A technical analysis of FTT:Heat - A simulation model for technological change in the residential heating sector

Technical Study on the Macroeconomics of Energy and Climate Policies

Prepared by

Florian Knobloch, Radboud University, The Netherlands
Jean-Francois Mercure, Radboud University, The Netherlands
Hector Pollitt, Cambridge Econometrics Ltd, UK
Unnada Chewpreecha, Cambridge Econometrics Ltd, UK
Richard Lewney, Cambridge Econometrics Ltd, UK

Contact:

Florian Knobloch
Department of Environmental Science
Radboud University
Nijmegen, The Netherlands
F.Knobloch@science.ru.nl

Richard Lewney
Cambridge Econometrics Ltd
Covent Garden
Cambridge, UK
CB1 2HT
richard.lewney@camecon.com

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Executive summary

This report introduces a new bottom-up model for simulating Future Technology Transformations in the European residential heating sector, FTT:Heat. Based on scenario inputs for the future demand for heating as an energy service, the model simulates the uptake and replacement of heating technologies by households in all 28 EU Member States up to 2050. It features an explicit representation of households' technology choices, based on market competition, climatic conditions, policies, and induced technological change.

As a simulation model, FTT:Heat aims at a realistic representation of how the residential heating systems in individual countries may develop in the future. The model simulates likely pathways, given different policies. Decision makers are modelled as individual households, which are subject to limited information and bounded rationality. Therefore, decisions do not necessarily result in an optimal outcome from a macroeconomic perspective, but reflect relevant behavioural factors and preferences on the micro level.

The model can be used to simulate the potential effect of different policies on the technology composition, future levels of final energy demand, fuel use, emissions, and investments – both per Member State, and aggregated for the European Union. The model is constructed as a sub-component for the global macro-econometric model E3ME, which allows for macroeconomic feedbacks between the heating sector and the wider economy (through fuel use, energy prices and investments). When testing a new policy for the heating sector, the combination of both models makes it possible to analyse the potential relative changes in all economic sectors and world regions, as well as the changes in macroeconomic indicators like household income, employment or GDP.

FTT:Heat is here applied for simulating a set of policies and scenarios. A baseline scenario is defined, which assumes the continuation of current policies and technology diffusion trends. Based on the identified trajectories, it is estimated that residential heating within the EU would become less carbon-intensive in the future: CO_2 emissions by residential heating are projected to decrease by around -22% until 2030 (relative to 2014), while household demand for heating would remain stable. A closer look at individual Member States, however, unveils large differences: while some countries are estimated to continue an ongoing transition towards renewable heating, others would hardly see any change in their heating systems under existing policies.

In addition to this baseline projection, several scenarios aiming at an increased share of renewable heating are simulated. For this purpose, different policies are successively added on top of each other, until an increase by at least ten percentage points is realized between 2018 and 2030. Eight Member States are projected to reach this objective without any additional policies, thanks to an ongoing diffusion of renewables technologies. For thirteen Member States, the model simulations suggest that the renewable heating objective could be fulfilled by introducing a combination of (additional) market-based policies from 2018 until 2030: a new carbon tax on the residential use of coal, gas and oil (starting at 50 € per ton of CO_2), which would need to be combined with capital subsidies on the upfront cost of renewable technologies in eight Member States (-30% on the installation costs, phased out after 2030). For the remaining group of seven Member States, even the combination of both price instruments is projected to be insufficient for reaching the renewable objective by 2030. In these countries, the current shares of (decentralized) renewable heating are so low that it would require additional 'kick start' policies (e.g., procurement policies targeted at publicly owned building) to enable a sufficiently fast growth of the incentivized technologies.[1] The results indicate that the envisioned increase in renewable heating share needs relatively more effort in countries with low starting values.

The increased share of renewable heating would imply a -39% reduction in on-site CO_2 emissions by residential heating by 2030 (compared to -22% in the baseline). Slightly increased emissions by power plants (due to a +50TWh/y increase in EU wide electricity demand) would be small in absolute comparison, allowing substantial net reductions of EU wide emissions. The induced substitution of fossil fuel based technologies does not occur instantaneously, however. Both due to the long technical lifetimes of heating systems and the inertia of technology transitions, substantial changes in market shares can only be observed after several years (or even decades). Even when costs change dramatically, many households will be 'locked' into their existing heating systems for a considerable time. During this transition period, when introducing new carbon taxes, households that still operate the old technologies would therefore face higher heating costs.

In addition to reaching the 2030 objectives of increasing renewable heating by ten percentage points, the implemented policies are projected to have large impacts long afterwards: emission levels remain constantly lower, renewables would keep on dominating sales, and hardly any new investments into fossil-fuel based heating systems are projected from 2040 onwards, resulting in a -83% emissions reduction by 2050 (relative to 2014, compared to -69% in the baseline). This is despite the fact that subsidies for renewables and the carbon tax are assumed to be discontinued after 2030. Continuing the simulated policies and extending them to all Member States after 2030 would set the EU residential heating system on track for a deep decarbonisation until 2050, resulting in a -98% emission reduction in 2050, according to the model estimates.

During the simulated policy-induced technology transition, annual household expenditures on heating systems are projected to be up to +45% (or +9 Billion 2005€ per year) larger than in the baseline projection, reaching their highest levels between 2030 and 2040 (if policies are continued beyond 2030). Overall additional expenditures between 2018-2050 accumulate to +94 Billion 2005€ if polices are discontinued after 2030, and to +176 Billion 2005€ if policies are extended up to 2050. In addition, the increased electrification of household heating would increase annual investments by the power sector by up to +6% (or +3,7 Billion 2005€ per year). At the same time, households would face additional tax payments on fossil fuels of up to 20 Billion 2005€ per year, while receiving capital subsidies on the purchase of renewable heating systems of up to 6 Billion 2005€ per year. The political acceptability of policies targeted at the residential heating sector may therefore depend on the way in which carbon tax revenues are redistributed to households.

From a macro-economic perspective, it is here assumed that the additional tax revenues would be used to reduce employers' contributions to social security payments, thereby incentivizing employment in all sectors. Estimated impacts on total employment are therefore slightly positive over most of the simulation period, despite small net reductions in employment in heating related sectors (where induced job creation in the electricity and manufacturing sectors is of a similar magnitude than job losses in the fossil fuel and energy network sectors). The EU wide GDP is projected to be up to +0,1% larger than in the baseline beyond 2030, and up to-0,1% smaller before 2030.

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[1] In Member States with large shares of district heating, the objective may alternatively be achieved by increasing the share of renewables in district heat plants, which are beyond the scope of this study.

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Part I. Introduction

Heating accounts for around half of the European Union's final energy consumption, 45% of which is attributed to the residential sector (European Commission, 2016a). Within the average European household, more than 80% of the overall energy consumed is used for heating. Given the EU's commitments to reduce its domestic greenhouse gas emissions, and in view of its strategic objective to become a world leader on renewable energy and to apply the "energy efficiency first" principle, reducing energy use and emissions in the residential heating sector is therefore of paramount importance.

While a certain reduction in residential demand for space and water heating is expected to result from improved building insulation, it will likely remain at substantial levels even under ambitious scenarios of building stock renovation (Connolly *et al.*, 2014). Further decarbonisations need to originate from technological change in the heating sector, both by replacing existing heating systems by more efficient ones, and by replacing fossil fuel based boilers by renewable heating technologies (e.g. see IEA 2012). For this purpose, both the EU and various Member States have enacted policies that affect the heating sector directly or indirectly. However, it remains unclear how an ambitious decarbonisation of the residential building stock can be realised (European Commission, 2016a).

The design of effective energy and climate policies requires analytical tools that can realistically simulate the outcome of different policy instruments. This, in turn, needs an accurate representation of household behaviour (Mercure et al. 2016). Household decisions for using a certain heating technology can be different from considerations of cost-optimality on a societal level, and can include dynamic effects of social influence, as well as aspects of bounded rationality (Knobloch and Mercure, 2016). Furthermore, the diffusion of heating technologies depends on the ability of industry to expand production, which implies industrial inertia (see Grubb 2014, ch. 10).

In this report, we present FTT:Heat as a new dynamic model for simulating *policy-induced technological change* in the residential heating sector. It includes explicit representations of diverse household behaviour, as well as social dynamics and industrial constraints. The choice of households between different technologies is modelled based on statistically distributed choice parameters, which leads to a diversity of choices, and reproduces the typical dynamics of technology transitions. Conceptually, FTT:Heat is a simulation model based a on robust mathematical background (Mercure, 2015). Additionally, costs of technologies are assumed to decrease with cumulative investment due to learning by doing, leading to endogenous technological learning and path-dependent technological transitions (Grübler, Nakićenović and Victor, 1999).

FTT:Heat is used to simulate the potential effect of different policies on the technology composition, future levels of final energy demand, fuel use, emissions, and investments – by Member State and aggregated for the European Union. It currently includes 13 different heating technologies, and can simulate 12 different market-based and regulatory policies (as well as combinations thereof). Due to the non-linear structure of the model, the outcome is dependent on the timing of policies. FTT:Heat is constructed as a sub-component for the global macro-econometric model E3ME, which allows for macroeconomic feedbacks between the heating sector and the wider economy (through fuel use, energy prices and investments).

It is of importance to note that FTT:Heat is a simulation model, which aims at a realistic representation of how the residential heating systems in individual countries may develop in the future, given households' individual decisions in a context of bounded rationality and limited information availability. Model simulations do not imply that a certain pathway is superior to others, or even optimal. In fact, FTT:Heat does not calculate cost-optimal solutions, but simulates likely pathways, and possible outcomes of policies. Furthermore, it is important to note that FTT:Heat does not aim at modelling the centralised heat generation outside of residential buildings, and therefore cannot represent technological change within district heating systems.[2] From the perspective of households' choices, these are represented as one homogenous technology.

This report is part of a European Commission funded study on the macroeconomics of energy and climate policies.[3] The important methodological differences between optimisation and simulation models are analysed in work package 2 of this project (see Mercure *et al.*, 2016).

The report is structured as follows. Part II describes FTT:Heat in detail, presenting the central model equations, the decision-making core and the resulting dynamic changes of the technology composition over time. Part III summarises the database that was created for FTT:Heat. This includes the reconstruction of historical data on the technology composition of the European residential heating sector, as well as the technology and cost data used for the model calibration. Part IV presents the results of several scenarios simulations: a current technology and policy trends scenario, and scenarios aiming at an increased uptake of renewable heating technologies by households. Part V concludes.

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[2] An accurate representation of technological change in district heating networks would require a separate model of district heat plants, which is beyond the scope of this study.

[3] For the Terms of Reference of this study, see the DG Energy website of the European Commission where calls for tender are listed: http://ec.europa.eu/energy/en/funding-and-contracts/calls-tender# (the call for this "Study on the Macroeconomics of Energy and Climate Policies" was closed on 22nd of June 2015).

Part II. Model description

Parts II and III provide a detailed description of FTT:Heat and its database, which may be skipped by readers who are primarily interested in the analysis of policy scenarios. Here we provide a non-technical summary of the methodology.

FTT:Heat is a *simulation model* of technological change in the residential heating sector. Instead of identifying cost-minimising solutions from the perspective of a central social planner, it allows the simulation of likely trajectories of heating technology diffusion, based on the bottom-up representation of household decisions. For each Member State, the starting point is an exogenous level of demand for residential space and water heating. The role of FTT:Heat is mainly to determine which heating technologies supply the given level of heat demand, and the resulting levels of fuel use, emissions and investments. The model includes 13 different heating technologies, and can simulate 12 different market-based and regulatory policies, such as carbon taxes or capital subsidies.

