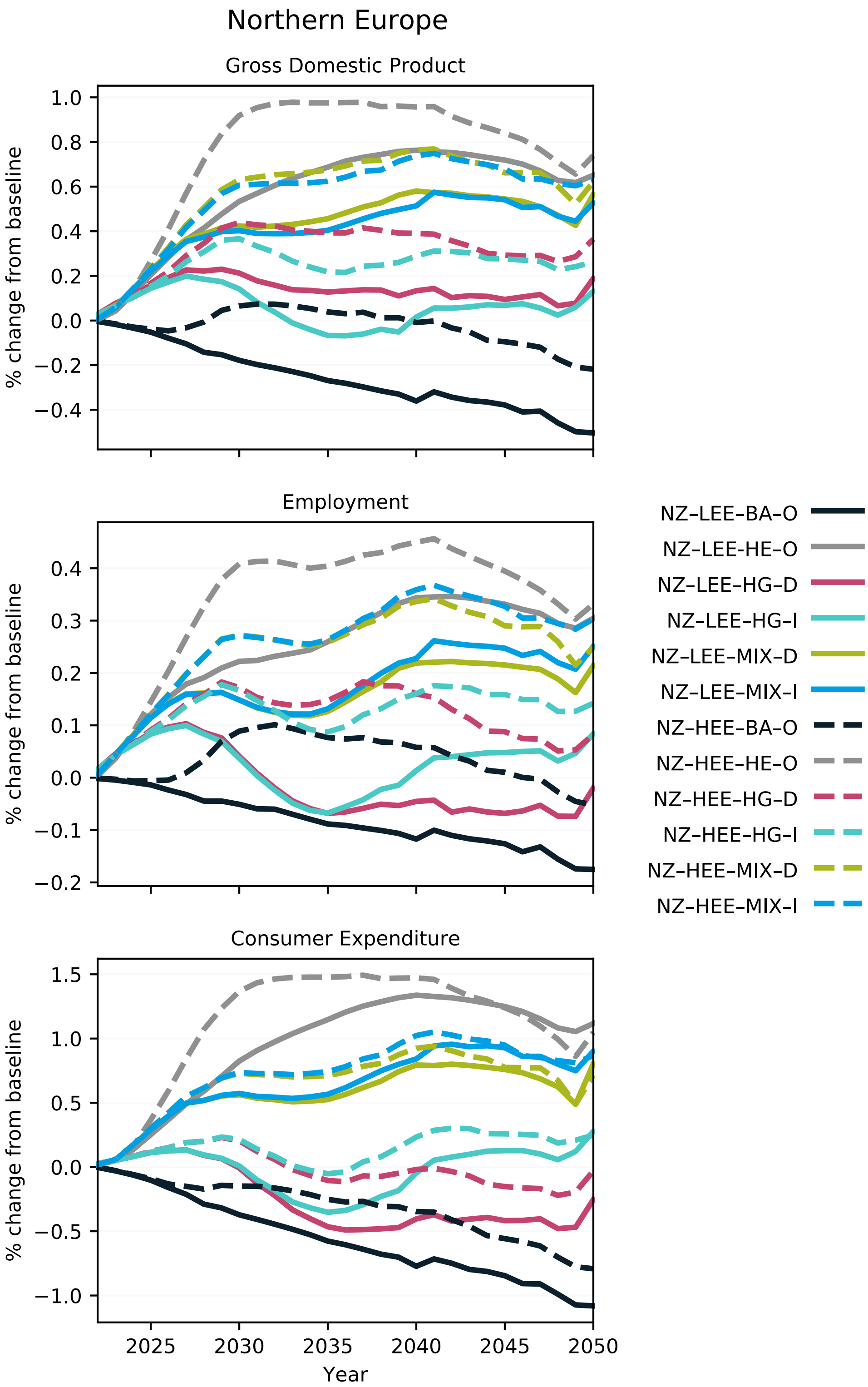

Figure B.2.12: GDP, employment, and consumer expenditure change.

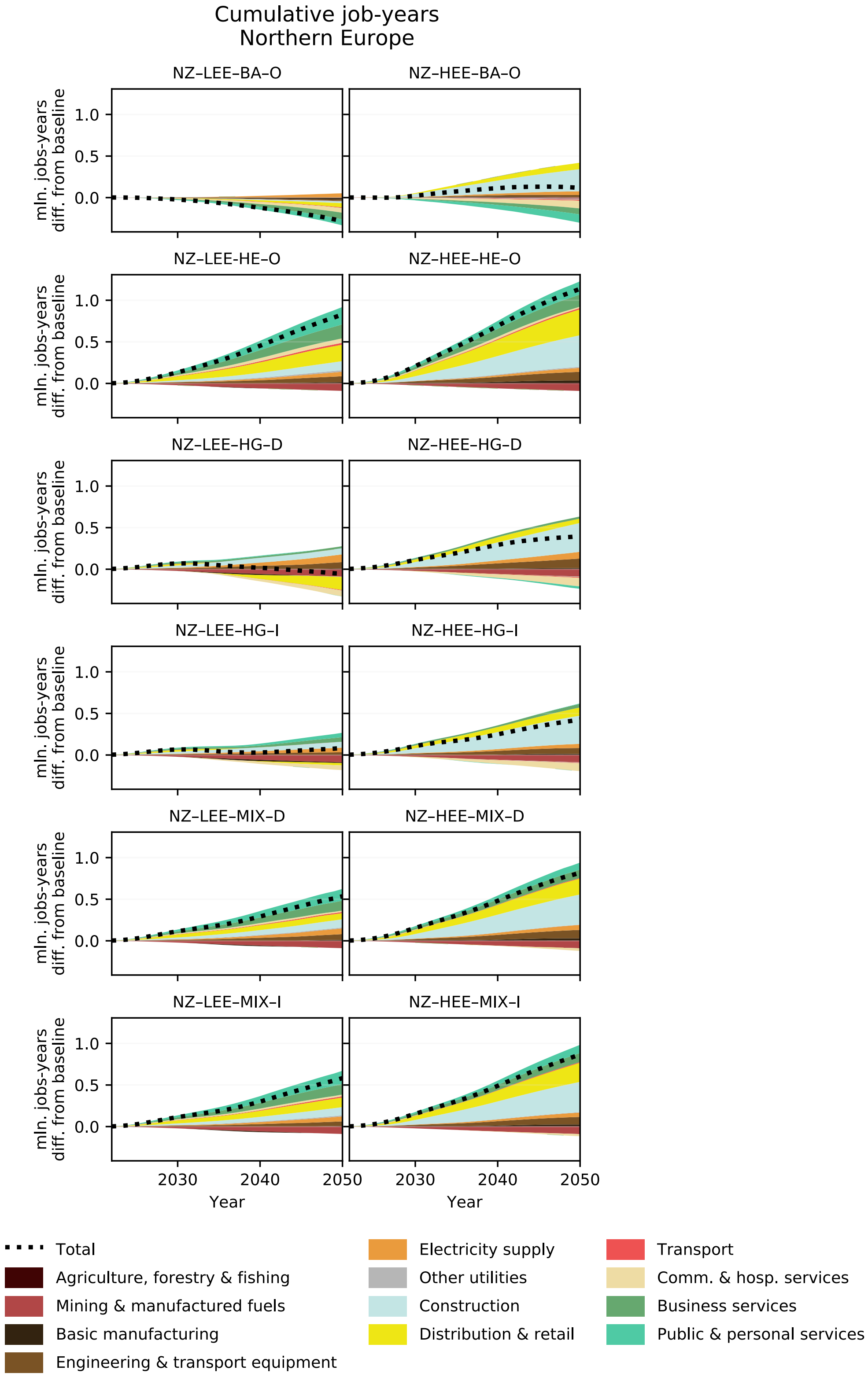

Figure B.2.13: Cumulative job-years change by sector.

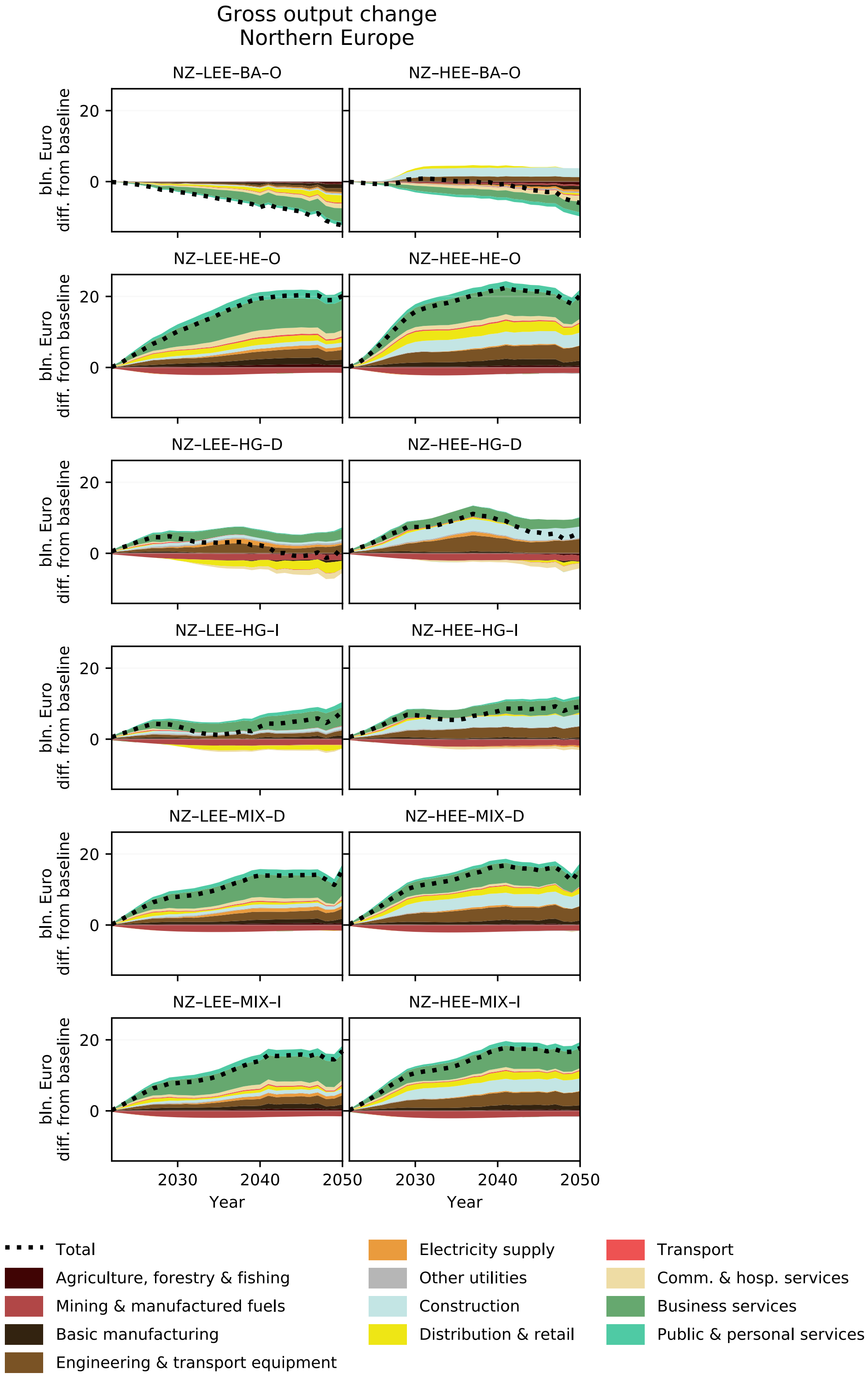

Figure B.2.14: Gross output change by sector.

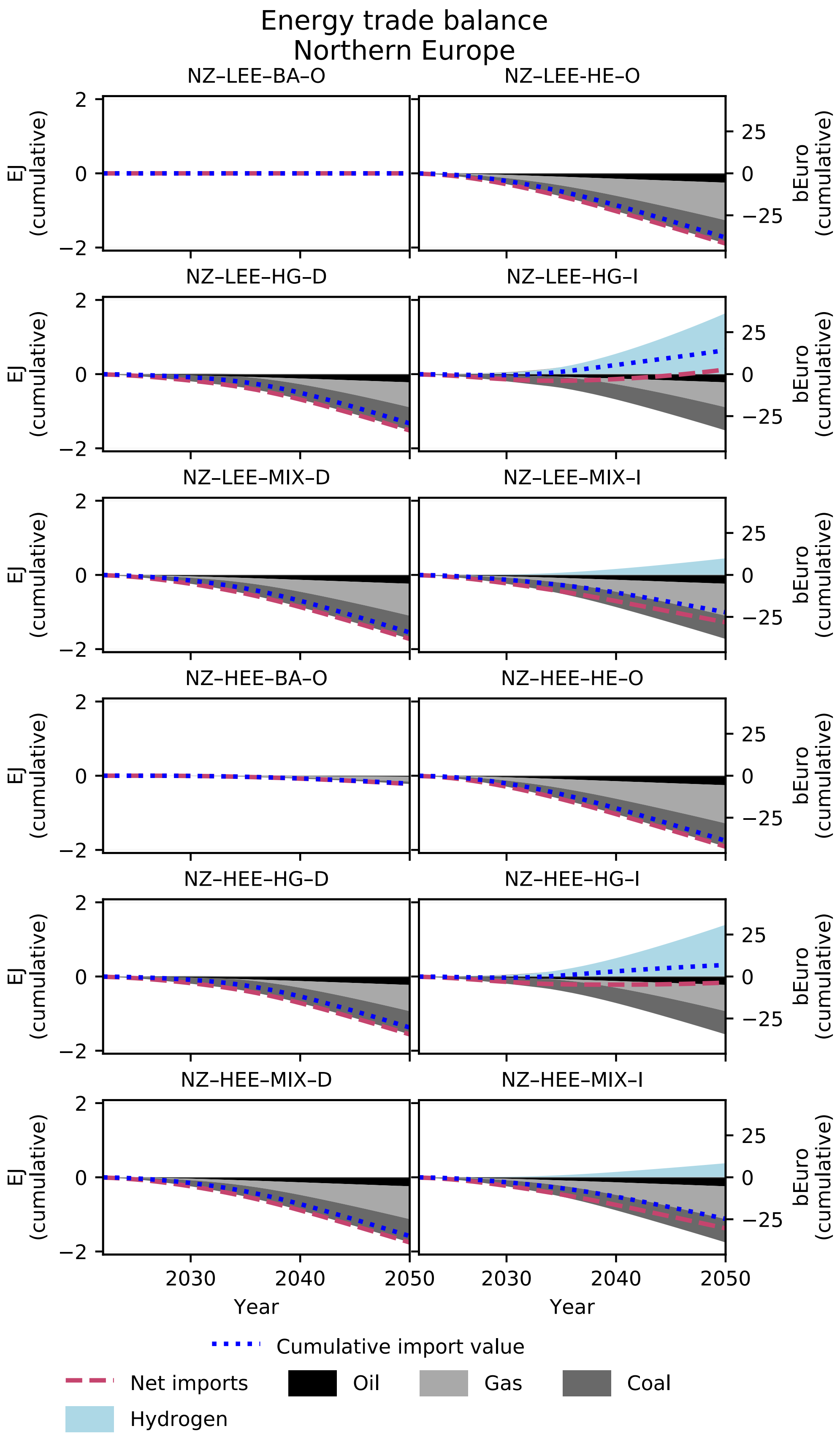

Figure B.2.15: Energy trade balance change by energy carrier.

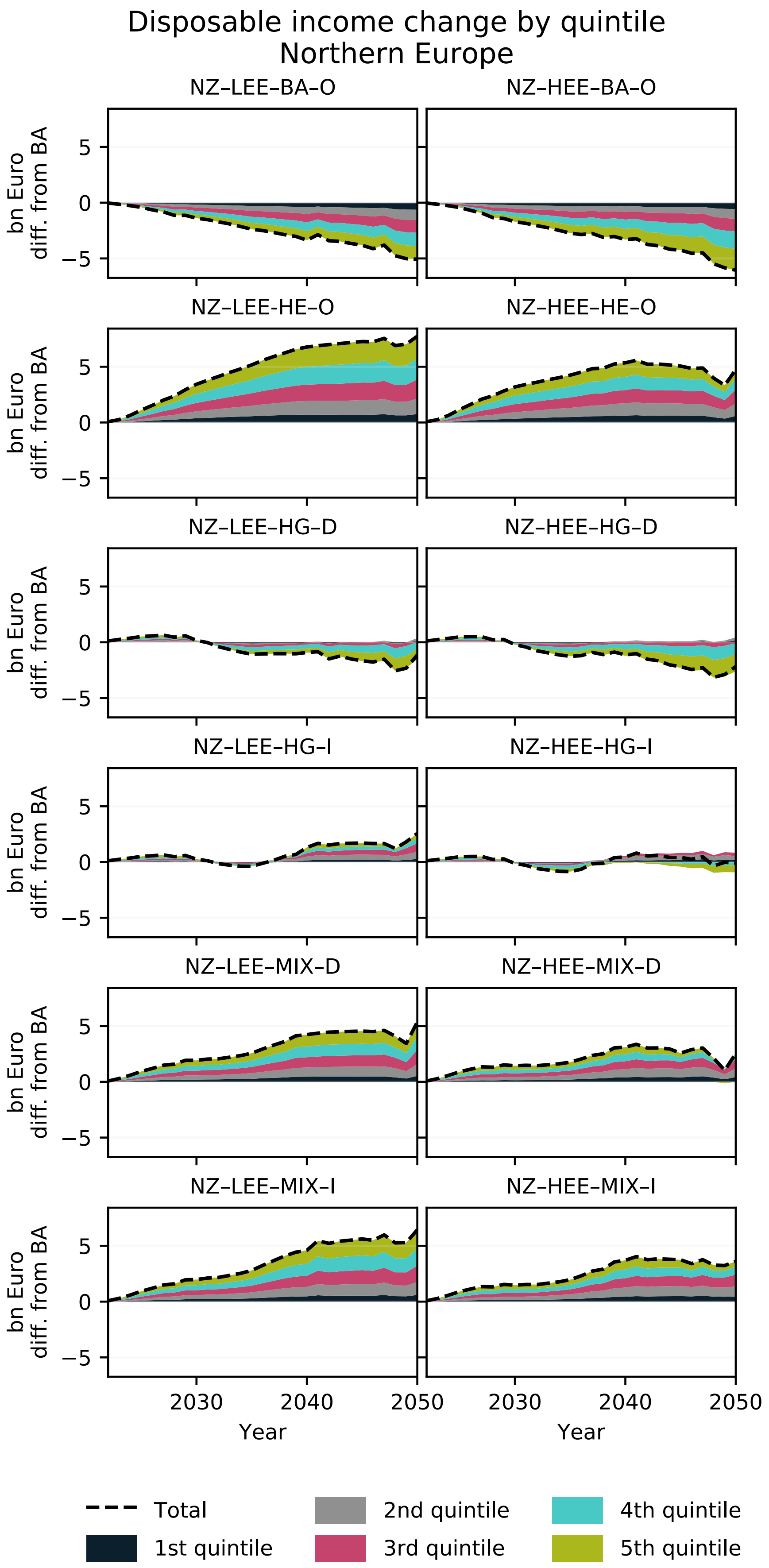

Figure B.2.16: Disposable income change by income quintile.

Climate zone: France + Benelux

France and Benelux have a high potential for hydrogen, where in the high gas scenarios, approximately 50% of the final energy demand for heating comes from hydrogen. Similarly for the high electrification scenarios, approximately 50% of the final energy demand is met by heat pumps. However, in both scenarios, district heating is playing a relatively minor role. In all of the scenarios, there is a net positive effect on GDP and employment, mostly driven by renovations. Consequently, the high energy efficiency scenarios have better economic outcomes compared to the lower energy efficiency, with a large quantity of the new jobs occurring in the construction sector.

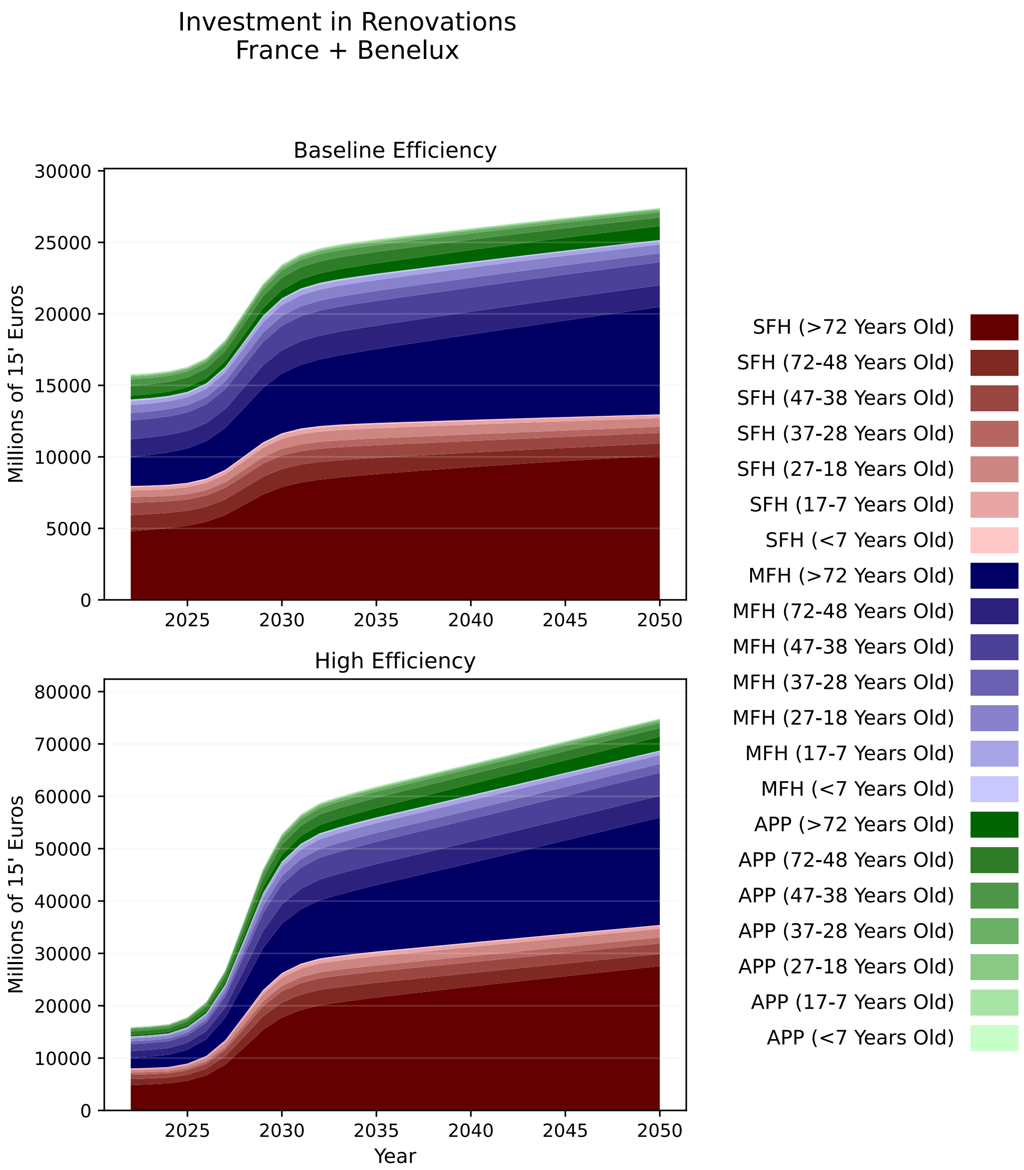

Figure B.3.1: Investments into renovations.

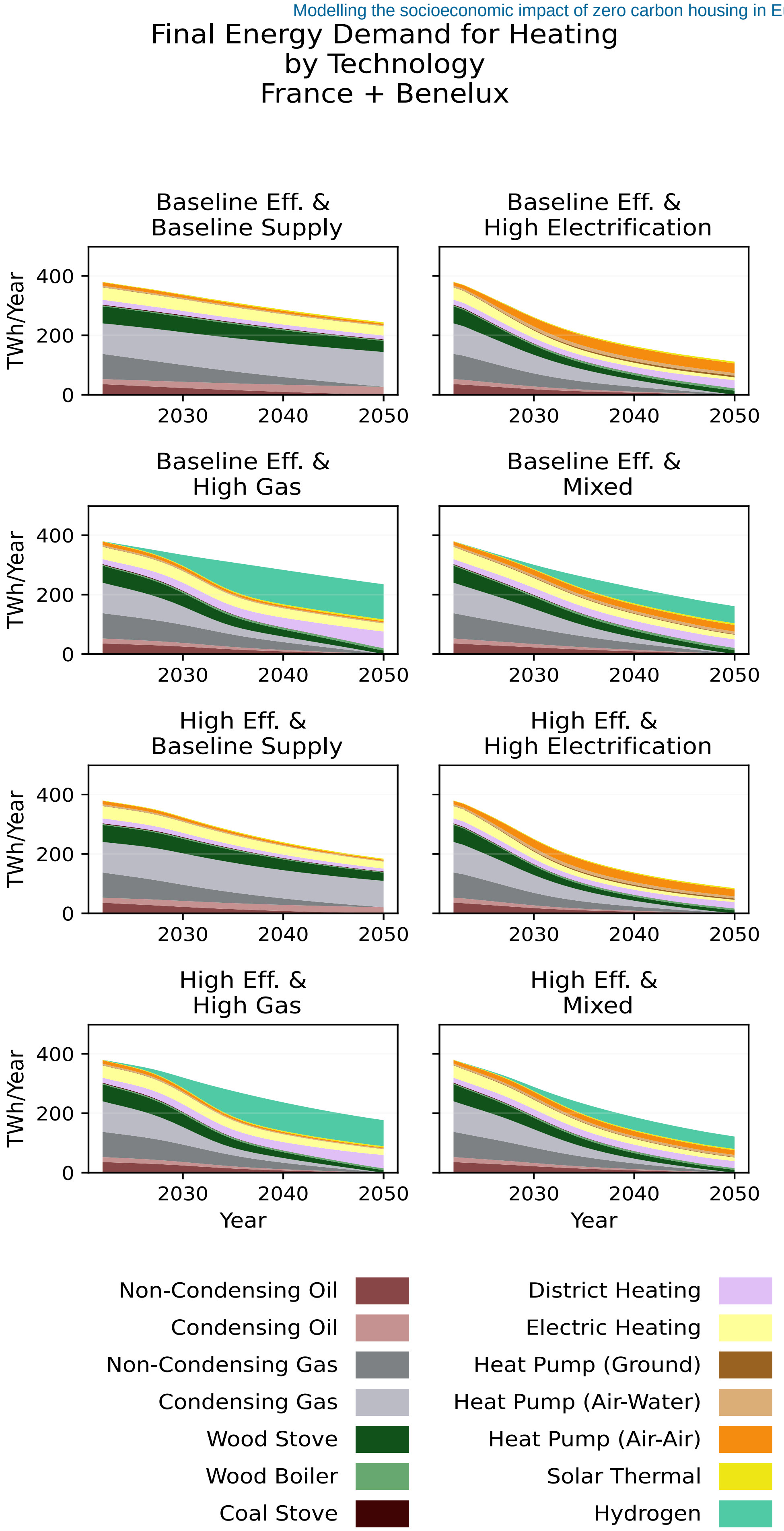

Figure B.3.2: Final energy demand by technology.

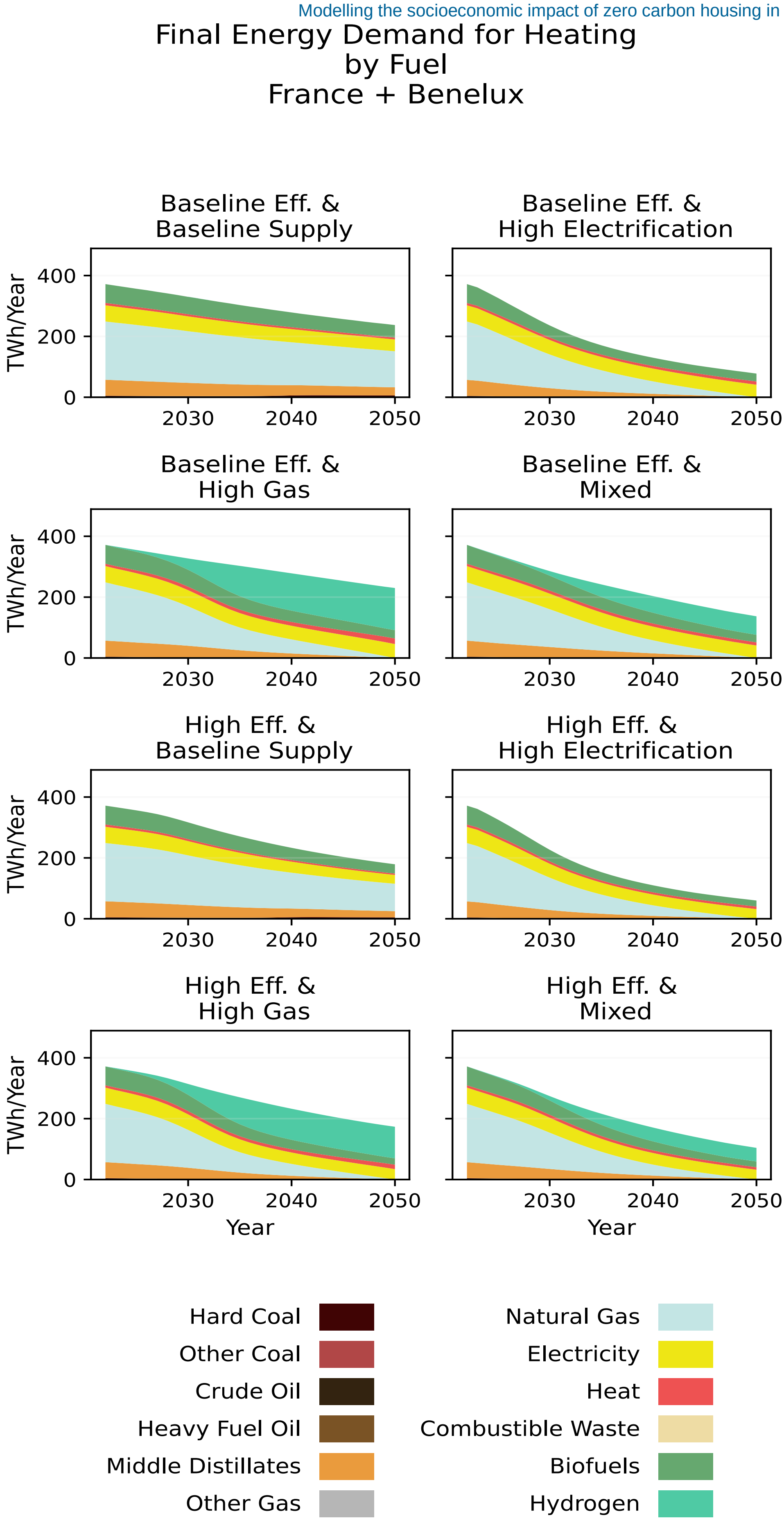

Figure B.3.3: Final energy demand by energy carrier.

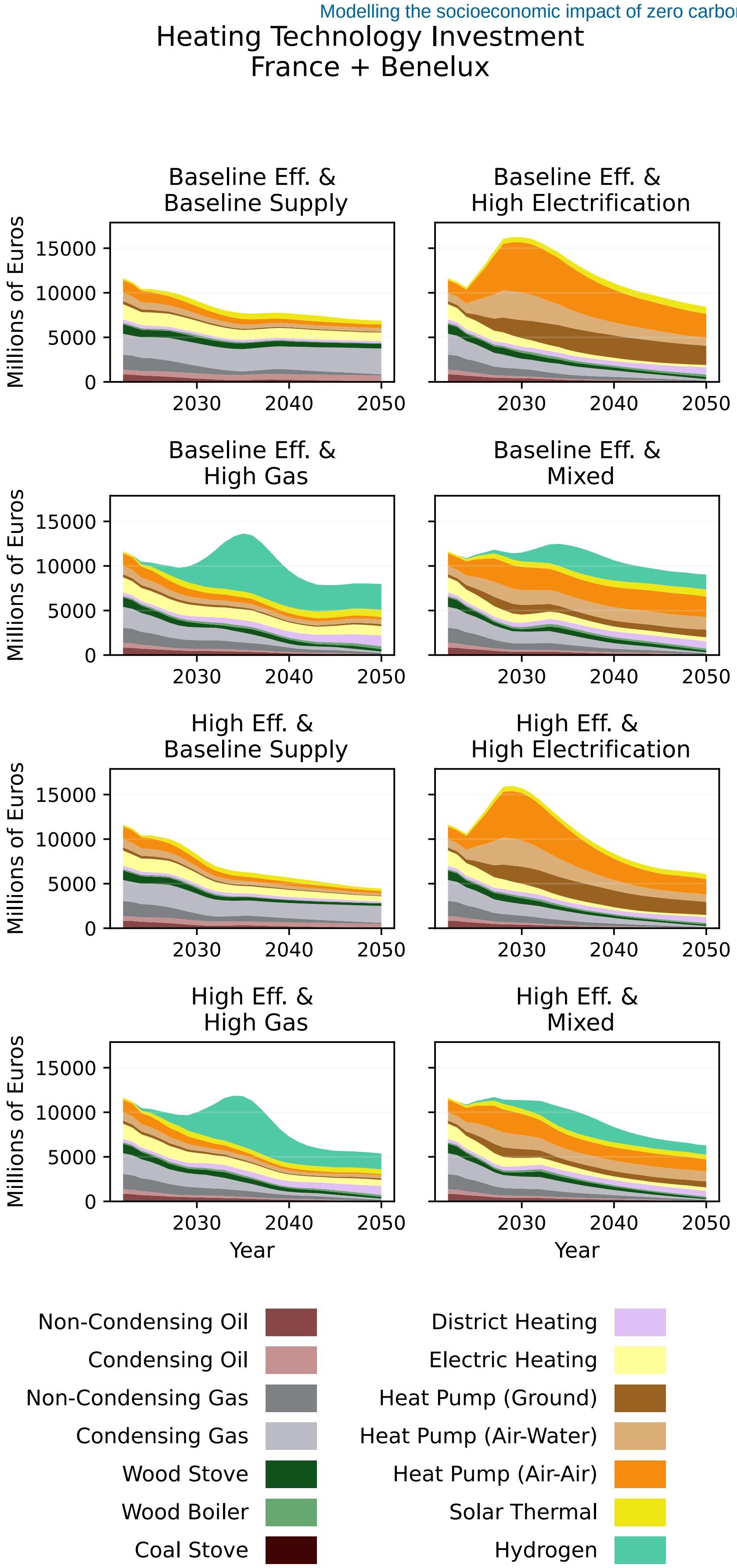

Figure B.3.4: Upfront investments in heating equipment by technology.

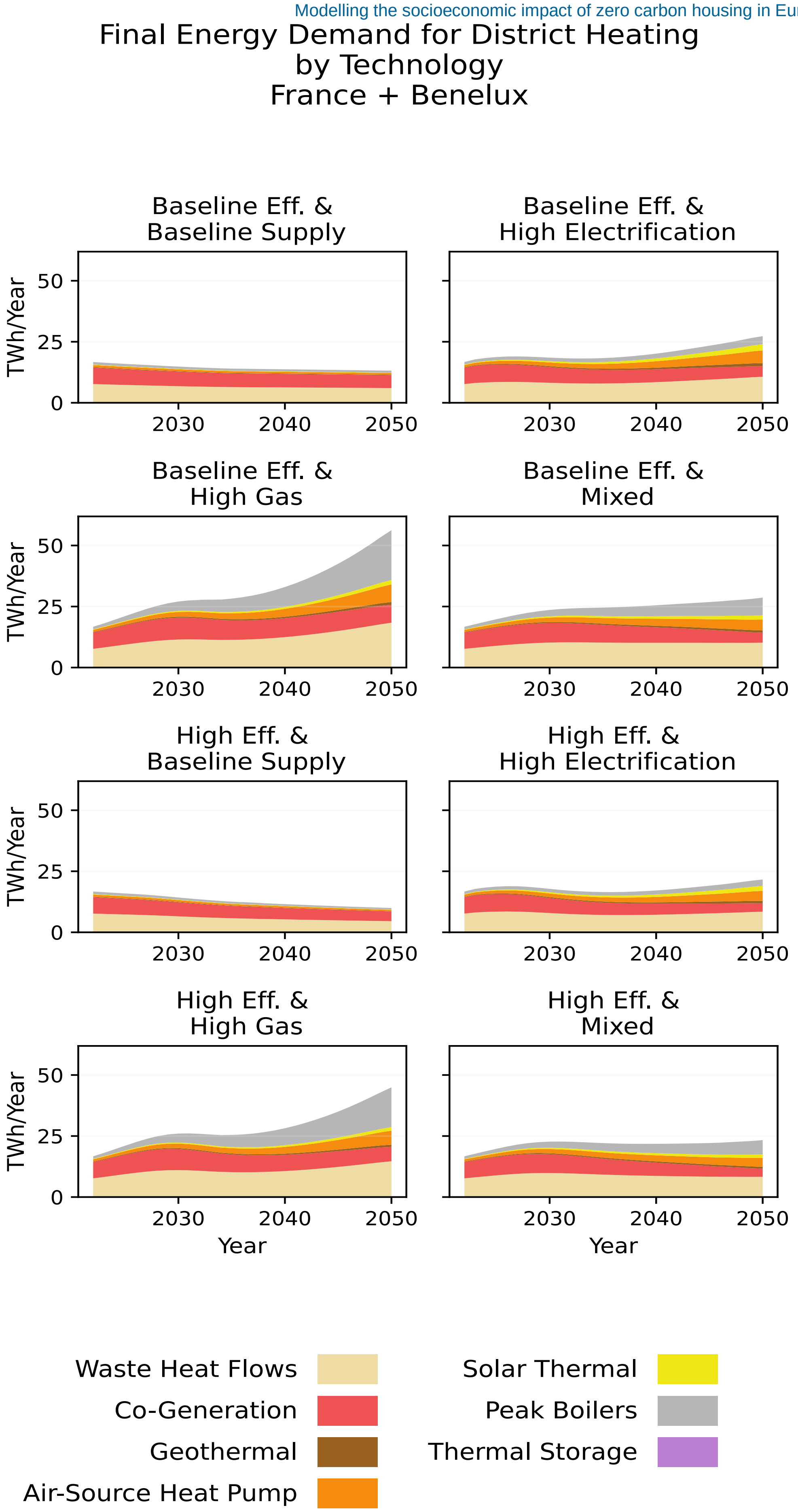

Figure B.3.5: Final energy demand in DH/C by configuration option.

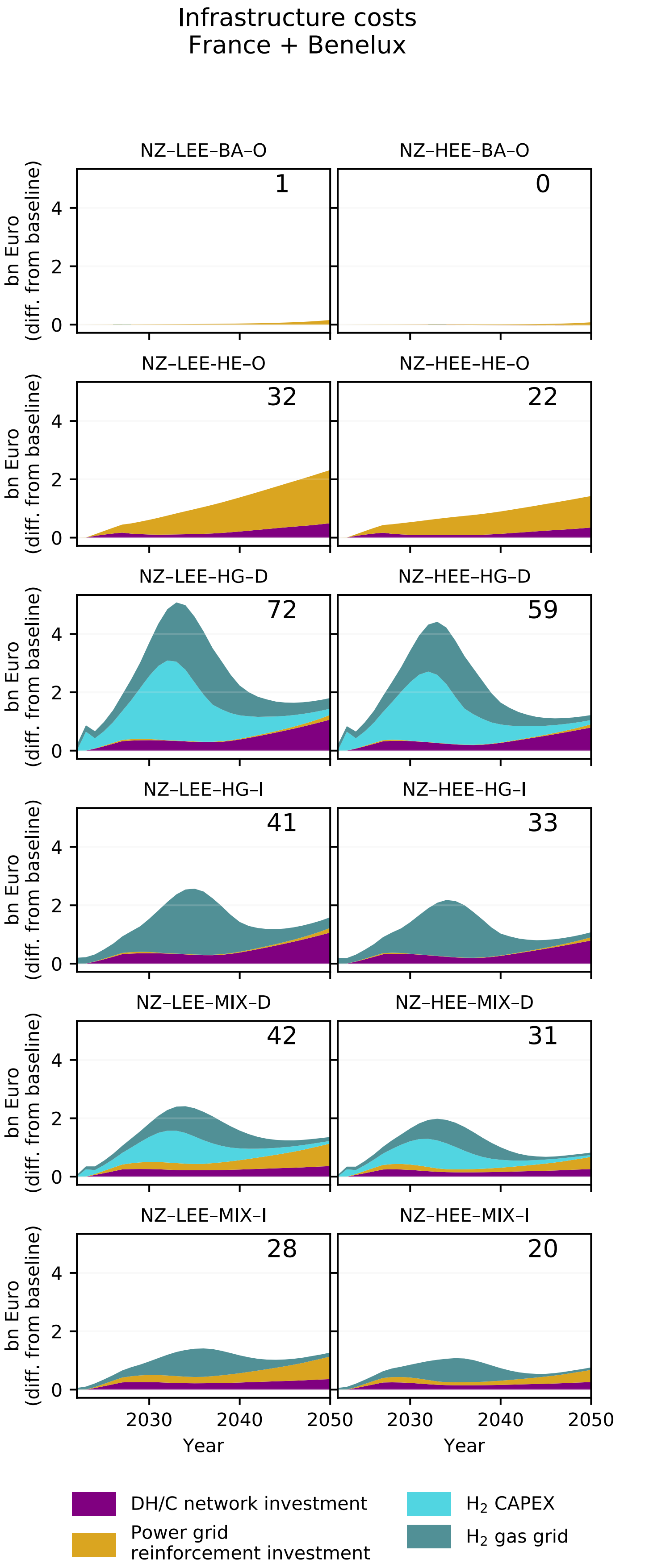

Figure B.3.6: Infrastructure investment. Numbers represent cumulative investment in billion Euro.

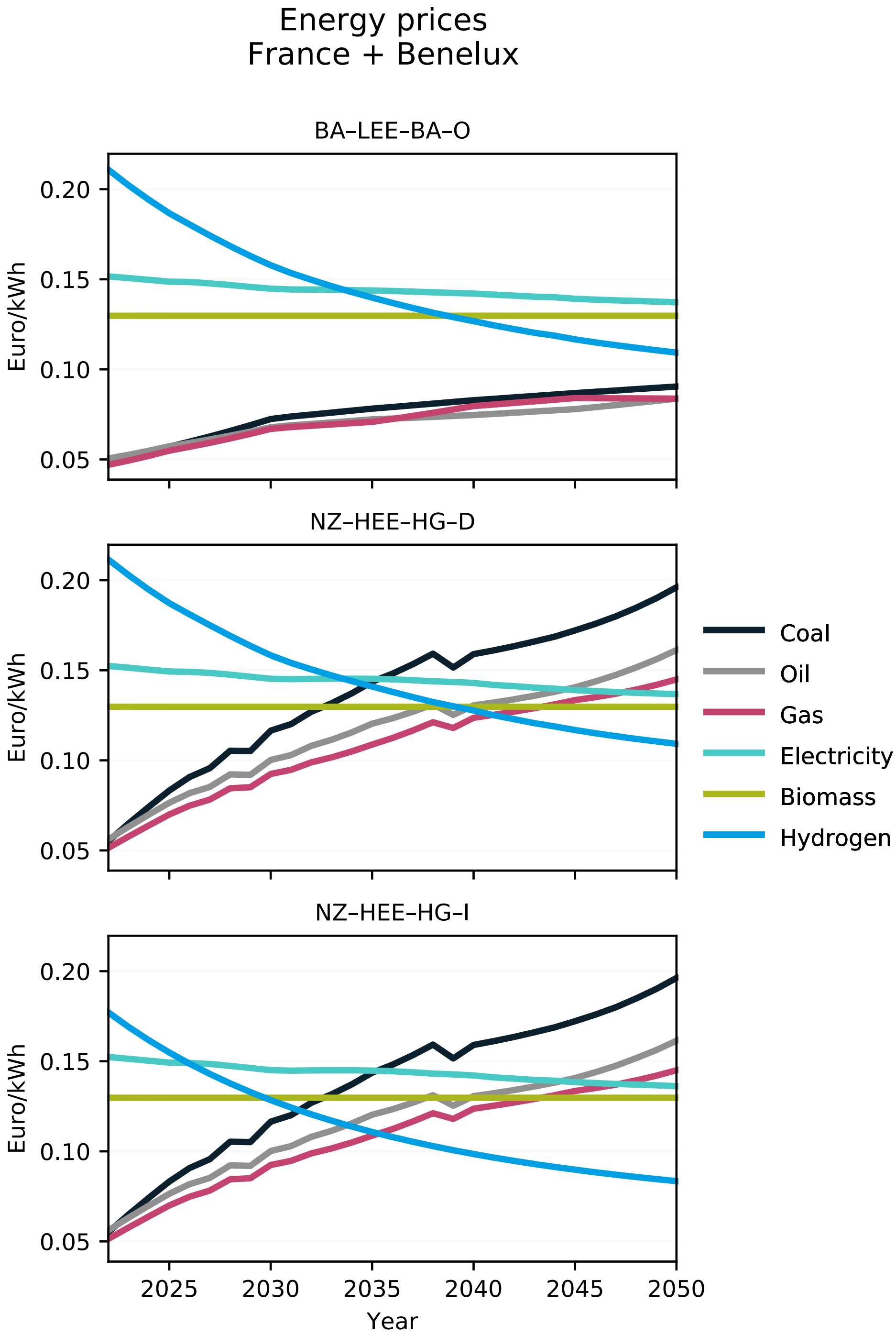

Figure B.3.7: Evolution of energy prices.

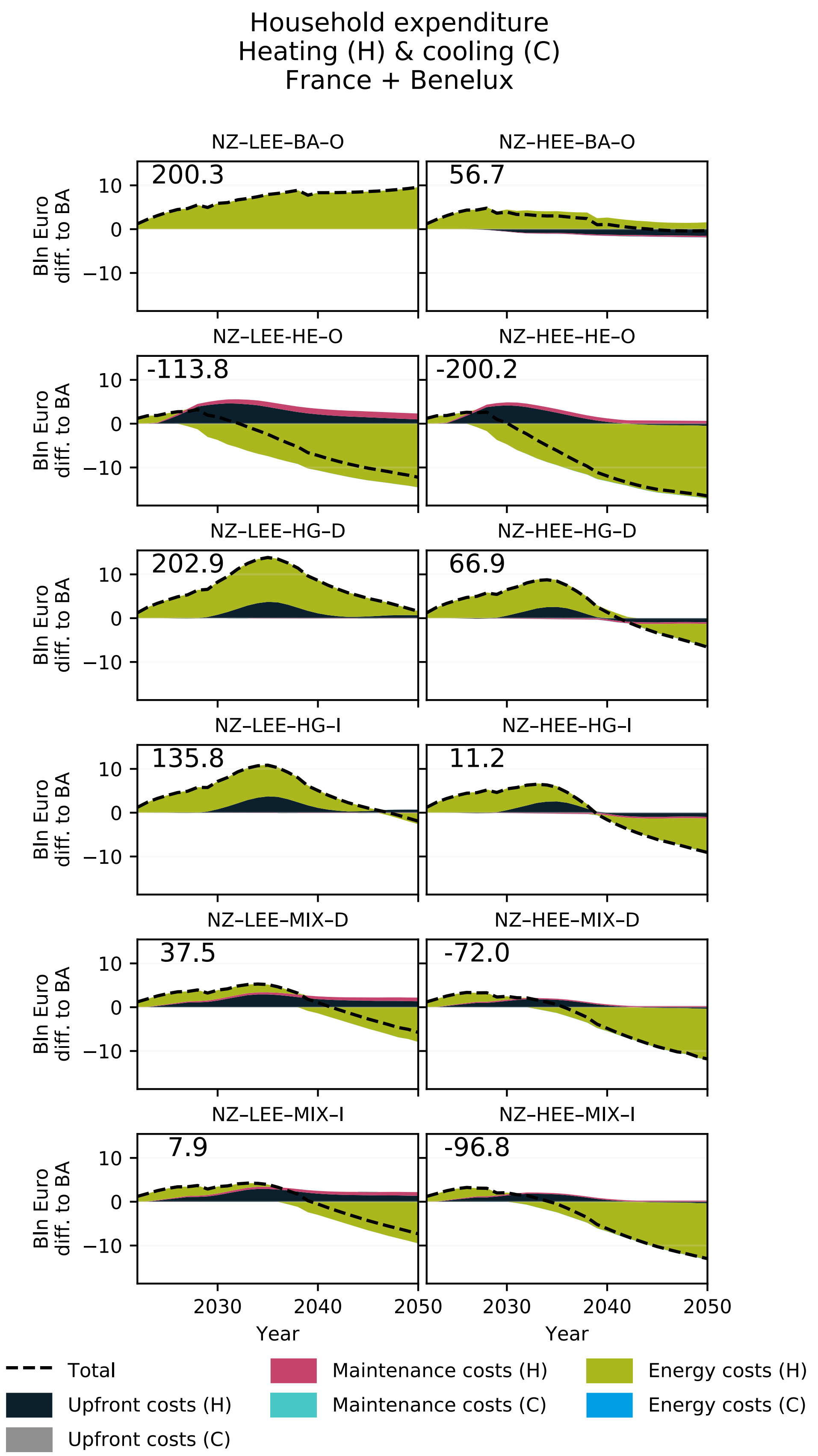

Figure B.3.8: Household expenditure on heating & cooling. Numbers represent cumulative expenditure.

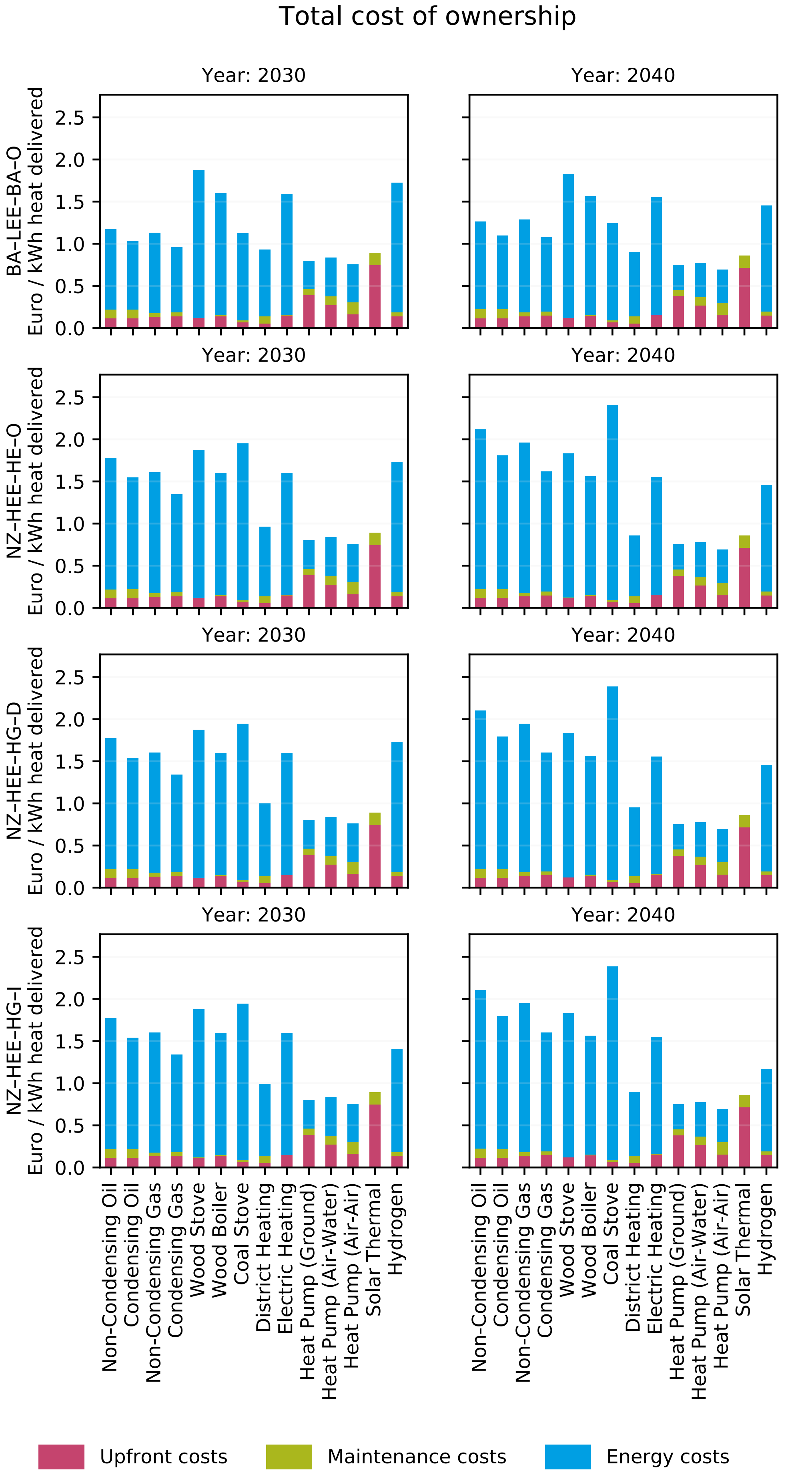

Figure B.3.9: Total cost of ownership by technology.

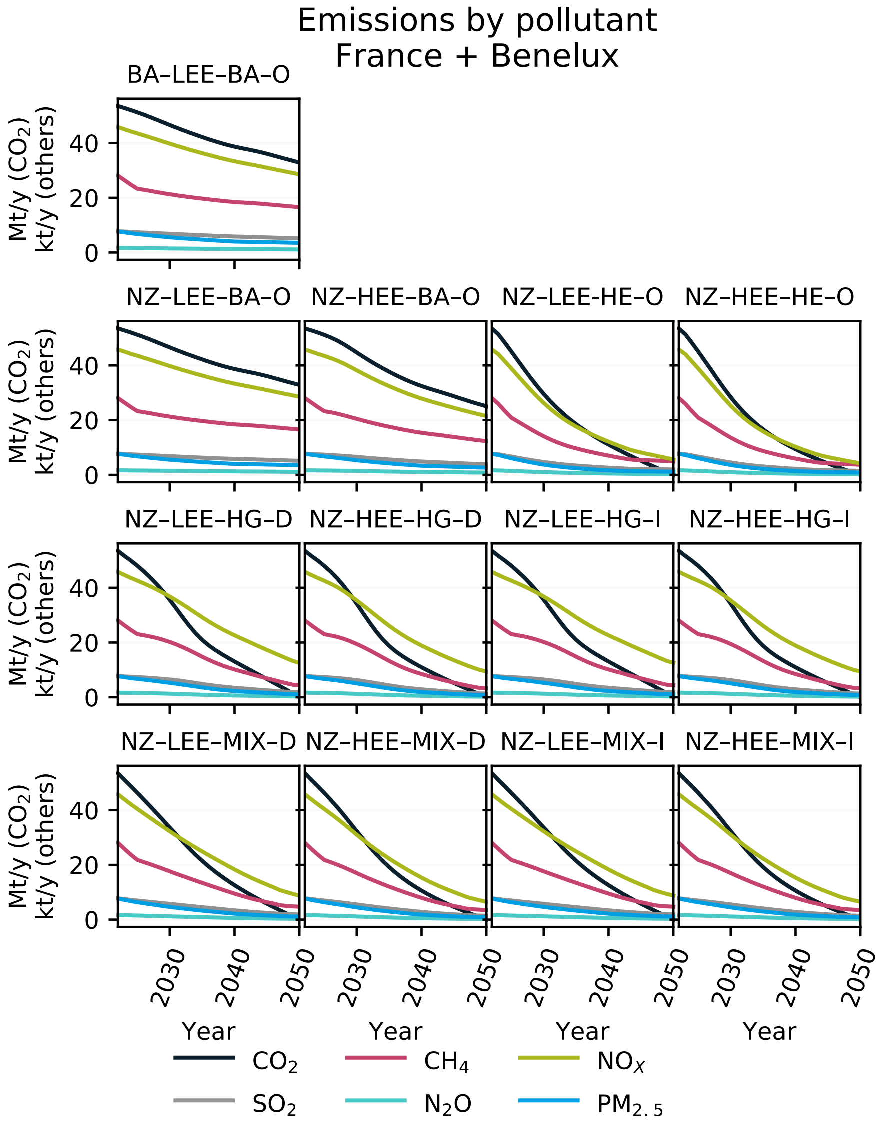

Figure B.3.10: Direct emissions by pollutant.

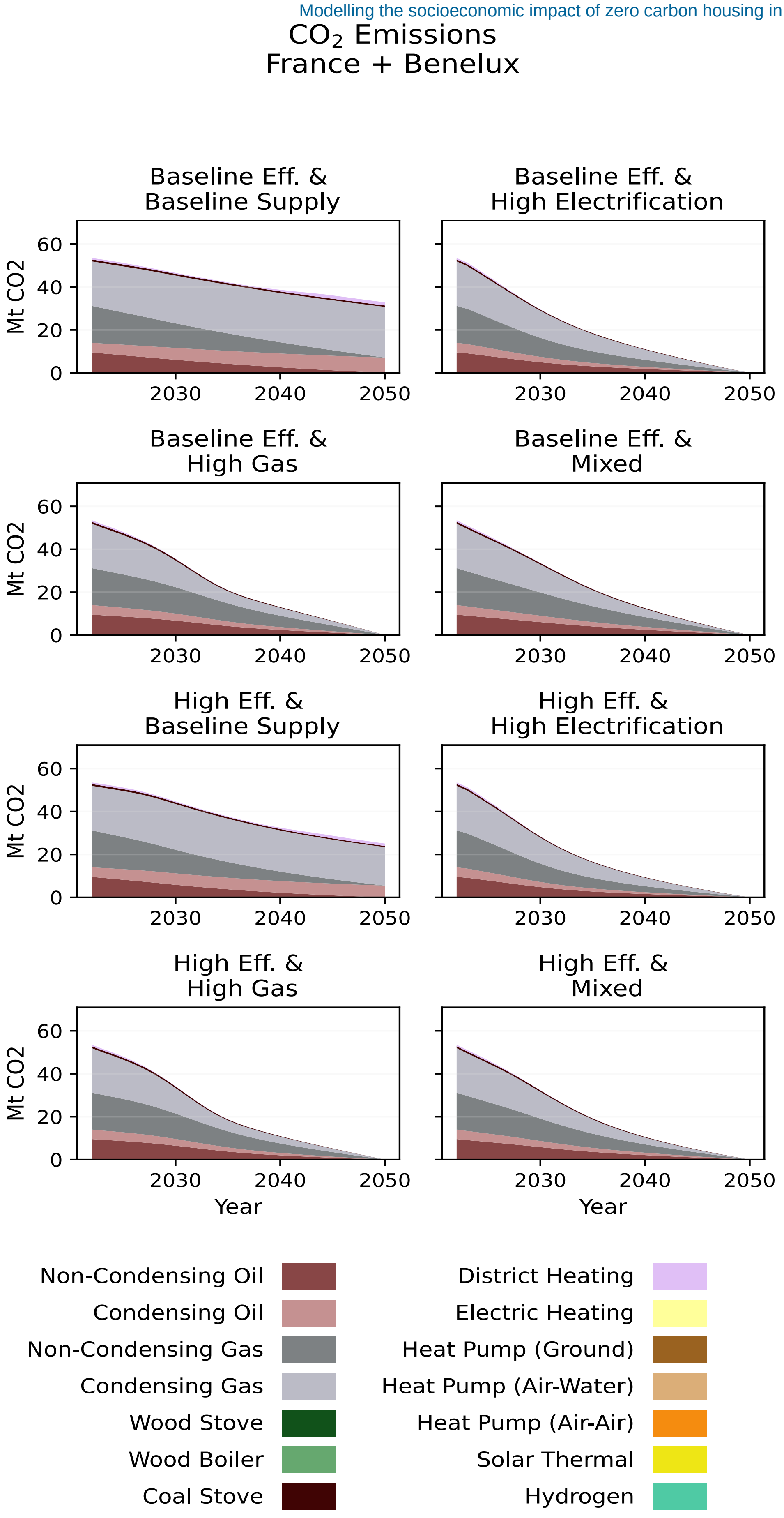

Figure B.3.11: Direct CO_2 emissions by technology.

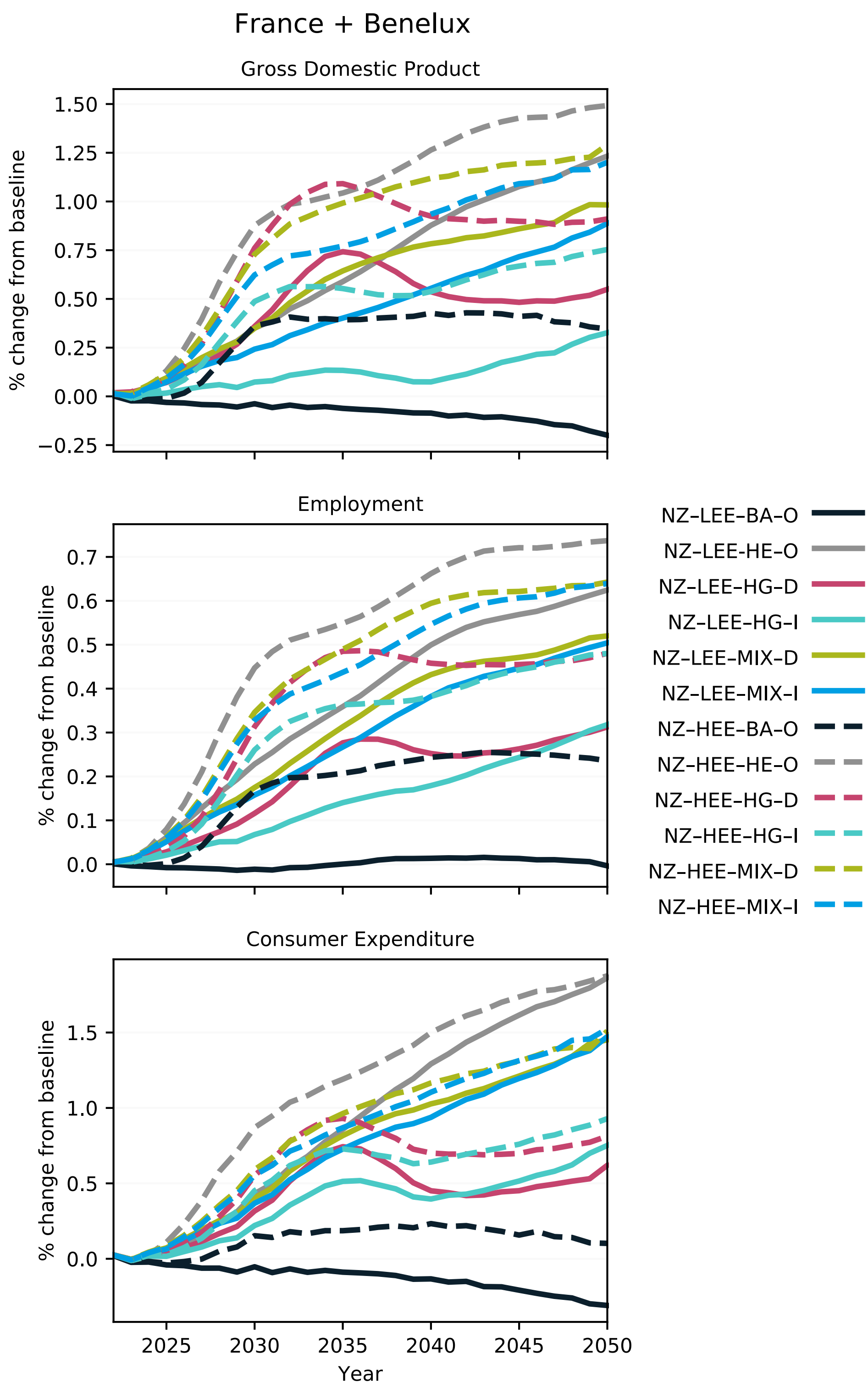

Figure B.3.12: GDP, employment, and consumer expenditure change.

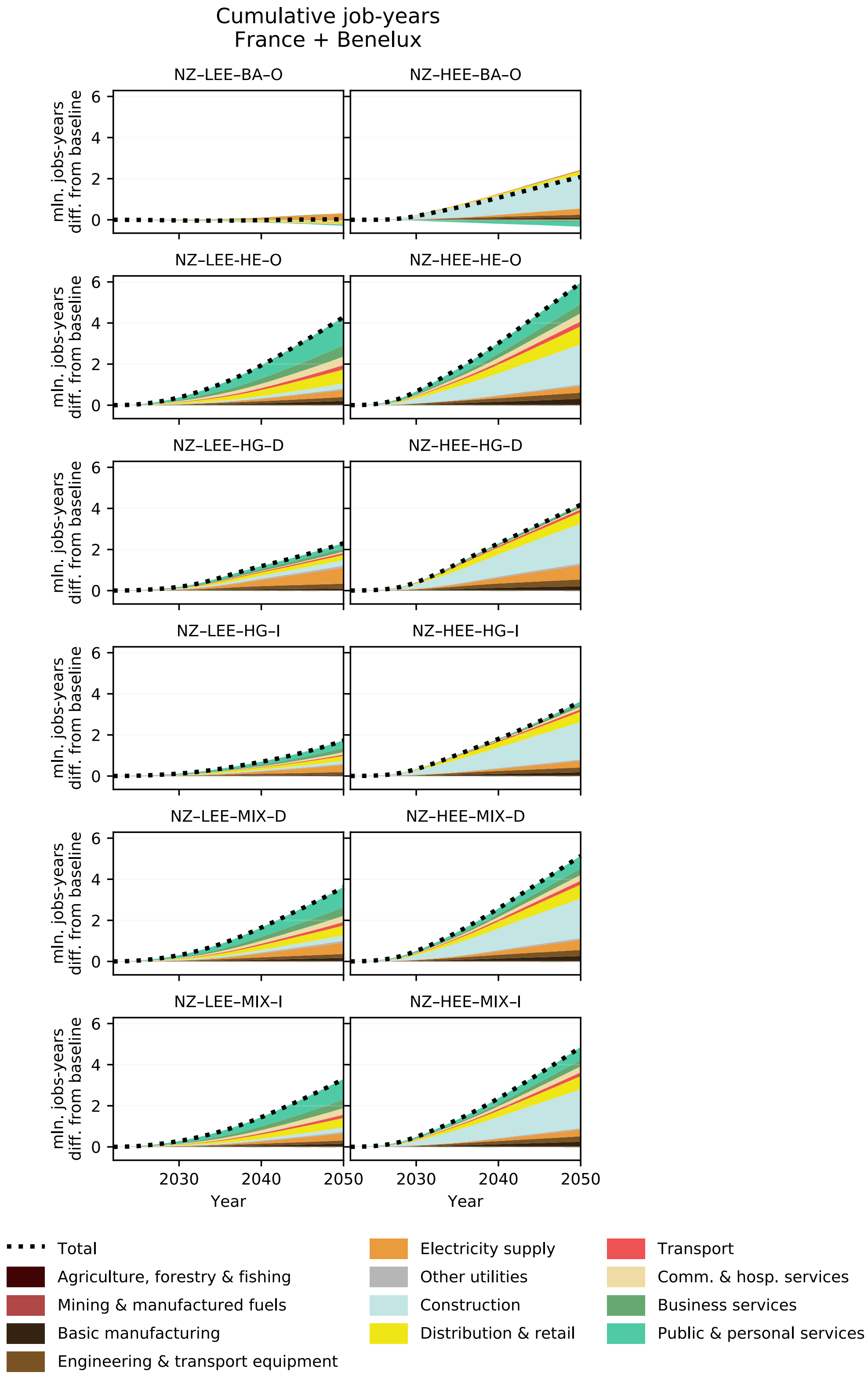

Figure B.3.13: Cumulative job-years change by sector.

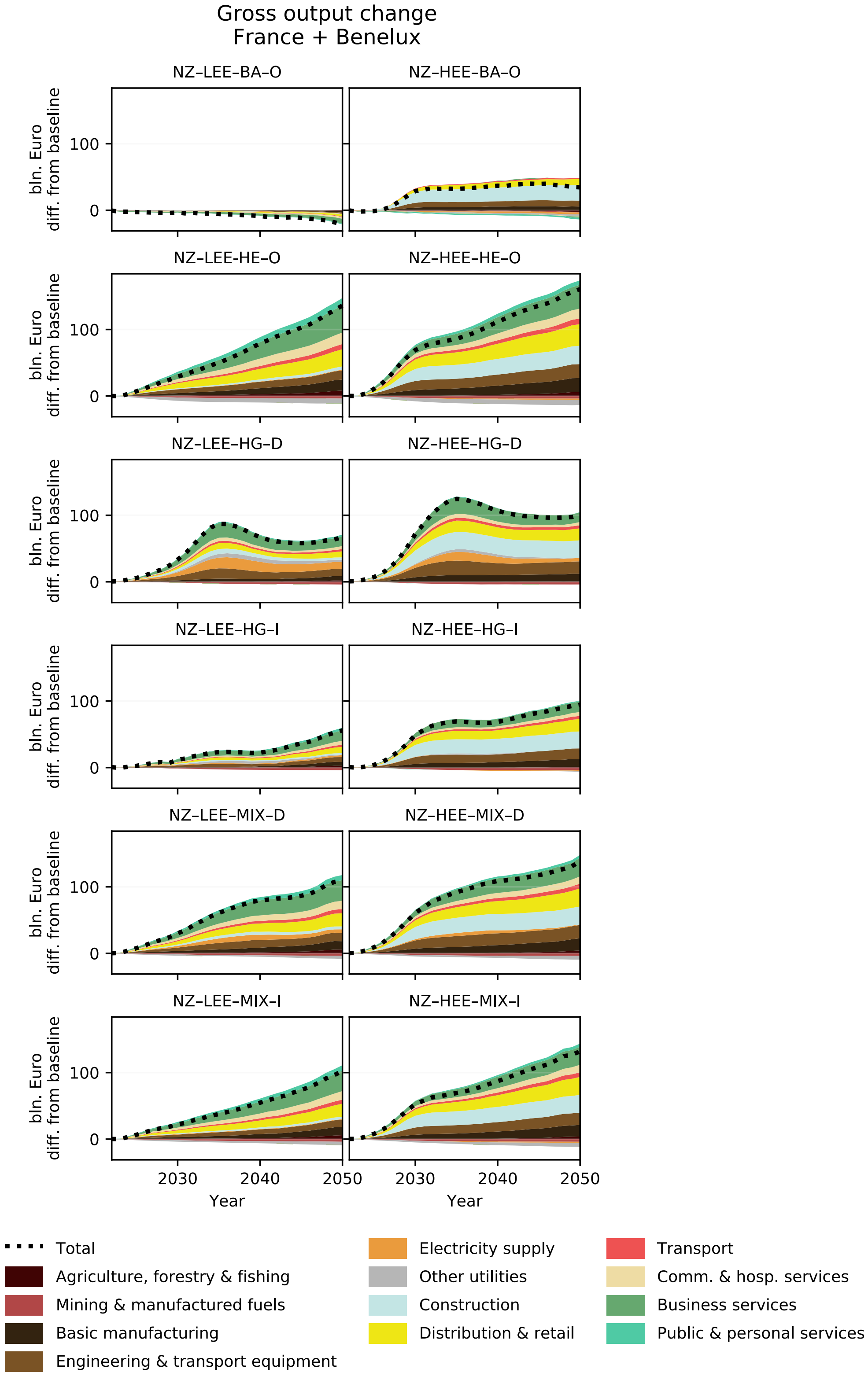

Figure B.3.14: Gross output change by sector.

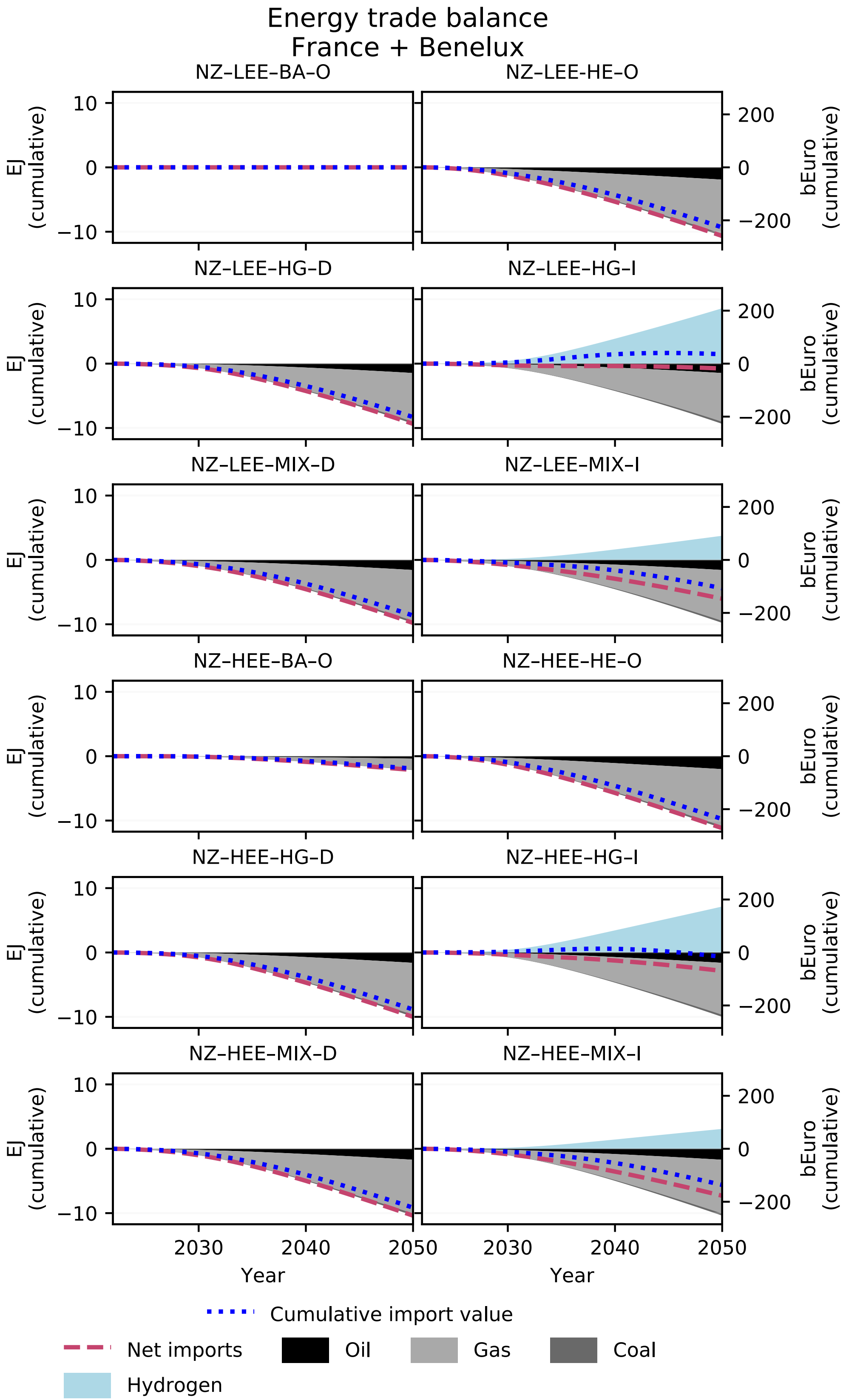

Figure B.3.15: Energy trade balance change by energy carrier.

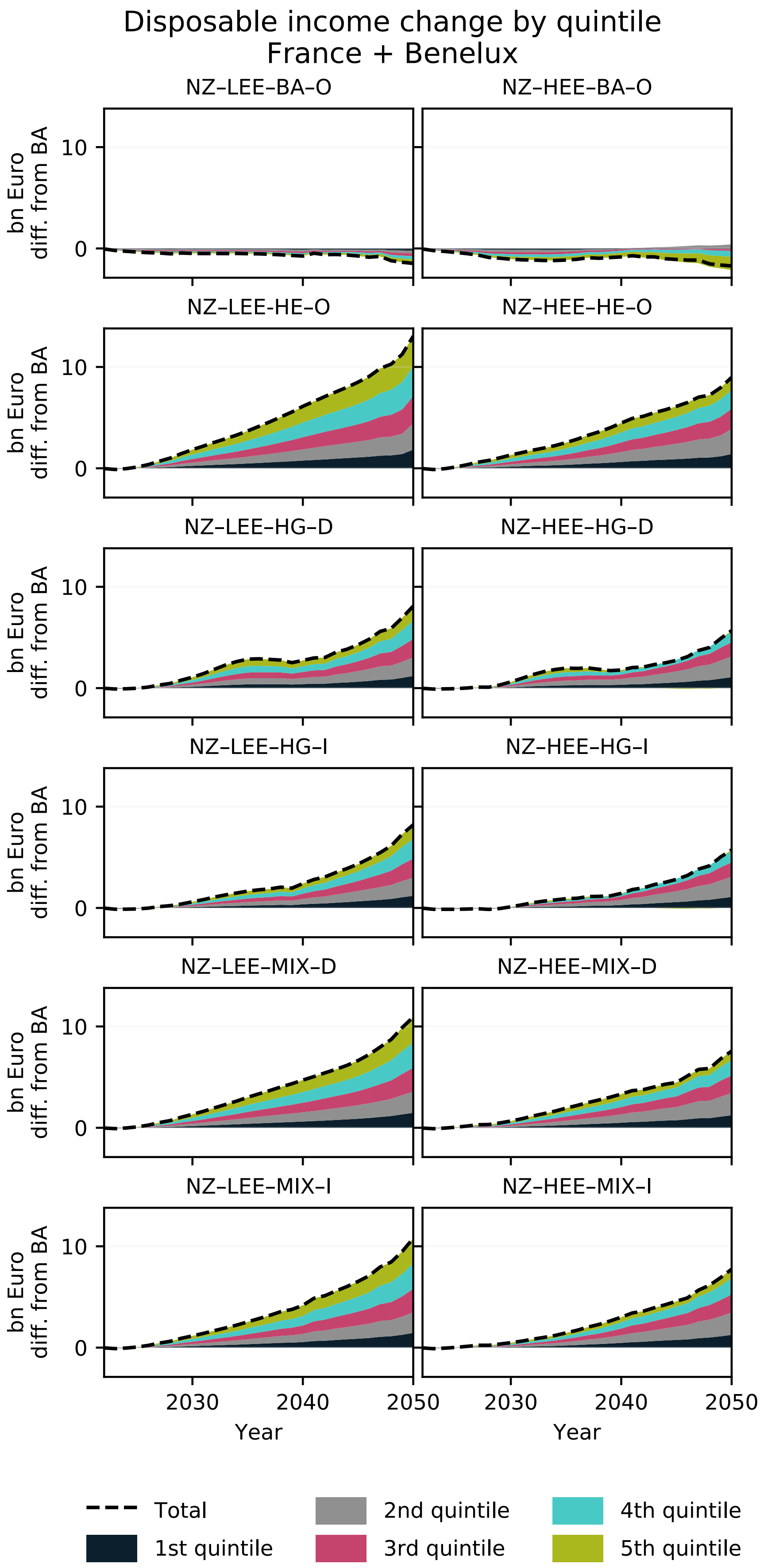

Figure B.3.16: Disposable income change by income quintile.

Climate zone: Central Europe

Central Europe sees a modest uptake in district heating technologies as well as hydrogen in the applicable scenarios. These results are mostly driven by changes happening in Germany. Hydrogen infrastructure see a peak in 2035, while investments into heat pumps are front loaded, with majority of the investments occurring by 2030. In the longer term, the investment into renovations and changes in the heating technologies will cut consumer expenditure on energy, seeing notable effects by 2040.