Conceptually, FTT:Heat is based on three central elements:

1. *Decision making* on buying and replacing heating systems is performed by households, who choose between different technologies for residential heating. They either decide to replace a heating system at the end of its technical lifetime, or prematurely (based on behavioural payback time thresholds). Decisions result from households' diverse preferences, which are represented as statistically distributed parameters, leading to a range of preferences and choices. In addition to investment and fuel cost, many additional aspects may impact household preferences, on which little information is available (such as perceptions of comfort or reliability). Such missing components are included in the decision-making as `intangibles', which are empirically calibrated to observed diffusion trends.
2. Households are assumed to have *restricted access to information on technologies*, and therefore do not choose what they do not know. Furthermore, industries are assumed to have *limited production capacities*, so that only a limited capacity of each technology can be produced (and set up) within each period. Both results in a model representation of technology uptake which resembles the typical s-shaped diffusion curves of technology transitions, and is subject to *inertia*: technological change does not occur instantaneously. There is a limit on the potential speed of diffusion of a technology, and this limit varies in proportion to its previous market share. The reaction to cost changes (like new taxes) is therefore not instantaneous.
3. Costs of technologies are assumed to decrease with cumulative investment due to *learning by doing*, leading to endogenous technological learning and path-dependent technological transitions.

Over time, the resulting dynamics gradually change the overall composition of the residential heating system in each Member State. The sum of diverse individual decisions may lead to outcomes which are sub-optimal from a normative societal perspective, but perhaps closer to reality.

FTT:Heat is fully integrated with the global macro-econometric model E3ME. Changes in the heating sector can have immediate impacts on other sectors (notably the production of heating equipment, power generation and the extraction and processing of fossil fuels) and macroeconomic developments, both of which are modelled in E3ME. When testing a new policy for the heating sector, the combination of both models makes it possible to analyse the potential relative changes in all economic sectors and world regions, as well as the changes in macroeconomic indicators like household income, employment or GDP.

FTT:Heat is a model of technological change in the residential heating sector, which is part of the macro-econometric model E3ME (see Cambridge Econometrics, 2014 for a model description). It is conceptually similar to other models built in earlier work for the power and transport sector, FTT:Power (Mercure, 2012) and FTT:Transport (Mercure *et al.*, 2017), using the same evolutionary economics approach and the replicator dynamics equation. The theory is presented here.

1 Definitions

Here, the key terms and concepts used within the model description are defined. Of central importance is the distinction between useful energy and final energy, as well as the definition of conversion efficiency.

1.1 Useful energy

Useful energy is defined as *'the energy effectively made available to the user in terms of the services delivered through end-user equipment and expressed in terms of consumption equivalents for the work performed by mechanical power, lighting, heat generation, and travel mileage*' (Madureira, 2014). As such, useful energy refers to the amount of energy that is provided as a specific energy service, after the last conversion made in energy conversion equipment. Consequently, useful energy equals final energy consumption minus conversion losses. In the context of this work, the energy services of interest are the provision of increased temperature levels for living areas and sanitary hot water, on a level as demanded by the residents of individual households. In this case, the conversion of final energy (in the form of fuels or renewable energy) into useful energy (in the form of heat as an energy service) is performed by different kinds of heating systems, such as boilers and heat pumps. Therefore, as suggested by Eurostat (1978), FTT:Heat calculates useful energy by multiplying final energy by the 'efficiency of the final apparatus used by the final consumer'.

Importantly, a household's useful energy demand for heating is assumed to be independent of the used heating technology, but determined by characteristics that are exogenous to the model - such as climatic conditions, building characteristics, the number of inhabitants per dwelling, household income, and individual preferences for room and water temperatures. For FTT:Heat, the annual level of useful energy demand for heating within a Member State is therefore defined as the exogenous model driver. While the model simulates which share of future useful energy demand will be provided by which heating technology, the overall level of useful energy demand per country remains unaffected by the model calculations. However, the factors mentioned above, as well as other energy system considerations, are taken into account by the energy models which derive projections of useful energy demand over time, which are then taken as an input to FTT:Heat.

Throughout the model description, useful energy demand is referred to as UD, and the units come with the subscript th for thermal (e.g., kWh_{th}). Total useful energy demand per country is denoted as UD_{tot}, while useful energy demand per technology category i in a country is denoted as UD_i.

1.2 Final energy

Eurostat defines final energy consumption as *'the total energy consumed by end users, such as households, industry and agriculture. It is the energy which reaches the final consumer's door and excludes that which is used by the energy sector itself*'. This includes external energy that enters the heating system in the form of fuel (such as oil, gas, coal, and biomass), as well as electricity and heat supplied by district heat systems.

In case of solar energy, only energy that is captured by a solar thermal heating system is considered when calculating final energy. For heat pumps, both the fuel that enters the heating system and the ambient heat that is captured by the system (coming from the heat pump's air, water or ground source for heat) are counted as final energy demand.

Different than *useful* energy demand, future levels of *final* energy demand per country depend on the technology composition within a Member State's residential heating sector, and are therefore fully endogenous to FTT:Heat.

Throughout this report, final energy demand is referred to as *D*, and the units are denoted without any subscript (e.g., kWh). Total final energy demand per country is denoted as D_{tot}, while final energy demand per technology category *i* in a country is denoted as D_i.

1.3 Conversion efficiency

Useful and *final* energy demand are connected by a technology's *conversion efficiency*, which is defined as the average annual ratio between useful energy and final energy, as experienced by the household:

$$CE_i = \frac{UD_i}{D_i}$$

Consequently, final energy demand can be calculated as the product of useful energy demand and the conversion efficiency of the respective heating system:

$$D_i = \frac{UD_i}{CE_i}$$

For heat pumps and solar heating systems, the conversion efficiency is defined as one, so that final energy demand equals useful energy demand. When calculating fuel use of heat pumps, conversion efficiency refers to their seasonal performance factor (SPF), which is defined as the annual average ratio of electricity (or other high energy) input to delivered heat.

The conversion efficiency reflects the total fuel efficiency, covering both space and water heating. The technical boundary of efficiency refers to the thermal energy 'leaving' the heating system (rather than the energy 'arriving' at a specific point). Any energy losses outside the heating system, such as heat losses through the building envelope, are not covered by conversion efficiency, but a determining factor of useful energy demand.

1.4 Capacity factor

How much heating capacity is required for a household, given its annual useful energy demand for heating? Or, the other way around: within a given period of time, how many units of heat are produced by each unit of installed heating capacity? In FTT:Heat, the capacity factor of a heating technology *i* is defined based on the latter formulation: as a technology's annual net delivery of heat, UD_i/y, per unit of thermal capacity, U_i:

$$CF_i = \frac{UD_i}{U_i * y}$$

Since CF_i results from dividing an amount of energy by a capacity, it is in principal unit-less, referring to the fraction of the year in which a heating system is operated (e.g., kWh_{th}/kW_{th} y = h/y, which is simply a ratio of two time periods).

1.5 The units of decision making and analysis

In FTT:Heat, the unit of decision making is defined differently from the unit of analysis.

Decision making on buying and replacing heating systems is performed by households, who can choose between different technologies. They decide to buy a heating system of some technology *i*, with has a certain level of thermal capacity U_i.

However, the actual thermal capacity U_i of heating systems in households is both subject to a large degree of heterogeneity, and remains ambiguous due to the very limited amount of data (apart from model estimations). Furthermore, households are not restricted to having only one type of heating system, but may use a combination of several systems - e.g., an electric room heating in addition to a gas based central heating system, or an oil heating in combination with a supplementary solar thermal heating system. As such combinations can essentially take any form, it would be infeasible to explicitly enumerate them in a model.

Therefore, the *unit of analysis* in FTT:Heat is not the *total heating demand* of a household, but the *demand for one unit of heat/useful energy*, normalised to 1 kWh_{th} per year. If, for example, the *total heating demand* of a household is 10 MWh_{th} per year, it may decide to fulfil this demand by a combination of different technologies (e.g., 8 MWh_{th} to a gas heating system, and 2 MWh_{th} to a solar heating system).

This approach allows FTT:Heat to simulate how the technology mix for residential heating systems changes over time, given the policy context. It is based on data for useful energy demand on a country-wide level, without a requirement for explicitly defining how this heating demand is distributed across individual households.

2 Core equations

In this section, a general overview of the equations and calculation steps in FTT:Heat is given. The decision-making core, which is at the heart of the model, is subsequently explained in more detail in section 3.

2.1 The dynamical evolution of technology shares

For each country, the starting point of FTT:Heat is an exogenous level of total annual demand for residential heating as an energy service, expressed in terms of useful energy demand, $UD_{tot}(t)$ (in GWh_{th} per year). $UD_{tot}(t)$ is the exogenous driver of the model. For European countries, its future level will mostly depend on future levels of building insulation, which are the target of various policies. Future demand levels are therefore not estimated econometrically, but exogenously calibrated to separate scenario assumptions.

The role of FTT:Heat is mainly to determine which heating technologies supply the given level of heat demand, and the resulting levels of fuel use and investments. Individual heating technologies (e.g., gas boilers, heat pumps), denoted with a subscript *i*, compete for market shares of the total demand, $S_i(t)$:

$$S_i(t) = \frac{UD_i(t)}{UD_{tot}(t)}, \qquad \sum_i S_i(t) = 1$$

The level of useful energy demand per technology, $UD_i(t)$ (in GWh_{th}/y), is given by:

$$UD_i(t) = S_i(t)UD_{tot}(t), \qquad UD_{tot}(t) = \sum_i UD_i(t)$$

At the start of the simulation, initial shares $S_i(t)$ are determined from historical data. Their future development in each period Δt is then simulated based on two replicator dynamics equations, which describe share changes due to (1) end of lifetime replacements (denoted with a subscript *e*) and (2) premature replacements (denoted with a subscript *p*), respectively (a detailed description follows in sections 4.2 and 4.3):

$$\Delta S_{i,e} = \sum_j S_i S_j (F_{ij} A_{ij} \tau_j^{-1} - F_{ji} A_{ji} \tau_i^{-1}) \Delta t$$

$$\Delta S_{i,p} = \sum_j S_i S_j (G_{ij} A_{ij} \delta_j^{-1} - G_{ji} A_{ji} \delta_i^{-1}) \Delta t$$

Flows from technology *j* to technology *i* are here determined by the current market shares of technologies *i* and *j* (S_i and S_j), the fraction of households preferring technology *i* to technology *j* (F_{ij} and G_{ij}, see section 4.2), exogenous restrictions (A_{ij}), and the share of households using technology *j* which either (1) have to replace their heating system due to the end of its technical lifetime (τ_j^{-1}), or (2) want to replace their heating system prematurely (δ_j^{-1}). *Net flows* from technology *j* to technology *i* are then obtained by subtracting the reverse flow from technology *j* to *i*. The *overall net flow* to technology *i* is the sum of all such pair-wise comparisons over all competing technologies *j*.

Based on the resulting shares, FTT:Heat calculates the new levels of useful energy demand per technology, in GWh_{th}/y:

$$UD_i(t + \Delta t) = S_i(t + \Delta t)UD_{tot}(t + \Delta t)$$

In this equation, the useful energy demand per heating technology can change for two independent reasons: (1) the total demand for heating, UD_{tot}, can change, and (2) the technology composition, S_i, can change.

2.2 Final energy demand, fuel use and emissions

As a next step, FTT:Heat divides the obtained set of useful energy demand per technology, UD_i, by technology-specific conversion efficiencies, CE_i, for obtaining the new levels of final energy demand per technology, D_i, and per country, D_{tot} (both in GWh/y):

$$D_i(t+\Delta t) = \frac{UD_i(t+\Delta t)}{CE_i}, \quad D_{tot}(t+\Delta t) = \sum_i D_i(t+\Delta t)$$

Multiplying D_i by fuel specific emission factors α_i (in tCO_2/GWh) yields the level of CO_2 emissions, per technology (E_i) and per country (E_{tot}) (both in tCO_2/y):

$$E_i(t+\Delta t) = D_i(t+\Delta t)\alpha_i, \quad E_{tot}(t+\Delta t) = \sum_i E_i(t+\Delta t)$$

Within FTT:Heat, emissions are defined as primary emissions that occur at the level of individual heating systems, so that only fuels burned on site are counted. This avoids double-counting emissions in case of electricity and district heating, where the energy conversion takes place at the level of power and heat plants, and the respective primary emissions are already correctly accounted for in other sectors of E3ME.

Finally, fuel use FU_i^k by technology *i* of fuel *k* (in GWh/y) is calculated by multiplying a technology's final energy demand with a matrix of fuel use factors θ_i^k, which assigns the use of (one or multiple) fuels *k* to each technology *i*:

$$FU_i^k(t+\Delta t) = D_i(t+\Delta t)\theta_i^k, \quad FU_{tot}^k(t+\Delta t) = \sum_i FU_i^k(t+\Delta t)$$

2.3 Investment, learning and cost reductions

For estimating investments and technical learning, FTT:Heat first calculates the thermal capacity per heating technology, U_i. Investments are then obtained by multiplying these capacities with each technology's current upfront investment costs, IC_i. These investment costs evolve with the cumulative production of heating systems due to learning by doing.

Given the amount of useful energy demand per technology UD_i, the matching amount of thermal capacity U_i (in GW_{th}) is determined by the (country- and technology specific) capacity factor, CF_i:

$$U_i(t+\Delta t) = \frac{UD_i(t+\Delta t)}{CF_i}$$

Each period, a certain amount ξ_i of heating equipment of type *i* comes out of factories. The production of ξ_i corresponds to:

- Positive increases in the useful energy demand served by technology *i* (UD_i), due to increases in its market share and/or increases in UD_{tot}: dUD_i/dt. This implies a capacity change by $\frac{dUD_i}{dt}\frac{1}{CF_i}$.
- The replacement of heating systems within category *i* that reached the end of their useful technical lifetime τ_i within this period: $\frac{U_i}{\tau_i} * dt$.

Meanwhile, negative changes in a technology's capacity correspond to decommissions that are not replaced. Summing over all possible combinations, capacity production of a heating technology *i* in period *t* is described by

$$\xi_i = \frac{dUD_i}{dt}\frac{1}{CF_i} + \frac{U_i}{\tau_i} * dt.$$

Newly produced heating systems ξ_i are sold at mean price IC_i, generating an investment per heating technology that equals

$$I_i = IC_i \xi_i.$$

Cost reductions in IC_i occur with the cumulative production of capacity of technology i, and are endogenously calculated based on learning curves. The usual form in which learning curves are expressed is

$$IC_i(t) = IC_{0,i}\left(\frac{W_i(t)}{W_{0,i}}\right)^{-a_i},$$

where $W_i(t)$ is the cumulative capacity of technology i at time t. The pair $IC_{0,i}$ and $W_{0,i}$ are initial costs and cumulative capacity at the start of the model simulation ($t=0$). a_i is the technology-specific learning exponent, related to the learning rate.[4] Learning however happens on a component level rather than at the technology level. For example, components such as motors or specific materials may be used in more than one type of technology, or installation companies may become more efficient in installing similar types of equipment. Therefore, capacity additions in one technology category may induce learning in other categories. A spill-over matrix B_{ij} is thus defined, mixing the learning between similar technologies, so that:

$$W_i(t) = \sum_j B_{ij} \int_0^t \xi_j(t')dt', \qquad W_{0,i} = \sum_j B_{ij} \int_0^{t_0} \xi_j(t')dt'$$

3 The decision-making model core

In this section, the decision-making core of FTT:Heat in the context of diverse households is explained in more detail.

3.1 Perceived costs and decision-making

The core of FTT:Heat is an aggregate representation of decision-making by diverse households, based on cost parameters that have statistical variations. Households evaluate all available heating technology options based on a single quantity, the generalised cost of heating, which features a quantification of all possible aspects that weigh in the decision-making balance (see section 3.4). This core model component is evaluated at every time step, and the decision-making determines the composition of new heating units purchased. Over time, the resulting dynamics gradually change the overall composition of the residential heating system in each Member State.

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[4] The learning exponent is $a_i = \ln(1 - LR_i)/\ln(2)$, where LR_i is the learning rate.

The diversity of households stems from different individual contexts and perceptions when they take a decision, which may originate from a large set of individual characteristics (of the household or the dwelling), preferences and constraints. Because it would be impossible to enumerate all of these in a model, this diversity is represented by statistical distributions of cost-parameters (see section 3.2).

Regarding the availability of technologies to individual households, it is assumed that technology and information access is restricted. Households most likely choose something they have seen being purchased, perhaps by someone they know such that they were able to gather information (i.e. they most likely do not choose something they know nothing of, and they gather reliable information predominantly through their peers). Their observations and knowledge of heating systems is a subset of what is installed in buildings. Households are most likely to choose amongst what their peers have previously chosen, which itself is a subset of what the whole market has to offer (i.e. their peers are a subset of the population, and their observations are a subset of all observations). In other words, households do not choose what they do not know, and they do not know all of the market (or even perhaps do not care for all of the market). Conceptually, the information transmission between households is captured within the dynamical shares equation (see section 4.2): the technology options available to households depend on the availability of information and production capacities, both of which are a function of a technology's market share in the previous period.

3.2 Diversity is crucial

Within the decision-making component of FTT:Heat, the importance of diversity is paramount. In basic diffusion theory, the market consists of different types of consumers: early adopters, middle adopters, followers, laggards (Rogers, 2010). This picture is useful here, as it connects the notion of diversity to a rate of technology adoption. In FTT:Heat, the diversity of households implies a similar differentiation of the market: when choosing between heating technologies, households take different decisions at different points in time for different reasons, which results in dynamics of technology uptake as described by diffusion theory.

The heterogeneity of households in FTT:Heat results from the variance in technology cost parameters (e.g., investment costs for technology i may be lower than average cost for household 1, but higher than average for household 2), which implies a heterogeneity of households' technology choices (e.g., technology j may be *less* attractive than technology i *on average*, but *more* attractive in the case of household 2). Hence, there is no explicit disaggregation of households in types (early adopters, laggards etc.). Instead, such a disaggregation does endogenously evolve from the variance in cost parameters (e.g., households for which a new technology j is more attractive relative to the average household will adopt technology j first, thereby becoming 'early adopters'). The variance in cost parameters is both due to the variability of technologies as such (e.g., having different producers for boilers), and the heterogeneity of households' characteristics (e.g., properties of the building, heating behavior, wealth and income).

The importance of diversity is illustrated by Figure 1, which shows diffusion profiles in the case of (1) all households being identical (left side of the panel) and (2) distributed preferences and costs.

In the first case, all households have identical preferences and constraints. If households were to choose between two options for heating systems, they would always all choose the same technology (as shown on the left panel of Figure 1). In the case that households know the market perfectly, and thus know about all the available heating systems, everyone keeps buying the least expensive alternative (in terms of generalised cost, as defined in section 3.4). Then, if a new technology would suddenly become cheaper than the incumbent technology, all households would simultaneously change their preference, so that the adoption of the new type of heating system would be instantaneous (were it not for probable industrial supply problems) – an unrealistic representation of energy technology diffusion, which is typically a gradual process (Grübler, Nakićenović and Victor, 1999; Grübler and Wilson, 2013).

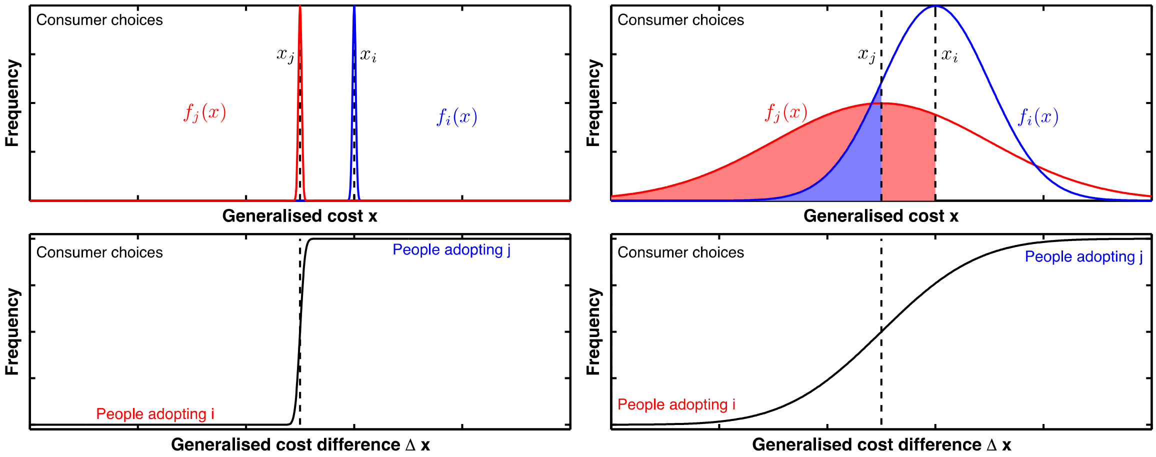

Figure 1: Illustration of the process of decision-making between two technologies under diversity of households. The blue curve represents the distribution of perceived generalised costs for one technology, and the red curve that of the other. In the left panel, if diversity is very low, choices can flip very abruptly as average costs change. This corresponds to the representative agent case. In the right panel, introducing significant diversity makes choices distributed and choices change very gradually as costs change (Mercure, 2015).

In the second case, the two technologies are purchased by a diverse group of households, each of which has different preferences and characteristics. Technology costs (and the cost difference between the two technologies) are distributed. Therefore, comparing both technologies based on households' diverse choices leads to a comparison of frequency distributions, shown in the right panel of Figure 1. These distributions have unequal means, which signifies that one technology, on average, is less costly to the user than the other. While this is the case for a majority of households, it does not mean that a technology is more attractive for all individual households (see section 3.4 for the potential sources of variation). Thus, if the generalised cost difference between both technologies gradually decreases, an increasing fraction of households will choose the alternative technology. Because all households have slightly different characteristics and perspectives, the resulting profile of adoption is then a very gradual one, the steepness of which depends on the widths of the distributions (see section 3.3).

3.3 Pairwise comparisons of distributed choices

Distributed choices by households are modelled as a pairwise comparison, which will be performed for all possible pairs of technologies, resulting in a complete order of distributed household preferences between all available options.

Given households' distributed choice preferences between heating technologies *i* and *j*, one can state what the probabilities of preferences between these two technologies are by counting how many households prefer which technology in a direct comparison (e.g. 70% of households choose *i,* and 30% choose *j*). Thus, given a choice between technologies *i* and *j*, the fraction F_{ij} of households tends to choose technology *i* and the fraction F_{ji} chooses *j*. These fractions depend on the difference between the generalised cost of technologies *i* and *j*, both of which are distributed. Therefore, the difference between both cost values is also distributed, and this joint distribution's empirical parameters result from the mean and standard deviations of both individual distributions.[5] For determining final preferences when there exist more than two technology options, the model goes through an exhaustive list of pairwise comparisons between heating technologies, comparing each technology *i* to all alternatives *j*.