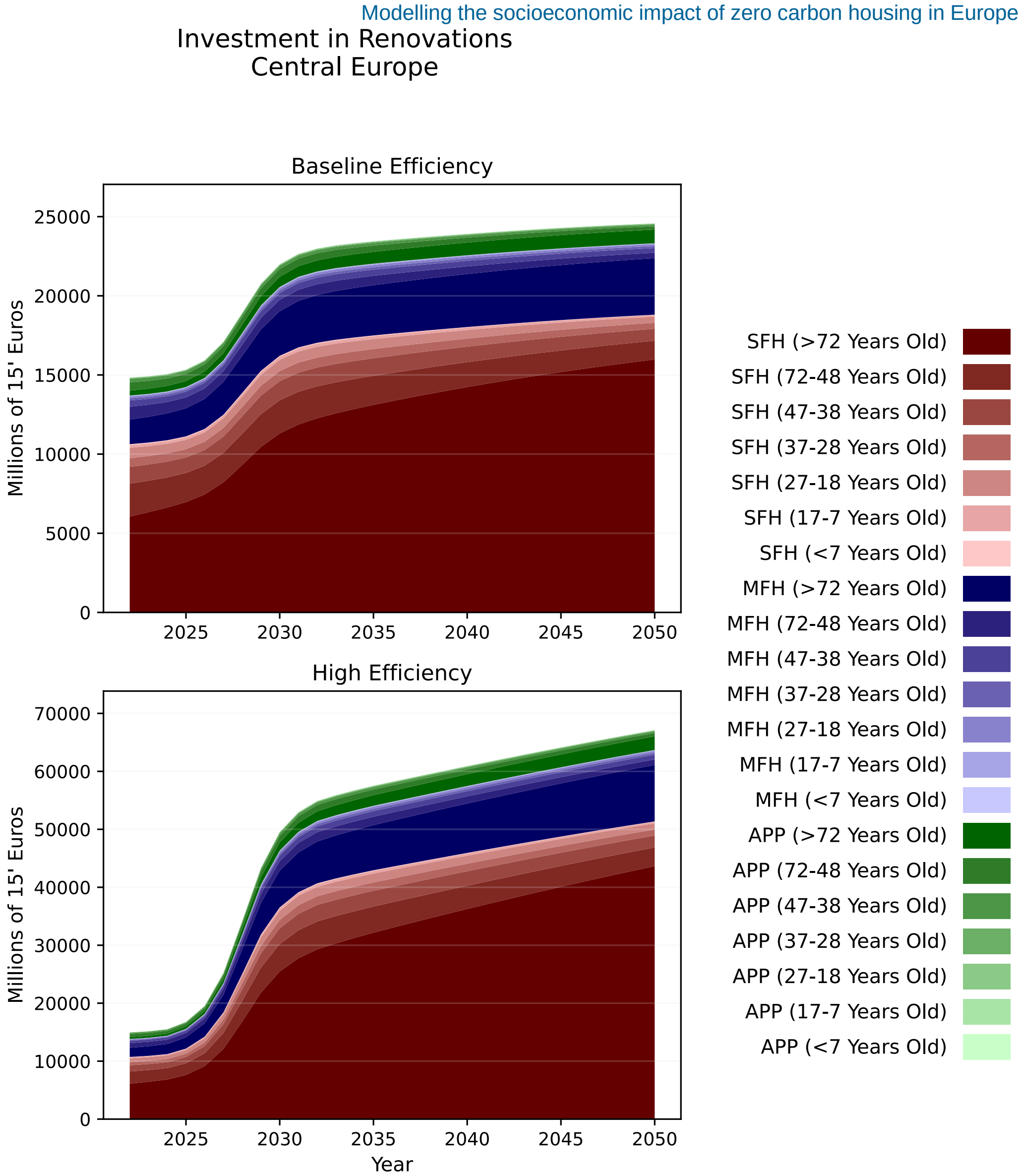

Figure B.4.1: Investments into renovations.

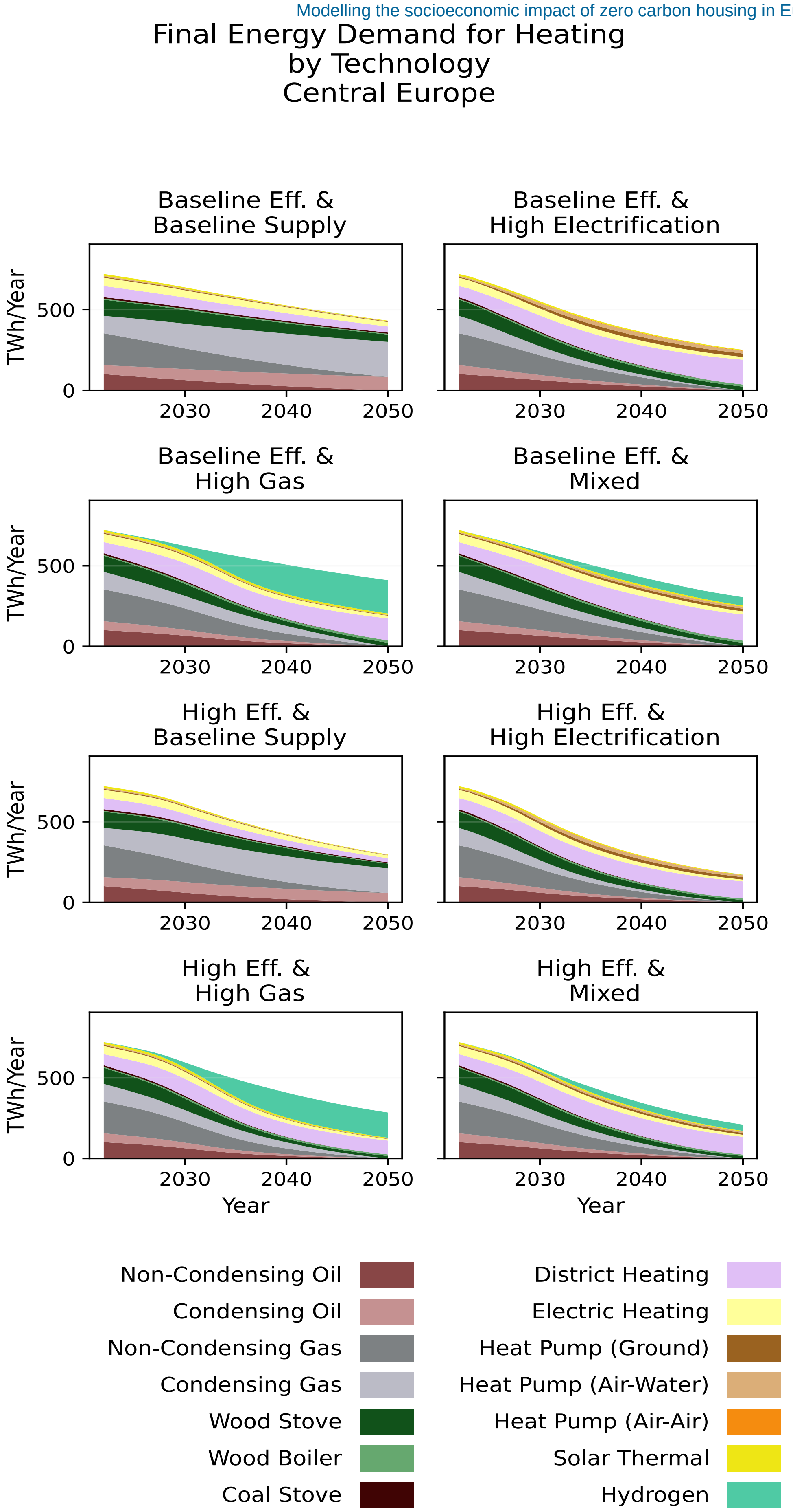

Figure B.4.2: Final energy demand by technology.

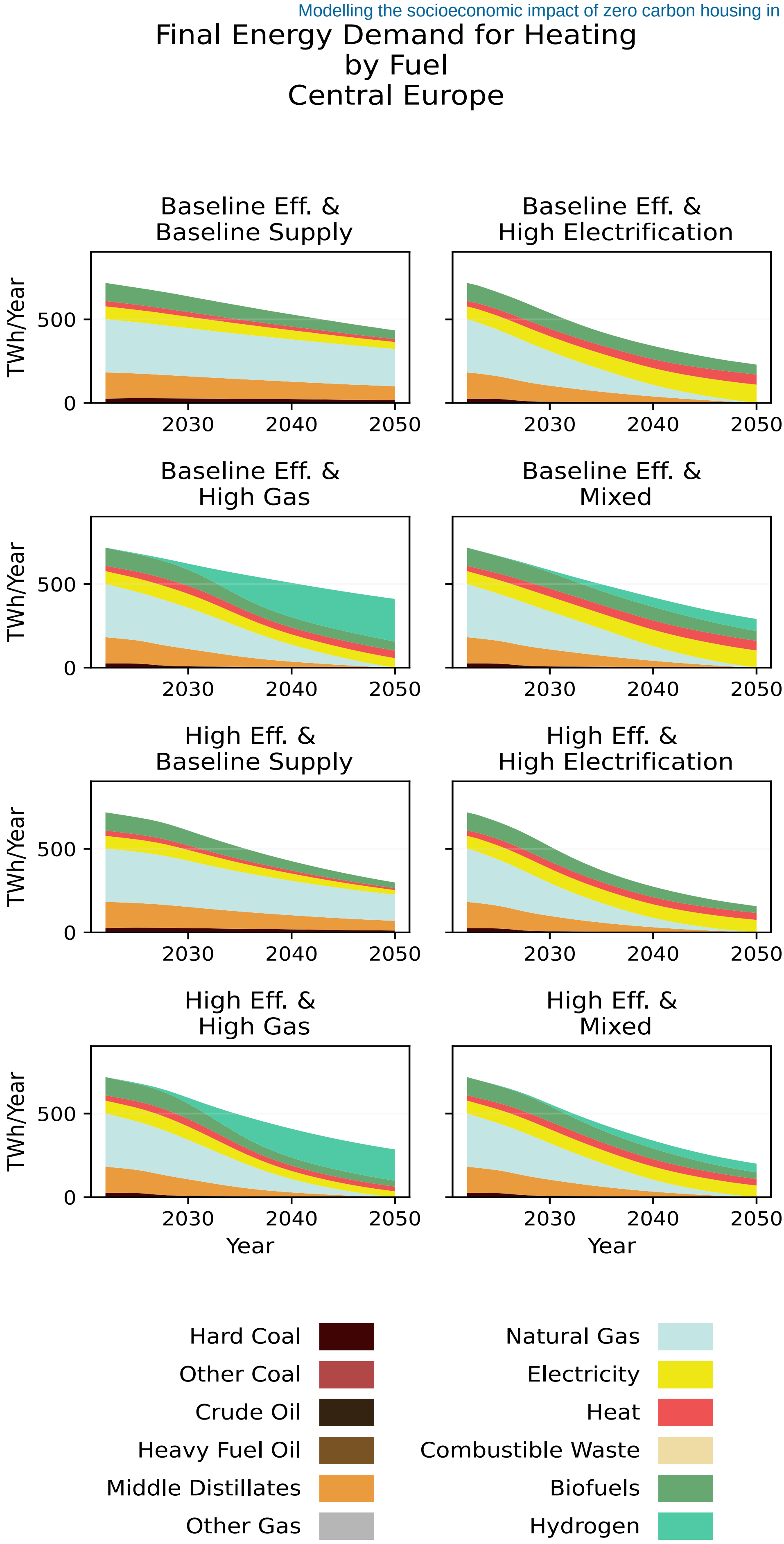

Figure B.4.3: Final energy demand by energy carrier.

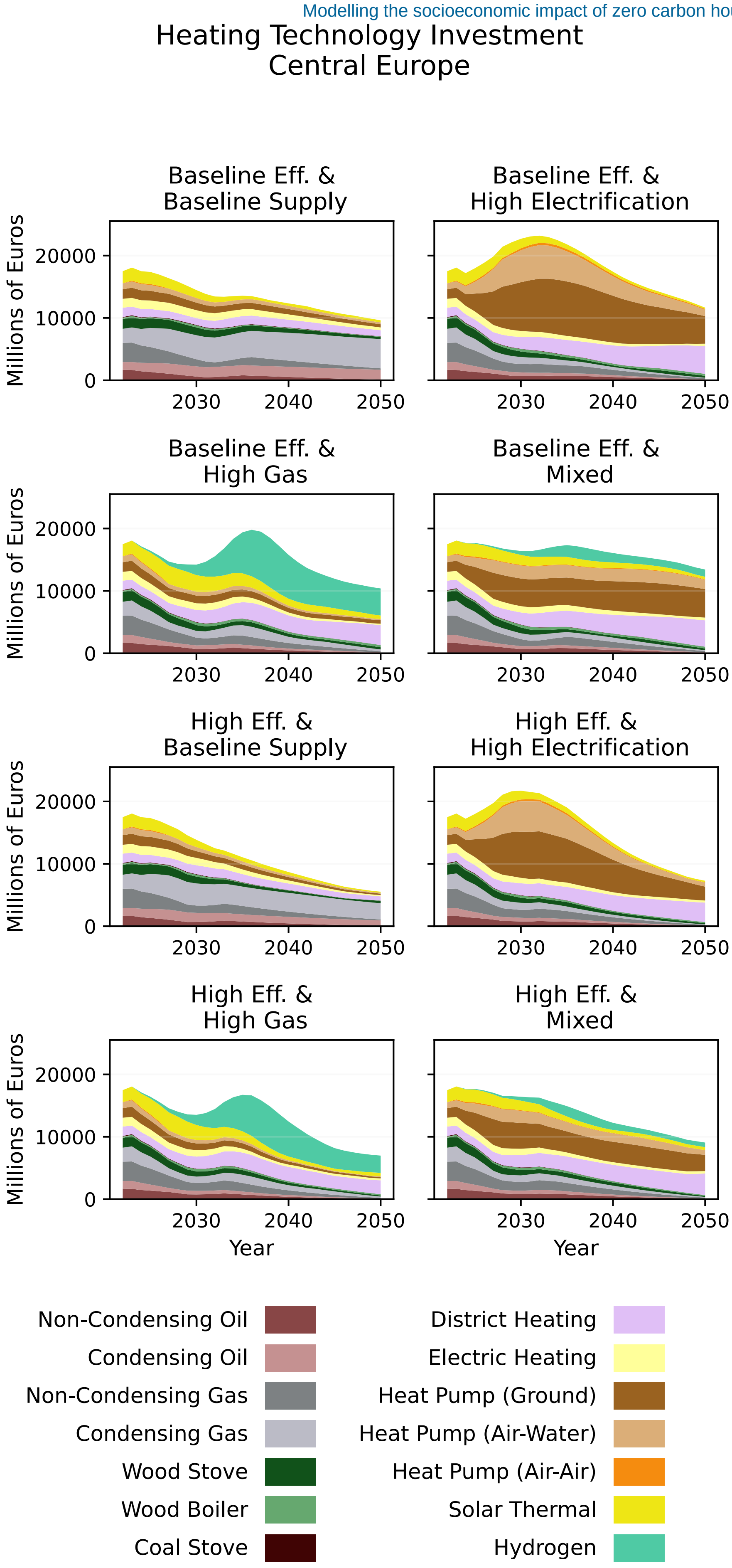

Figure B.4.4: Upfront investment in heating equipment.

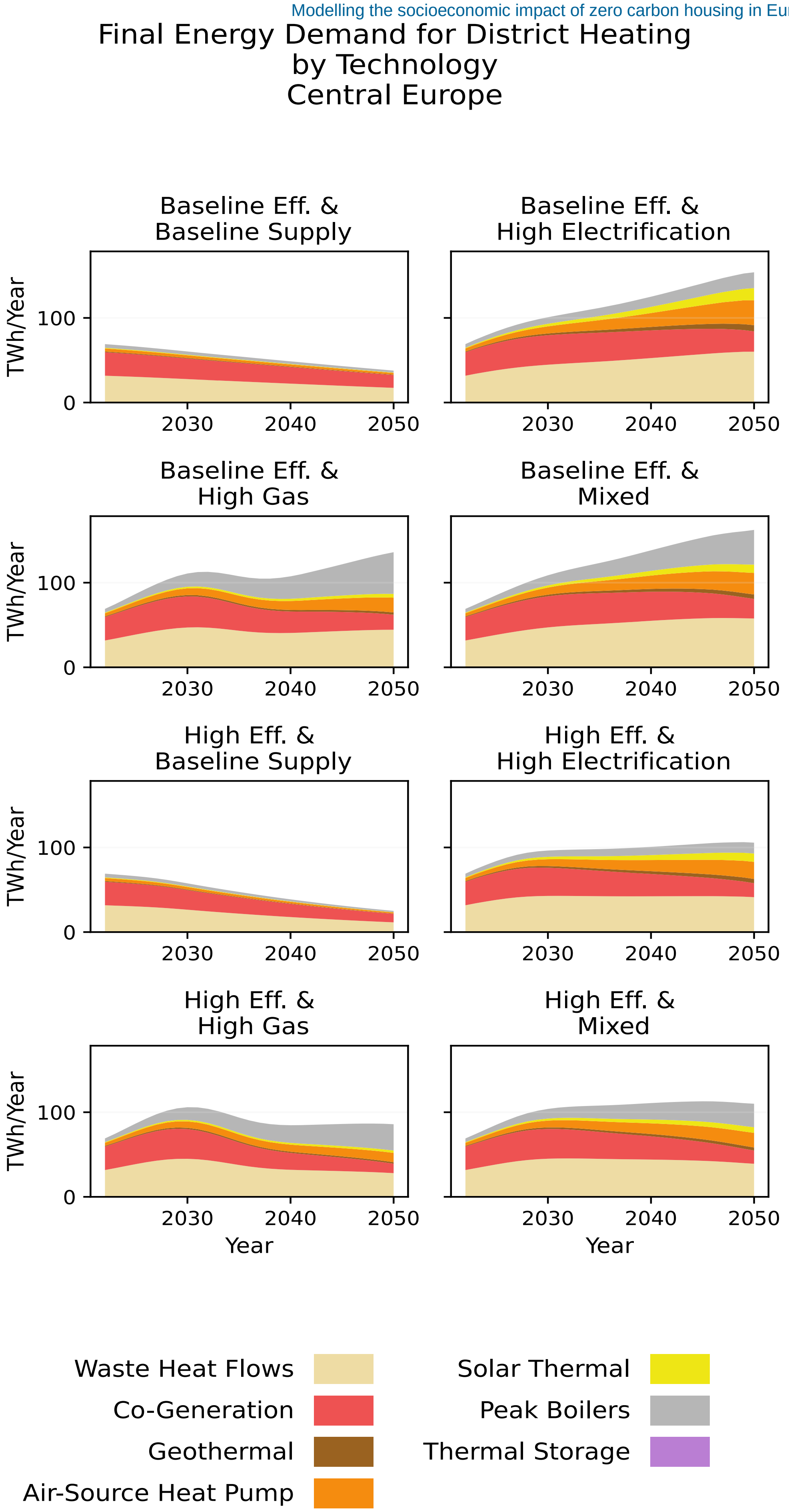

Figure B.4.5: Final energy demand in DH/C by configuration option.

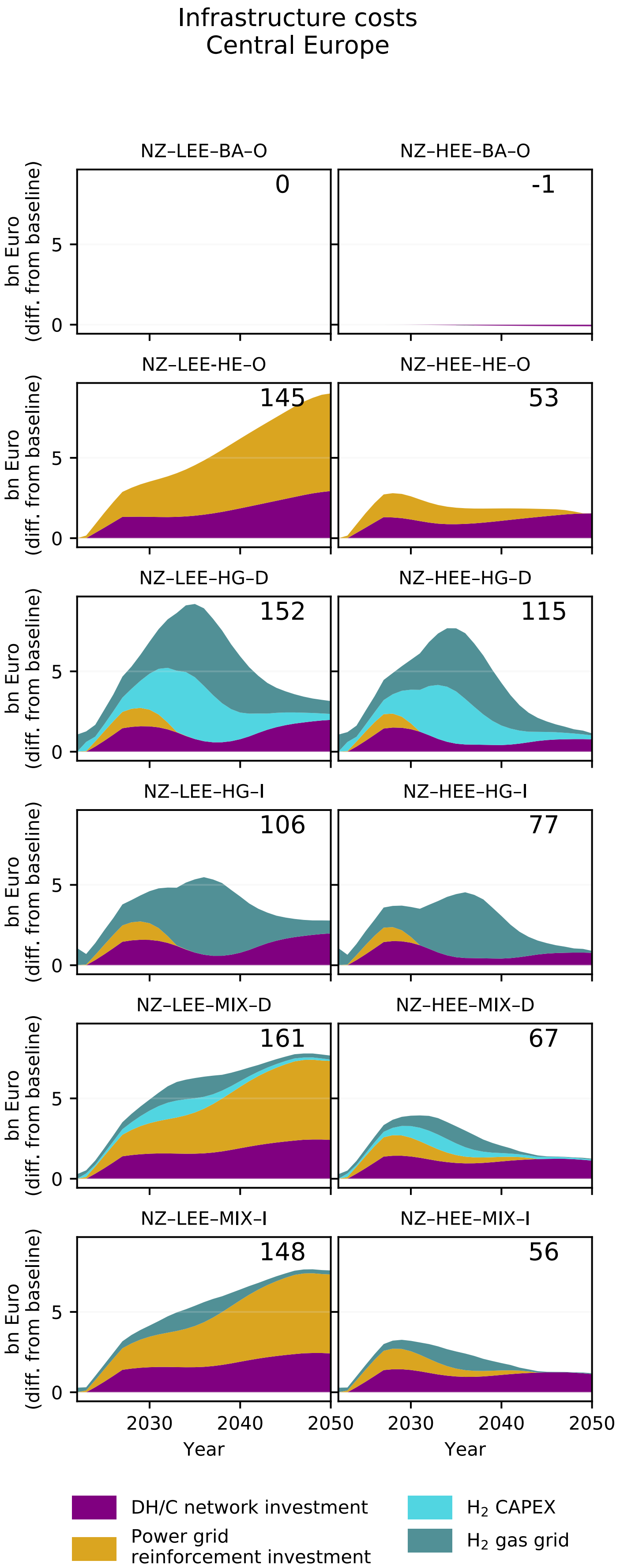

Figure B.4.6: Infrastructure investments. Numbers represent cumulative investment in billion Euro.

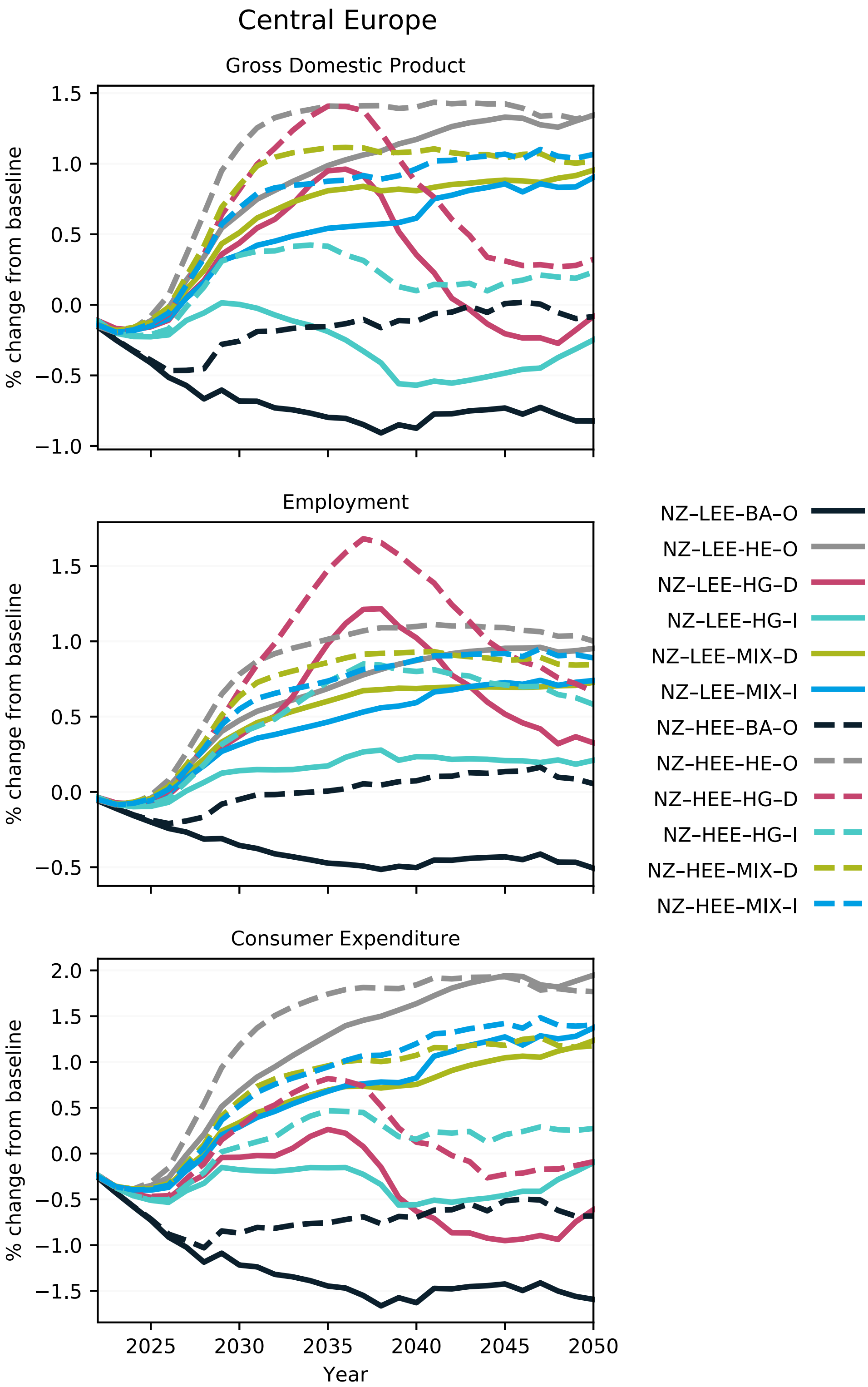

Figure B.4.7: GDP, employment, and consumer expenditure change.

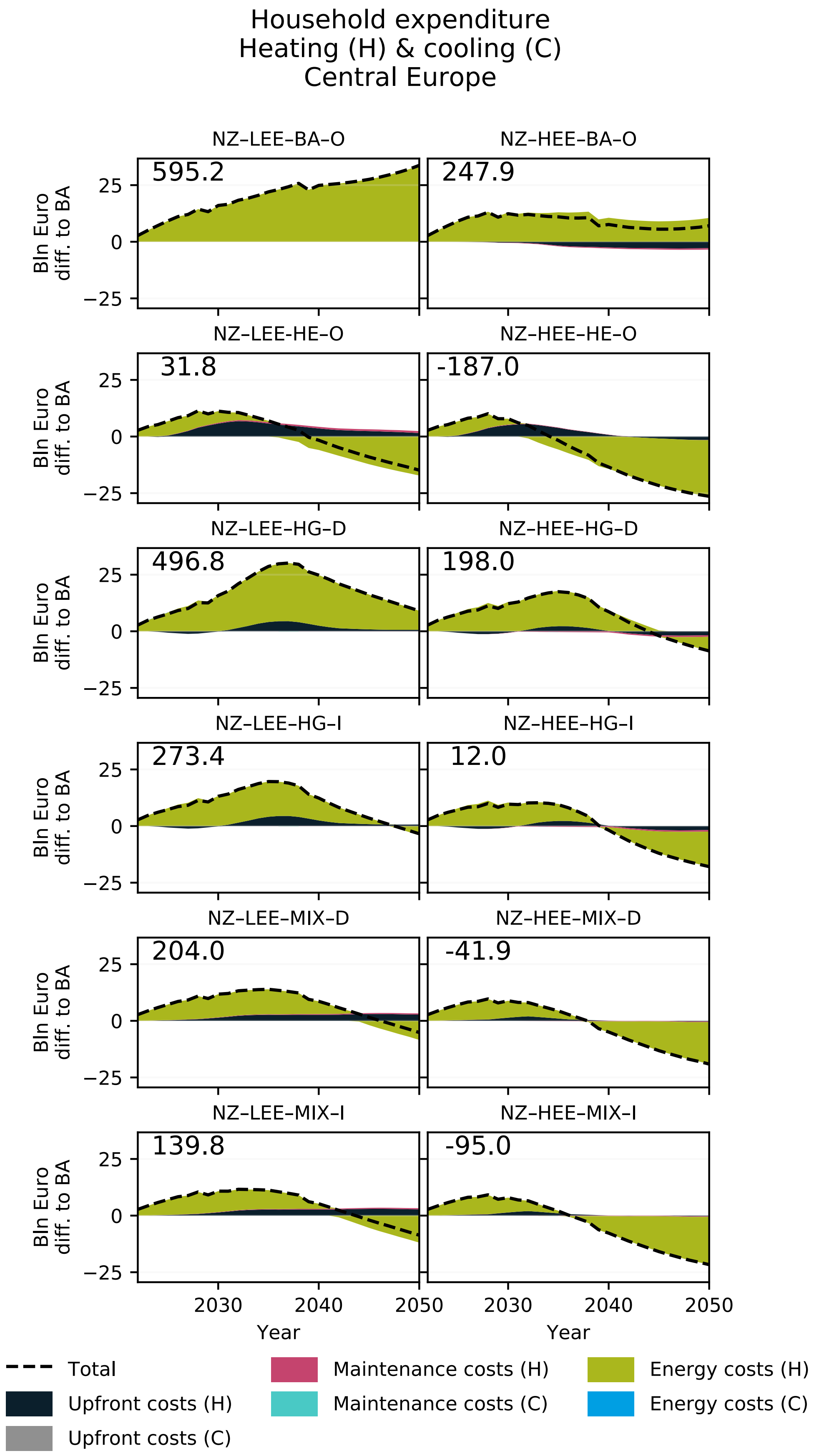

Figure B.4.8: Household expenditure change in heating & cooling. Numbers represent cumulative expenditure in billion Euro.

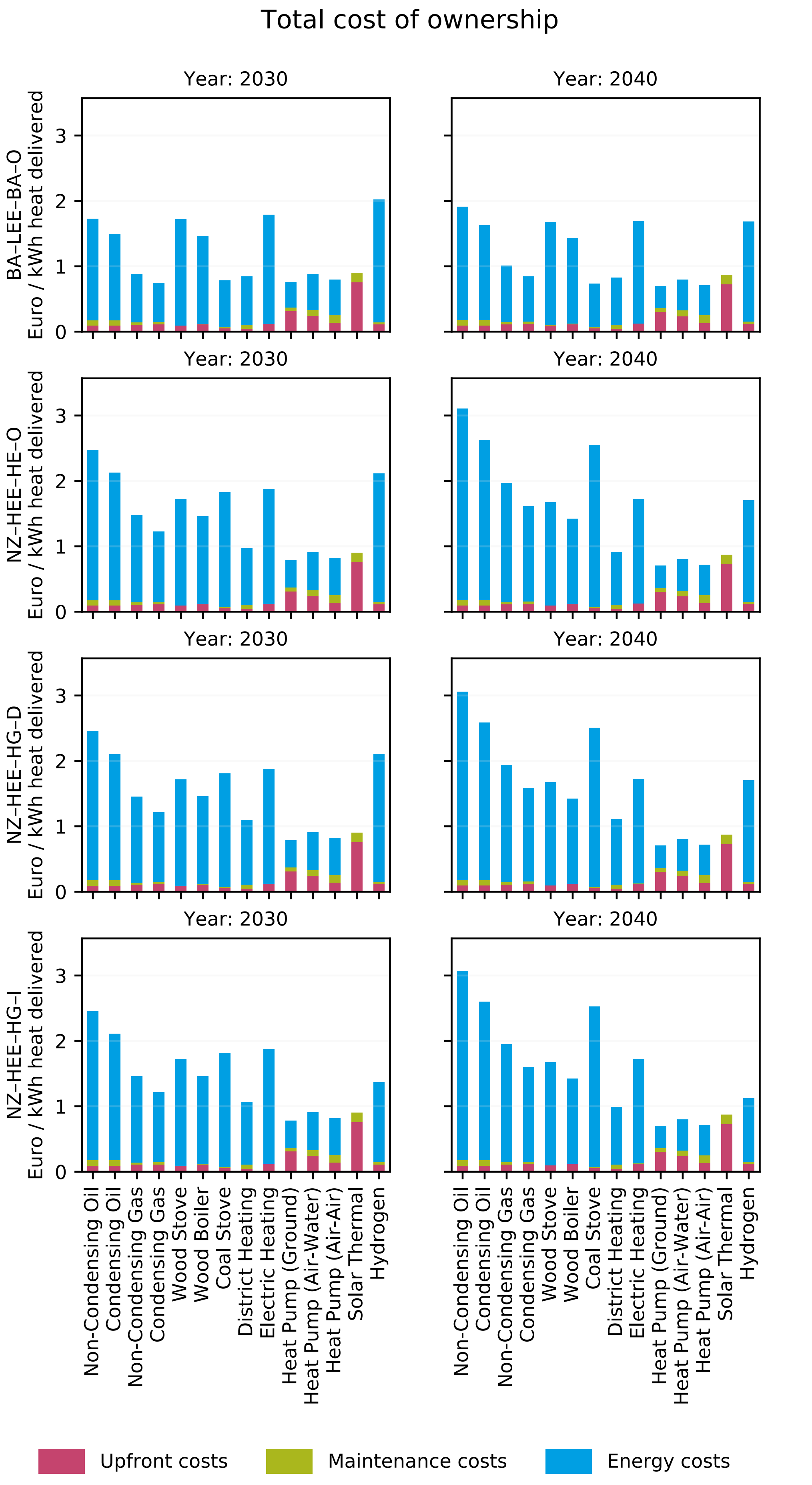

Figure B.4.9: Total cost of ownership by technology.

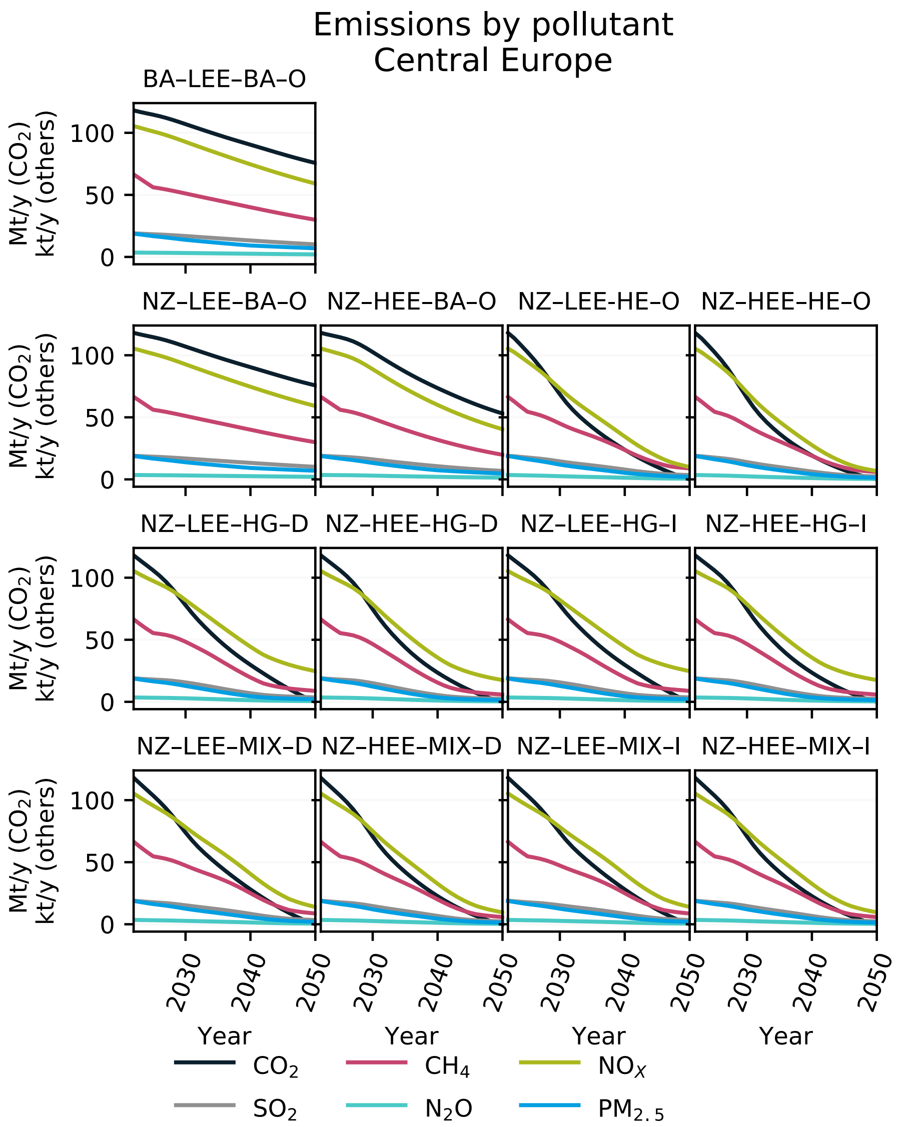

Figure B.4.10: Direct emissions by pollutant.

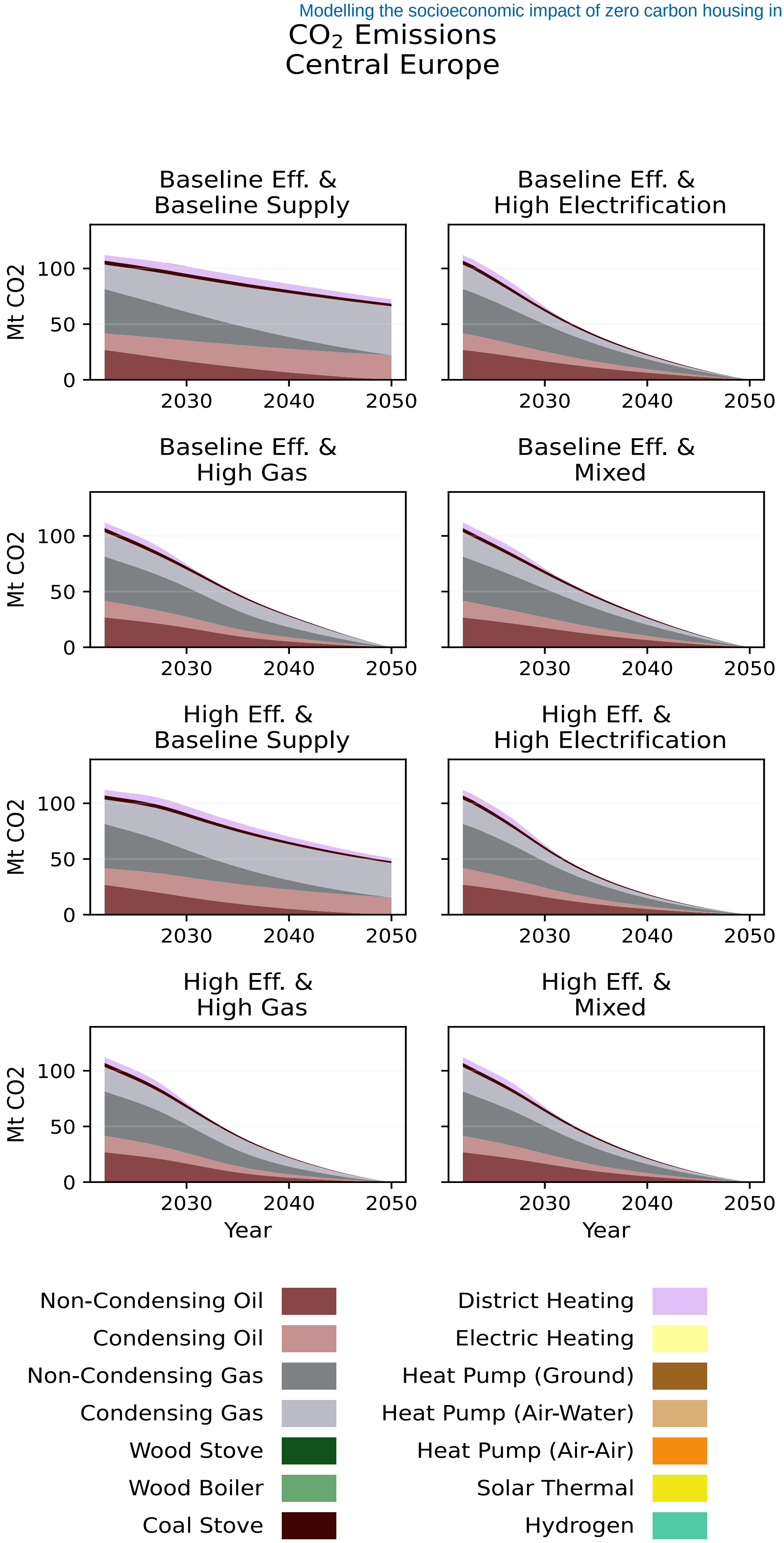

Figure B.4.11: Direct CO_2 emissions by technology.