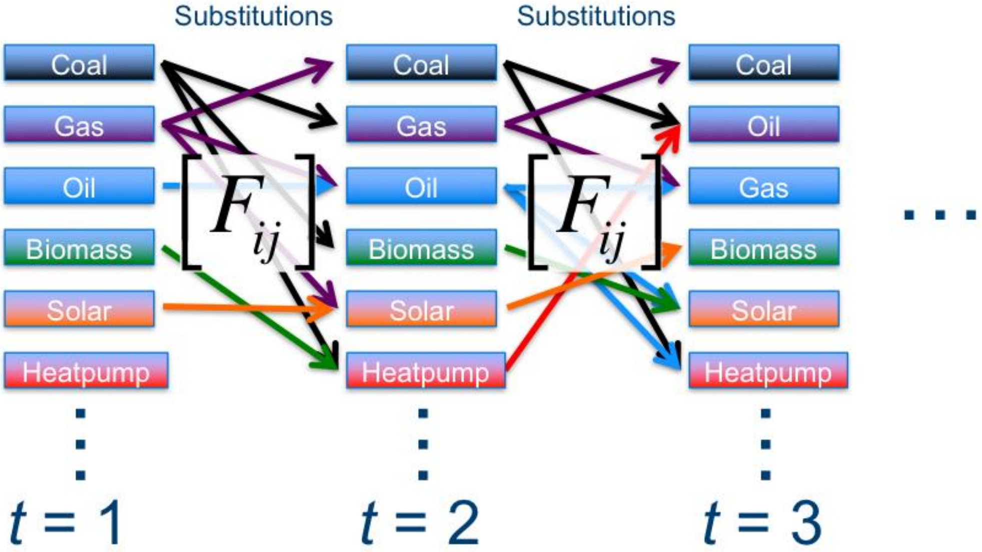

Figure 2: Illustration of technology substitution in FTT:Heat. In each period, a fraction of households decides between available heating systems. The matrix F_{ij} describes households' distributed preferences for technologies, which are based on generalized perceived costs. Over time, this results in gradual substitution and diffusion of technologies.

An important implication of having distributed preferences is that the elasticity of household choices with regard to price changes is inversely proportional to household diversity. This can be understood as follows: when diversity is low, households tend to all act similarly simultaneously, and this results in price changes having an impact on the whole population, leading to important changes of preference. Meanwhile, when the diversity is high, price changes may have an impact only on a subset of the population, leading to small changes of preference.

3.4 The Levelised Cost of Heating

The (distributed) cost of heating as an energy service, as perceived by the household, should include all components relevant to the decision-making. When a heating system is purchased, an initial investment is made, or a loan is obtained. Henceforth fuel and maintenance costs are incurred for the lifetime of the heating system. In addition to this, taxes and subsidies may be added.

For constructing a measure that allows to compare all these characteristics between heating technologies, FTT:Heat builds on the well-established concept of *Levelised*

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[5] This model is equivalent in many respects to a binary logit model, as initially derived by McFadden (see Ben-Akiva 1985 for a detailed description).

Cost of Energy (LCOE), which calculates the cost per unit of energy generated by technology *i* as:

$$LCOE_i = \sum\nolimits_t \frac{C_{i,t}}{(1+r)^t} \Big/ \sum\nolimits_t \frac{E_{i,t}}{(1+r)^t}$$

Where $C_{i,t}$ are the total costs of producing energy within period t, and $E_{i,t}$ the quantity of produced energy within period t. To make costs and produced energy from different future time periods comparable, all values are discounted to present values by a discount rate r, and summed over all periods t within the technology's expected lifetime.

Similar, as a component of the decision-making process in FTT:Heat, the *Levelised Cost of Heating* ($LCOH_i$) is defined as a present value cost of operating a heating system during its lifetime, normalised for the production of one unit of heat per year ($E_{i,t}$ =1 kWh_{th}):

$$LCOH_i = \sum\nolimits_t \frac{\frac{IC_{i,t}}{CF_i} + \frac{MR_{i,t}}{CF_i} + \frac{FC_{i,t}}{CE_i}}{(1+r)^t} \Bigg/ \sum\nolimits_t \frac{1}{(1+r)^t}$$

$IC_{i,t}$, $MR_{i,t}$ and $FC_{i,t}$ are upfront investment costs (only incurred in the first period, $t=0$), maintenance-repair costs, and the fuel price, in €/kW_{th}, €/ kW_{th} and €/kWh, respectively. For obtaining the investment and maintenance-repair costs per unit of heat (1kWh_{th}), costs per kW are divided by a technology's capacity factor, CF_i. The technology-specific fuel costs for generating one unit of heat are calculated by dividing the fuel price $FC_{i,t}$ by the technology's conversion efficiency, CE_i.

In addition to this basic specification of $LCOH_i$, policies can be imposed. A technology-specific subsidy/purchase tax on upfront investment costs is defined as $T_{i,t}$ (negative values are a subsidy, positive values a tax), and a fuel tax as $FT_{i,t}$ (which can be specified for each fuel type and technology). Furthermore, a technology-specific feed-in-tariff $FiT_{i,t}$ is introduced, which pays a pre-defined subsidy for each unit of produced heat.

The $LCOH_i$ inclusive of these market-based policies is referred to as $LCOHT_i$:

$$LCOHT_i = \sum\nolimits_t \frac{\frac{IC_{i,t}(1+T_{i,t})}{CF_i} + \frac{MR_{i,t}}{CF_i} + \frac{FC_{i,t}+FT_{i,t}}{CE_i} + FiT_{i,t}}{(1+r)^t} \Bigg/ \sum\nolimits_t \frac{1}{(1+r)^t}$$

Several terms in $LCOHT_i$ are distributed, while others are single valued. Investment cost distributions reflect a distribution of individual characteristics of the household or the dwelling, such as different installation costs, or preferences for specific brands. Meanwhile, the probability distributions associated with $FC_{i,t}$ and $MR_{i,t}$ correspond to the volatility of fuel prices and maintenance costs. The distribution of the sum of two distributions corresponds to their convolution, and therefore the sum of several distributions corresponds to a chain of all respective convolutions (Mercure, 2015). As a result, means are added, while the standard deviations are combined using the root of the sum of the squares of the individual standard deviations, as follows:

$$\Delta LCOH_i = \sum\nolimits_t \frac{\sqrt{\frac{\Delta IC_{i,t}^2}{CF_i^2} + \frac{IC_{i,t}^2}{CF_i^4}\Delta CF_{i,t}^2 + \frac{\Delta MR_{i,t}^2}{CF_i^2} + \frac{MR_{i,t}^2}{CF_i^4}\Delta CF_{i,t}^2 + \frac{\Delta FC_{i,t}^2}{CE_i^2}}}{(1+r)^t} \Bigg/ \sum\nolimits_t \frac{1}{(1+r)^t}$$

3.5 The relevance of intangible preferences

The decisions between different heating technologies may not only be determined by the explicitly defined set of cost characteristics in *LCOHT$_i$*, but a wider set of variables, which remain unspecified (and may differ between households). For example, a household may perceive some technologies as more convenient or otherwise more attractive relative to other technologies, related to reasons other than pure costs (like personal preferences or building characteristics). Similarly, a household may attribute a certain co-benefit to a technology (like the additional functionality of reversible heat pumps as air cooling devices in summer).

Overall, many additional aspects are valued by the household, on which little information is available. In FTT:Heat, these missing components are defined as `intangibles'. The value of the intangibles, denoted γ_i, is an empirical parameter, which can be derived from historical data: it is the value that captures the difference between the generalised cost, which leads to observed diffusion in historical data, and the *LCOHT$_i$* as calculated from technical and economic properties of heating systems. This yields the generalised cost of heating as perceived by households. It is referred to as *LCOHP$_i$*:

$$LCOHP_i = LCOHT_i + \gamma_i$$

The reasoning goes as follows. The diffusion of heating technologies takes place at the expense of one another, with individual technologies either gaining or loosing shares. As described in section 3.3, the choice of households between technologies is made based on a pairwise comparison of generalised cost distributions, *LCOHT$_i$*. This gives rise to a rate of diffusion, which may or may not correspond to historical diffusion. In the absence of a change of policy or context at the starting time of the simulation, there is no reason to expect a change of rate of diffusion, given the fact that the simulation starting time could be set to any year. γ_i ensures that the diffusion of heating technologies in the simulation is consistent with the historical rate.

If the meaning of the *LCOHT$_i$* is changed for any reason (e.g. if parameter assumptions within the LCOH are changed), the empirical γ_i must be recalculated, since their meaning also changes. In this sense the γ_i contain everything of relevance that is not represented in the *LCOHT$_i$*. The generalised cost *LCOHP$_i$* thus has the same distribution as the *LCOHT$_i$*, albeit with this cost offset.

Note that since generalised cost differences already exist in the baseline, diffusion trends exist in the baseline, a fact that is observed in the data. Hence, the parameter γ_i also implicitly captures any existing policies that have influenced the historical trend of technology diffusion, but remain unspecified in the model. The more policies are specified explicitly in the model, the less they are represented implicitly in the γ_i parameters, and conversely. Future work may address such an explicit inclusion of existing policies.

4 Technology diffusion as a result of decision-making

The changes in the technology composition of the residential heating sector depends on the length of time that heating systems are used by households – how long they 'survive' for – which is described by standard survival (or reliability) analysis. A detailed theoretical analysis is given in Mercure (2015).

4.1 Technology diffusion as population dynamics

In general, heating systems may come to the end of their useful life through various events or processes, such as technical failures or scrapping decisions. The rate of changes in the system depends on this length of time, which determines the size of the market for new heating systems. It also determines at which rate the technology composition can physically be transformed.

Based on this kind of survival analysis or technology demography, one can derive population dynamics identical to that of competing species in an ecosystem (a Lotka-Volterra set of differential equations, sometimes also called `Replicator dynamics', see Hofbauer and Sigmund, 1998). As opposed to many empirical works, these differential equations are here not taken by assumption, but derived from simple arguments of industrial dynamics and reliability theory. This is done in detail in in Mercure (2015), and summarised here.

New purchases of heating systems cover both replacements and increases in total population (if a country's building stock is growing). In the European context, annual construction rates for new houses are well below 1% for most countries, and the heat demand of existing buildings is expected to decrease due to improved thermal insulation. As a result, sales for replacements largely dominate the market.

During a time span Δt, out of a total number of new heating systems in a country, a certain fraction of sales will be allocated to different technology categories according to household preferences F_{ij} (and G_{ij} in case of premature scrapping) (defined in sections 4.2 and 4.3), and replacement rates. These two parameters determine the rate of influx and outflux of shares in and out of technology categories *i* and *j*, in a set of n possibilities. The variable N_i refers to the population of heating systems in category *i*. Increases in N_i resulting from the replacement of heating systems scrapped in category *j* then correspond to:

$$\Delta N_{j\to i} = \begin{bmatrix} Fraction\ of \\ production \\ capacity \\ belonging\ to\ i \end{bmatrix}_i \begin{bmatrix} Household \\ preferences \end{bmatrix}_{ij} \begin{bmatrix} Number\ of \\ decommissions \\ in\ category\ j \end{bmatrix}_j$$

Decommissions of heating systems of category *j* are allocated across all available categories according to households' preferences, which direct flows of units between categories. For all flows $\Delta N_{j\to i}$ of substitutions between *i* and *j* exists a reverse flow $\Delta N_{i\to j}$, and thus a net trend.

Meanwhile, the number of heating systems purchased that are not replacements are

$$\Delta N^{\uparrow}_{j\to i} = \begin{bmatrix} Fraction\ of \\ production \\ capacity \\ belonging\ to\ i \end{bmatrix}_i \begin{bmatrix} Household \\ preferences \end{bmatrix}_{ij} \begin{bmatrix} Population \\ increase \end{bmatrix}_{tot}$$

In FTT:Heat, decommissions of installed heating systems can occur for two reasons:

1. **End-of-lifetime replacements:** a system needs to be replaced at the end of its technical lifetime (it 'breaks down').
2. **Premature replacements:** a household may decide to replace a system that is still in working condition when it is perceived as being uneconomical to continue its operation.

4.2 The dynamics of end-of-lifetime replacements

For end-of-lifetime replacements, the number of 'deaths' for technology *j* can conveniently and safely be approximated with the total population N_j divided by its life expectancy τ_j. If τ_j is given in years, the number of deaths per year equals N_j/τ_j. Consequently, in each year of the model simulation, a fraction $1/\tau_j$ of households need to replace their heating systems, and need to make a choice between the competing technologies. Since households may not want to wait until their heating system breaks down, instead replacing their heating systems slightly earlier than implied by the pure technical life expectancy, τ_j is here defined as the *useful* life expectancy of technology *i*. In the model, it can be parameterised independently of the *technical* life expectancy, and may have lower or higher values - implying a faster or slower rate of decision-making by households.

If it comes to the point that a household decides to replace its heating system, the decision-making core of FTT:Heat performs the pairwise comparison of all available heating technologies, as described in section 3.3. Based on the distribution of technology costs, the fraction of households preferring technology *i* over technology *j* is the fraction of households for which the generalised cost of technology *i*, $LCOHP_i$, is less than the generalised cost of technology *j*, $LCOHP_j$. This fraction can be calculated as an integral, and equals

$$F_{ij}\left(\Delta C_{ij}\right) = \int_{-\infty}^{\infty} F_j(C) f_i(C - \Delta C_{ij}) dC, \quad \Delta C_{ij} = LCOHP_i - LCOHP_j.$$

Since in such a pairwise comparison each household needs to have a preference for either *i* or *j*, so that $F_{ij} + F_{ji} = 1$, the fraction of households preferring technology *j* over *i* is simply given by

$$F_{ji}\left(\Delta C_{ji}\right) = 1 - F_{ij}\left(\Delta C_{ij}\right).$$

The production capacity for each technology category *i* changes through sales and re-invested income, which can be approximated as proportional to the current population of technology *i*. For a detailed demonstration, see Mercure (2015). The basic reasoning is that the production capacity of an industry is financed out of income made on selling units in the past, such that a growing/declining technology population is associated with a growing/declining industry.

Furthermore, we introduce the matrix *A*, which can be used to impose exogenous restrictions in addition to *F* (such as that households would not switch to far less convenient technologies than they already use). Each element A_{ij} can take values between 0 and 1, where A_{ij}=0 would entirely preclude any flows from *j* to *i*.

Combining the choice-based matrix of household preferences *F* with technology shares *S* and the fractions of end-of-lifetime replacements $1/\tau_j$, we can derive the flow of market shares from heating technology *j* to *i* in period Δt (Mercure, 2015):

$$\Delta S_{j\to i} = S_j A_{ij} F_{ij} \tau_j^{-1} S_i \Delta t$$

Conversely, the reverse flow of market shares from heating technology *i* to *j* is given by:

$$\Delta S_{i\to j} = S_i A_{ji} F_{ji} \tau_i^{-1} S_j \Delta t$$

The *net flow of market shares* from technology *j* to *i* is then obtained by combining both formulas, so that:

$$\Delta S_{ij} = S_i S_j (A_{ij} F_{ij} \tau_j^{-1} - A_{ji} F_{ji} \tau_i^{-1}) \Delta t$$

Last but not least, the *combined net flow of market shares* to technology *i* is the sum of all pair-wise comparisons with all alternative technologies. We sum over all flows to and from technology *i*, from and to all other technologies *j*, and obtain the *replicator dynamics* equation of evolutionary theory:

$$\Delta S_i = \sum_j S_i S_j (A_{ij} F_{ij} \tau_j^{-1} - A_{ji} F_{ji} \tau_i^{-1}) \Delta t,$$

in which the net flow of shares is regulated by the product of the matrices A_{ij} and F_{ij}, minus its transpose. It is a standard representation of the process of *selection*, identically used in evolutionary biology and economics. This non-linear equation encapsulates very compactly all relevant population dynamics.

As this is perhaps the central equation within FTT:Heat, it is worth analysing its components in more detail. In particular, each single flow from a technology *j* to an alternative technology *i* is determined by three separate elements:

1. The *structure* of flows from *j* to *i*: which fraction of households *would* prefer *i* to *j*, given that they were to buy a heating system within period Δt? It is determined by the matrix F_{ij}, which represents household choices according to the decision-making model, and the matrix A_{ij}, which can be used to impose additional assumptions (independently of F_{ij}).
2. The *magnitude* of flows from *j* to *i*: how many heating systems of technology *j* are replaced within period Δt? This magnitude is determined by a) the market share S_j of technology *j*, and b) the annual fraction of deaths within the population of *j*.
3. The *restrictions* of flows from *j* to *i*: given preferences and replacement needs, which fraction of flows from *j* to *i* can be realized? The flow is restricted for two reasons: a) households have restricted access to information on different technologies, so that only a subset of households has the necessary information on *i*, and b) industries have limited production capacities, so that only a limited output of *i* can be produced (and set up) within each period. Both

restrictions are approximated as being proportional to the current market share S_i of technology *i*.

The third element is of central importance, as it distinguishes FTT:Heat from a pure cost-optimisation model (with distributed costs and capital vintages). Without the restrictions imposed by a technology's current market share, one would implicitly assume that (1) all households have perfect information on all technologies at all times, and (2) that industry could immediately scale up its production of any technology, without any limits. So as soon as a hypothetical technology *k* is introduced which is sufficiently attractive that all households would prefer it to any alternative technology, such a technology would immediately gain a 100% market share in sales. In reality, however, new technologies diffuse gradually, and their increase in market share over time typically follows an s-shaped trajectory, which is ensured by the mathematical formalism given here, but not by optimisation models.

By introducing the described *restrictions*, FTT:Heat becomes a *simulation* model, and its representations of technology uptake do resemble s-shapes diffusion curves - not by assumption, but derived from bottom-up population and industry dynamics. As a central implication, the technology composition in FTT:Heat is subject to *inertia*: technological change does not occur instantaneously. Instead, at any given time there is a limit on the potential speed of diffusion of a technology, and this limit varies in proportion to the technology's previous market share. Thus, FTT:Heat cannot identify 'optimal' technology portfolios, but instead, attempts to project the evolution of the market, given existing incentives.

4.3 The dynamics of premature replacements

A question arises here as to whether the frequency at which heating installations are replaced is necessarily as slow as the useful life expectancy implies. In addition to end-of-lifetime replacements, households may consider to scrap their working heating system ahead of time, based on economic considerations - a process that is here referred to as *premature replacements*.

Theoretically, for a household with perfect information and without risk-aversion, prematurely replacing a heating system of category *j* by an alternative technology *i* would be beneficial if the marginal running costs of operating *j* exceed the full costs of buying and operating *i*, so if

$$LCOHP_i < MC_j.$$

MC_j is defined as the marginal cost of generating one unit of heat per year with technology *j*, which largely depend on fuel cost, and is completely independent of the system's initial investment costs (but includes all relevant policies, and the same 'intangibles', γ_i):

$$MC_j = \frac{MR_{j,t}}{CF_j} + \frac{FC_{j,t} + FT_{j,t}}{CE_j} + FiT_{j,t} + \gamma_i$$

However, households may only consider the premature replacement of a functioning heating system if such an investment amortizes itself within a limited period of time - the so-called *payback time*. It is defined as the average time it takes households to get back the initial money they invested, here mainly through reduced energy costs. The maximum *payback time* for which a household still considers an investment as attractive is then the *payback threshold*. Empirical studies show that such *payback thresholds* can be much shorter than an investment's expected useful lifetime (only a fraction of potential savings is taken into account) (Sorrell *et al.*, 2004; Gillingham and Palmer, 2014; Knobloch and Mercure, 2016). As a guide, the IEA (2012a) states a maximum *payback threshold* of 5-7 years for energy efficiency investments in buildings. For the case of heating systems, results from choice experiments with 15,000 households in eight Member States indicate that the mean accepted *payback time* for a premature replacement of existing gas boilers is as low as three years (incl. of subsidies) (Olsthoorn *et al.*, 2017). While it remains subject to debate if such behaviour is an expression of bounded rationality, or can be explained by rational risk aversion (Jaffe and Stavins, 1994), the resulting *payback thresholds* (equivalent to high implicit discount rates for investment decisions) accurately describe household behaviour in many cases of energy efficiency investments.

In the model, the premature replacement of technology *j* by technology *i* is considered as sufficiently attractive if (and only if) the savings (due to reduced operating costs *MC*) exceed the investment costs IC_i of another technology (inclusive of an eventual subsidy T_i) within the considered *payback period,* which is given as b_i (in years), so that:

$$\sum_{t=0}^{b_i}\left(MC_{j,t}-MC_{i,t}\right) > \frac{IC_{i,t}(1+T_{i,t})}{CF_i}$$

For the case in which households see the cost difference (MC_j-MC_i) *as* being constant within the considered time period ($t=0$ until $t=b_i$), the above expression is equivalent to

$$MC_j > MC_i + \frac{IC_{i,t}(1+T_{i,t})}{CF_i}\frac{1}{b_i} := PB_i.$$

Here, the marginal cost of the incumbent technology *j* is compared to the alternative technology *i*'s marginal cost *plus* investment costs, for the hypothetical case in which *i* would only be operated for b_i years. For the decision-making component of FTT:Heat, the right hand-side of above equation is defined as PB_i. Different than $LCOHP_i$, which looks at a technology's full technical lifetime and discounts future cash flows, PB_i is calculated based on a simple payback calculation, with b_i being the (distributed) *payback threshold* in years. For the case in which the required payback time is considerably shorter than the investment's technical lifetime ($b_i < \tau_i$), this is a much stricter condition to fulfil.

In case of such an evaluation, the fraction of households making the choice to prematurely replace technology *j* by *i* is given by (for the same arguments as described in section 4.2):

$$G_{ij}\left(\Delta C_{ij}\right) = \int_{-\infty}^{\infty} F_j(C) f_i(C-\Delta C_{ij})dC, \quad \Delta C_{ij} = PB_i - MC_j$$

The resulting preference matrix is called *G*, and serves the same purpose as the preference matrix *F* for end-of-lifetime replacements. Different than for end-of-lifetime replacements, though, technologies *i* and *j* are now compared to each other based on two different measures (*PB* and *MC*), by two different groups of households (e.g. owners of an oil-based heating considering a switch to heat pumps, versus heat pump owners considering a switch to oil), so that $G_{ji} \neq 1 - G_{ij}$. Instead, the reverse preference relation is given by:

$$G_{ji}\left(\Delta C_{ji}\right) = \int_{-\infty}^{\infty} F_i(C) f_j(C - \Delta C_{ji}) dC, \quad \Delta C_{ji} = PB_j - MC_i$$

Furthermore, $1/\delta_j$ is defined as the fraction of households which consider a premature replacement of their heating system of category *j* within any year. This fraction $1/\delta_j$ depends on (1) the frequency of decision making β_j (every how many years a household considers a premature replacement), and (2) the fraction of end-of-lifetime replacements within a period, $1/\tau_j$ (for this fraction, by definition it is too late for a premature replacement):

$$\frac{1}{\delta_j} = \frac{1}{\beta_j} * (1 - \frac{1}{\tau_j})$$

On average, each household is assumed to consider a premature replacement every β_j years (equivalent to a fraction $1/\ \beta_j$ of households within any year). At the same time, within each year, a fraction $1/\tau_j$ of heating systems reaches the end of their expected useful lifetime, and cannot be replaced prematurely any longer.

Analogous to end of lifetime replacements, the *net change in shares* for any technology *i* due to premature replacements is then given by:

$$\Delta S_{i,p} = \sum_j S_i S_j (A_{ij} G_{ij} \delta_j^{-1} - A_{ji} G_{ji} \delta_i^{-1}) \Delta t$$

What is the frequency of decision making β_j? On the one hand, it seems unreasonable to assume that households would replace their working heating system every year (β_j =1) - due to restrictions on the financing of such investments, and due to the search and transaction costs that come along with such replacements (if we assume that households do not want to spend excessive amounts of their time on evaluating the economics of their heating system).[6] On the other hand, it seems equally unreasonable to assume that households will never make such evaluations prematurely, and always wait until their heating system breaks down ($\beta_j = \tau_j$) - even when replacing it would potentially yield huge benefits within short periods of time.