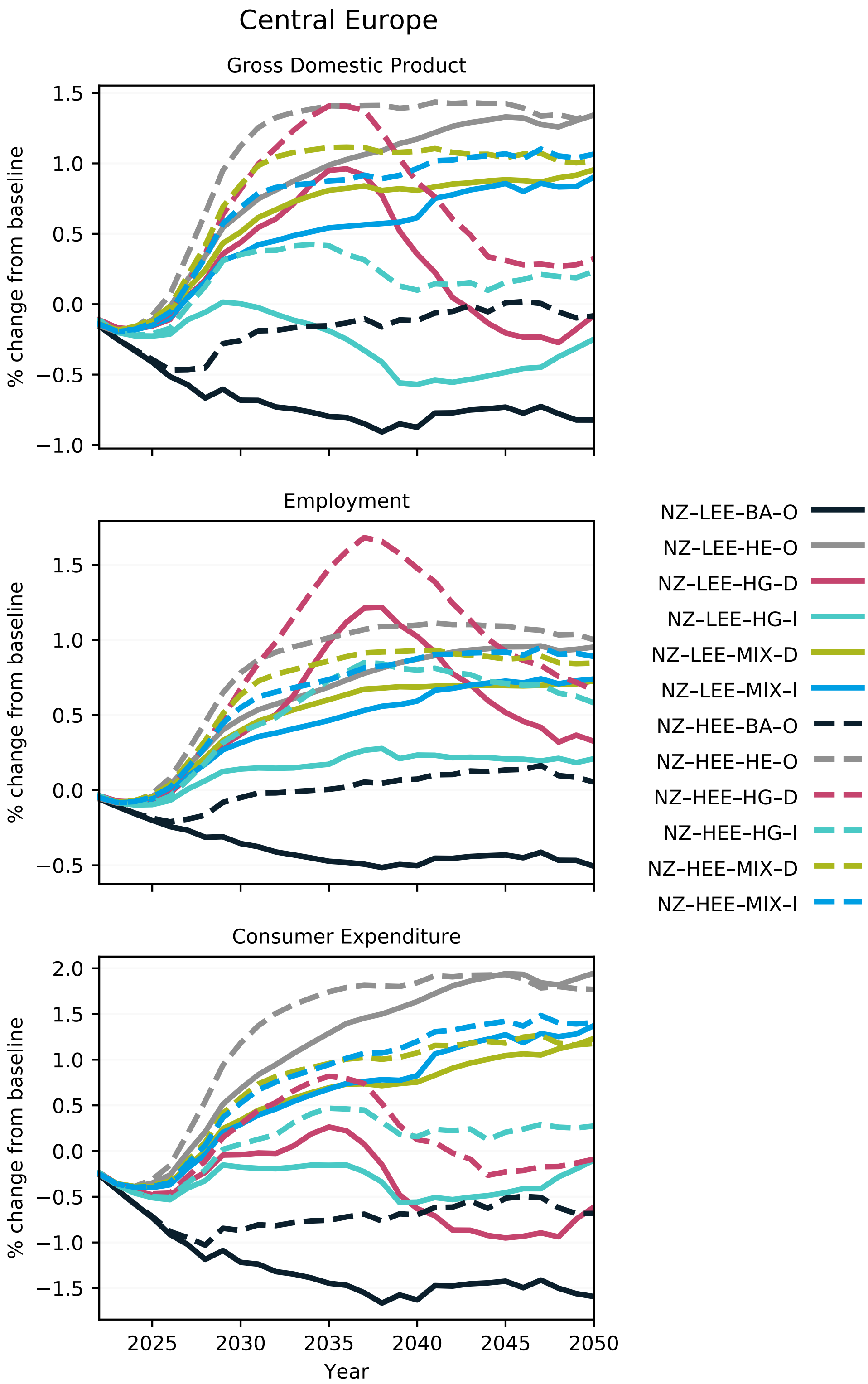

Figure B.4.12: GDP, employment, and consumer expenditure change.

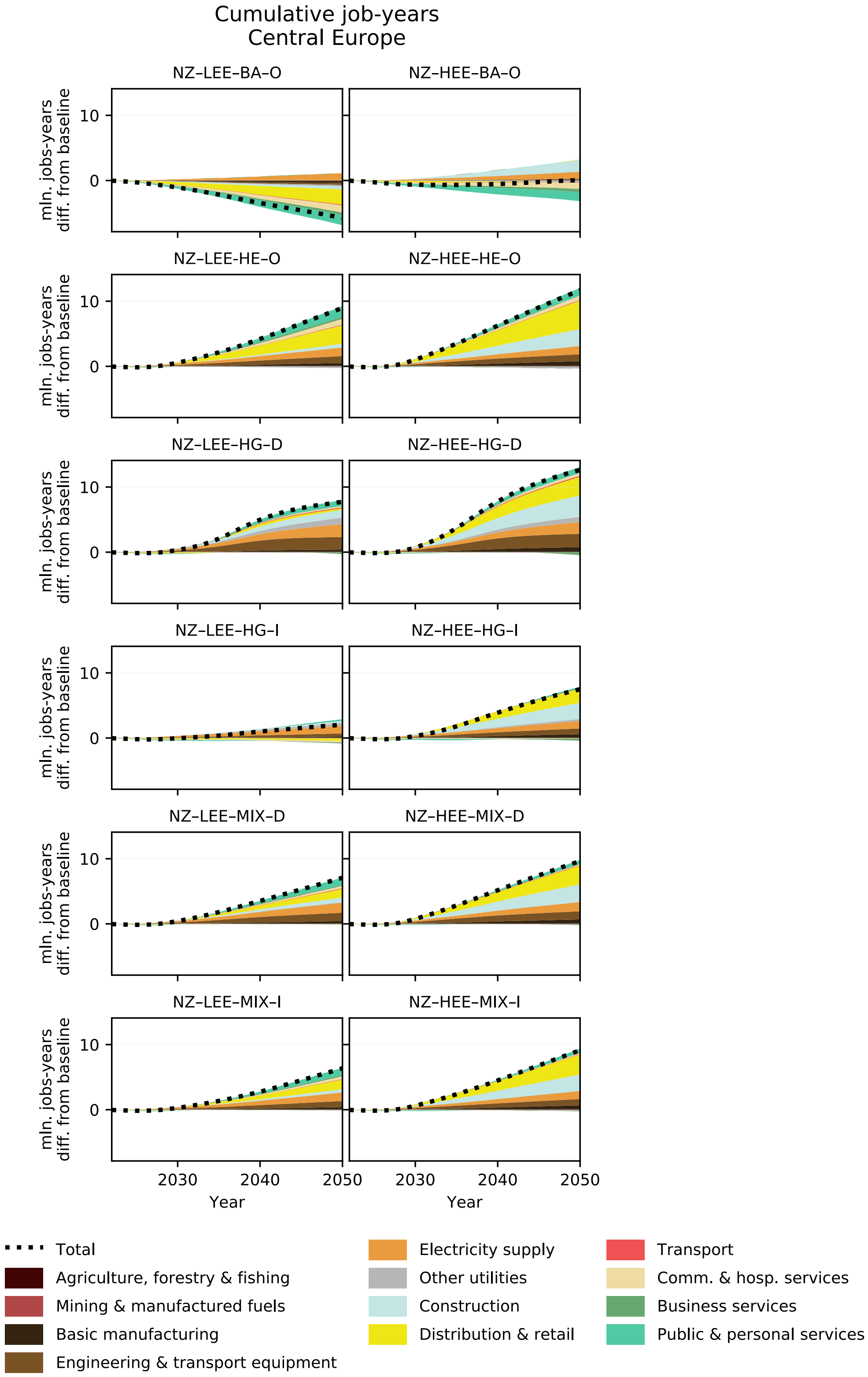

Figure B.4.13: Cumulative job-years change by sector.

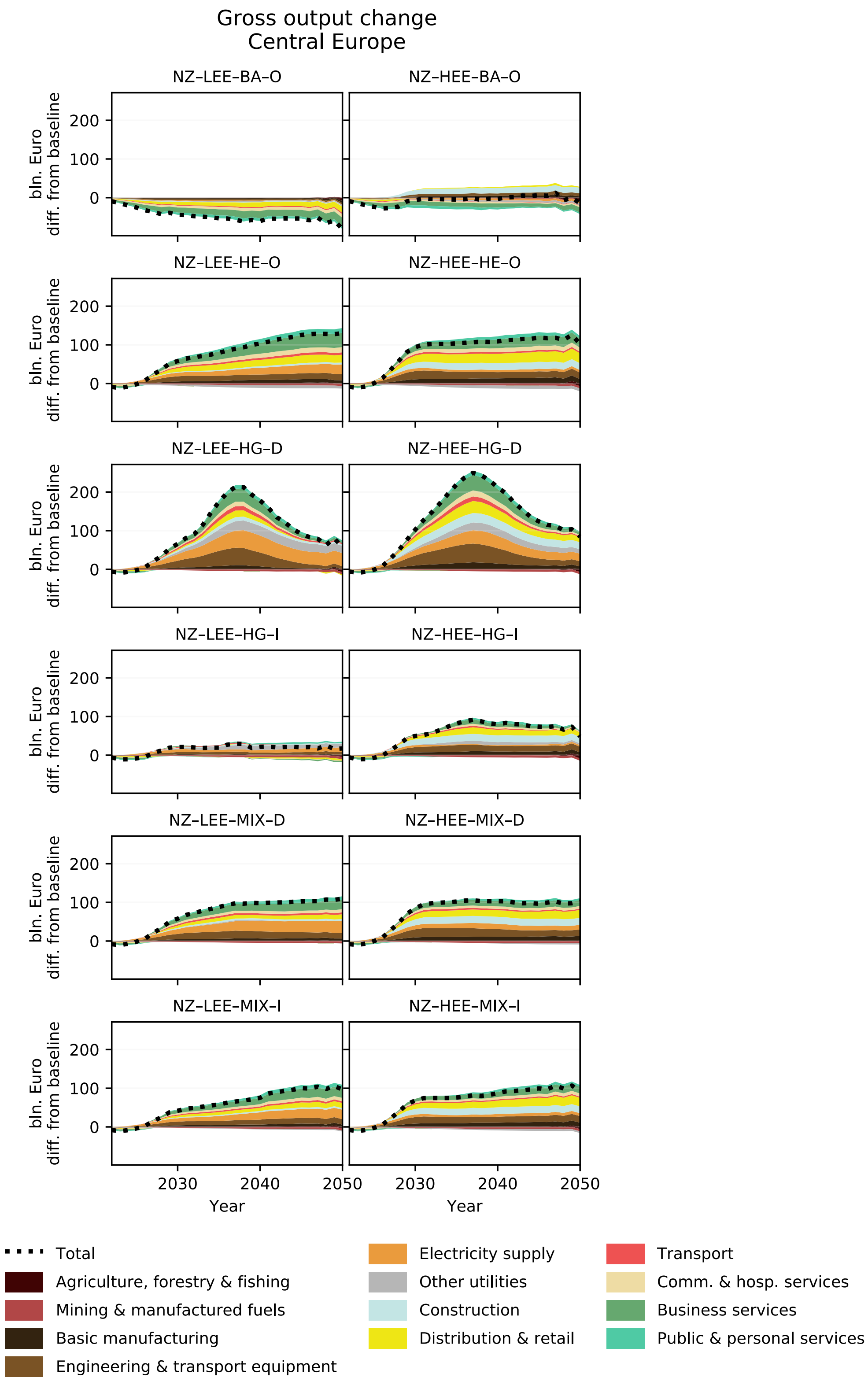

Figure B.4.14: Gross output change by sector.

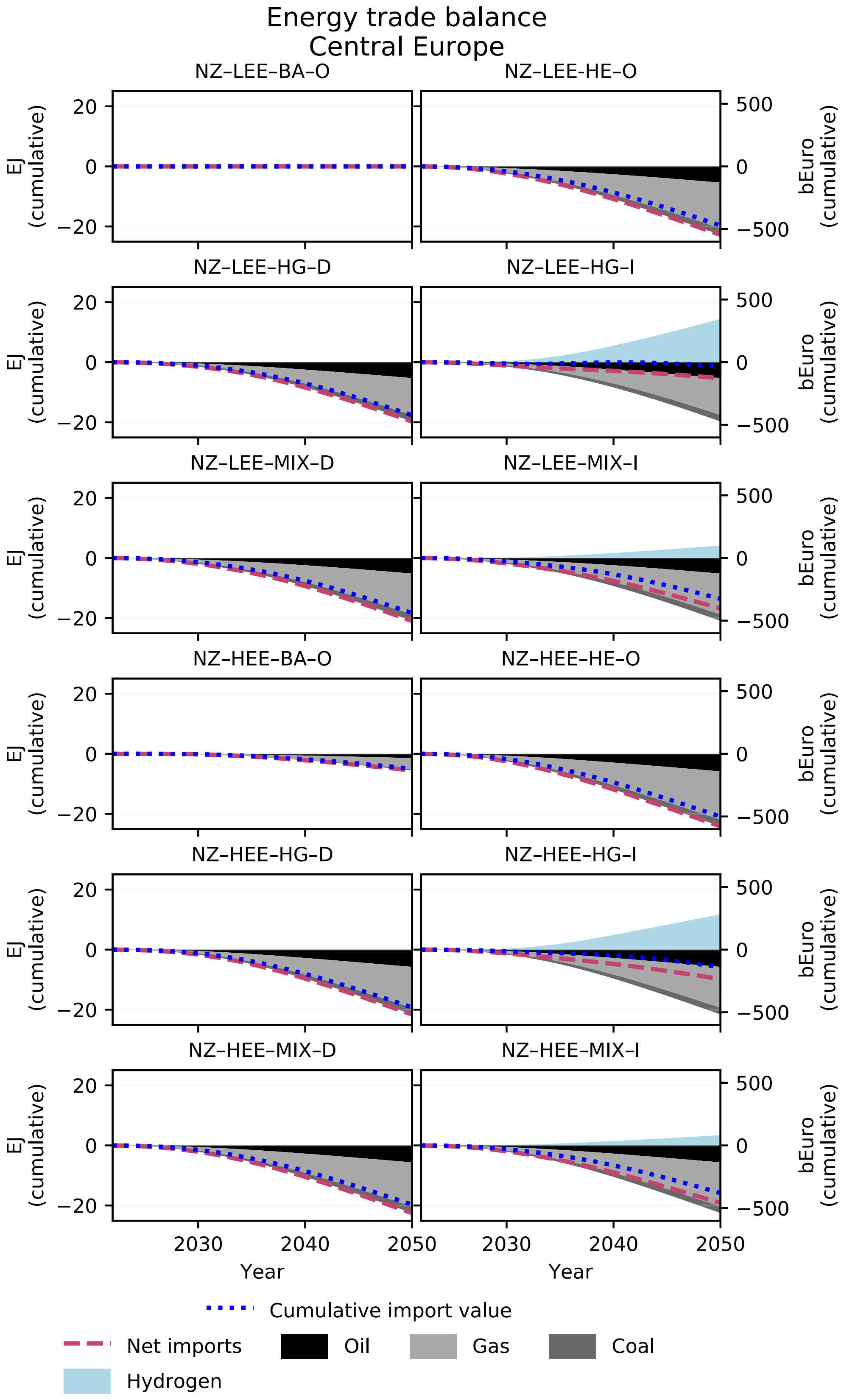

Figure B.4.15: Energy trade balance change by energy carrier.

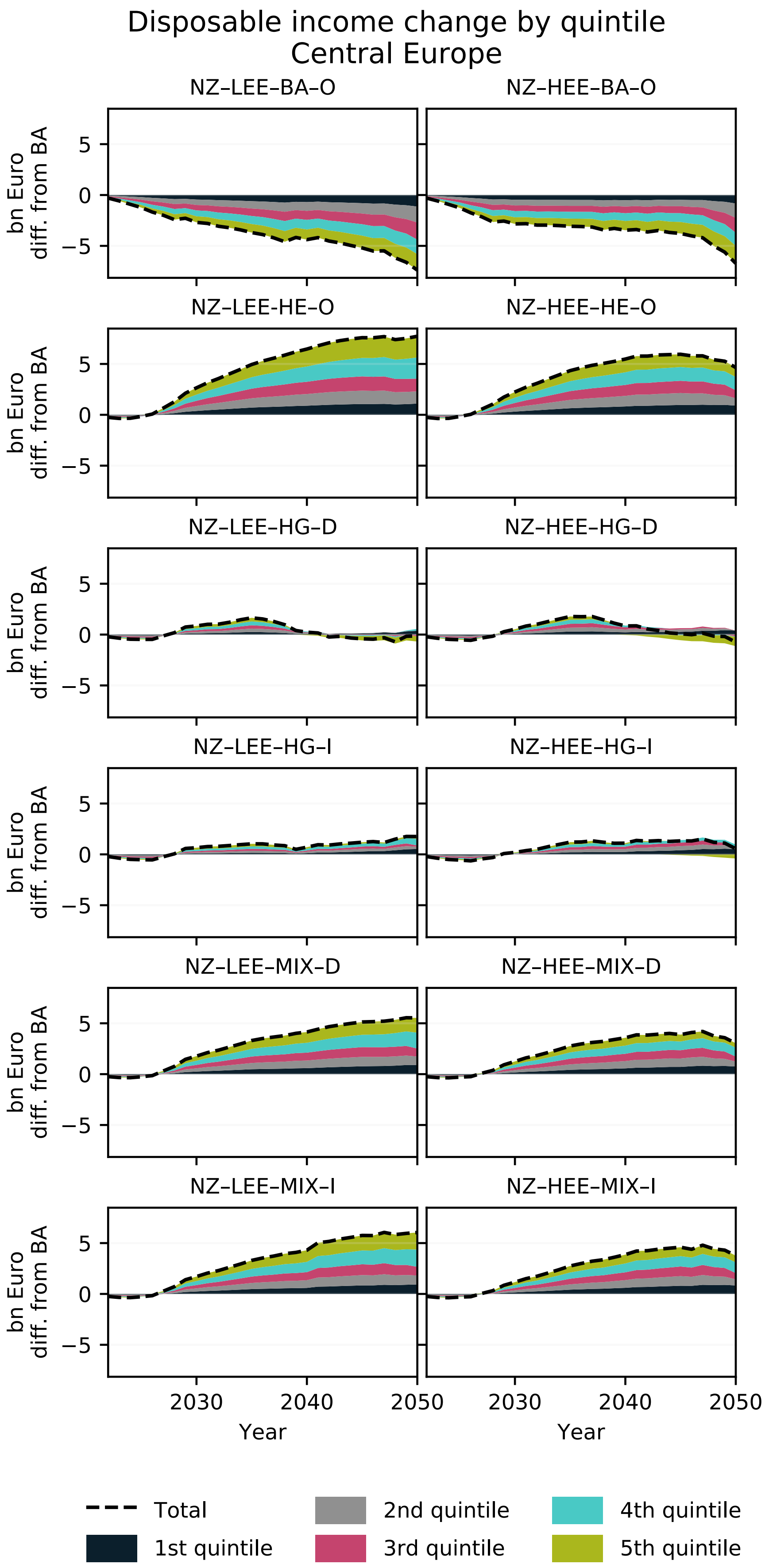

Figure B.4.16: Disposable income change by income quintile.

Climate zone: Eastern Europe

Eastern Europe will see continued large investments in to district heating technologies and the district heating grid. By 2050, majority of the final energy demand for heating will be met by district heating technologies. Hydrogen uptake is relatively low, however, seeing a slight investment boost into the hydrogen infrastructure by 2035. Operation, maintenance, and upfront cost for different heating technologies will rise, but overall, most scenarios see a reduction in the total consumer expenditure on heating technologies. This effect is being dominated by longer-term reductions in the energy costs.

In the shorter term, the investment into heating and renovation effects will result in large job creation and boost GDP. However, in the longer term, a debt repayment phase will result in a falling GDP relative to baseline and the amount of job opportunities returning to baseline levels. However, these it is important to note that environmental externalities are not accounted for in the GDP calculations. Overall, Eastern Europe could see short term gains, however, the region is likely to be one of the worse-off regions in Europe; seeing reductions in GDP in the long run, and return of jobs to baseline levels by 2050. To a large degree this can be attributed to the loss of jobs resulting from decarbonisation in the coal mining industry (mainly in Poland)

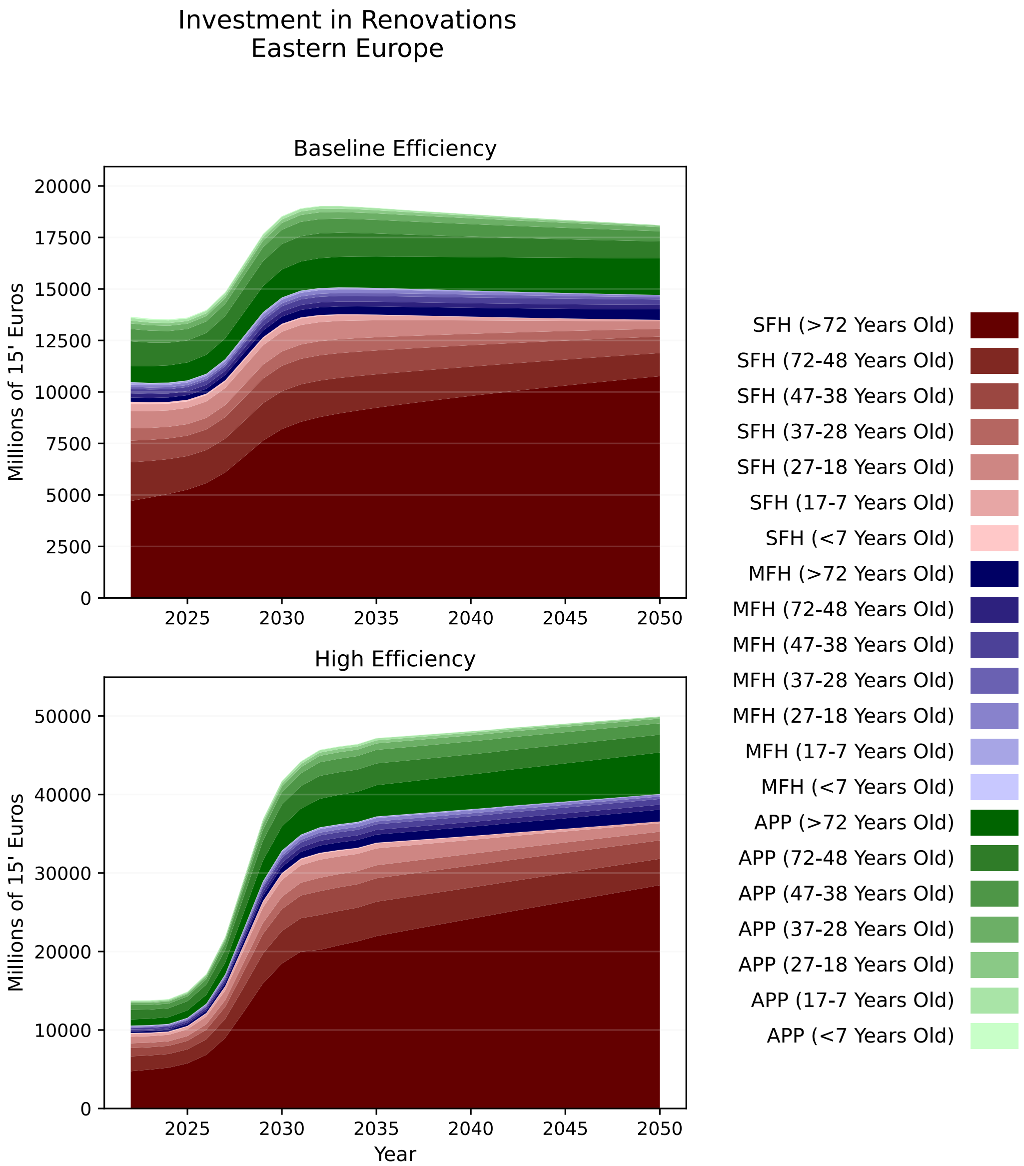

Figure B.5.1: Investments into renovations.

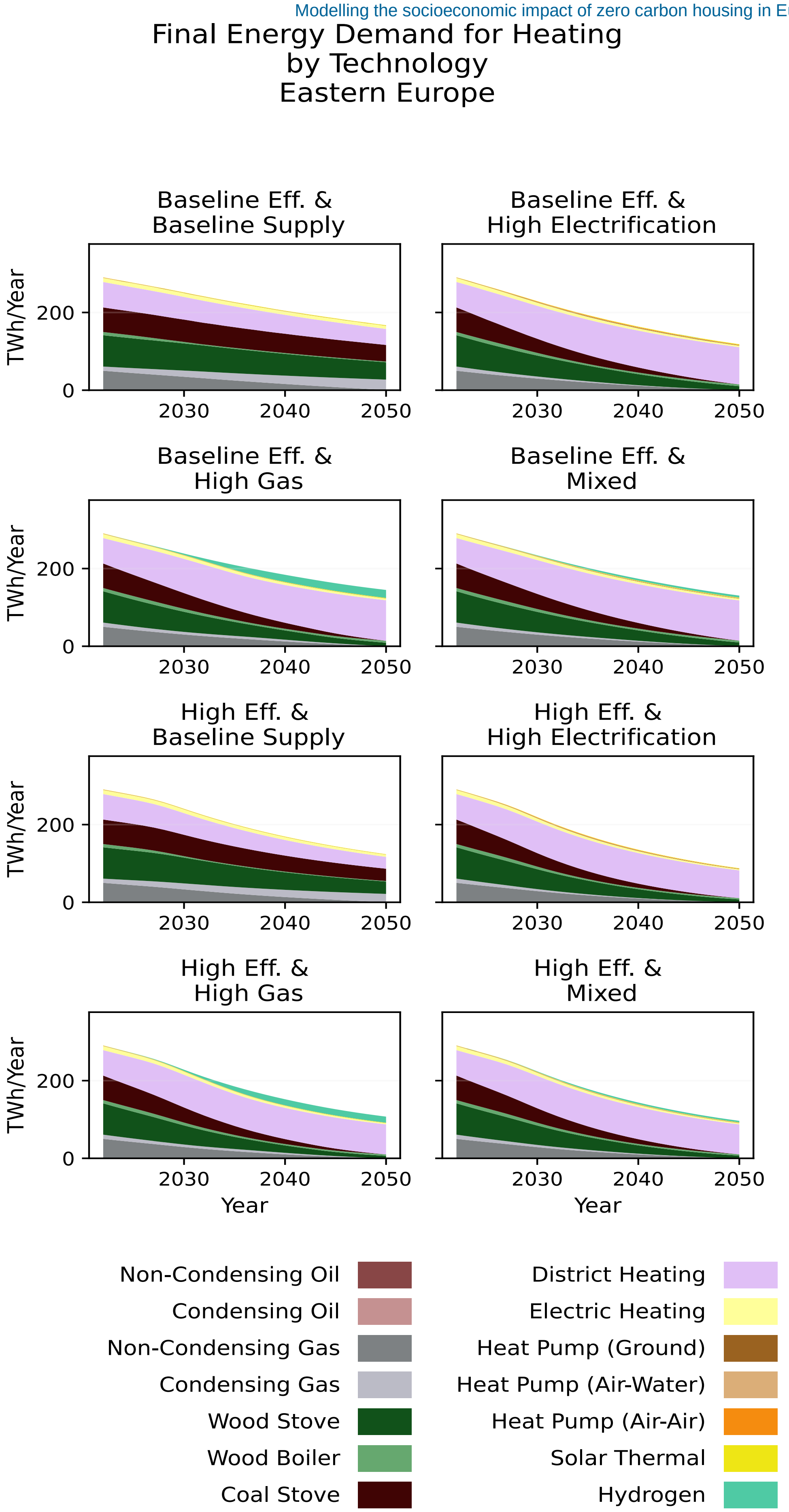

Figure B.5.2: Final energy demand by technology.

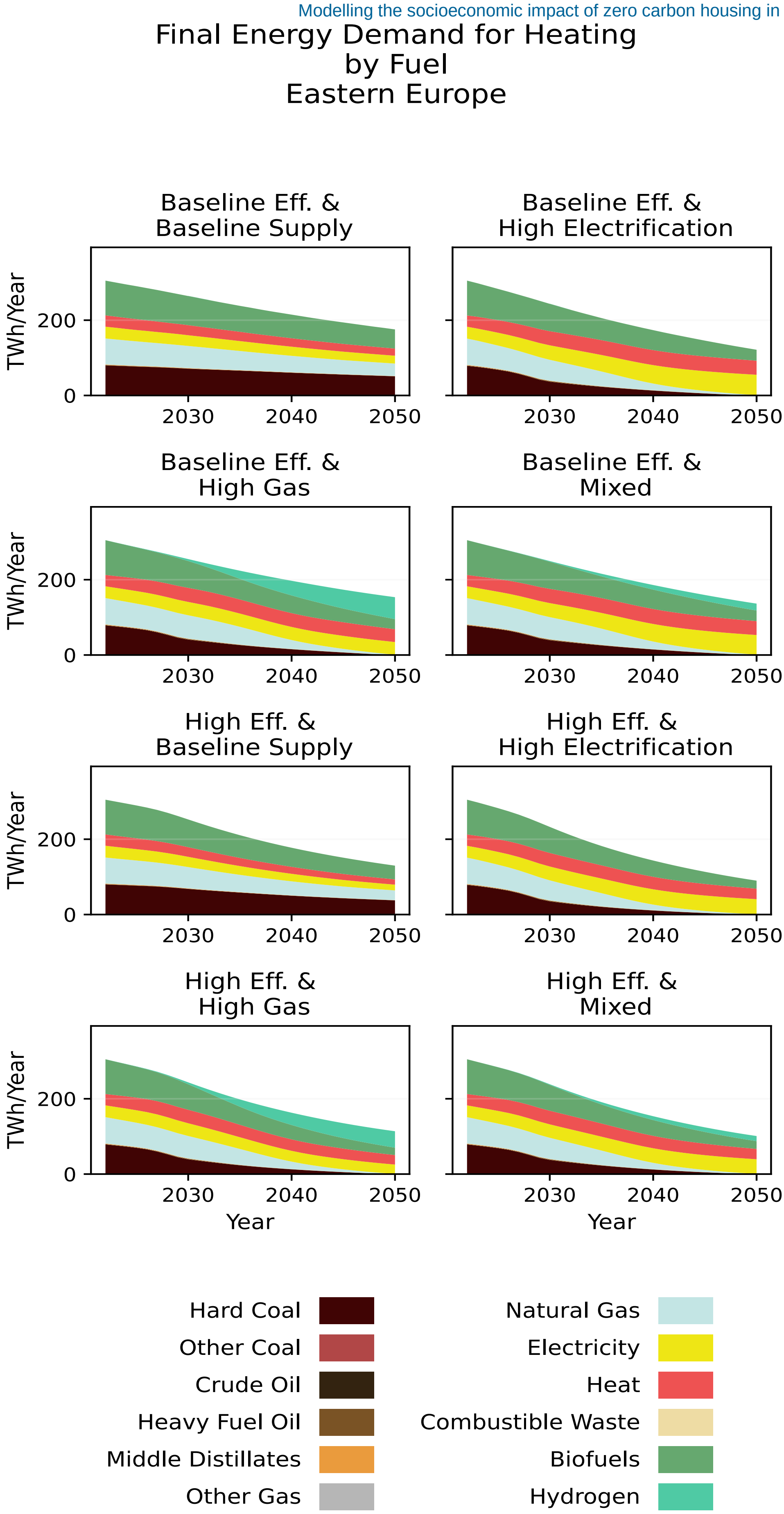

Figure B.5.3: Final energy demand by energy carrier.

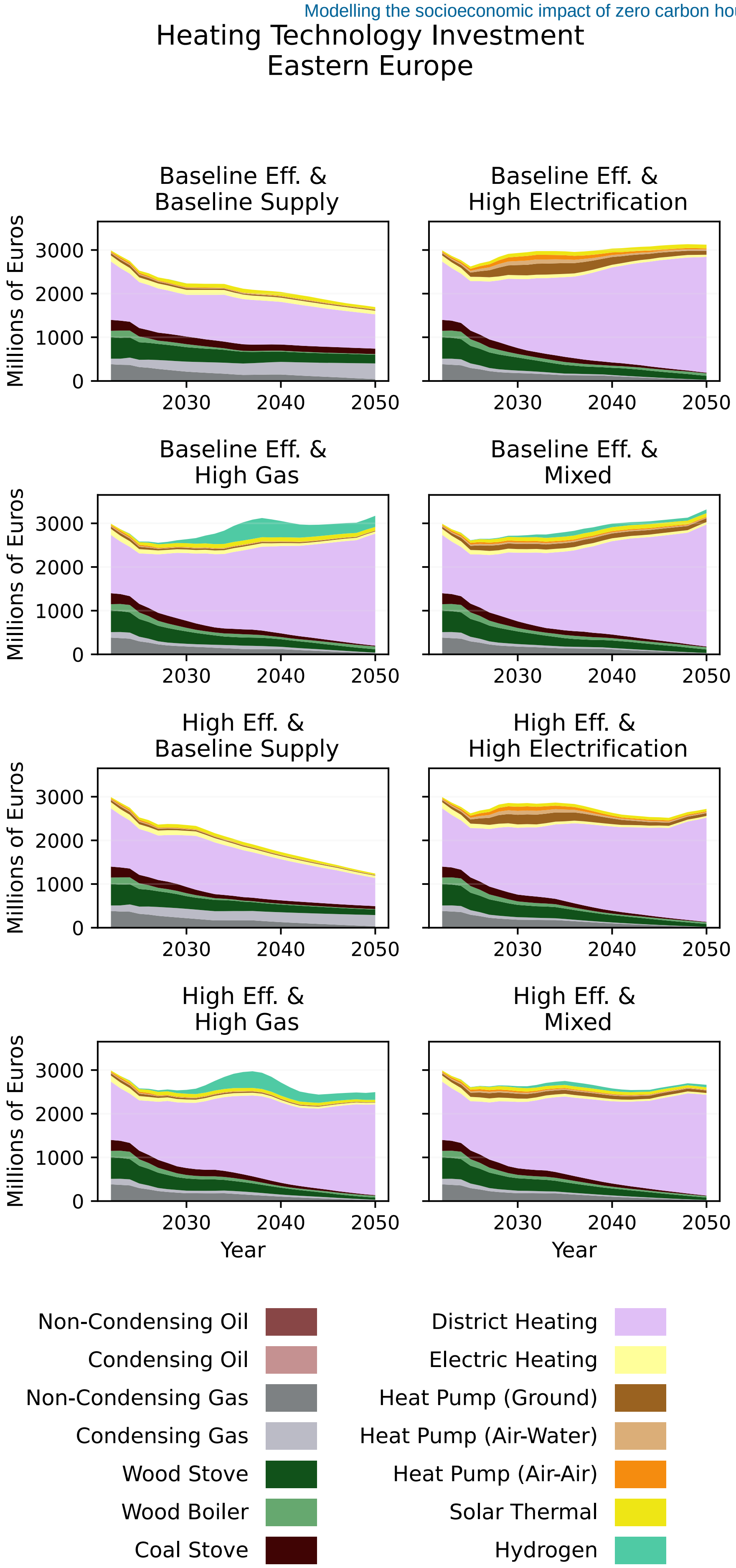

Figure B.5.4: Upfront investment in heating equipment.

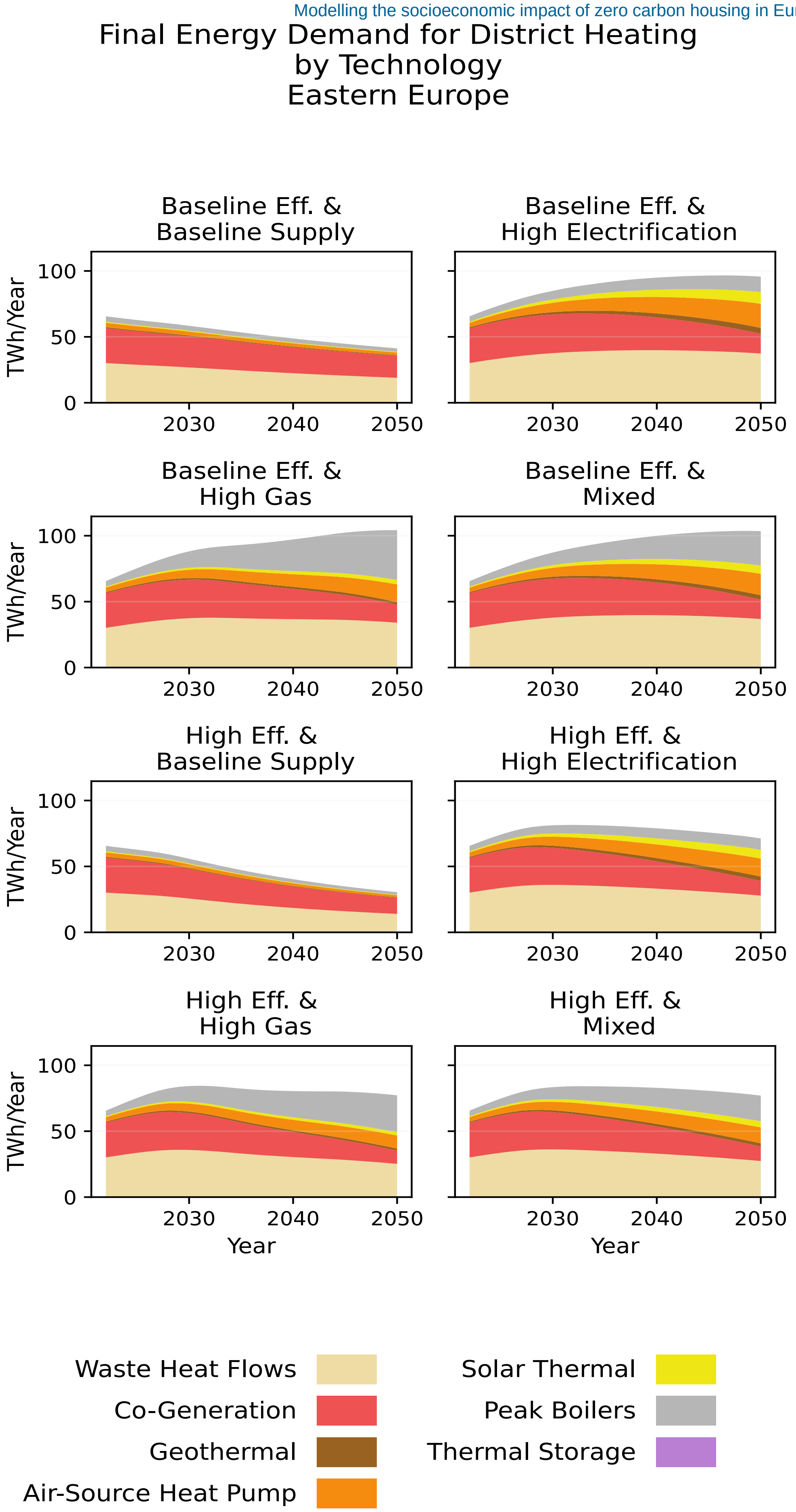

Figure B.5.5: Final energy demand in DH/C by configuration option.