Based on these considerations, FTT:Heat makes the assumption that the average rate of decision making for premature replacements β_j is determined by the average *payback threshold* b_j that households apply for evaluating the attractiveness of such an investment, so that:

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[6] In modelling terms, if β_j was very small, households could switch their heating system every month, or even every minute, following price fluctuations in real time.

$$\beta_j = b_j$$

If, for example, the average household does only invest in premature replacements with a maximum payback time of three years, it is assumed that on average, a household would consider such an investment not more often than every three years. The intuition is that once the investment is paid back, there is the opportunity (and the necessary finance) for a new investment.

It is important to note that the average *rate of decision-making* is not equivalent to the actual *rate of premature replacement*. Instead, the former presents a maximum value for the latter: the *rate of premature replacement* cannot be faster than the *rate of decision-making*. The *rate of decision*-making describes every how many years a household does evaluate the economic attractiveness of a premature replacement, which does only lead to an actual replacement for the fraction of households for which the payback criterion is fulfilled.

In FTT:Heat, the mean and standard deviation of b_j are exogenous parameters, which can be calibrated based on observed consumer choices (a common estimate in the empirical literature on energy efficiency investments is a range between 3 and 5 years).

Combining the changes in market shares due to end-of-lifetime replacements and premature replacements, the *overall net change in market shares* for any technology *i* is given by the sum of both shares equations:

$$\Delta S_i = \Delta S_{i,e} + \Delta S_{i,p}$$

5 Simulation of policies in FTT:Heat

Due to the explicit bottom-up description of household decision-making, FTT:Heat can be used to simulate a diverse set of policies individually, and combinations thereof. This section gives a short overview of the policies that are currently integrated into FTT:Heat, how they are defined, and how they impact the diffusion of technologies.

In general, all policies in FTT:Heat are defined on the level of Member States, and can be changed on an annual basis (e.g., a technology subsidy scheme for country x could be introduced in 2018, with an annually decreasing subsidy rate, and be discontinued five years later). All policies can be easily specified in a transparently designed Excel spreadsheet, where one cell represents a policy value for one technology in one specific year.

5.1 Market-based policies

Table 1 summarises all policies which primarily work through costs and prices, and can be simulated within FTT:Heat.

Table 1: Market-based policies which can be simulated by FTT:Heat.

Policy	**Definition**	**Impact**	**Resolution**
Carbon tax	Absolut increase in fuel price FC_t, by an amount CT_t, depending on a fuel's carbon content	An *increase* in running costs for technologies using this fuel makes them relatively *less attractive*	Carbon prices can be specified per country, per year
Fuel tax	Absolut increase in fuel price FC_t, by an amount FT_t	An *increase* in running costs for technologies using this fuel makes them relatively *less attractive*	Can be specified per fuel or per technology, per country, per year
Fuel rebate	Absolut decrease in fuel price FC_t, by an amount FT_t	A *decrease* in running costs for technologies using this fuel makes them relatively *more attractive*	Can be specified per fuel or per technology, per country, per year
Purchase tax	Relative increase in investment costs IC_t, by a rate T_t	An *increase* in its purchase price makes a technology relatively *less attractive*	Can be specified per technology, per country, per year
Purchase subsidy	Relative decrease in investment costs IC_t, by a rate T_t	A *decrease* in its purchase price makes a technology relatively *more attractive*	Can be specified per technology, per country, per year
Feed-in-tariff	A subsidy FiT_t *is paid for every unit of produced heat*	Similar to a fuel rebate, but independent of conversion efficiencies	Can be specified per technology, per country, per year
Low-interest loans	Offering subsidised access to capital at a rate $r_{s,t}$	A *decrease* in the cost of finance makes a technology relatively *more attractive*	Can be specified per technology, per country, per year

5.2 Regulatory policies

Table 2 presents all policies which primarily work through regulations, and can be simulated within FTT:Heat.

Table 2: Regulatory policies which can be simulated by FTT:Heat.

Policy	**Definition**	**Impact**	**Resolution**
Phase-out (in sales)	A technology is gradually phased out from sales (but can still be used)	The market share of the technology will gradually decrease, as old capacity is replaced	Can be specified per technology, per country, per year
Phase-out (in stock)	The share of stock that needs to be replaced within one year is set as an exogenous parameter	Old capacity of a technology will be replaced at a higher rate	Can be specified per technology, per country, per year
Regulated market share	A technology is not allowed to have a market share larger than *x%*	The market share of the technology will either gradually decrease to *x%*, or its growth will stop at *x%*	Can be specified per technology, per country, per year
Procurement/ 'Kick start'	The share of a technology is exogenously increased by *x%*	By establishing an initial share, the technology can grow within the market	Can be specified per technology, per country, per year

5.3 Information policies

In principle, FTT:Heat can also be used to simulate the effect of information policies, such as labelling or information campaigns. Ideally, such policies would be modelled based on empirical information regarding how they would change households' perceptions of specific technologies – for example, having the effect of making future energy savings more credible to a given extent. As such information is not easily available, the modelling needs to rely on ad-hoc assumptions. Within the European Commission's technical assessment of the EUCO energy efficiency scenarios, the effect of labelling policies is expressed by lowering the discount rates of households by 0.5 percentage points (EUCO27 and EUCO30 scenarios) and 1 percentage point (EUCO33), respectively (E3MLab and IIASA, 2016). Comparable assumptions can be included into FTT:Heat scenario simulations.

6 Integration of FTT:Heat and E3ME

FTT:Heat is developed as a sub-module of the macroeconometric simulation model E3ME. The models are linked to each other by several feedback mechanisms, which allows analysis of the wider macroeconomic effects of policies which are primarily targeted at the residential heating sector. The three main mechanisms for such feedback effects are fuel use, the overall expenditure for heating systems, and policies, described in turn below.

6.1 Fuel use feedbacks

Based on the simulated diffusion of different heating technologies over time and the overall demand for heating as an exogenous parameter, FTT:Heat calculates the fuel use for residential heating within each EU Member State (see section 2.2). Thus, the model projects the residential heating sector's annual demand for the following six fuel types: coal, oil, gas, electricity, district heat, and biomass/wood.

The feedback mechanism for fuel use follows a three-step approach:

1. Each fuel type is matched to the standardised E3ME fuel classification (see table Table 3).
2. The fuel use as simulated by FTT:Heat is converted into units that are consistent with the E3ME time series on *total* (i.e. for all purposes, not just heating) fuel use by households. This involves (i) a conversion of physical units (from GWh to toe), and (ii) a scaling based on the respective ratio of FTT:Heat fuel use relative to E3ME fuel use in 2014, for each fuel type.
3. The resulting fuel use is given to E3ME, where it replaces the heating part within the total residential demand for each fuel. For all fuels but electricity, it is assumed that heating accounts for 100% of the residential fuel demand, so that the econometric estimation of future demand is completely replaced by the FTT:Heat estimation. In the case of electricity, the relative share of non-heating in total residential electricity demand is calculated based on historical data for each Member State. E3ME does then use the FTT:Heat simulation for the heating share, but performs an independent estimation for non-heating related electricity demand.

Table 3: Matching of FTT:Heat fuel types to E3ME standardized fuel categories.

FTT:Heat	**E3ME**
coal	hard coal
oil	middle distillates
gas	natural gas
electricity	electricity
district heat	heat
Biomass/wood	biofuels

Within E3ME, the residential fuel demand for heating as obtained from FTT:Heat is then taken as an input to household expenditures on energy consumption in the home, fuel imports and CO_2 emissions by households. Via E3ME, the demand for electricity is an input to FTT:Power, a separate sub-module which simulates the electricity generation sector.

6.2 Expenditure feedbacks

The second feedback mechanism is the overall amount of household expenditure on heating systems, which is calculated by FTT:Heat based on simulated future technology shares, costs, and required heating capacities (see section 2.3).

Within the national accounts classification used by E3ME, the purchase of heating systems by households is part of households' overall consumer spending (more specifically, within the Classification of Individual Consumption According to Purpose classification by the United Nations Statistics Division, space and water heaters belong to the sub-category of households' expenditures on 'major household appliances whether electric or not').

It is assumed that households pay for heating systems out of their income. Therefore, households reduce other expenditure when they increase their spending on heating systems relative to the baseline, which implies a crowding-out of some consumer spending on other consumption categories in the short term. The relevant baseline spending on heating systems is estimated based on the FTT:Heat 'current technology and policy trends scenario' (see section 9.2). Any policies that are additional to those in the baseline will then lead to an overall increase or decrease in expenditure on heating systems, which is added to the E3ME econometric estimation of future consumer spending on household appliances.

Overall, any change in the future diffusion of heating technologies leads to changes in the composition of consumer spending. Within E3ME, this will then have various implications, such as a change in demand for the respective producing industries.

6.3 Policy feedbacks

When a market-based policy targeted at residential heating is simulated (e.g., a tax on specific fuel types or a subsidy on the purchase price of specific technologies), the resulting monetary flows can impact macroeconomic variables and sectors outside of FTT:Heat.

For example, if a new tax on the residential use of specific fuels is simulated, the resulting price changes do not just impact households' choices between heating technologies, but also change household expenditure on energy. Higher fuel prices may lead to higher inflation, lower real disposable household income, and lower consumers' expenditure. In turn, such a tax may generate additional government revenues. Within the exogenous model assumptions, the user can choose how these revenues are used. Possible examples are the financing of other policies within the residential heating sector (such as a subsidy for the purchase of specific heating technologies), or an equivalent reduction of other taxes (such as income tax). The overall impact of a policy on macroeconomic indicators then depends on the dynamic interactions between all economic sectors.

Part III. The FTT:Heat database

This section describes the collection, transformation and aggregation of data that is used as an input for FTT:Heat. Basically, the required data can be grouped into two categories:

- Data on the energy use for residential heating, by country and technology
- Data and assumptions on the costs and characteristics of different heating technologies

For the model database, this information was gathered for all 28 Member States of the European Union. Where not available, the necessary data was constructed by way of mathematical approximations.

7 Final and useful energy demand by country

The focus of FTT:Heat is on households' demand for heat as an energy service, which can be fulfilled by various competing heating technologies. Therefore, the model requires data on useful energy demand for residential heating on the Member State level, further disaggregated into useful energy demand by technology. As such data is not readily available, it was calculated by combining data on the final energy demand for residential heating by fuel type, market shares of different heating technologies, and time series on the energy production by heat pumps and solar thermal installations.

Standard energy statistics (such as those published by Eurostat) do report the final energy demand by fuel type for households, but do not differentiate by end-use application (i.e., which fraction of a respective fuel was used for heating, and which for other purposes). Data on final energy demand for residential heating by fuel type was therefore taken from the ODYSSEE (2017) database,[7] which is co-funded by the EU Horizon 2020 programme and covers energy consumption by end-use for all 28 Member States, and has annual time series for the period 1990-2014, disaggregated by six fuel types: coal, oil, gas, heat, wood, and electricity. Total final energy demand for residential heating was calculated by adding the values for space heating and water heating. However, data was not available for all years for all countries (see Table 4). For four countries, the last available data is for 2013. For another four countries, the latest data originates in 2010-2012. The respective gaps were filled with data from the IEA energy tables: if values from the IEA and ODYSSEE were not identical for the last available year, the growth trend in IEA data was used to continue the ODYSSEE time series. Regarding historical data, the time series for all but seven countries reach back to 1990. Missing historical values were also filled based on IEA data.

For heat pumps, we use a dataset provided by the European Heat Pump Association (EHPA) (2016),[8] which contains time series on installed capacities and useful energy production by different types of heat pumps for 19 Member States (see Table 4). Available observations do at least cover the period 2010-2015 for all covered countries, and go back as far as 1989 for some countries. For Bulgaria, Greece, Luxembourg, Malta and Slovenia, data on energy production by heat pumps was obtained from the Eurobserv'ER database.[9] No data on heat pumps could be found for Croatia, Cyprus, Latvia, and Romania, for which we assume incremental market

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[7] http://www.odyssee-mure.eu/

[8] http://www.ehpa.org/market-data/

[9] https://www.eurobserv-er.org/

shares of 0,1% at the start of the model simulation. Useful energy production by heating technology is grouped into three heat pump sub-categories: ground source heat pumps (brine/water and water/water), aerothermal air/water heat pumps, and aerothermal air/air heat pumps.