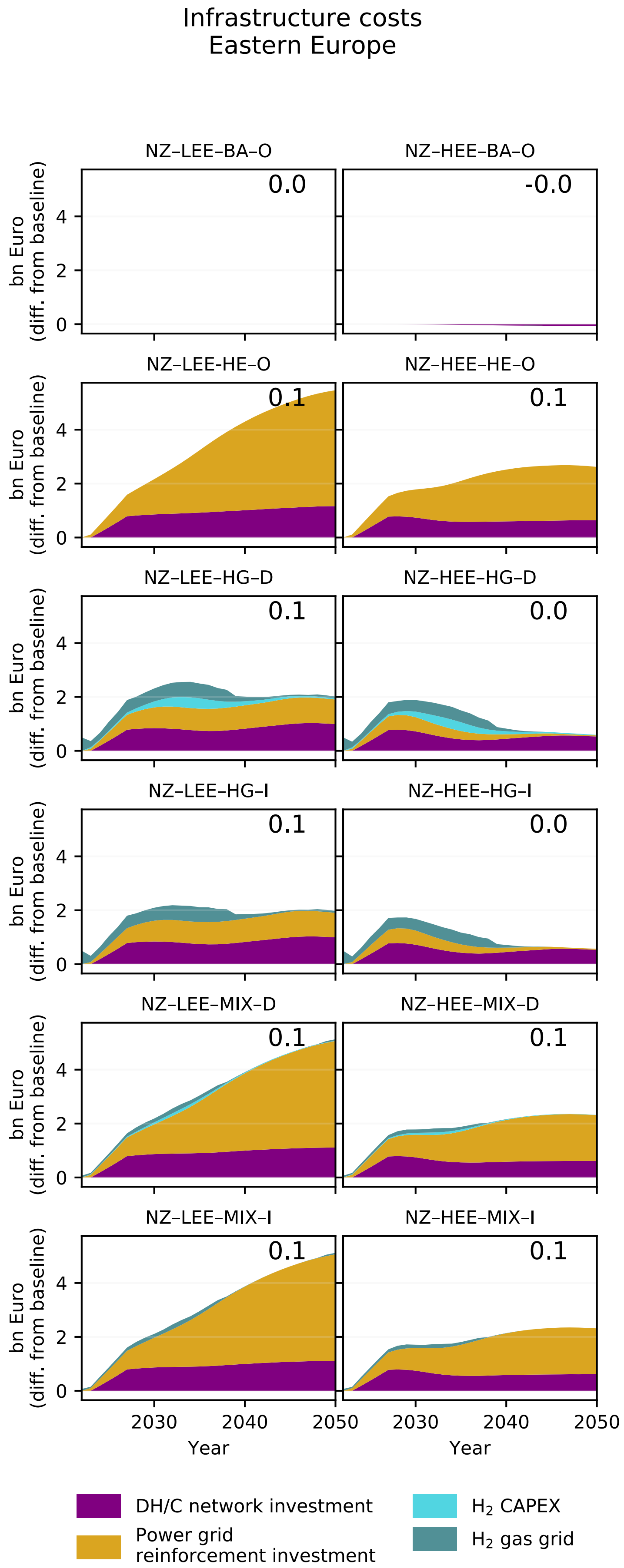

Figure B.5.6: Infrastructure investments.

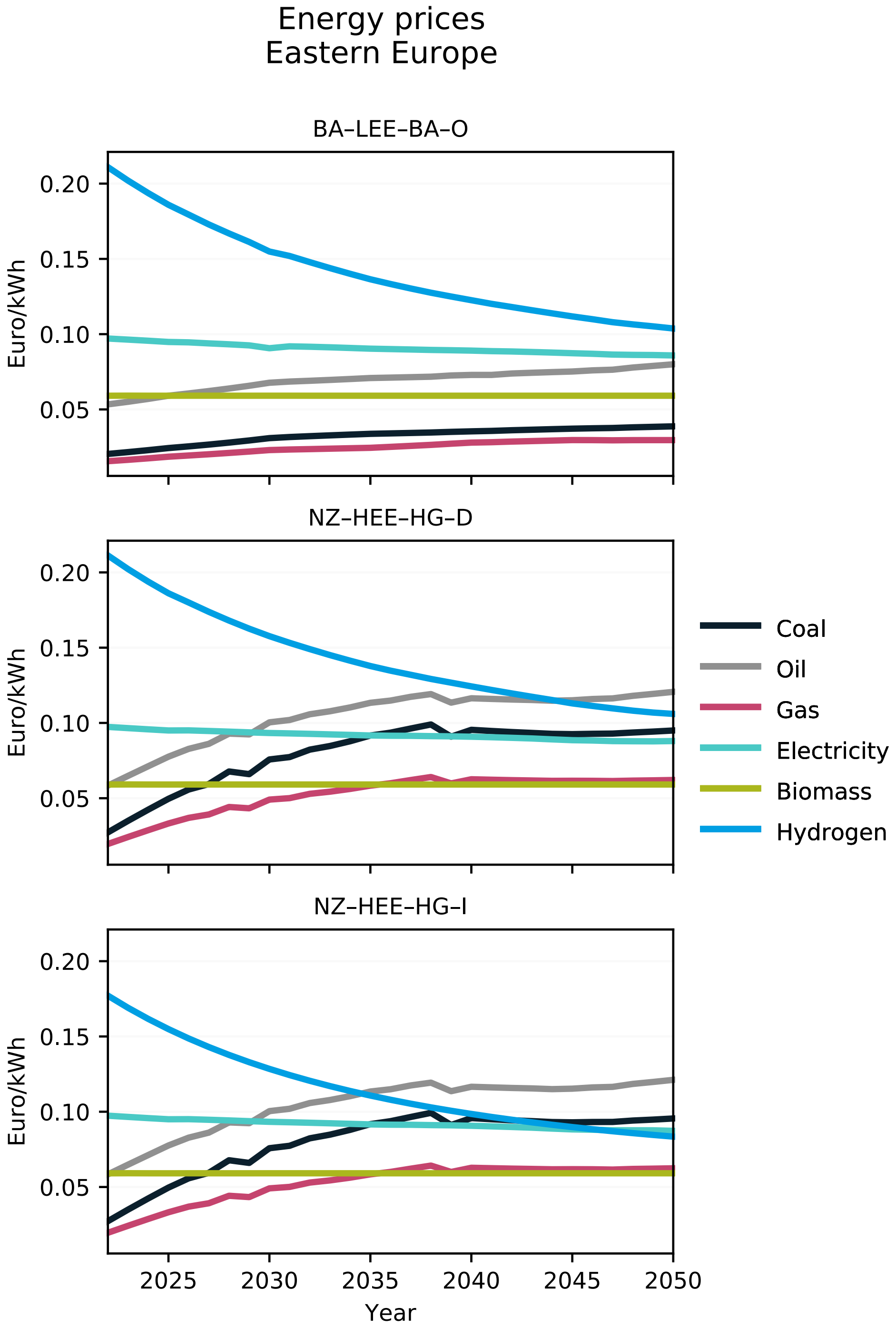

Figure B.5.7: Evolution of energy prices.

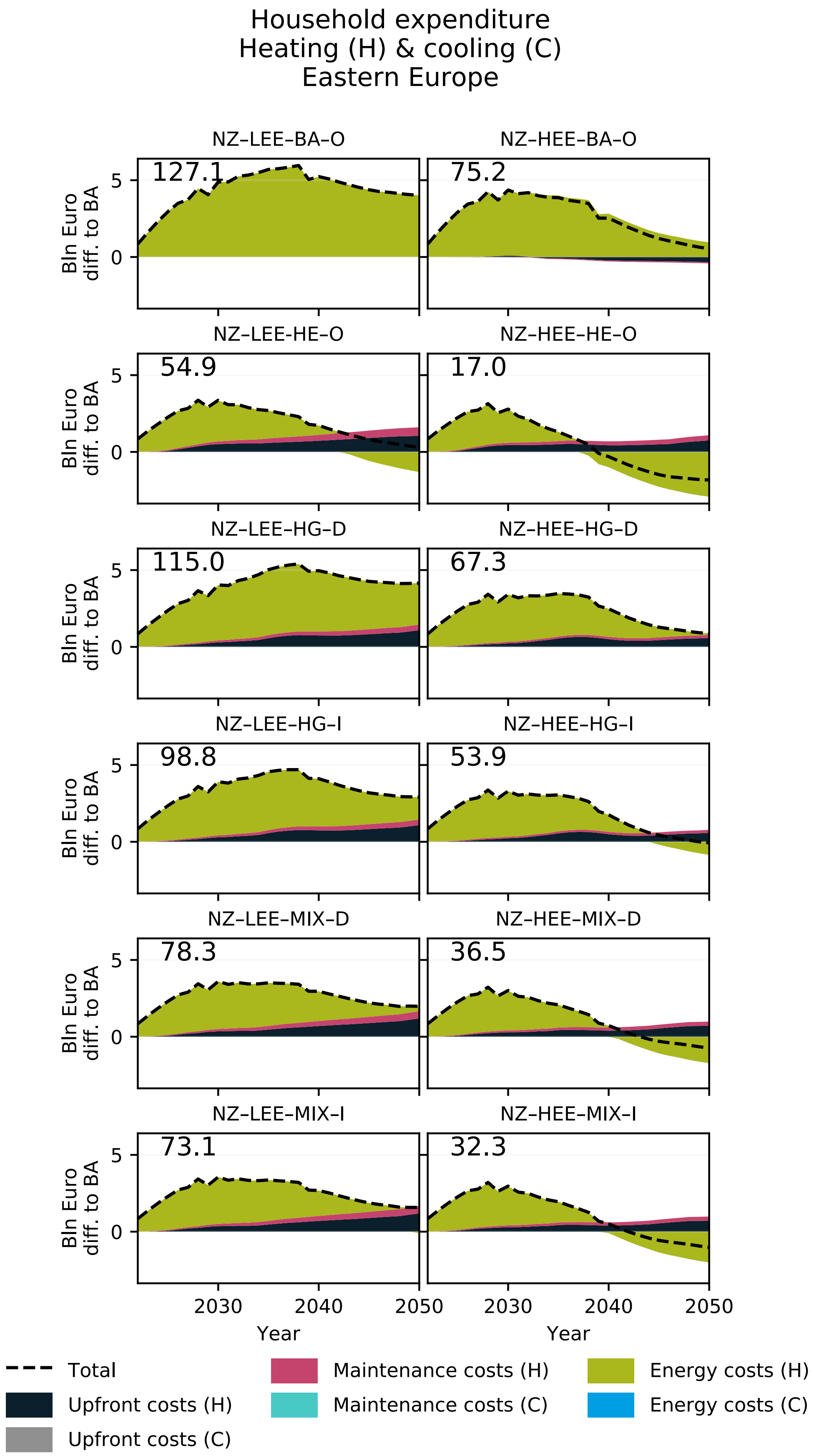

Figure B.5.8: Household expenditure change in heating & cooling. Numbers represent cumulative expenditure in billion Euro.

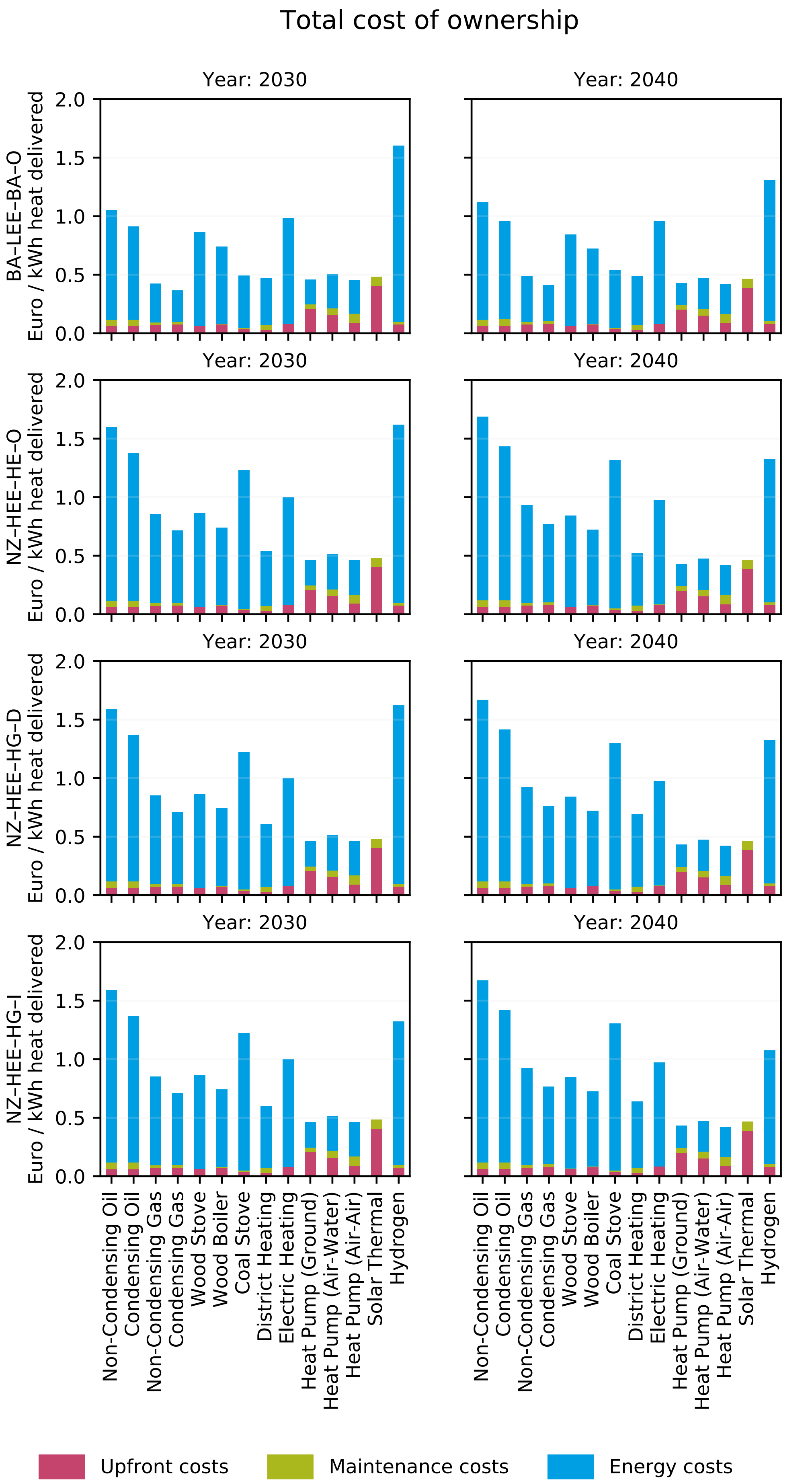

Figure B.5.9: Total cost of ownership by technology.

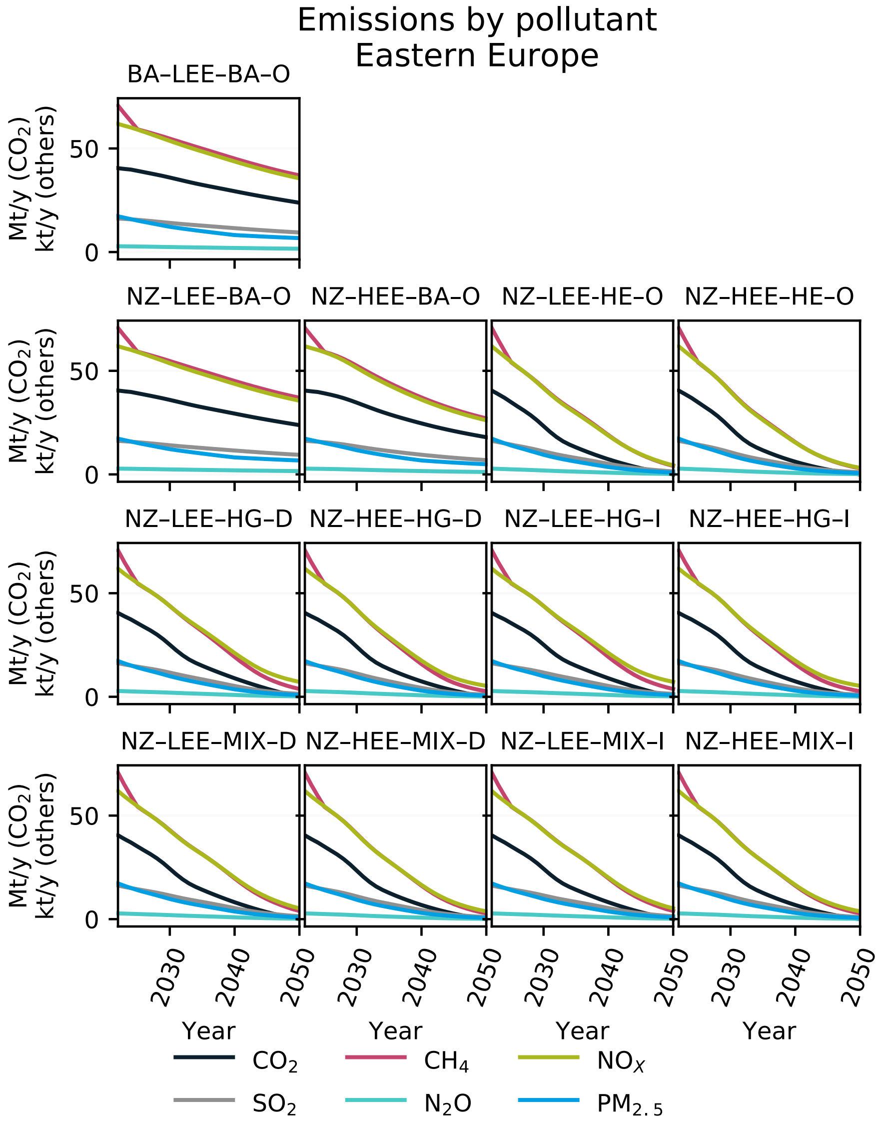

Figure B.5.10: Direct emissions by pollutant.

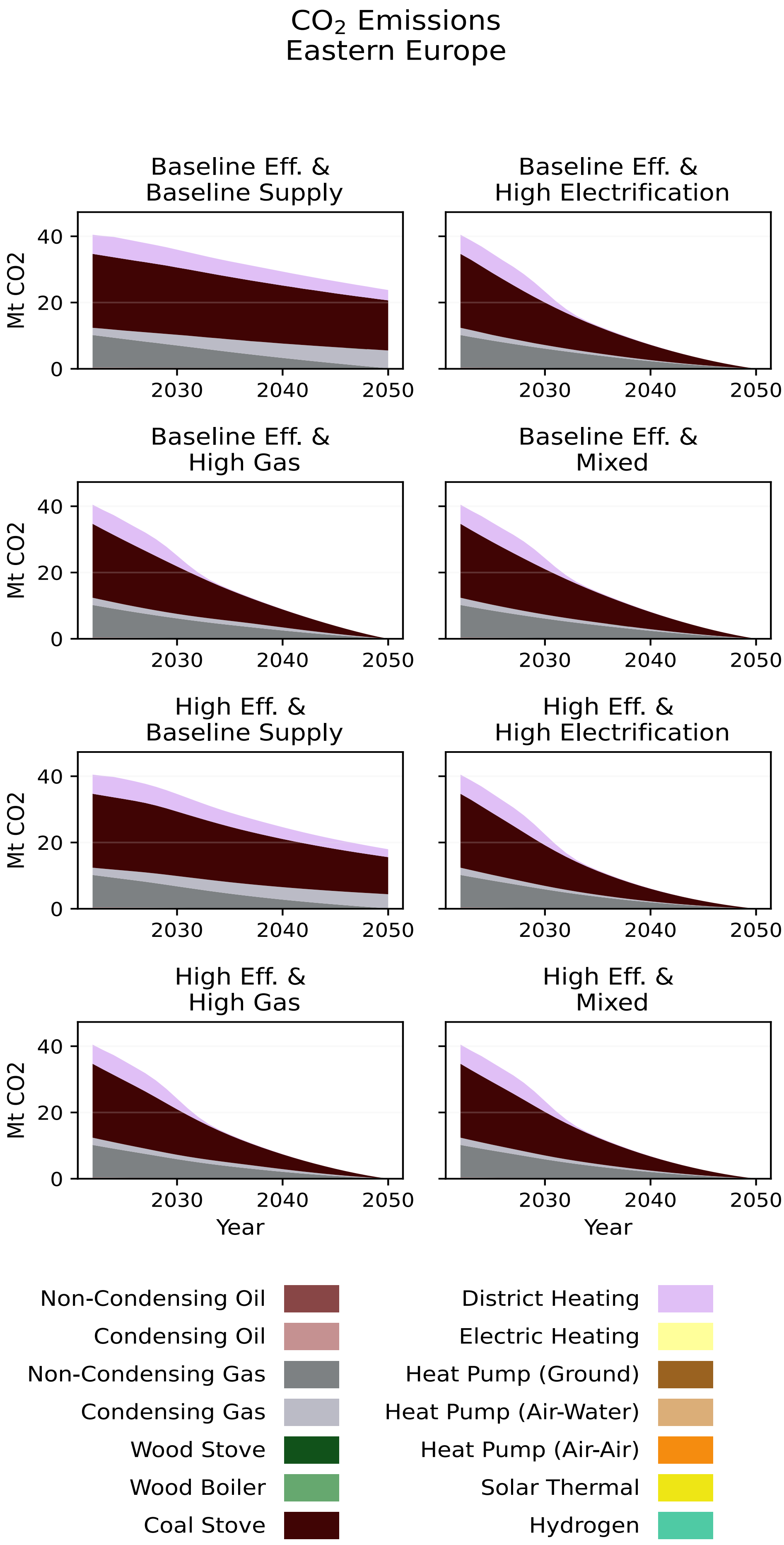

Figure B.5.11: Direct CO_2 emissions by technology.

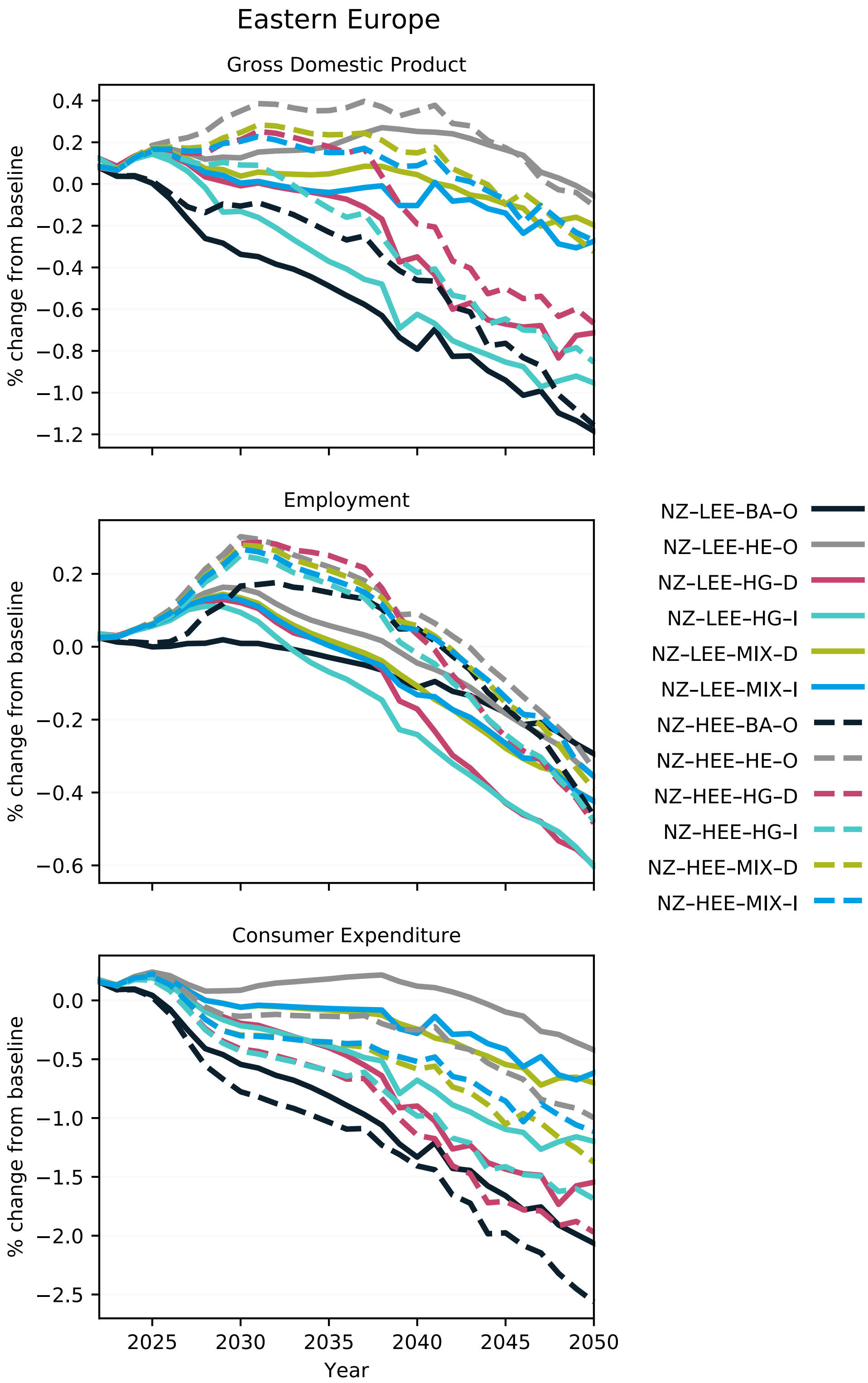

Figure B.5.12: GDP, employment, and consumer expenditure change.

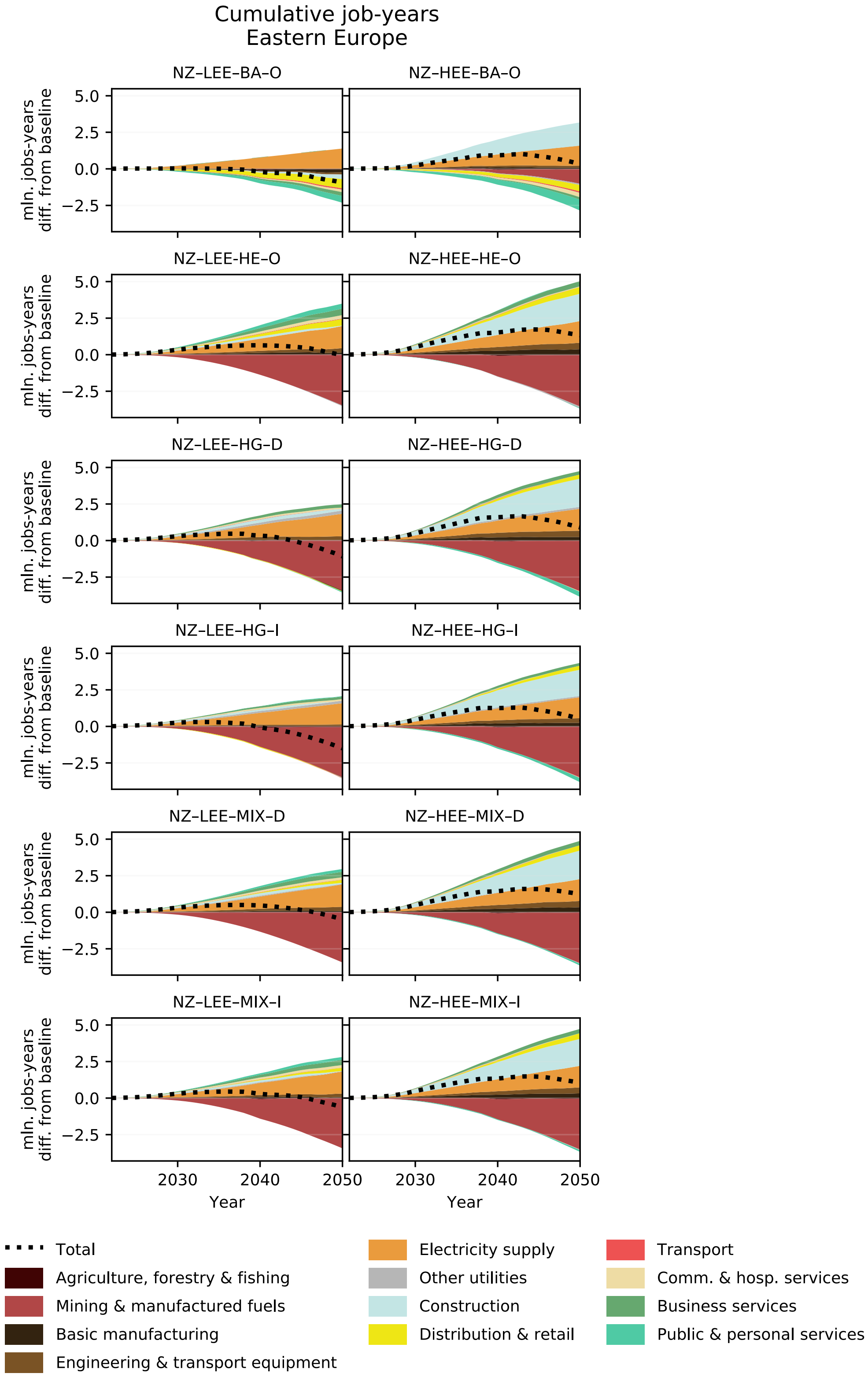

Figure B.5.13: Cumulative job-years change by sector.

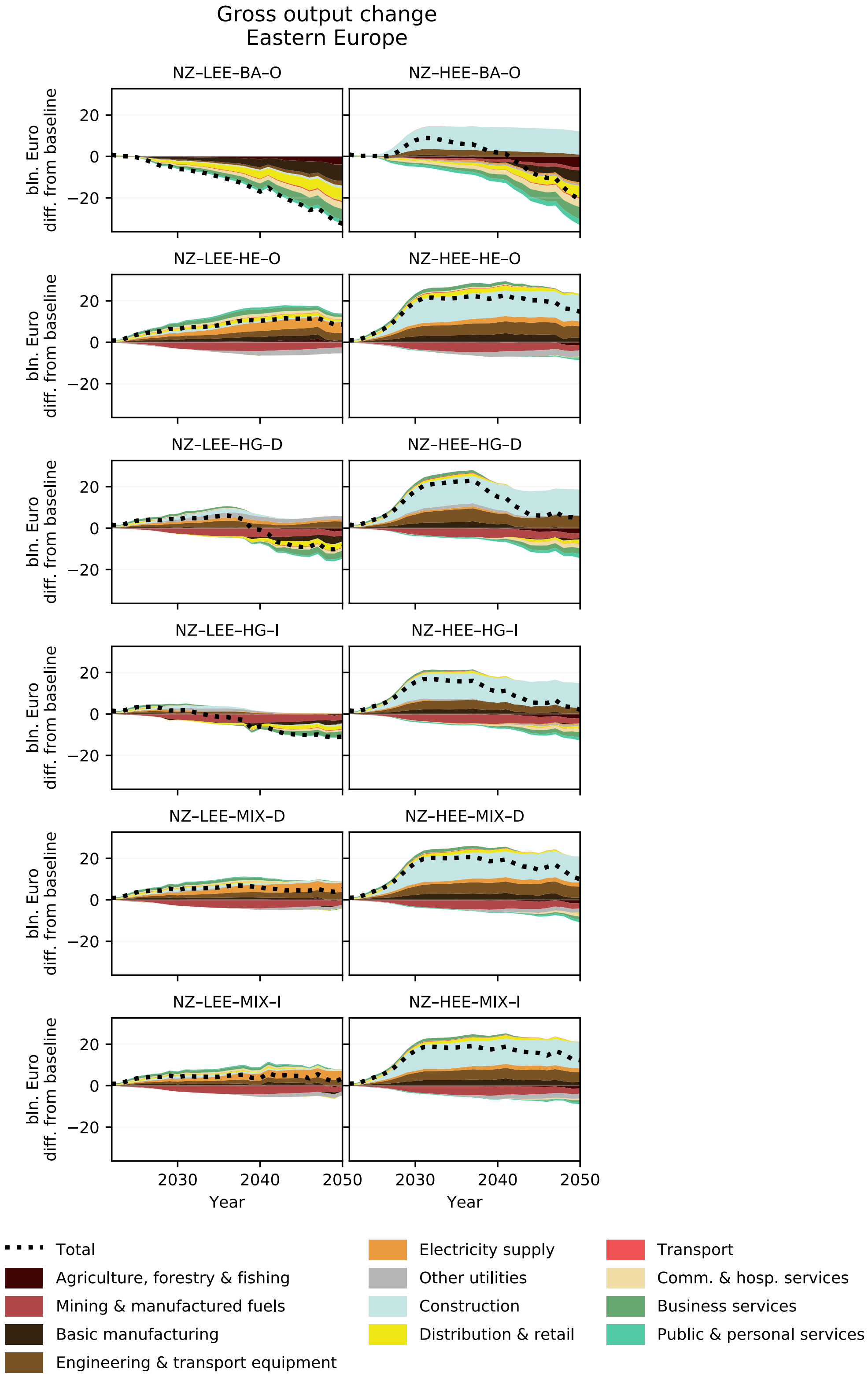

Figure B.5.14: Gross output change by sector.

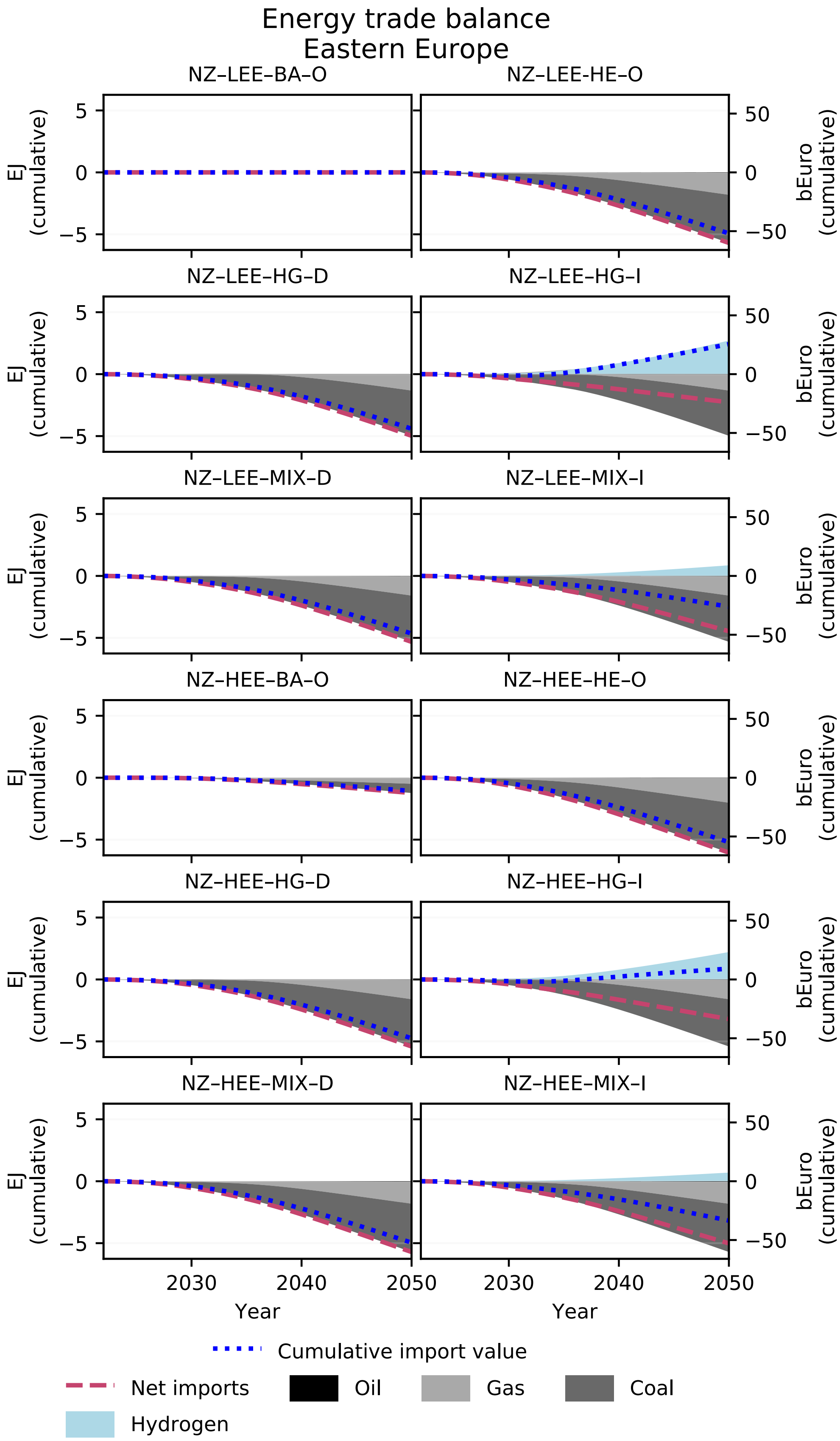

Figure B.5.15: Energy trade balance change by energy carrier.

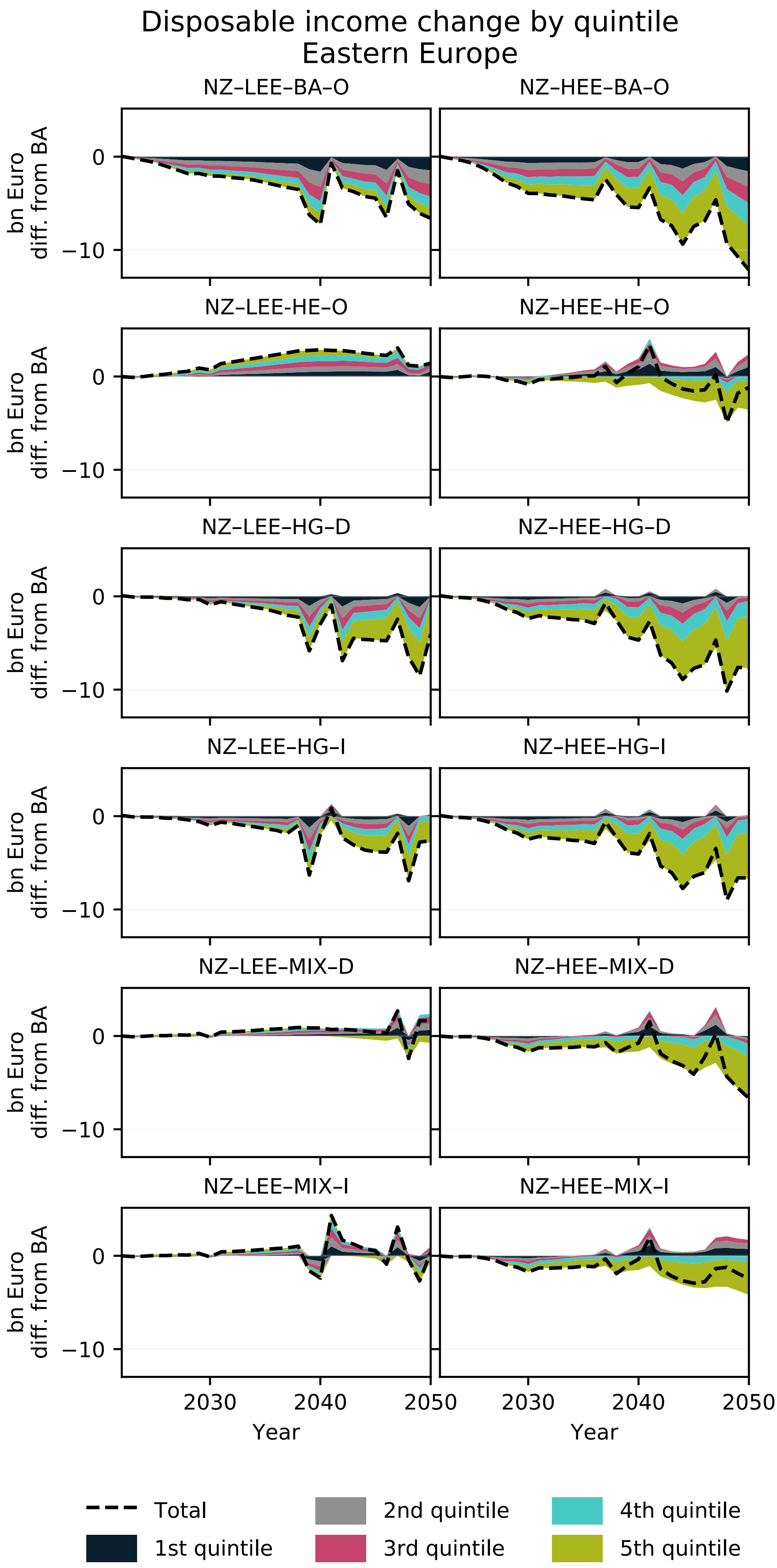

Figure B.5.16: Disposable income change by income quintile.

Climate zone: Iberian Peninsula

The technology evolution in the Iberian Peninsula will mostly be driven by the uptake in heat pumps, which are able to serve both cooling and heating demands. Because of the high cost of heat pumps relative to other technologies, there is a relatively large investment into heat pumps between present and 2030. However, due to a rapid uptake of heat pumps, consumer expenditure on heating technologies will quickly fall resulting in prominent increases in GDP. Due to the climate and conditions in the Iberian Peninsula being favourable for heat pumps, the scenarios which push for an uptake of hydrogen perform relatively poorly compared to the high electrification scenarios. It's worth noting that this is the case, even with relatively low hydrogen prices. Similarly, to other regions, investment from renovations have a large impact on employment, where a large amount of employment is expected to occur in the construction industry.

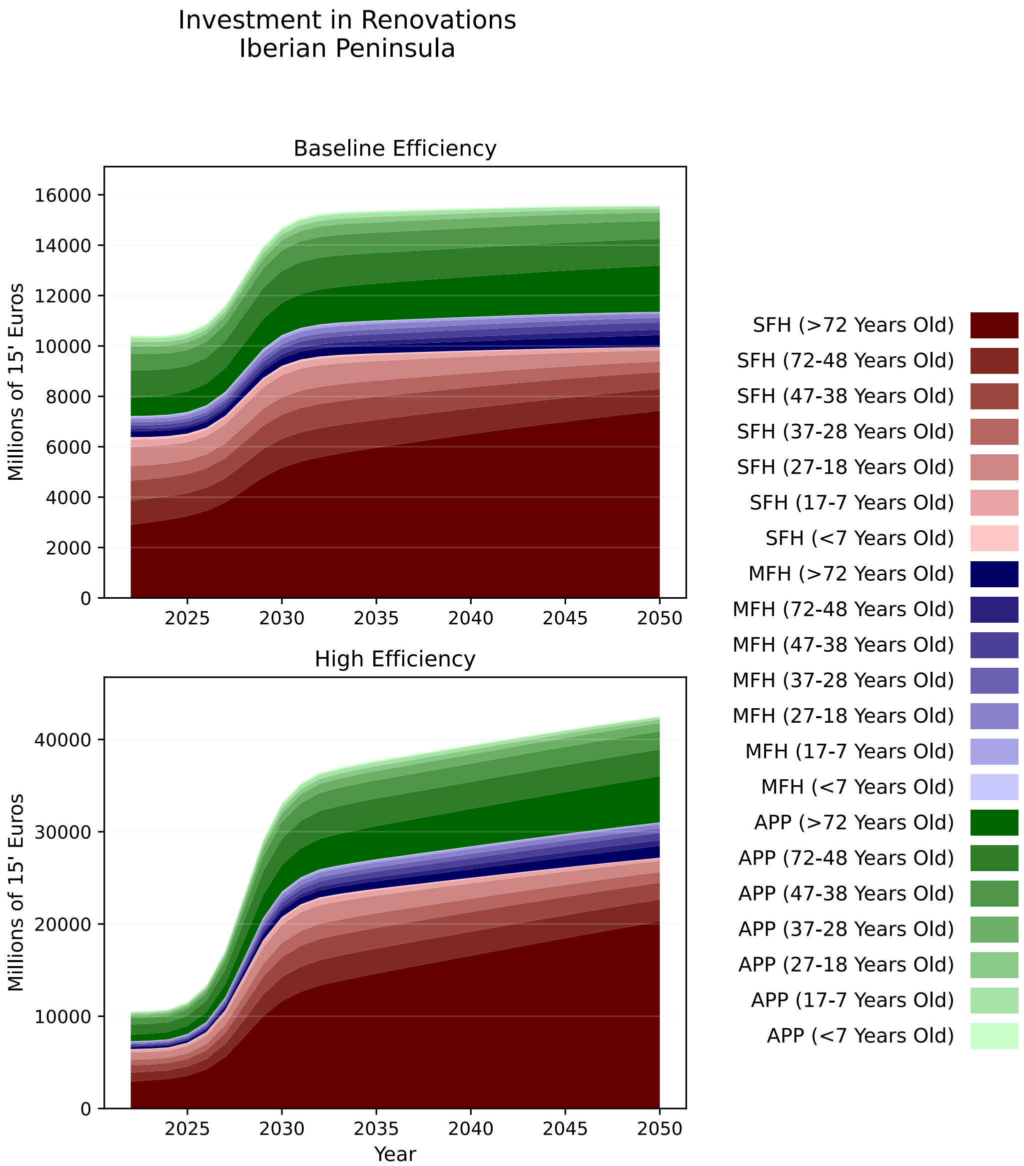

Figure B.6.1: Investments into renovations.

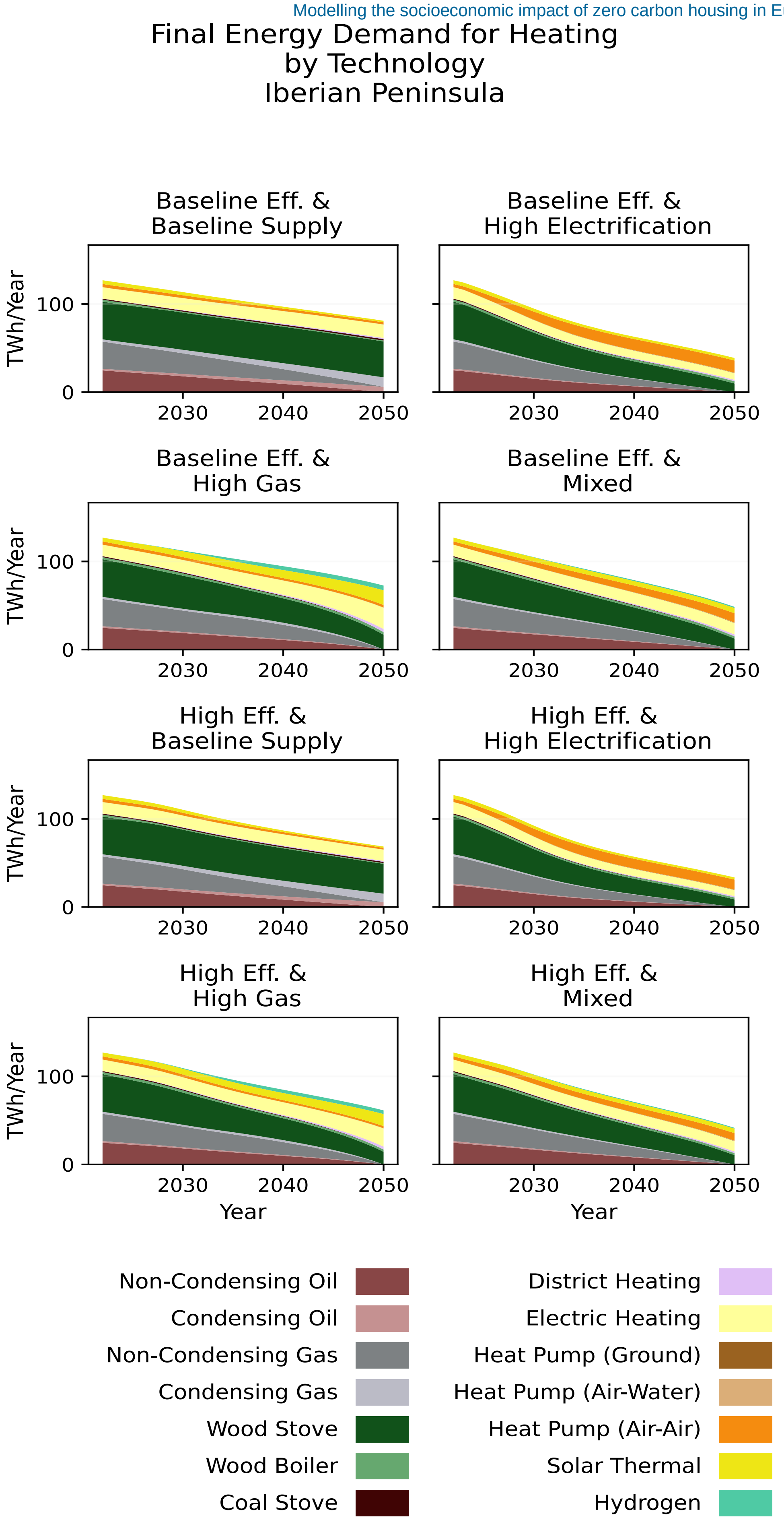

Figure B.6.2: Final energy demand by technology.

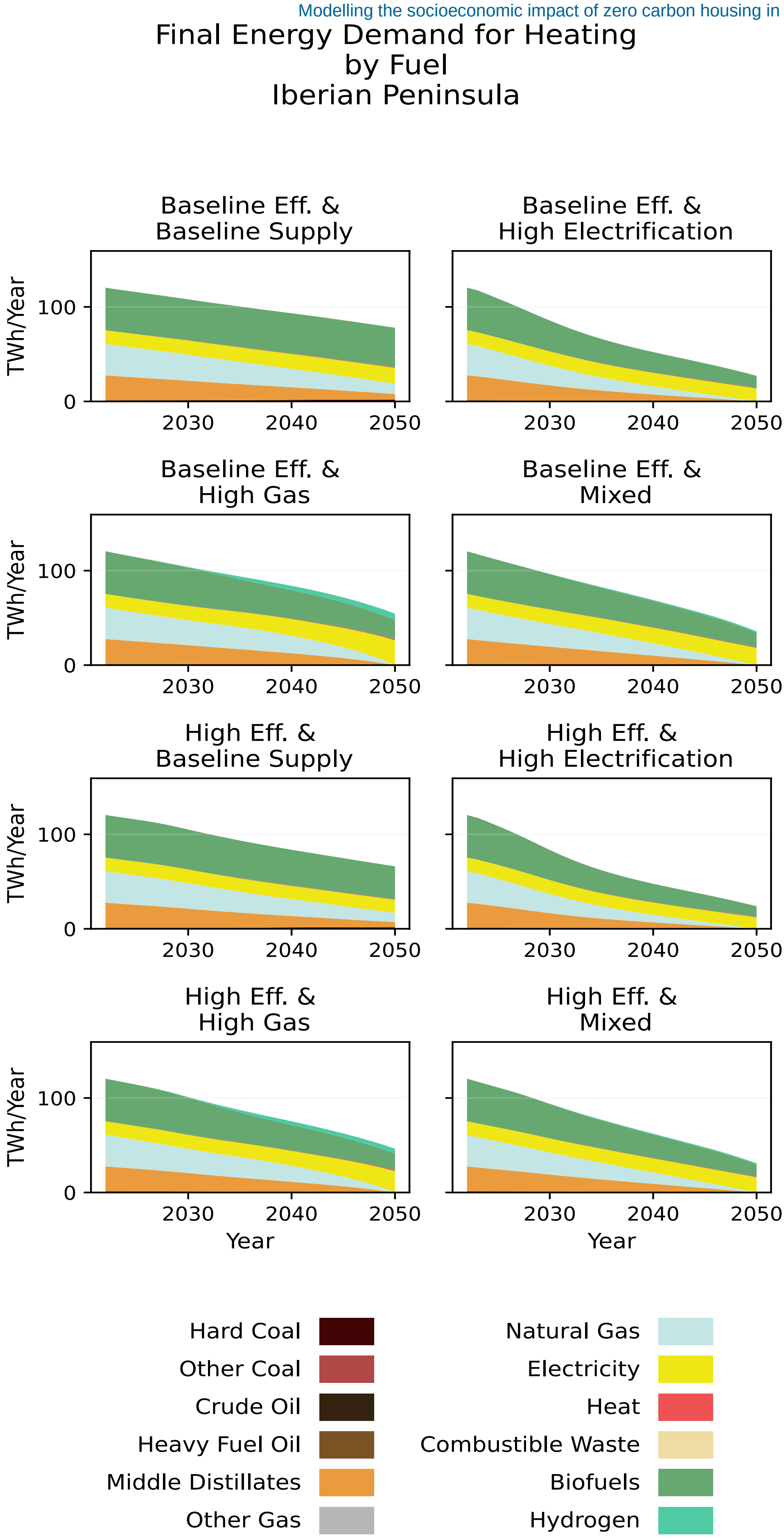

Figure B.6.3: Final energy demand by energy carrier.

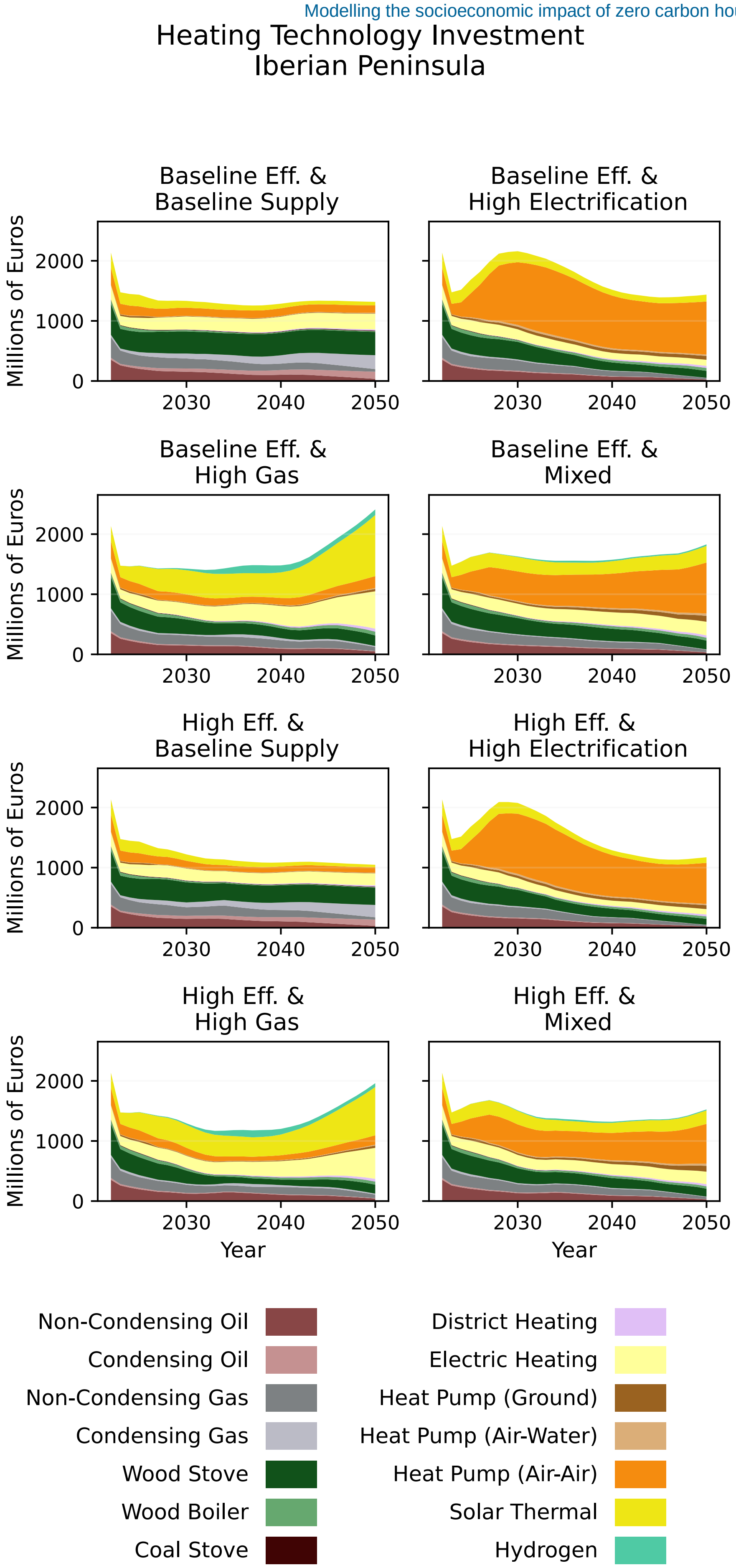

Figure B.6.4: Upfront investments in heating equipment.

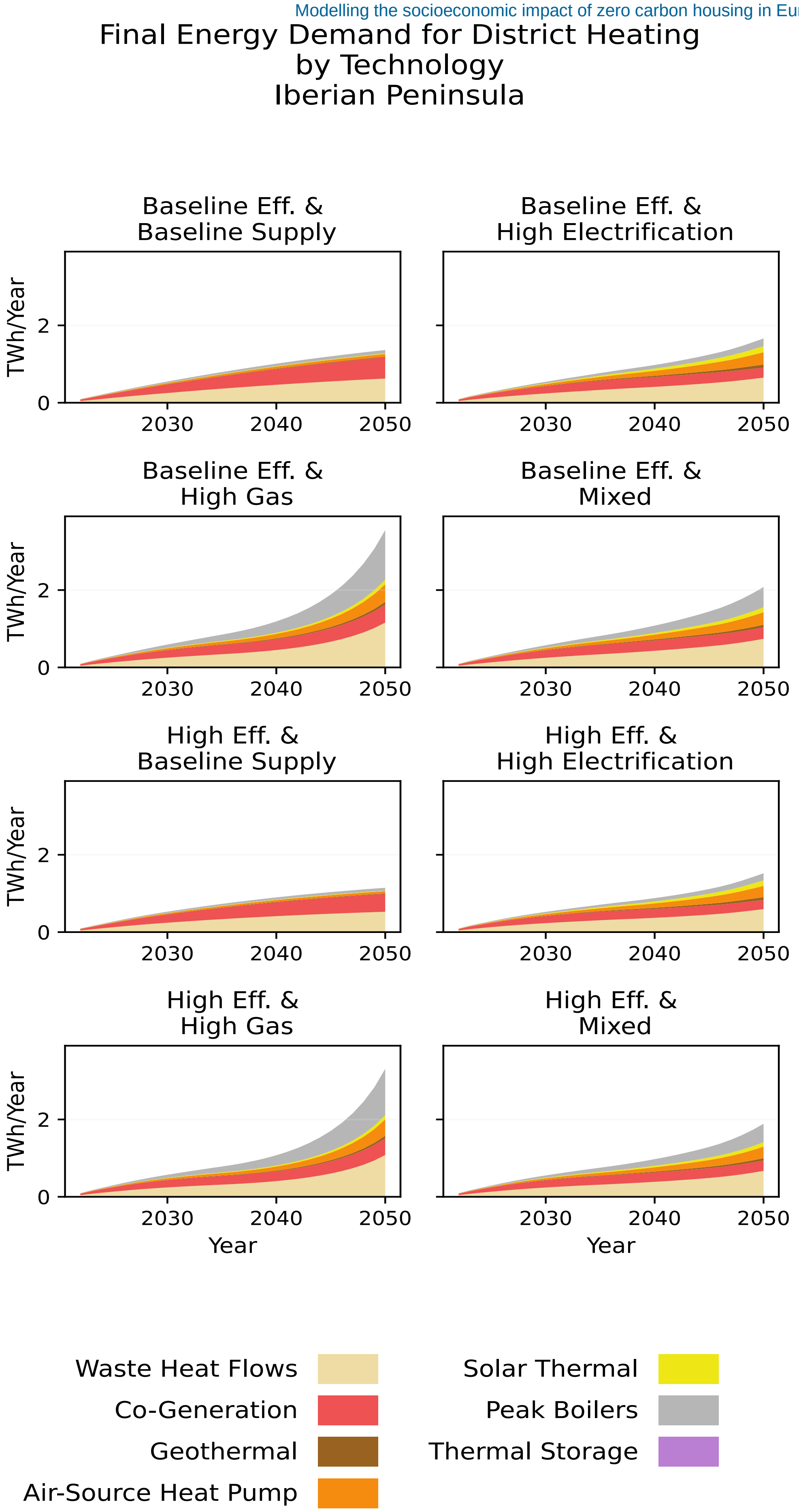

Figure B.6.5: Final energy demand in DH/C by configuration option.

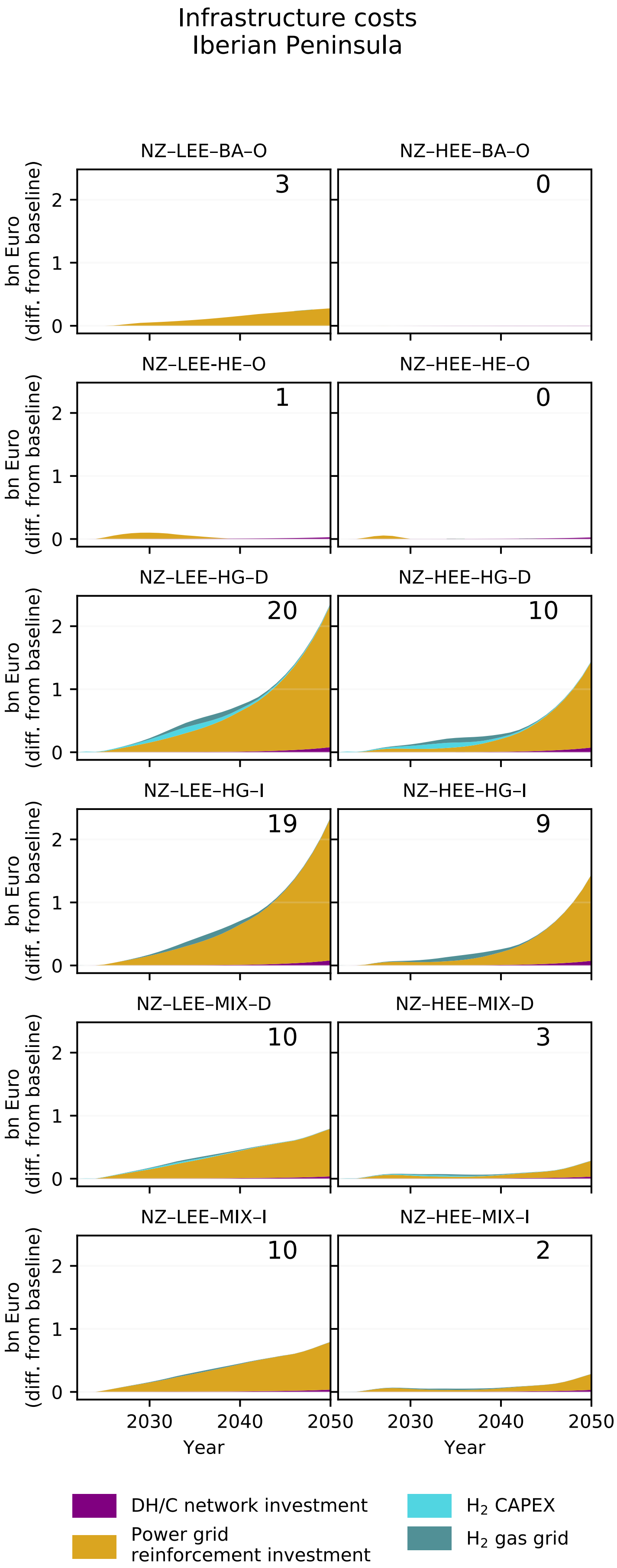

Figure B.6.6: Infrastructure investments. Numbers represent cumulative investment in billion Euro.

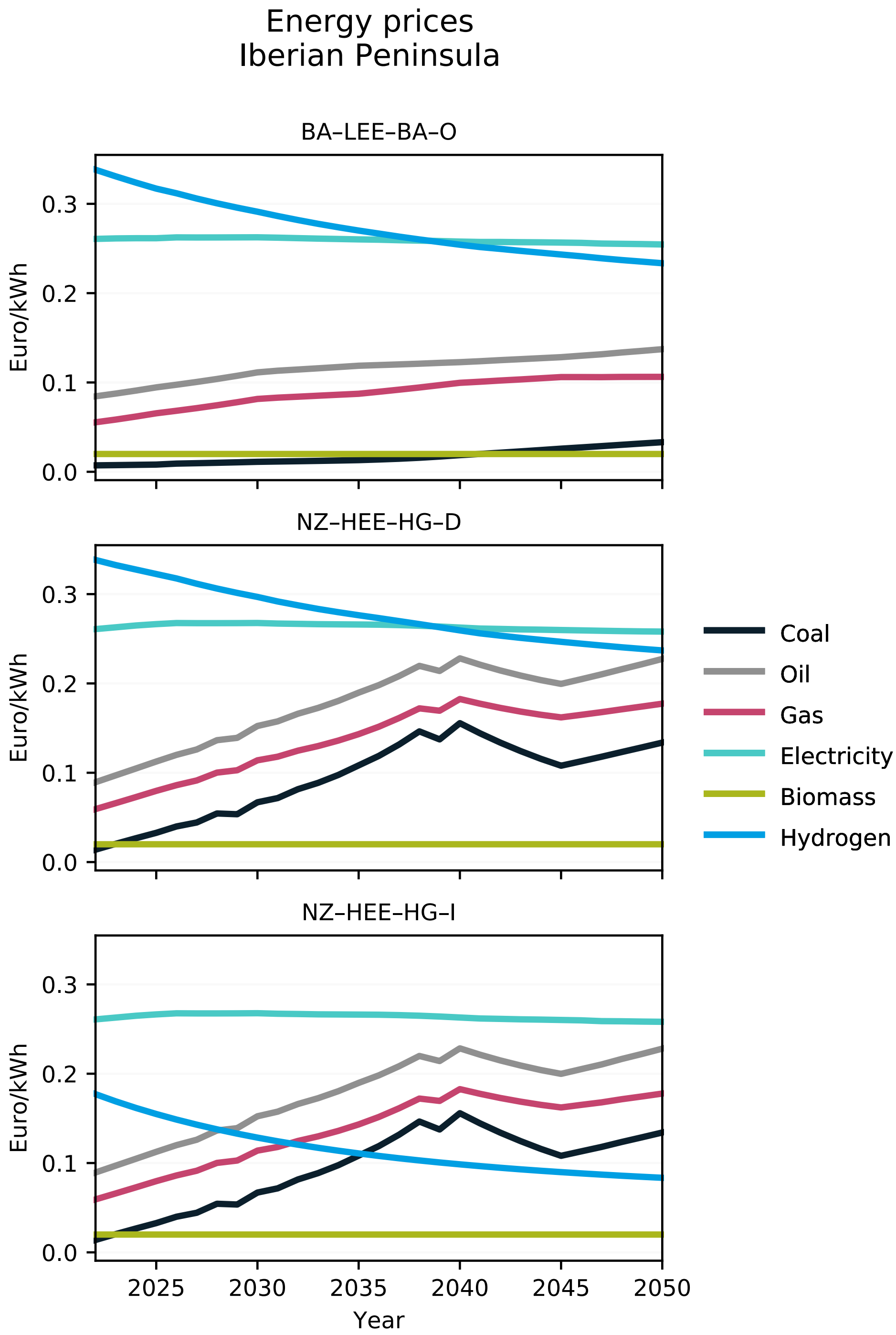

Figure B.6.7: Evolution of energy prices.

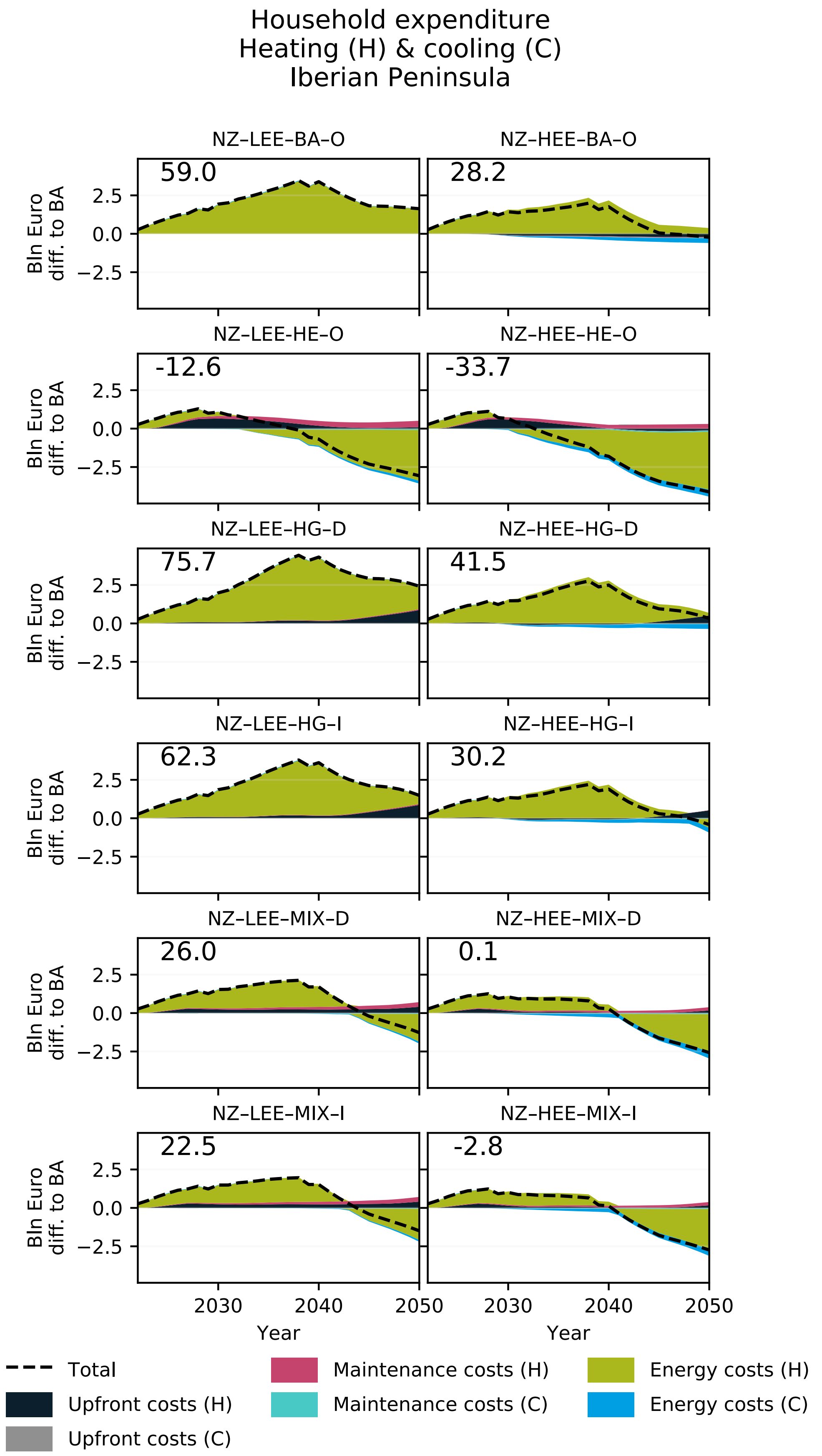

Figure B.6.8: Household expenditure change on heating & cooling. Numbers represent cumulative expenditure.

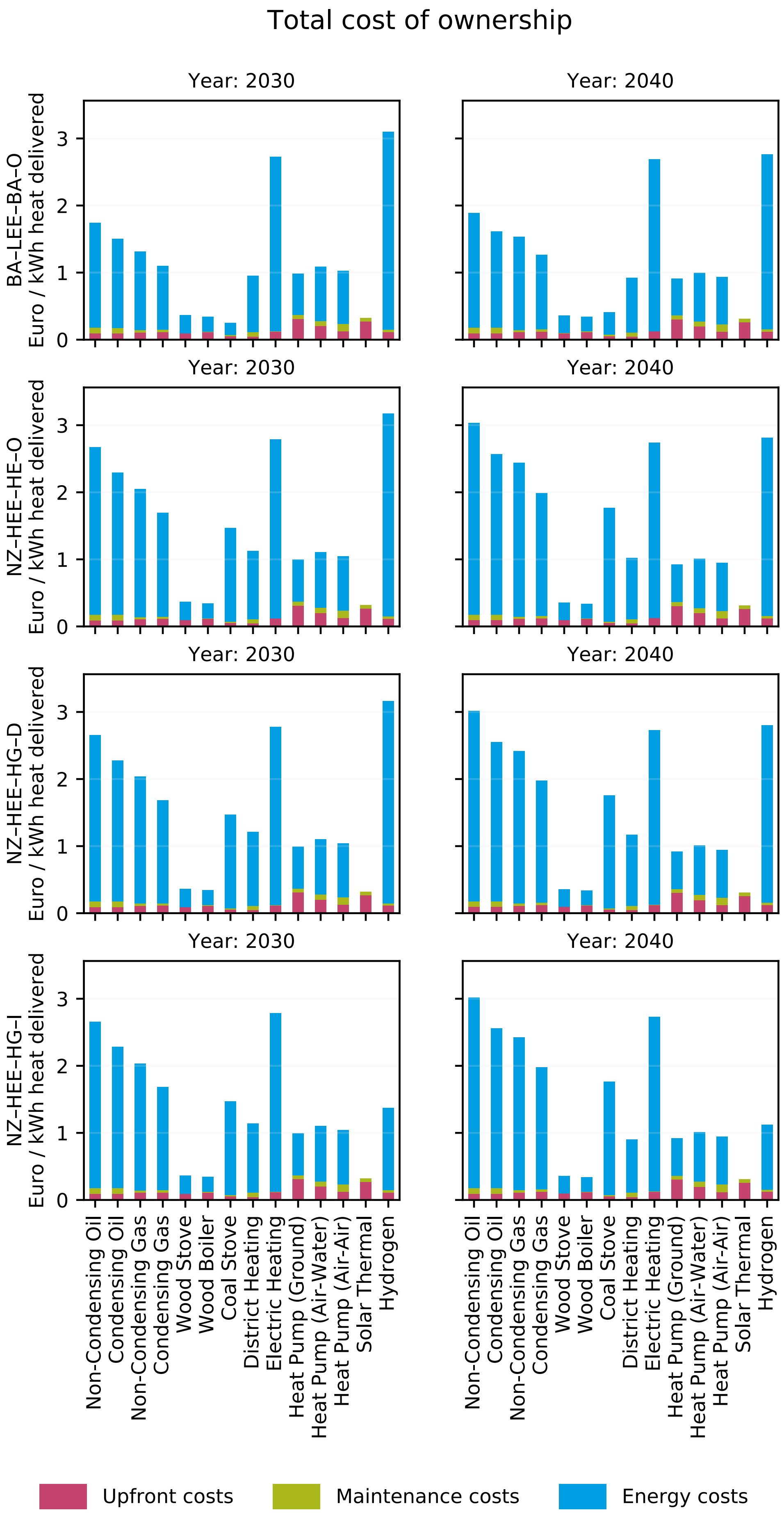

Figure B.6.9: Total cost of ownership by technology.

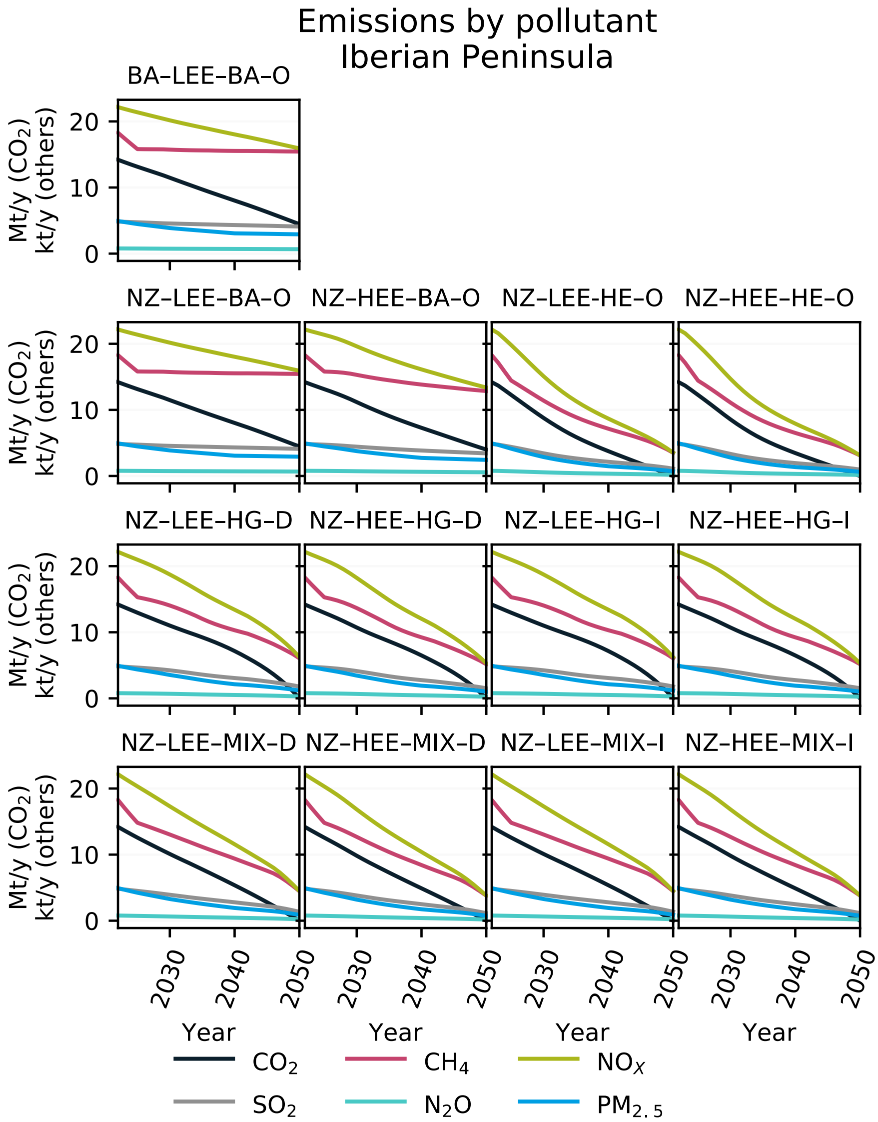

Figure B.6.10: Direct emissions by pollutants.

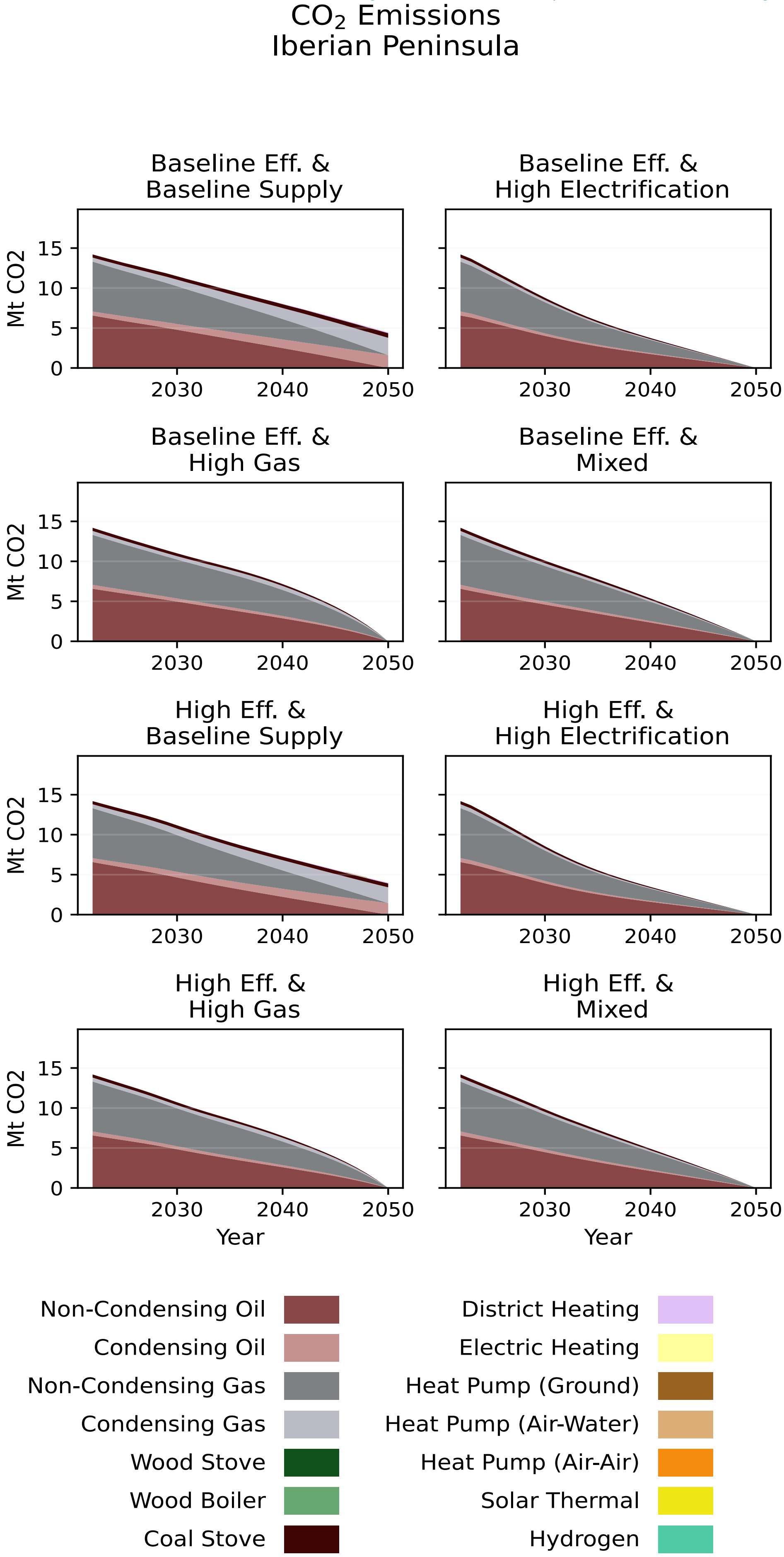

Figure B.6.11: Direct emissions by pollutants.