Table 4: Years of data availability on final energy demand for space and water heating, useful energy generation by heat pumps, and useful energy generation by solar thermal.

	Final energy demand (by fuel type)	**Heat pumps** (by technology)	**Solar thermal** *(by country)*
Austria	1990–2014	1989–2015	2006–2014
Belgium	1990–2013	2009–2015	2006–2014
Bulgaria	1990–2014	*2011–2014*	2006–2014
Croatia	1990–2014	—	2012–2014
Cyprus	1991–2014	—	2006–2014
Czech Republic	1990–2014	2005–2015	2006–2014
Denmark	1990–2014	2007–2015	2006–2014
Estonia	1995–2014	2007–2015	2006–2014
Finland	1995–2014	2005–2015	2006–2014
France	1990–2014	2005–2015	2006–2014
Germany	1990–2014	1989–2015	2006–2014
Greece	1990–2013	*2012–2014*	2006–2014
Hungary	1990–2010	2009–2015	2006–2014
Ireland	1990–2014	2009–2015	2006–2014
Italy	1990–2014	2005–2015	2006–2014
Latvia	1996–2014	—	2006–2014
Lithuania	1990–2012	2009–2015	2006–2014
Luxembourg	2008–2014	*2011–2014*	2006–2014
Malta	1990–2012	*2013–2014*	2006–2014
Netherlands	1990–2014	2006–2015	2006–2014
Poland	1990–2014	2010–2015	2006–2014
Portugal	2000–2013	2005-2015	2006–2014
Romania	1992–2011	—	2008–2014
Slovakia	1990–2014	2009-2015	2006–2014
Slovenia	2000–2014	*2003–2014*	2006–2014
Spain	1990–2014	2010–2015	2006–2014
Sweden	1990–2014	1994–2015	2006–2014
United Kingdom	1990–2013	2005–2015	2006–2014
Source:	ODYSSEE, IEA	EHPA, *Eurobserv'ER*	IEA
Data used:	Final energy	Heat generation, capacities, costs	Heat generation, capacities

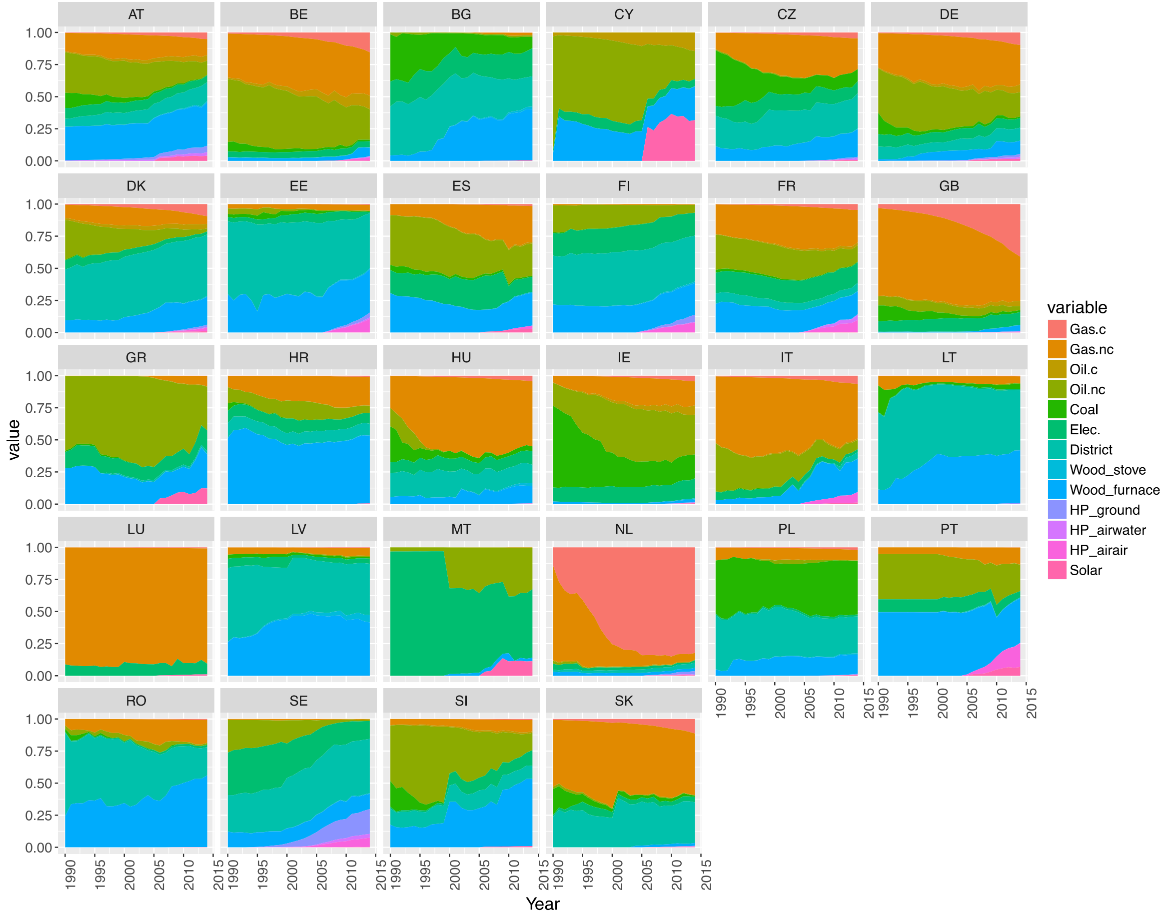

Figure 3: Historical development of heating technologies' relative shares in total useful energy demand for residential heating, by EU Member State, 1990–2014. Estimates according to the sources and methodology as described for the FTT:Heat database.

Time series on solar thermal heating were compiled from the yearly statistics of the IEA's 'Solar Heating & Cooling Programme',[10] which provides country-level annual data on heat generation and installed capacities. The respective data is available for all EU Member States, and covers the entire period 2006-2014 in all but two cases (see Table 4).

Data on final energy demand by fuel type was further disaggregated into final energy demand by heating technology, based on available information on installed capacities. In the cases of oil and gas, the respective final energy demand was divided between non-condensing and condensing boilers, according to their shares in the overall stock of heating systems as given by the EU Buildings Database[11] (see Table 20 in the appendix). The final energy demand for wood was sub-divided between conventional biomass stoves (in which wood is burned to provide space heating only) and higher-efficiency modern biomass heating systems, such as biomass boilers (in which wood is burned to heat a fluid, so that it can be used for both space- and water heating), based on capacity shares as given in a recent report for DG Energy (Fleiter, Steinbach and Ragwitz, 2016). Because the shares were only available as point estimates for one year, historical time series were estimated based on an assumed annual growth rate of 10% (Weiss *et al.*, 2009). Capacity shares per technology were transformed into the corresponding shares of final energy demand based on a technology's technical

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[10] https://www.iea-shc.org/solar-heat-worldwide

[11] http://ec.europa.eu/energy/en/eu-buildings-database

conversion efficiency (output of useful heat per unit of fuel consumed, see Table 7). In case of heat pumps, final energy demand in terms of electricity consumption was estimated by dividing reported heat production by seasonal performance factors, and subtracted from the overall electricity demand for residential heating (the remaining fraction of electricity use being classified as direct electric heating).

Finally, we combined the available data on final energy demand by fuel type, capacity shares by technology, energy production by heat pumps, and energy production by solar thermal into a database of final energy demand by heating technology for all 28 Member States, for a total of 13 heating technologies.

The corresponding time series for useful energy demand for each heating technology are obtained by multiplying a technology's estimated final energy demand by its conversion efficiency (following the approach described in section 1.3).

Figure 3 presents the shares of all 13 considered heating technologies in total useful energy demand over the entire period, 1990-2014.

8 Technology specific data

In FTT:Heat, households are assumed to choose between different heating technologies based on their economic and technological characteristics. Therefore, we collected the following data as inputs for the model's simulation of decision making: upfront investment costs, operation and maintenance costs, fuel costs, conversion efficiencies, capacity factors, technical lifetimes, and learning rates.

8.1 Investment costs

Table 5 shows the assumed mean upfront investment costs for all heating technologies, which are defined inclusive of installation costs and taxes (but exclusive of subsidies). Cost estimates for most conventional heating technologies are taken from a recent study for the European Commission, Fleiter et al. (2016), based on values given in Connolly et al. (2013). As this source does not include cost data for biomass boilers and district heating, this data was instead taken from a report by the Danish Energy Agency (2013). Following Fleiter et al. (2016), up-to-date values for heat pump investment costs are extracted from the dataset provided by the EHPA (2016), which is collected by a network of expert contacts across all European countries. Investments costs for solar heating systems are directly taken from Fleiter et al. (2016). No cost data was available for standard non-condensing oil and gas boilers, since they are effectively phased out within the EU and no longer available. For comparison of overall heating costs, we extrapolated their investment cost based on price ratios from IEA ETSAP (2012b).

As in Fleiter et al. (2016), the stated investment costs were converted to country-specific values based on relative cost differences across countries, following the methodology described by Connolly et al. (2013), yielding the same results as documented in Fleiter et al. (2016). This accounts for the fact that cost levels are generally not the same in all Member States (e.g., due to different wage levels and building regulations). No country factor was available for Croatia, for which we approximated a value based on its GDP. The applied country factors can be found in the Appendix (Table 21).

Table 5: Mean upfront investment costs (incl. of installation costs, excl. of subsidies) for residential heating technologies, in € per kW of thermal capacity.

	Investment cost (€/kW$_{th}$)	**Source**
Oil boiler	471	*extrapolated*
Oil condensing boiler	512	Fleiter et al. (2016)
Gas boiler	391	*extrapolated*
Gas condensing boiler	434	Fleiter et al. (2016)
Biomass stove	440	Danish Energy Agency (2013)
Biomass boiler	523	Danish Energy Agency (2013)
Coal boiler	247	Fleiter et al. (2016)
District heating	265	Danish Energy Agency (2013)
Electric heating	538	Fleiter et al. (2016)
Heat pump - ground source	1400	EHPA (2016)
Heat pump - air/water	750	EHPA (2016)
Heat pump - air/air	510	EHPA (2016)
Solar thermal	773	Fleiter et al. (2016)

Investment costs for heating systems do not only vary between different countries, but also within countries. For example, this may be the case due to economies of scale, different characteristics of individual buildings, or price differences between producers/retailers/installation companies. Furthermore, most boilers are only produced in pre-defined sizes, so that some households may end up paying for an oversized system - which effectively increases the cost per kW of required capacity. Therefore, in addition to mean investment costs, FTT:Heat considers distributions of investment costs. Based on the cost ranges given by the Danish Energy Agency (Danish Energy Agency, 2013, 2016) and the U.S. National Renewable Energy Laboratory (2016), a standard deviation equivalent to 1/3 of the mean investment costs is assumed for all technologies.

8.2 Operation and maintenance costs

Operation and maintenance costs include all costs that are incurred to operate a heating system other than fuel costs. For example, this includes insurance, payments for O&M service agreements, consumption of auxiliary materials, spare parts, and repair costs. Estimates for annual operation and maintenance costs in € per kW of thermal capacity are summarised in Table 6. Since O&M costs can develop over time, the stated values are average costs over the entire lifetime of the technology.

For most heating technologies, it was possible to use the same source of data as for investment costs (Fleiter et al. 2016 and Danish Energy Agency 2016). As Fleiter et al. (2016) do not include O&M costs for solar and heat pumps, the respective estimates were also taken from the Danish Energy Agency (2013; 2016). While Fleiter et al. (2016) state annual O&M costs as a percentage value of upfront investment costs, the Danish Energy Agency (2016) gives ranges of absolute monetary values (in €/kW), which we converted into percentage values for convenience of comparison. The percentage values were used to calculate O&M costs for each Member State as a fraction of their country-specific investment costs. As for investment costs, there is no data that specifically refers to non-condensing boilers, so that we assume the same values as for condensing boilers.