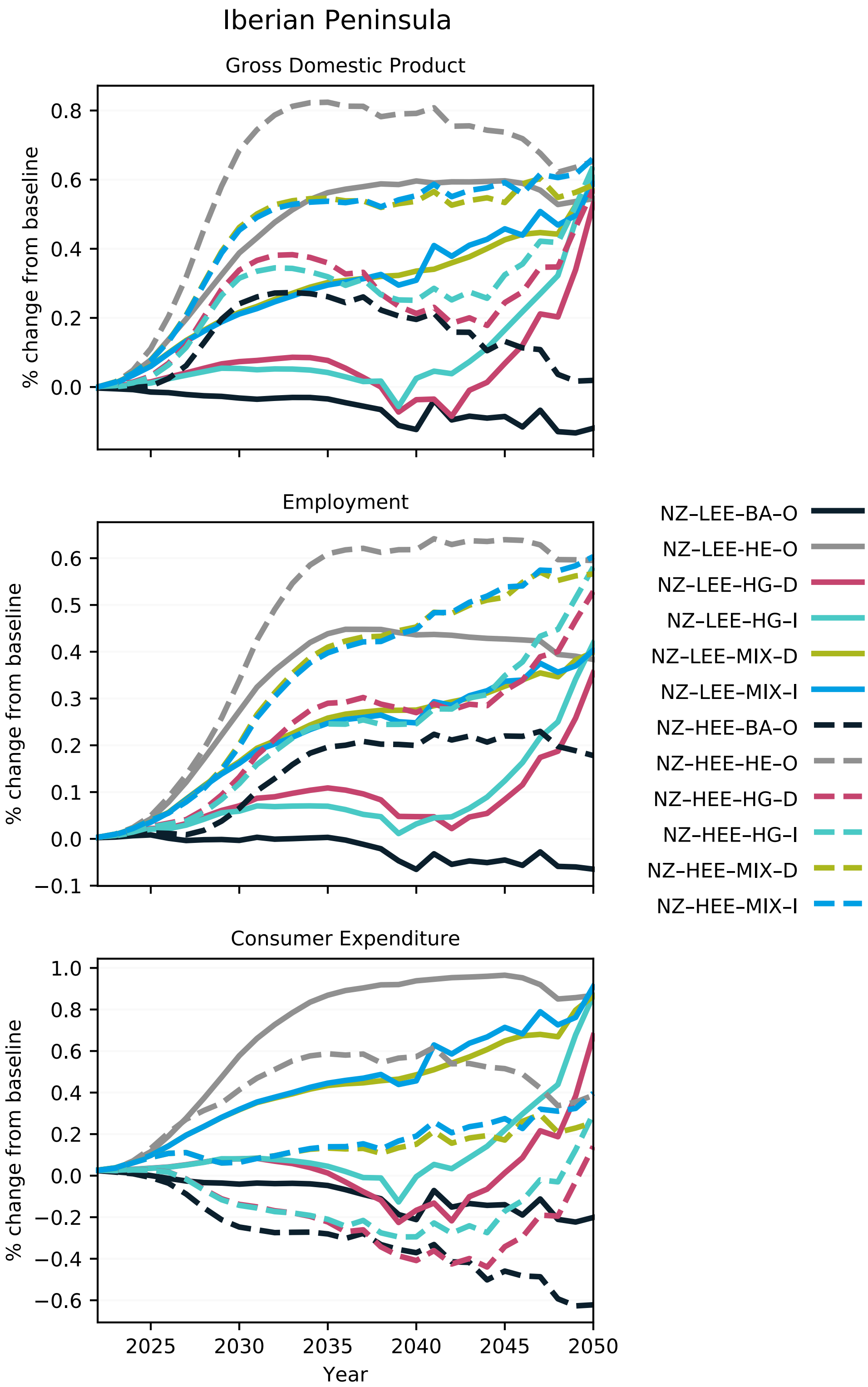

Figure B.6.12: GDP, employment, and consumer expenditure change.

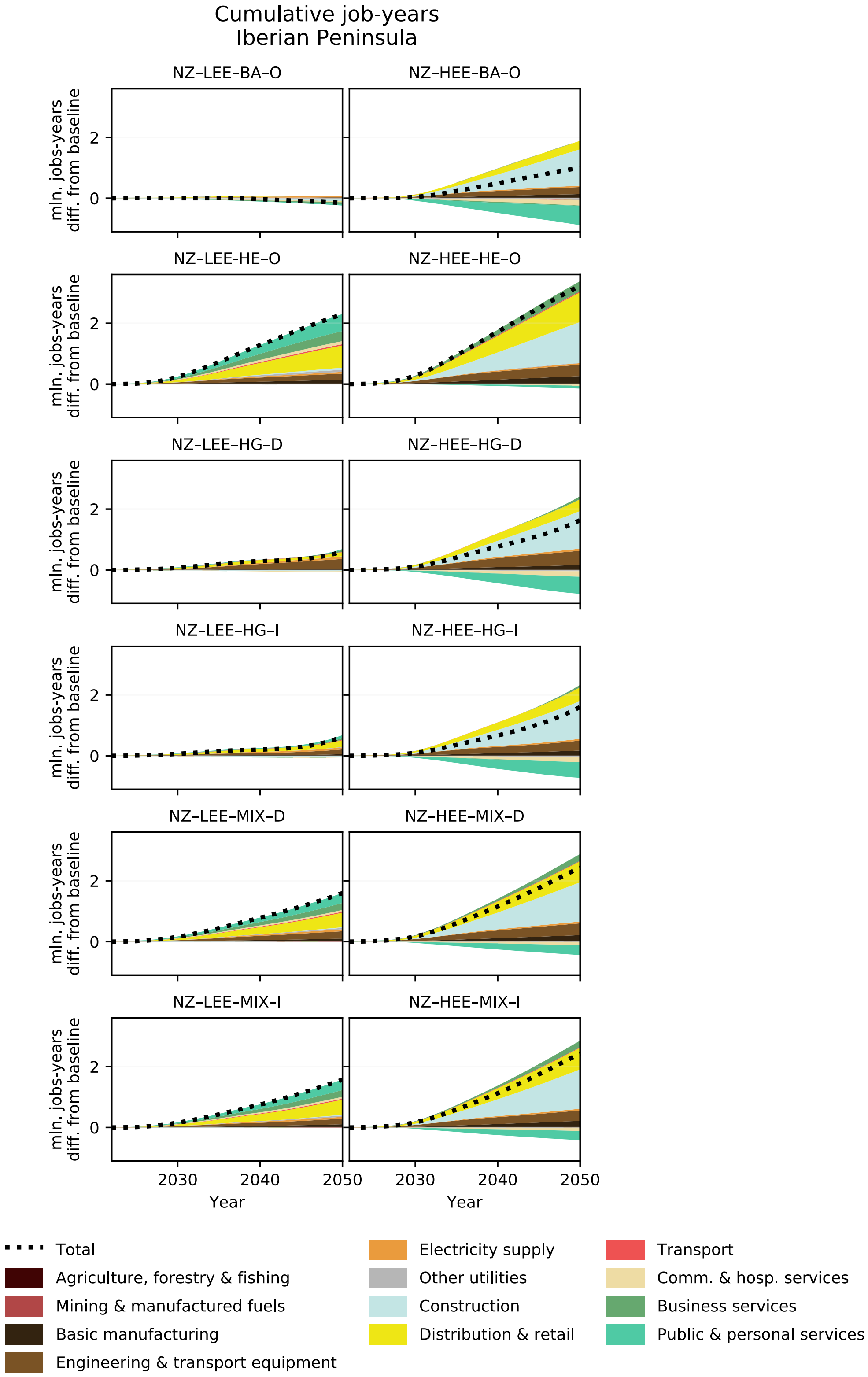

Figure B.6.13: Cumulative job-years change by sector.

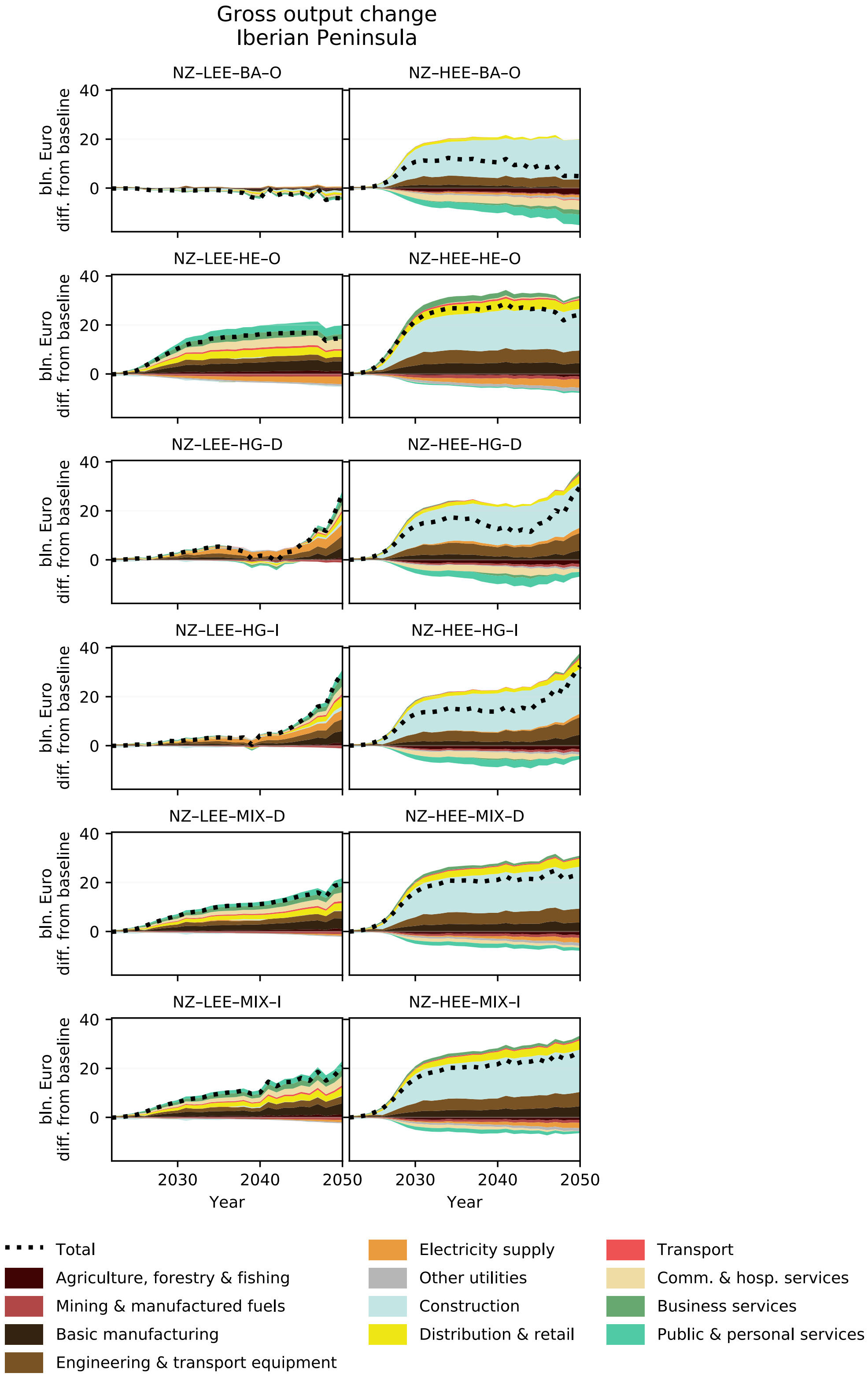

Figure B.6.14: Gross output change by sector.

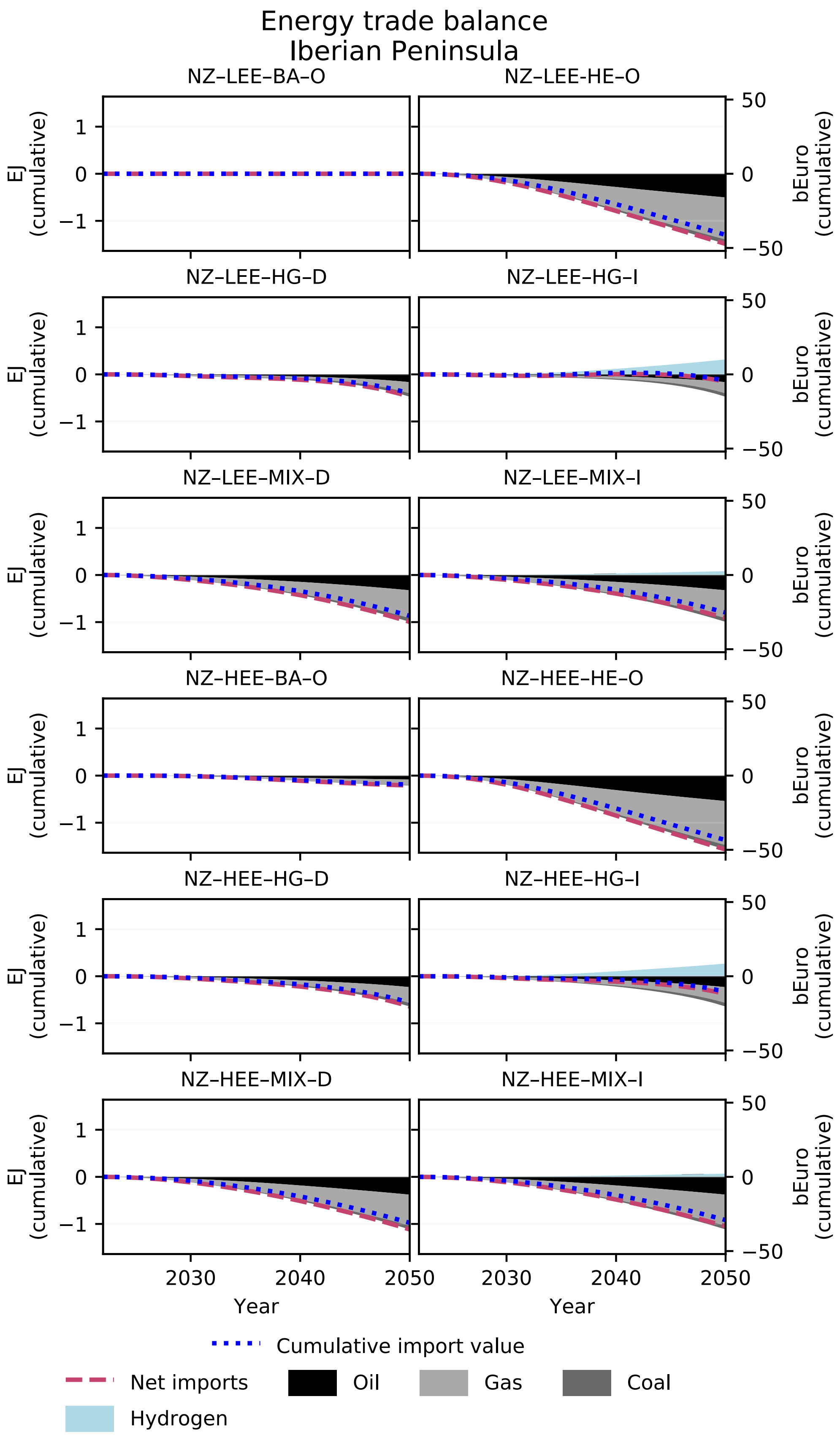

Figure B.6.15: Energy trade balance change by energy carrier.

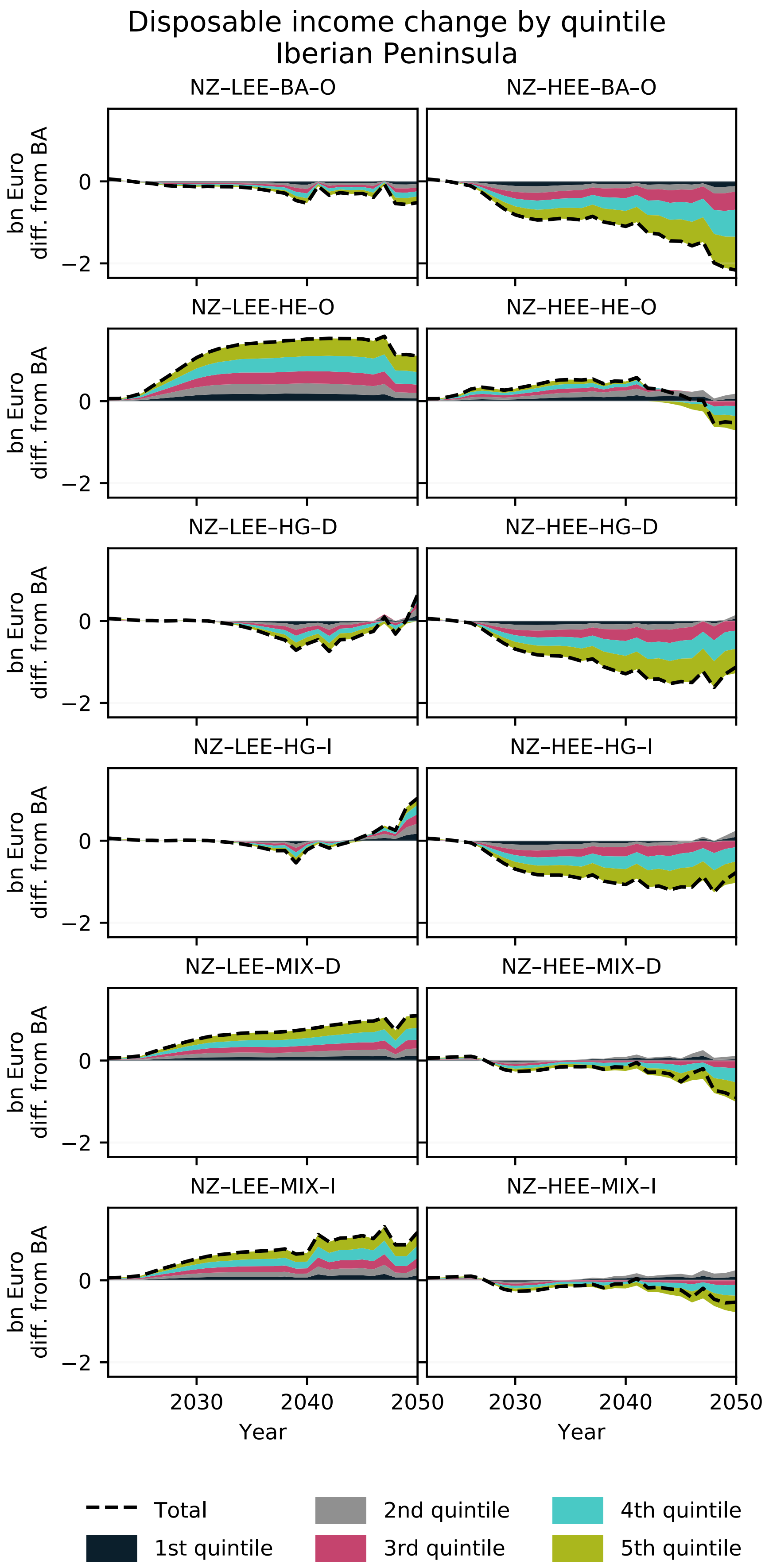

Figure B.6.16: Disposable income change by quintile.

Climate zone: Mediterranean Region

The technology evolution in the Iberian Peninsula follow similar patterns to the Iberian Peninsula, with the results mostly be driven by the uptake in heat pumps, which are able to serve both cooling and heating demands. Because of the high cost of heat pumps relative to other technologies, there is a relatively large investment into heat pumps between present and 2030. However, due to a rapid uptake of heat pumps, consumer expenditure on heating technologies will quickly fall resulting in prominent increases in GDP, and sustained higher levels of employment relative to baseline. Due to the climate and conditions in the Iberian Peninsula being favourable for heat pumps, the scenarios which push for an uptake of hydrogen perform relatively poorly compared to the high electrification scenarios. However, for the Mediterranean Region, the results are even more prominent that for the Iberian Peninsula.

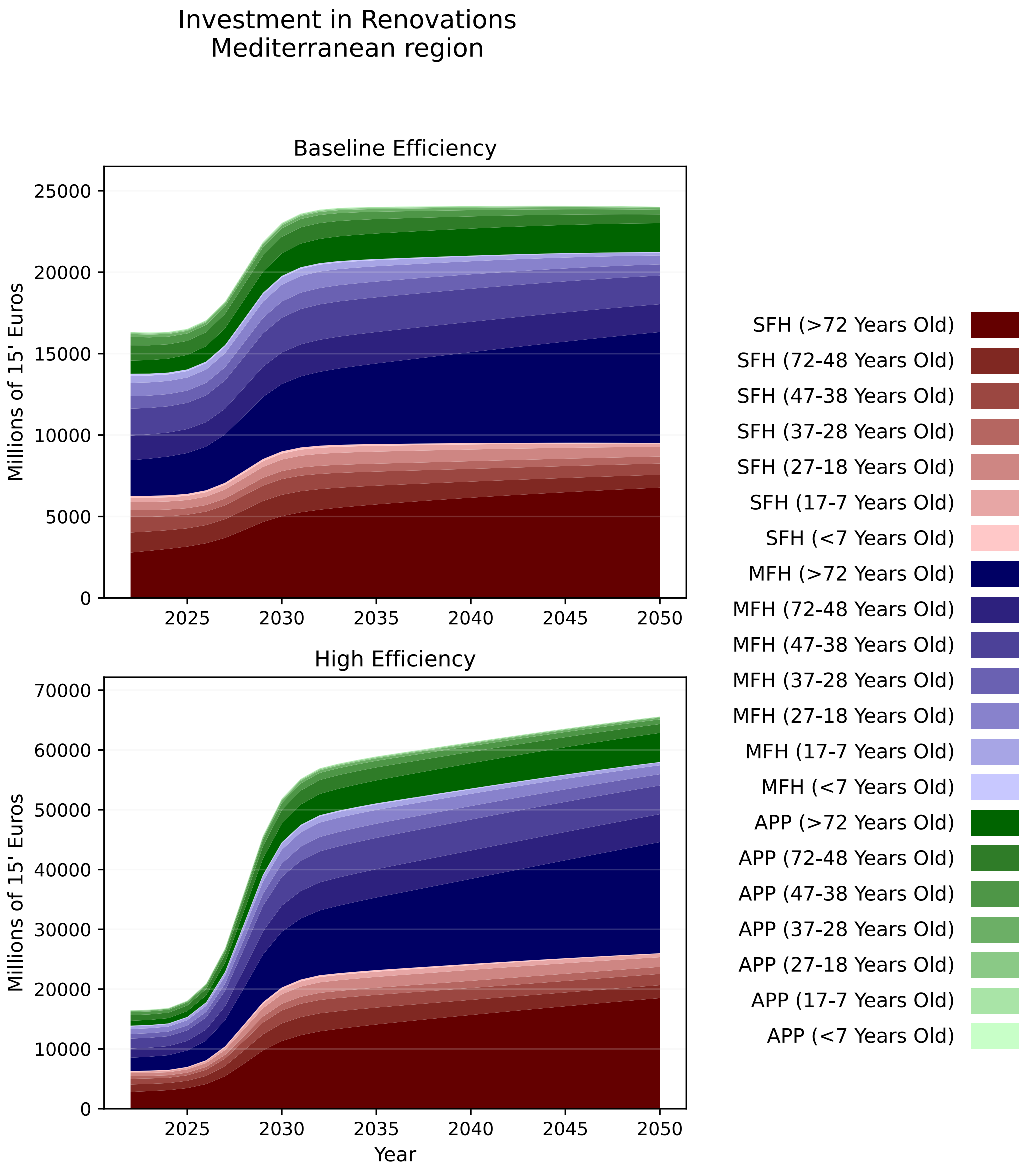

Figure B.7.1: Investments into renovations.

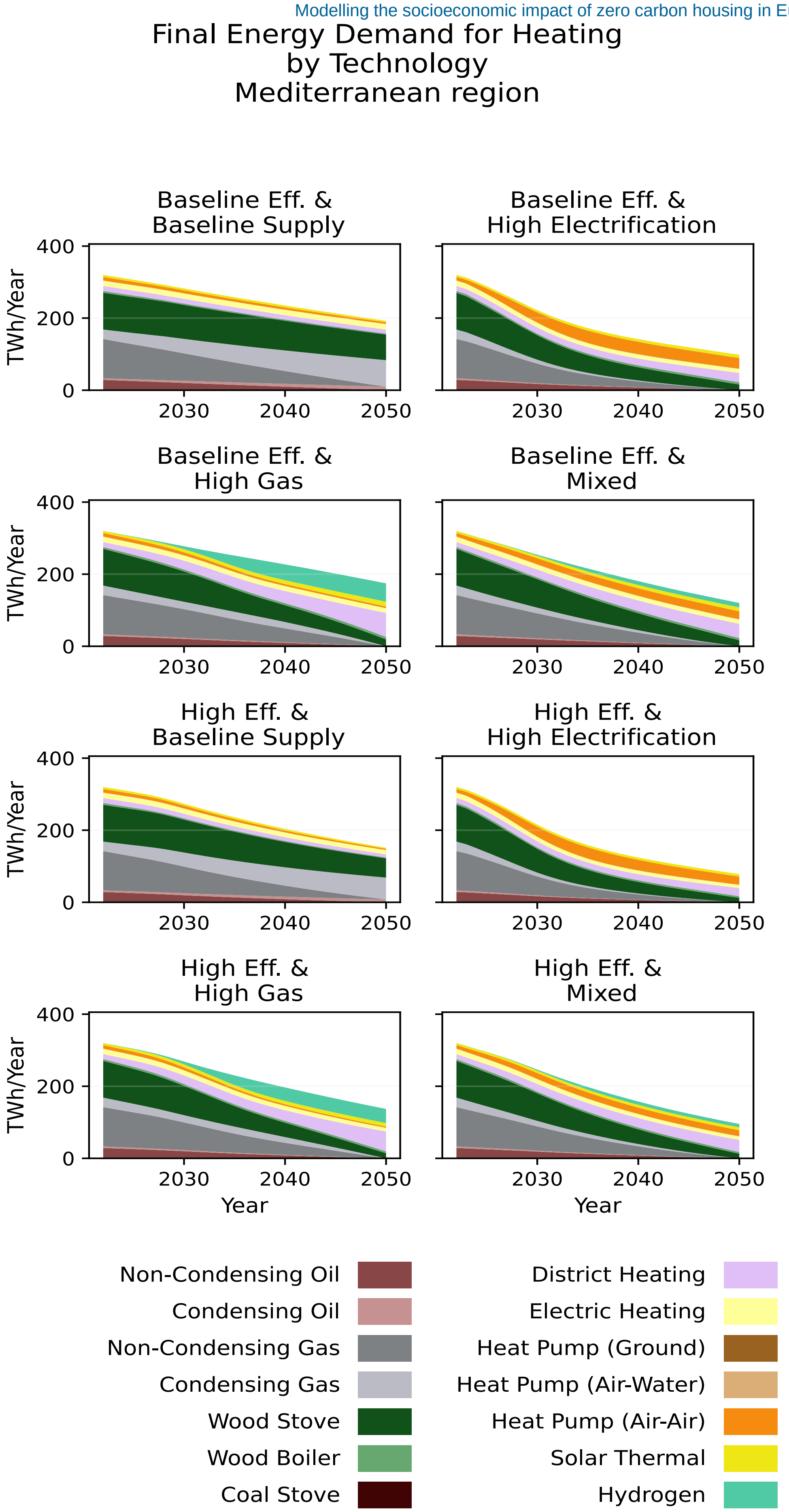

Figure B.7.2: Final energy demand by technology.

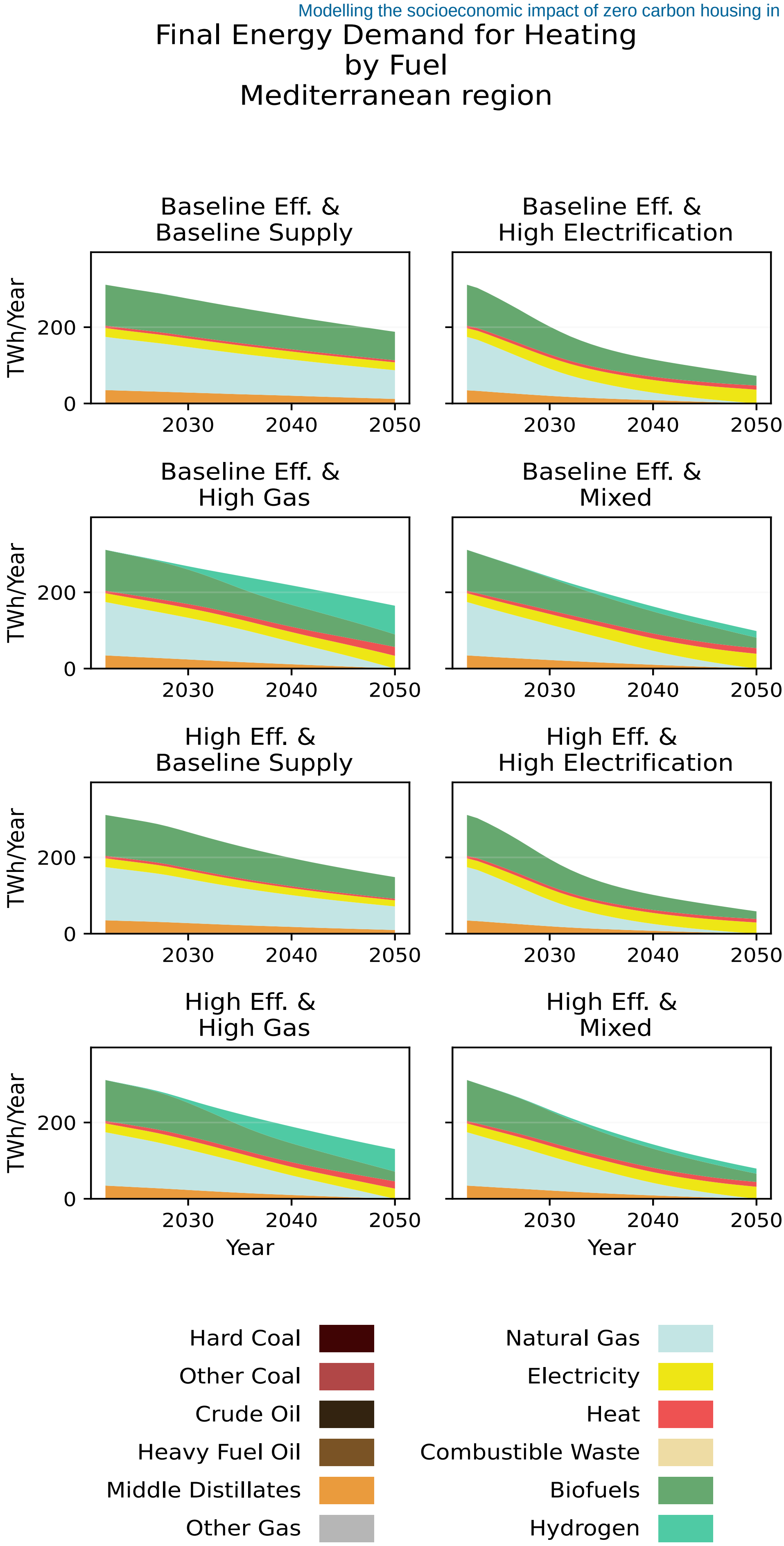

Figure B.7.3: Final energy demand by energy carrier.

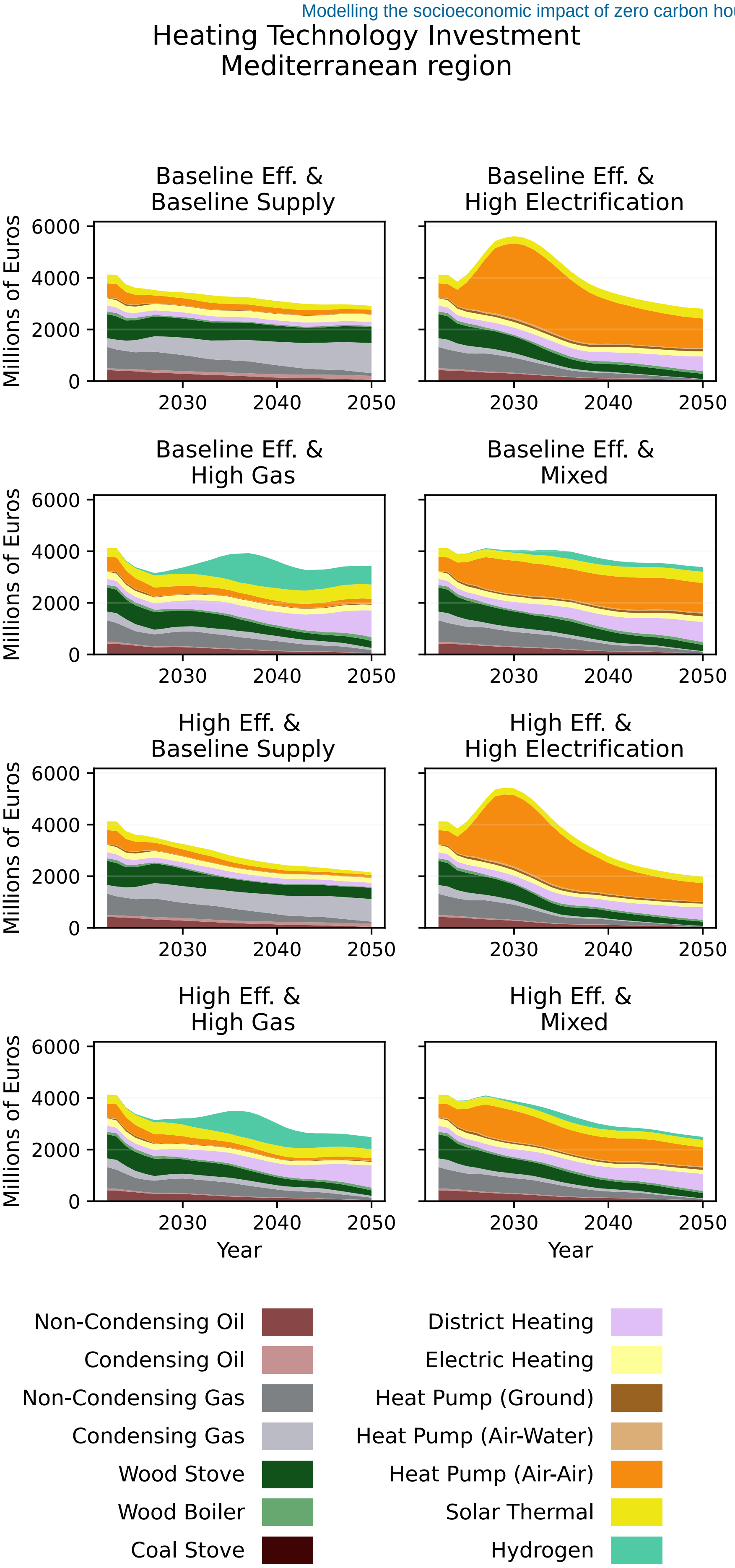

Figure B.7.4: Upfront investment in heating equipment.

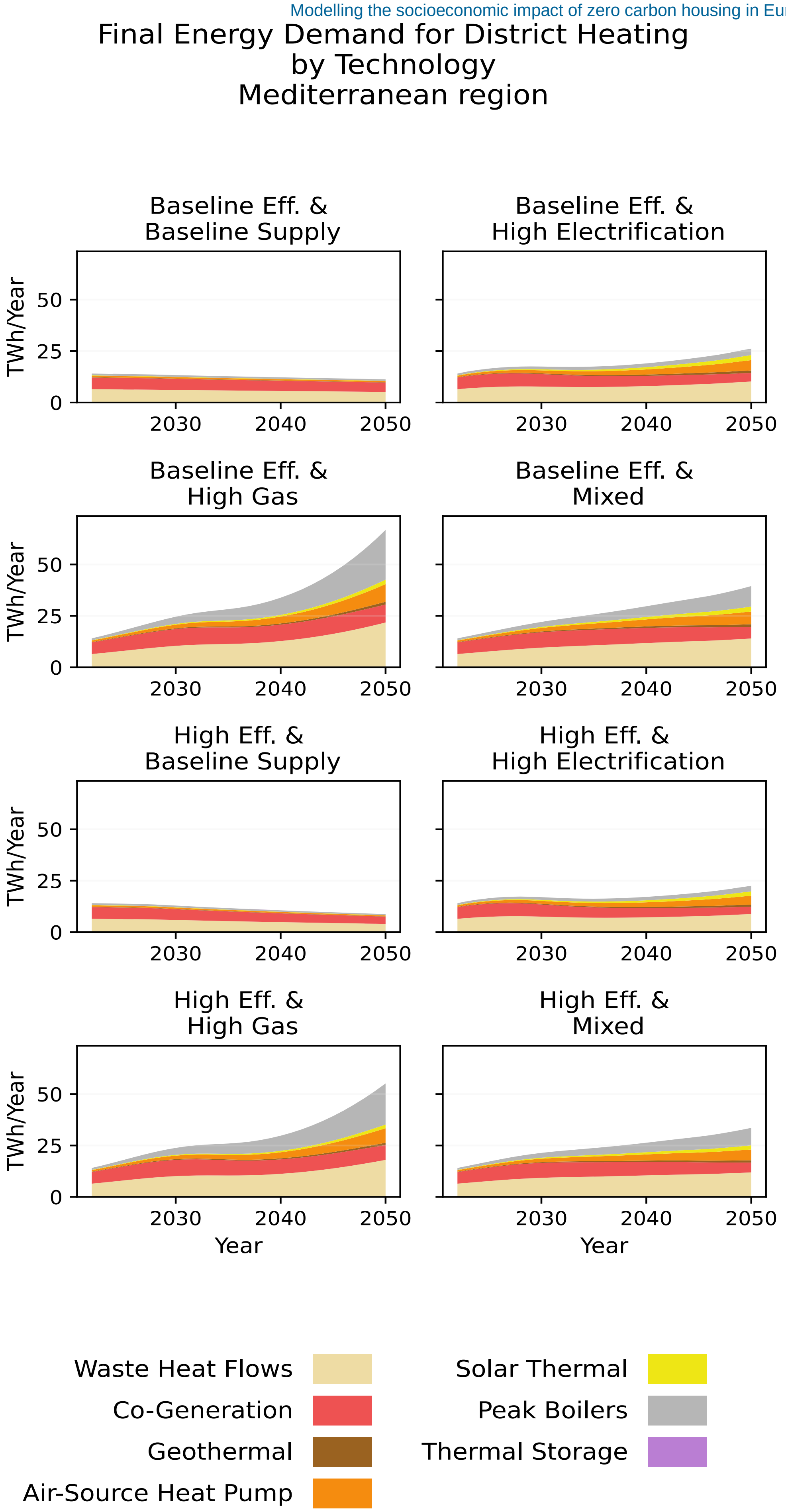

Figure B.7.5: Final energy demand in DH/C by configuration option.

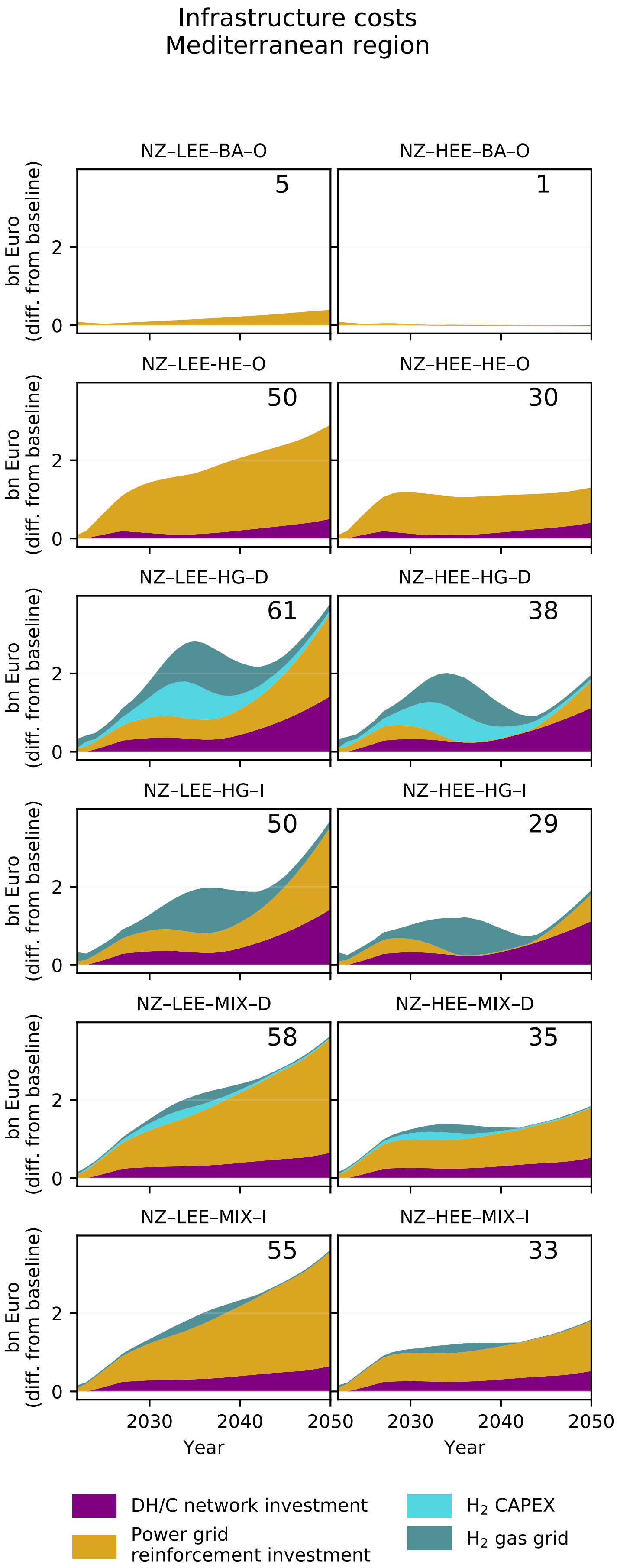

Figure B.7.6: Infrastructure investments. Numbers represent cumulative investment in billion Euro.

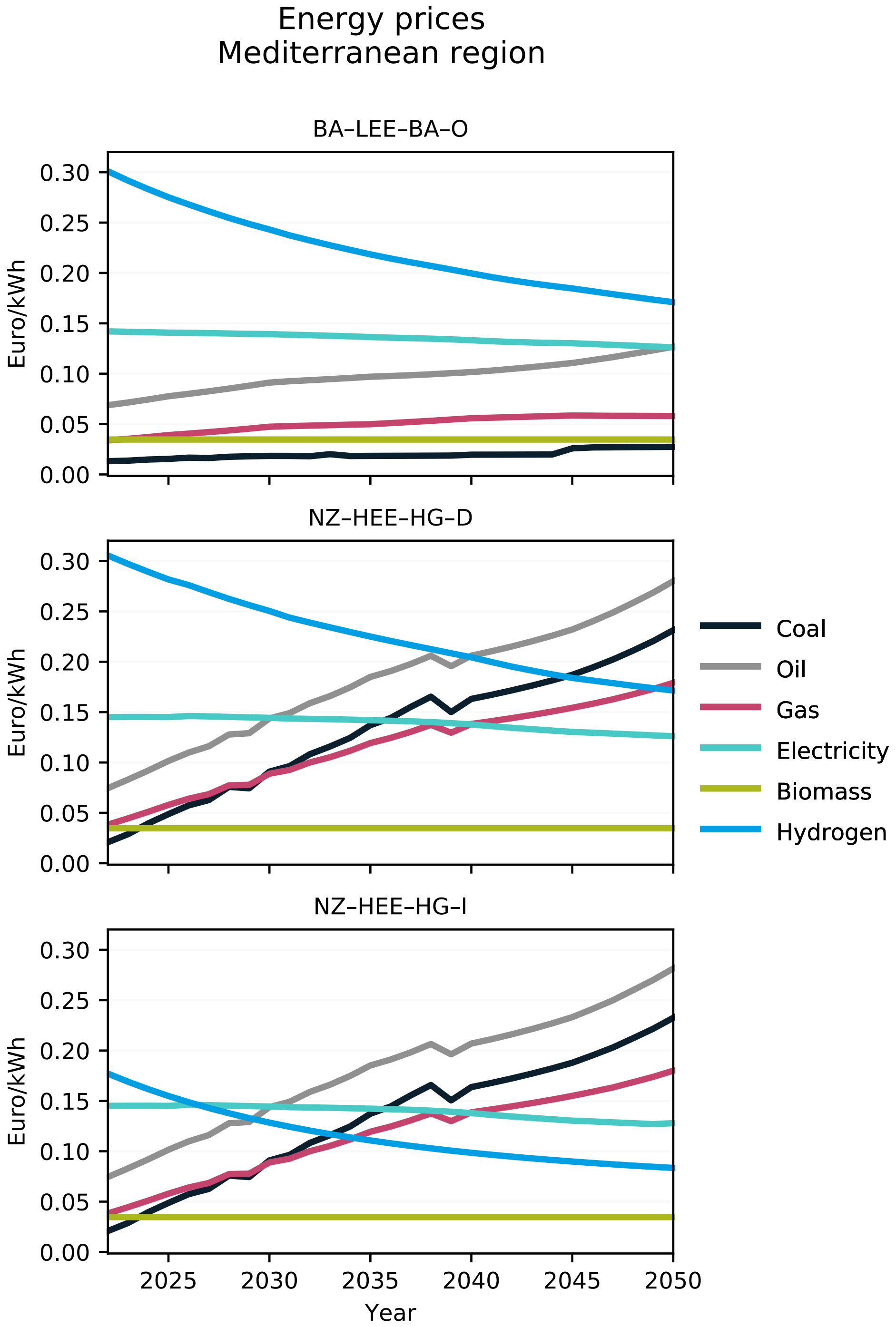

Figure B.7.7: Evolution of energy prices.

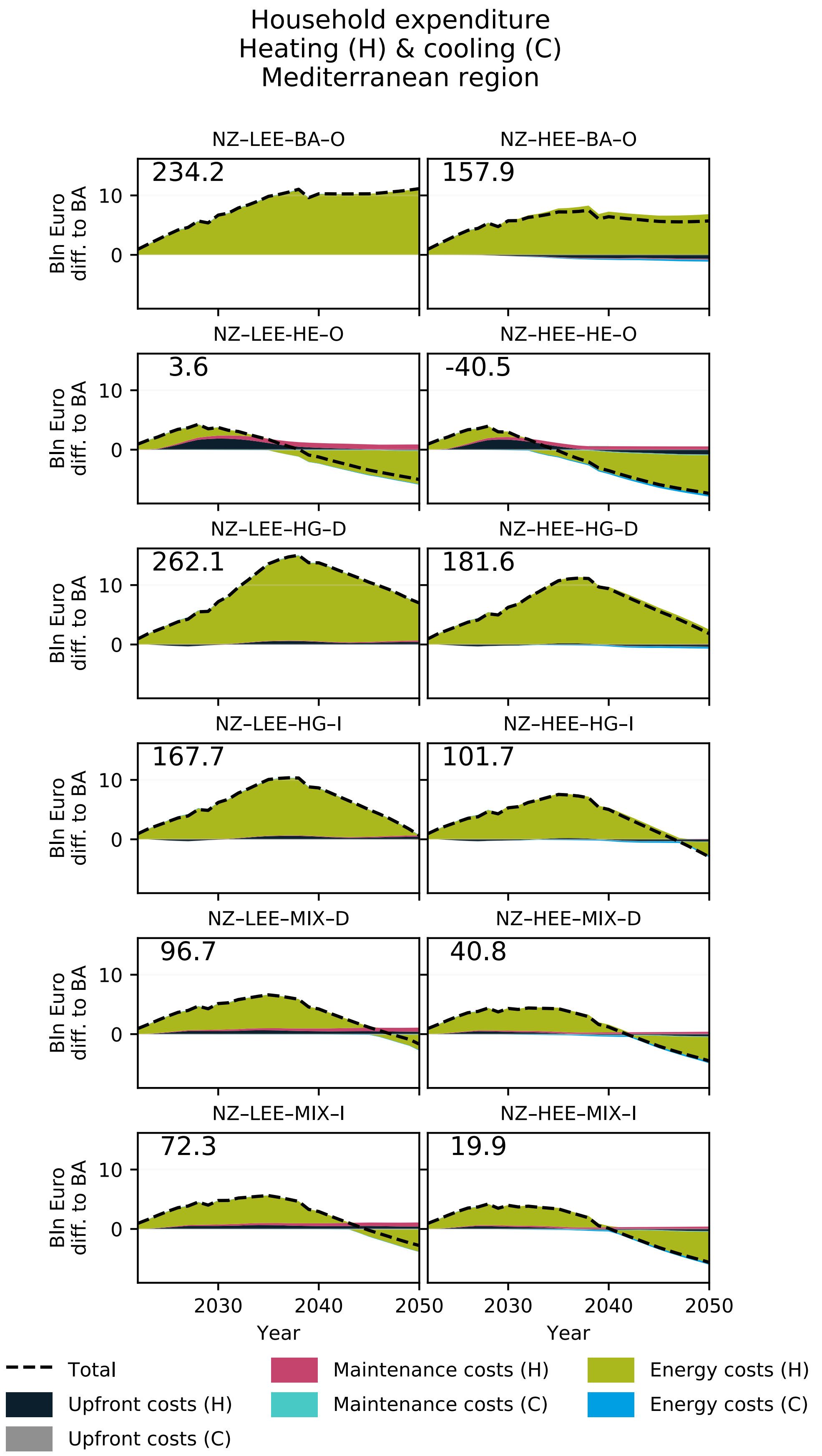

Figure B.7.8: Household expenditure change on heating & cooling. Numbers represent cumulative expenditure in billion Euro.

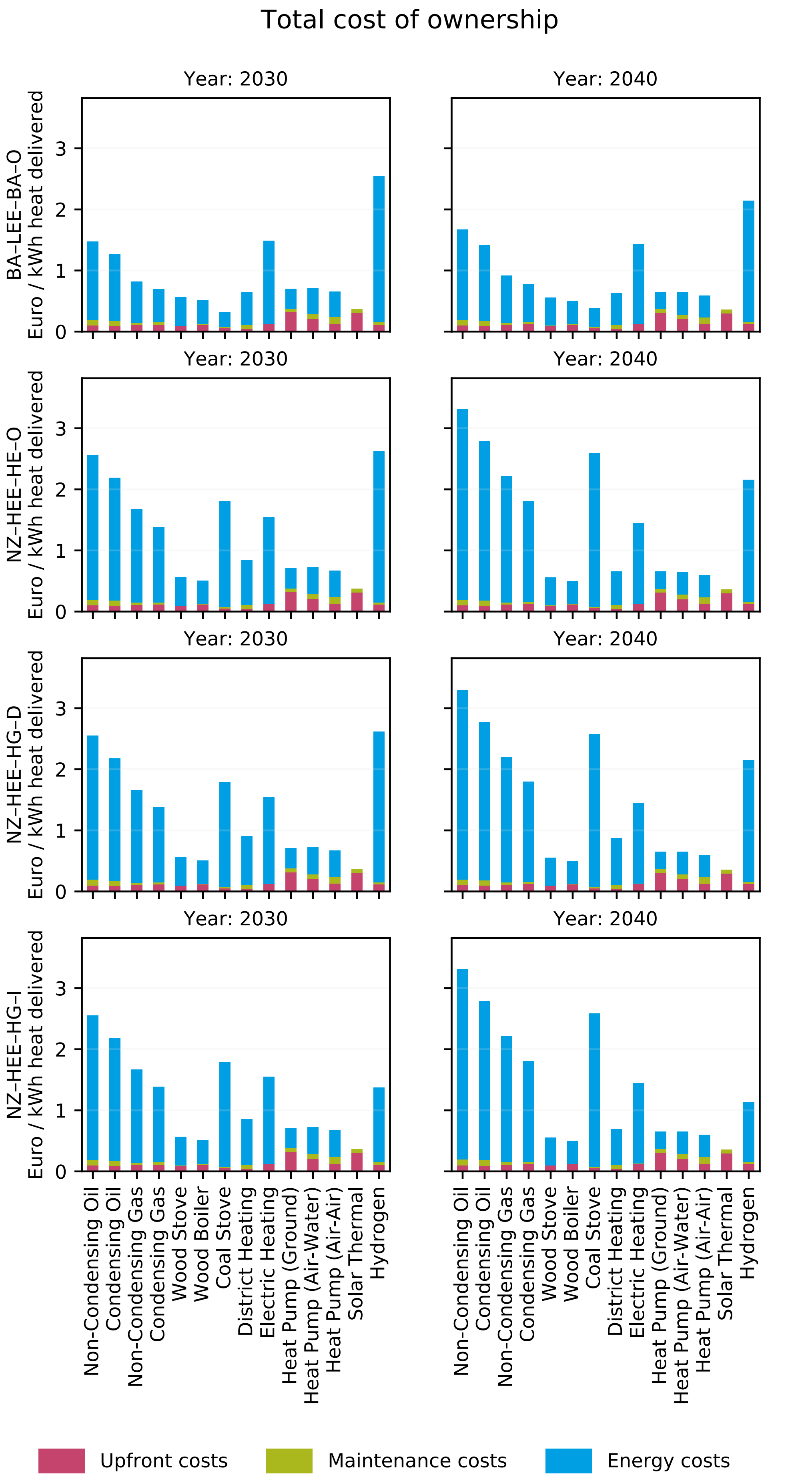

Figure B.7.9: Total cost of ownership by technology.

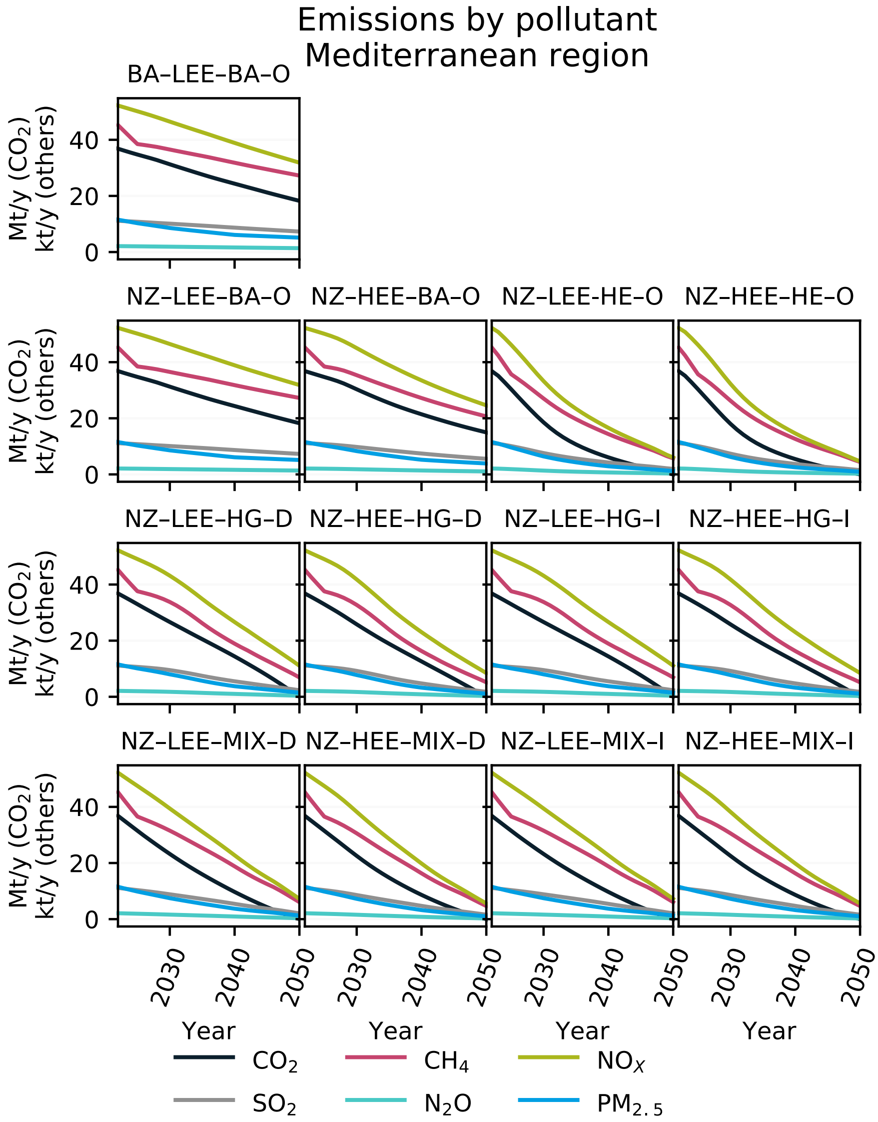

Figure B.7.10: Direct emissions by pollutant.

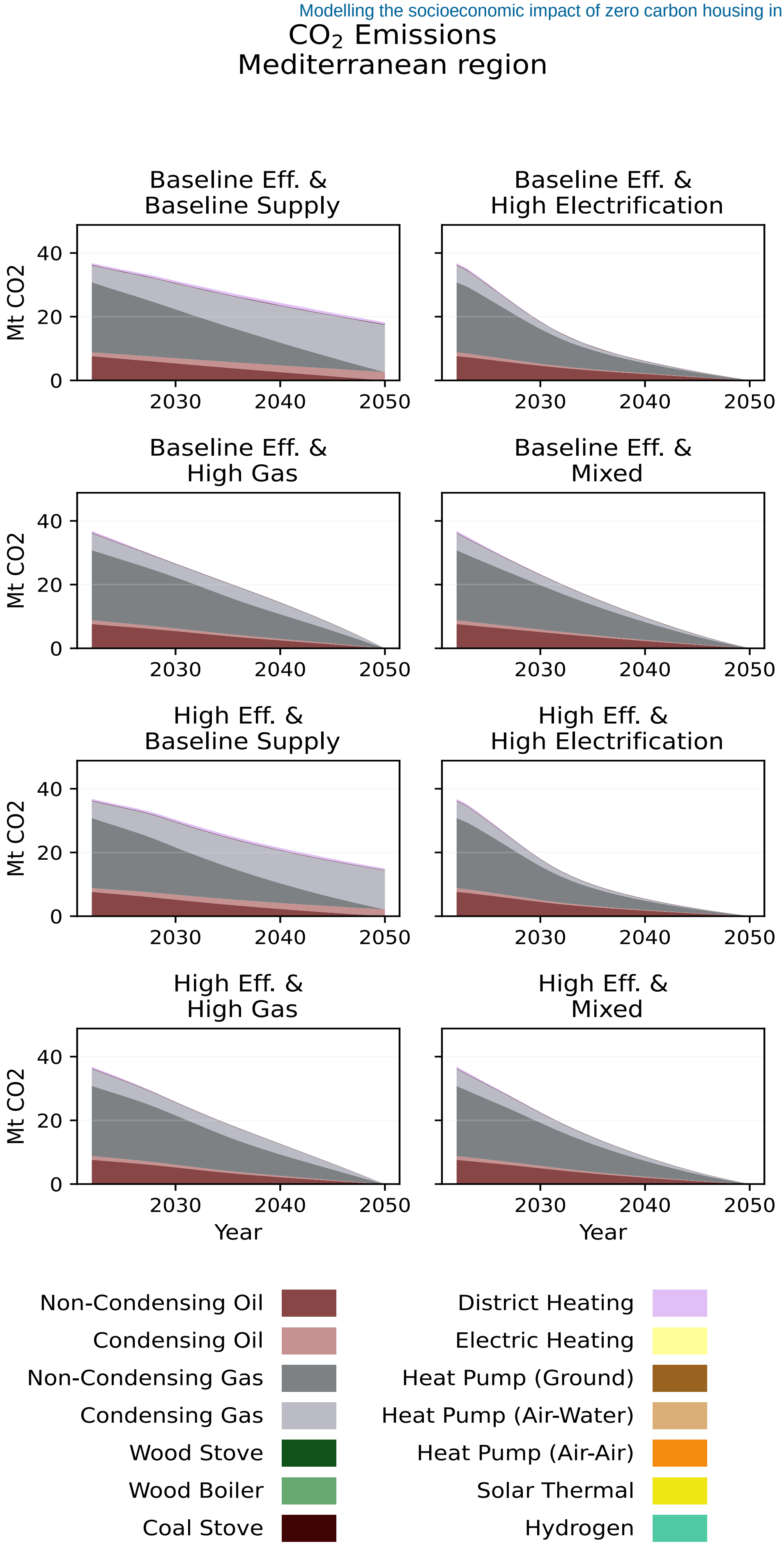

Figure B.7.11: Direct CO_2 emissions by technology.

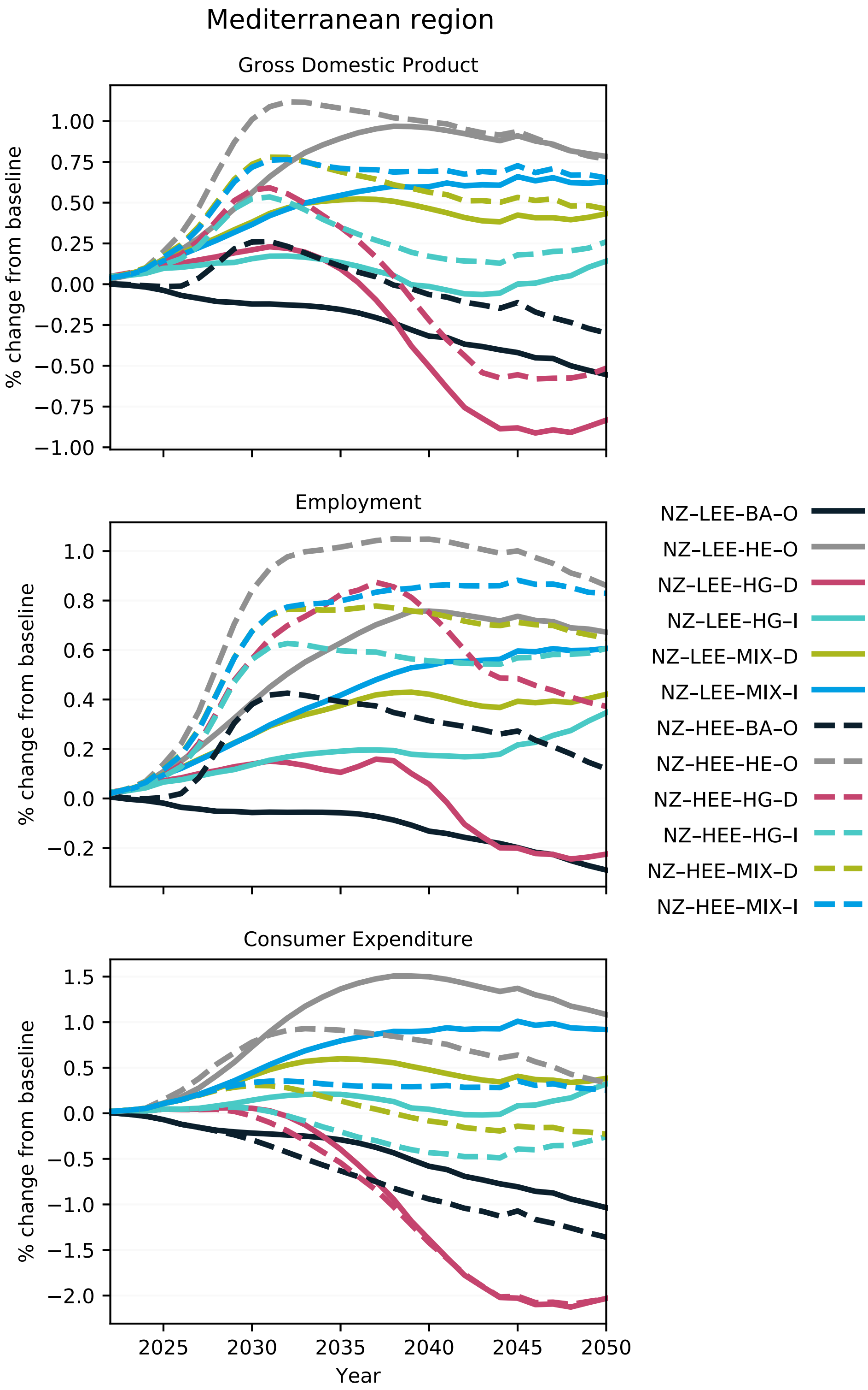

Figure B.7.12: GDP, employment, and consumer expenditure change.

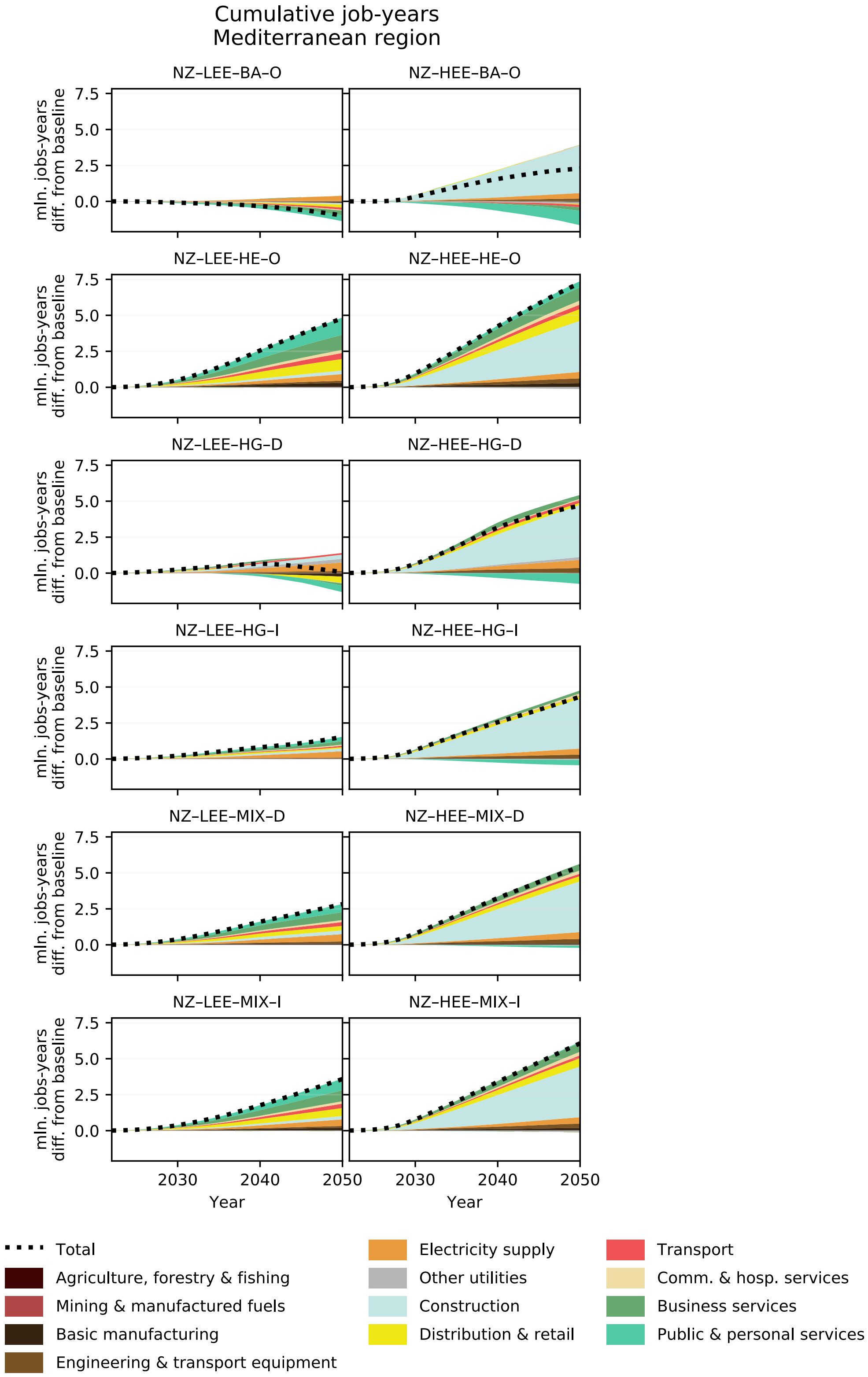

Figure B.7.13: Cumulative job-years change by sector.

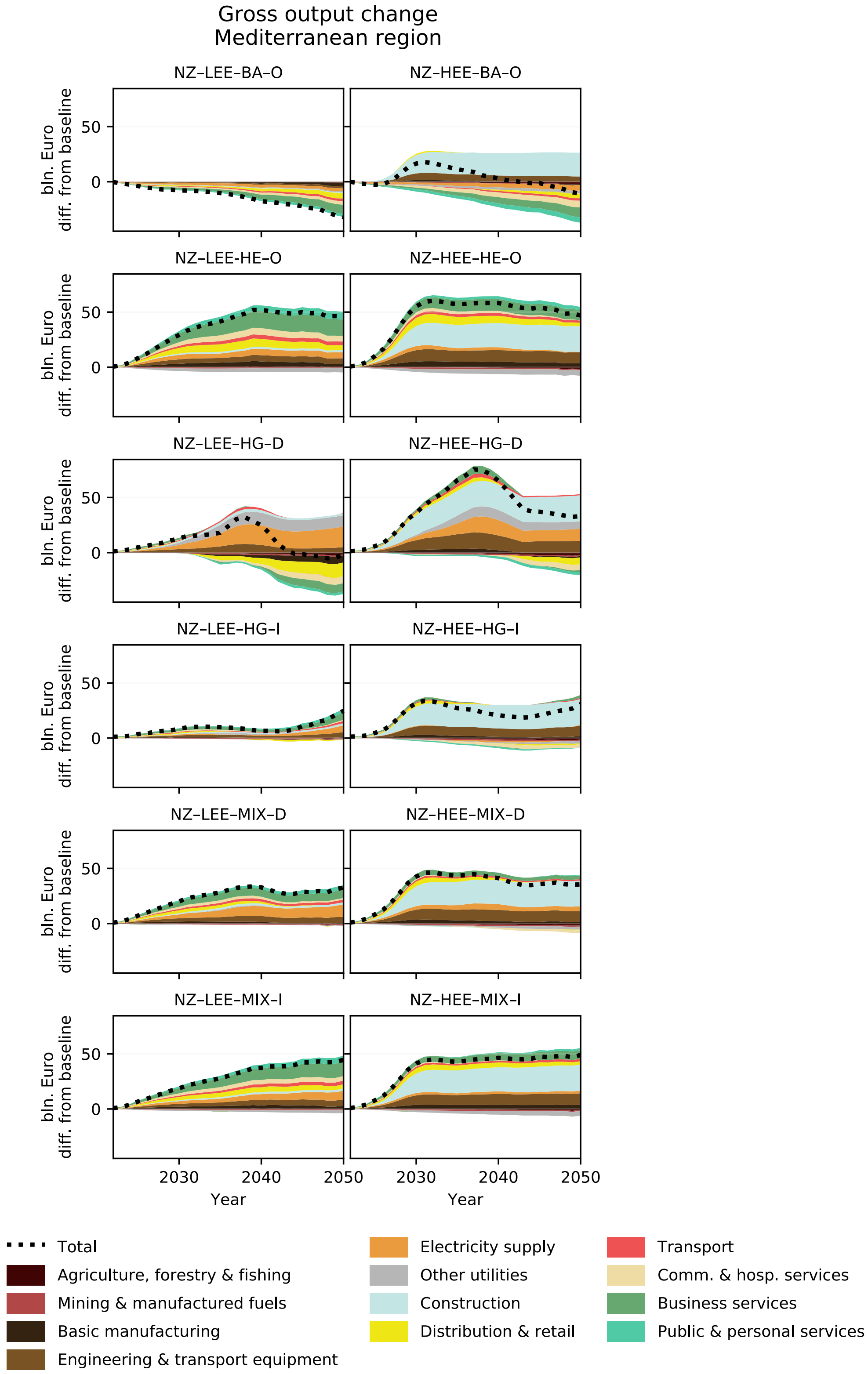

Figure B.7.14: Gross output change by sector.

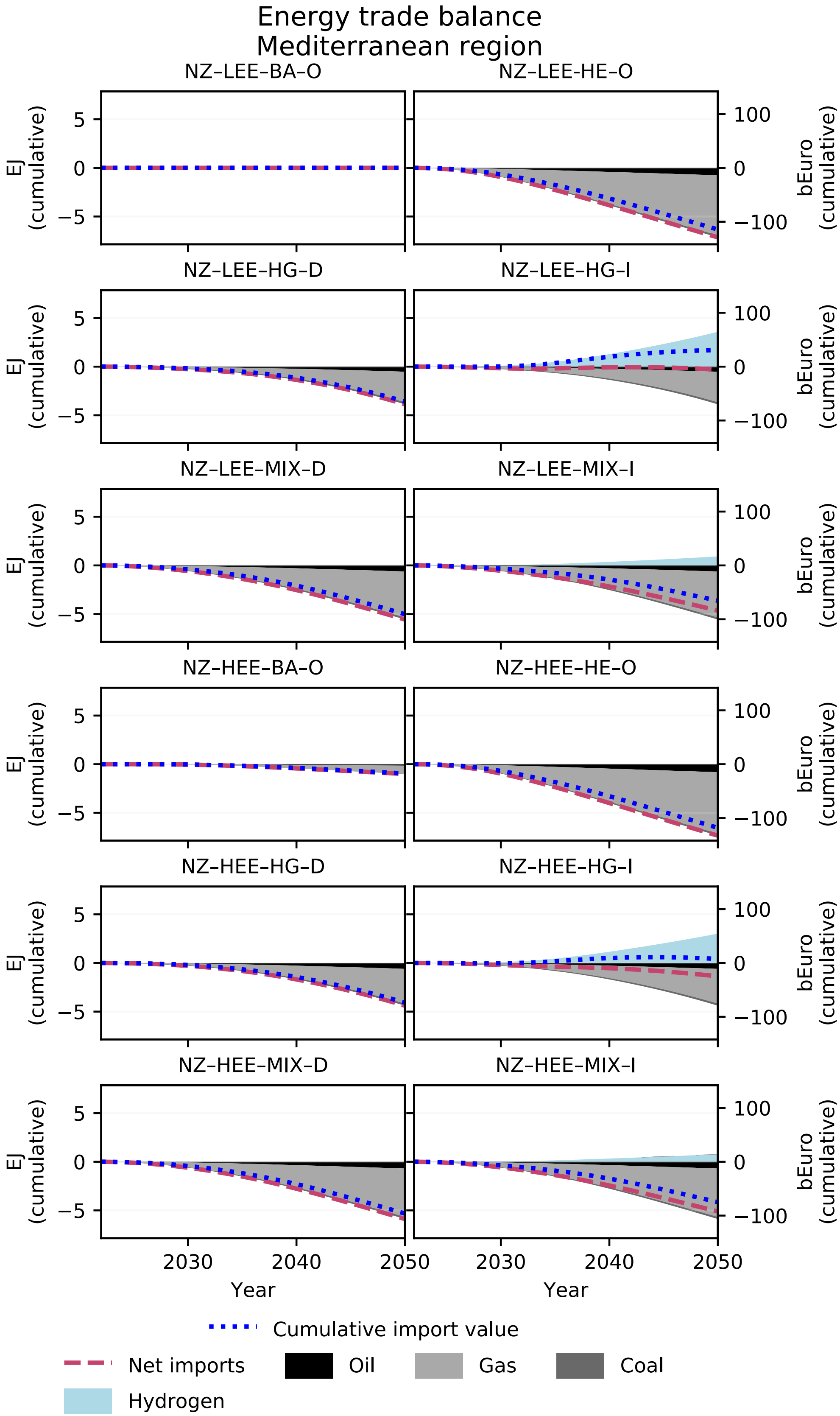

Figure B.7.15: Energy trade balance change by energy carrier.

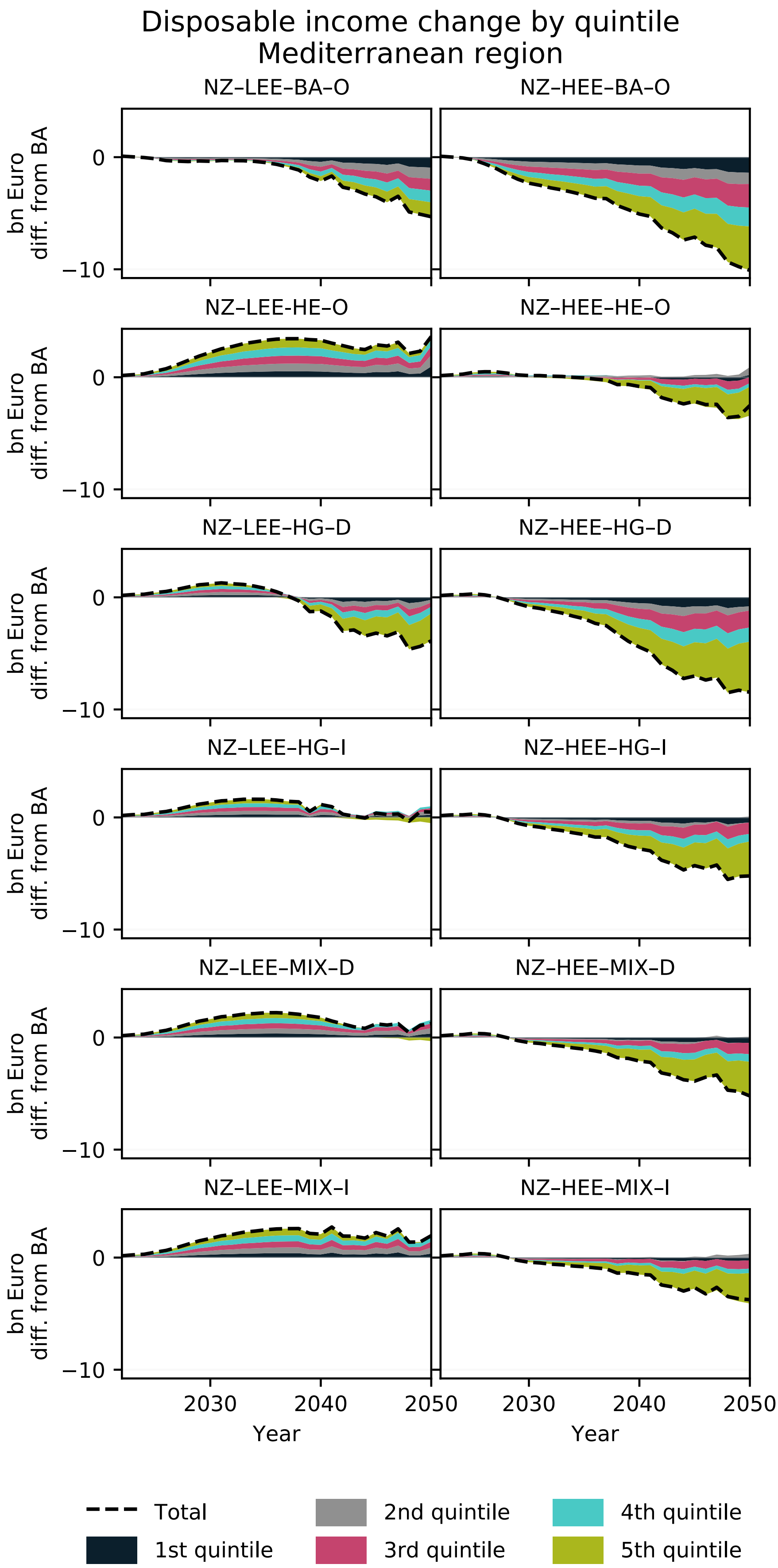

Figure B.7.16: Disposable income change by income quintile.