Table 6: Operation and maintenance costs of residential heating systems, in € per kW of thermal capacity, and relative to investment costs/kW.

	€/kW$_{th}$ per year	% of investment costs, per year	Source
Oil boiler	—	—	—
Oil condensing boiler	29	4	Fleiter et al. (2016)
Gas boilers	—	—	—
Gas condensing boiler	9	2	Fleiter et al. (2016)
Biomass stove	0.1	0.025	Danish Energy Agency (2013)
Biomass boiler	2	0.4	Danish Energy Agency (2013)
Coal boiler	5	2	Fleiter et al. (2016)
District heating	16	6	Danish Energy Agency (2013)
Electric heating	0.5	0.1	Fleiter et al. (2016)
Heat pump - ground source	14	1	Danish Energy Agency (2016)
Heat pump - air/water	15	2	Danish Energy Agency (2016)
Heat pump - air/air	51	10	Danish Energy Agency (2016)
Solar thermal	8	1	Danish Energy Agency (2016)

Standard deviations for operation and maintenance costs are assumed to be 1/3 of the mean for all technologies, based on the ranges in Danish Energy Agency (2013; 2016).

8.3 Fuel costs

In FTT:Heat, it is assumed that decisions between heating systems in any year are based on cost values as observed in the previous year. As the model's simulation starts in 2015, the initial calibration values for fuel prices are therefore taken from 2014. All fuel costs are given in the Appendix (Table 22). Note that these are only starting values for the calibration of FTT:Heat. Any future fuel price developments are either specified as exogenous assumptions or can be endogenously determined by E3ME and its respective sub-models, depending on assumptions on future policies and the model's projections for future fuel use (e.g., FTT:Power simulates future levels of electricity prices).[12]

Fuel costs for oil, gas and electricity were taken from the IEA's (2016) data on energy end-use prices for households in USD/toe converted using exchange rates, which we converted into €/kWh (using the exchange rates and conversion factors given by the IEA). Specifically, we used the 2014 values of the time series 'Light fuel oil prices for households in USD/toe (NCV basis)', 'Natural gas prices for households in USD/toe (NCV basis)' and 'Electricity prices for households in USD/toe (NCV basis)'. For the following countries, oil prices were not available in the IEA data, and were instead taken from DG Energy's 'Weekly Oil Bulletin' (20/10/2014)[13]: Bulgaria, Croatia, Cyprus, Hungary, Lithuania, Malta, and Romania. In case of natural gas, IEA

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[12] For consistency with other analysis by the European Commission, all scenario simulations in this report use exogenous fuel price trends (see section 9 on scenario assumptions).

[13] http://ec.europa.eu/energy/observatory/reports/2014_10_20_with_taxes_1725.pdf
(The weekly oil bulletin is not used as our default source here because it reports prices on a weekly basis, instead of annual averages.)

household prices were not available for the following countries, and therefore substituted by Eurostat's time series on 'Gas prices for domestic consumers - bi-annual data (from 2007 onwards)' (nrg_pc_202)[14]: Bulgaria, Croatia, Latvia, Lithuania, and Romania. No natural gas prices were available for Cyprus, Malta, and Finland (natural gas is not used for heating on Cyprus and Malta), in which cases we used the IEA's mean price for Europe as a substitute.

Cost data for district heating is more difficult to obtain, as prices can largely differ between regions, and no standardised statistics exist. Werner (2016) estimates an 'European District Heating Price Series' for most EU Member States, with the latest available values being for 2013. We converted the stated cost estimates from €/GJ to €/kWh. Furthermore, as the price series is exclusive of taxes, we calculated the effective household prices by adding the VAT (value added tax) for district heating in the different Member States, according to the applicable tax rates as stated by the European Commission.[15] No district heating prices were available for Greece, Spain, Ireland, Luxembourg, Portugal, Cyprus, and Malta. In these countries, district heating does only have a significant market share in Greece, and is mostly (or completely) non-existent in the others. In these cases, we used the mean price of district heating in other Member States as a substitute.

There is hardly any statistical data available on household prices for coal and solid biomass. For solid biomass, the association of the Austrian wood pellet industry provides time series on average annual prices for pellets, firewood and wood chips in Austria[16], which is one of the major European producers of solid biomass fuels. We use the 2014 price of firewood (0.046 €/kWh) as an estimate for all Member States. Similarly, household prices for coal are estimated based on market data for Poland, the largest consumer of coal for residential heating (0.022 €/kWh). However, as the uptake of coal and wood heating technologies is not just determined by economic fundamentals, but largely depends on households' preferences in terms of convenience and comfort, fuel cost data is of a relatively minor importance in both cases.

As for investment and O&M costs, fuel costs per kWh are not the same for every household. Within a Member State, fuel prices can differ both spatially (between regions, e.g. in case of district heating systems) and temporally (e.g., a household's effective oil price depends on the exact timing of its bulk delivery). Furthermore, households purchase their fuels from different suppliers, and pay market prices based on individual contract conditions (e.g., electricity and gas prices differ between companies). Prices also depend on total energy demand, with effective prices per kWh usually decreasing with a household's annual consumption of a fuel. In the case of solid biomass, some households may benefit from collecting locally sourced wood logs free of charge, while others rely on professional suppliers. Therefore, fuel costs in FTT:Heat are distributed around the mean fuel prices as shown in Table 22, with an assumed standard deviation of 15% (30% for wood, based on the estimate by the National Renewable Energy Laboratory 2016).

8.4 Conversion efficiencies

Table 7 shows the assumed conversion efficiencies that are used in FTT:Heat. For oil, gas and biomass boilers, the resulting net delivery of useful energy is smaller than final energy demand, because a fraction of energy input cannot be converted into heat

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[14] http://ec.europa.eu/eurostat/statistics-explained/index.php/Natural_gas_price_statistics

[15] http://ec.europa.eu/taxation_customs/sites/taxation/files/resources/documents/taxation/vat/how_vat_works/rates/vat_rates_en.pdf

[16] http://www.propellets.at/en/pellet-price/details/

as an useful output. In case of direct electric heating and district heating, the conversion of primary energy does not take place on site, but in electricity and heat plants, respectively. Therefore, the technical conversion efficiency on site is virtually one, and final energy demand equals useful energy delivery. For heat pumps, useful energy delivery is larger than final energy demand (in terms of electricity) by a factor between 2.5 and 3.5, since each unit of electricity allows to deliver more than one unit of heat (either from a ground or water source, or the ambient air). The exploited fraction of renewable heat is not counted as fuel. For solar thermal heating systems, only the captured amount of solar energy is counted as final energy, so that the conversion efficiency equals one. (Spatial differences in solar irradiation are accounted for by the country-specific capacity factors of solar thermal heating systems, as given in the Appendix, Table 23 – see section 8.6 for more details).

Table 7: Technical conversion efficiencies of individual heating technologies (output of useful energy per unit of fuel consumed on site).

	Climate	Conversion efficiency (kWh_{th}/kWh)	Source
Oil boiler	all	0.75	IEA ETSAP (2012b)
Oil condensing boiler	all	0.86	IEA ETSAP (2012)
Gas boilers	all	0.75	IEA ETSAP (2012)
Gas condensing boiler	all	0.9	IEA ETSAP (2012)
Biomass stove	all	0.7	IEA ETSAP (2012)
Biomass boiler	all	0.85	IEA ETSAP (2012)
Coal boiler	all	0.75	IEA ETSAP (2012)
District heating	all	0.98	Danish Energy Agency (2016)
Electric heating	all	1.00	Fleiter et al. (2016)
Heat pump - ground source	all	3.50	EC (2013)
Heat pump - air/water	cold	2.50	EC (2013)
	average	2.60	EC (2013)
	warm	2.70	EC (2013)
Heat pump - air/air	cold	2.50	EC (2013)
	average	2.60	EC (2013)
	warm	2.70	EC (2013)
Solar thermal		---	---

8.5 Lifetimes

For calculating a technology's overall heating costs inclusive of upfront investment costs, it is necessary to include an estimate of its expected useful lifetime. Ideally, one would need to know for how long a household expects to use a piece of equipment. As an upper limit, this would be the time after which a heating installation breaks down and can no longer be used - i.e., its expected technical lifetime. Table 8 summarises the respective estimates from different sources. For almost all technologies, the reported values for technical life expectancies are between 15 and 25 years, clustering around a central estimate of 20 years. Gas boilers, biomass stoves and electric heating are generally assumed to last slightly longer (22-30 years), while air source heat pumps may have slightly lower life expectancies (15-20 years).

However, it is important to note that these estimates do only give limited information on actual lifetimes, and should rather be interpreted as an assumed useful life for given pieces of equipment. Especially for newer technologies, they can only partially include statistical data on lifetimes of actual projects, but reflect engineering estimates of experts in the field. In reality, heating systems may be operated for longer or shorter times. For example, Fleiter et al. (2016) report that more than half of installed coal and oil boilers in Europe are older than 20 years. The other way around, a household may decide to prematurely replace a working heating system, for example to realize cost savings or increase its level of comfort.

For not distorting the model results by rather uncertain differences in estimated life expectancies between technologies, FTT:Heat is calibrated based on a central estimate of 20 years for all technologies.

Table 8: Technical life expectancies of residential heating systems, in years.

Source:	Danish Energy Agency (2013; 2016)	Fleiter et al. (2016)	IEA ETSAP (2012)
Oil boiler	—	—	15-25
Oil condensing boiler	20	20	15-25
Gas boilers	—	—	15-25
Gas condensing boiler	22	22-25	15-25
Biomass stove	24	25	15-25
Biomass boiler	20	25	15-25
Coal boiler	—	—	15-25
District heating	20	—	—
Electric heating	30	30	20
Heat pump - ground source	15-25	20	15-20
Heat pump - air/water	15-20	20	15-20
Heat pump - air/air	10-15	20	15-20
Solar thermal	20-25	25	—

8.6 Capacity factors

Besides technical lifetimes, the capital cost per unit of produced heat does also depend on capacity factors. Table 9 shows the capacity factor that are assumed in FTT:Heat, differentiated by climatic conditions. Table 23 (in the Appendix) presents the climatic conditions, heating degree-days and annual solar yield per Member State.

The capacity factor does depend on various factors, and the correct sizing of heating installations in each individual case does require detailed building-physics calculations. For the purpose of our model, we do not perform such individual calculations, but look at the load-duration curve under different climatic conditions as a simple average relation between heating capacities and useful energy demand. In general, the necessary thermal heating capacity as an absolute value (in kW_{th}) does depend on a household's peak-load heat demand: the higher the maximum expected heat demand within a year, the more heating capacity is needed. In most cases, the peak-load will occur when the difference between the outside temperature and the target indoor temperature is largest, so during the coldest periods of European winter. The capacity factor as a relative value (in $MWh_{th}/kW_{th}*y$) does then depend on the overall level of heat demand (in MWh_{th}/y), which reflects the length and intensity of heating throughout the year. As an approximation, CF_i can therefore be expressed as a function of the annual operation hours (CF_i =h/y), which are determined by the heating period within a given climate (e.g., October to April).

Table 9: Capacity factors of residential heating technologies (annual net delivery of heat, per unit of thermal capacity), by climatic conditions and technology group.

	Climate	**Capacity factor** (MWh_{th}/kW_{th})	**Source**
Oil, gas, biomass, coal, district and electric heating	cold	2.47	EC (2013a)
	average	2.07	EC (2013a)
	warm	1.34	EC (2013a)
Heat pump – ground source	cold	2.47	EC (2013b)
	average	2.07	EC (2013b)
	warm	1.34	EC (2013b)
Heat pump - air/water	cold	1.71	EC (2013b)
	average	1.64	EC (2013b)
	warm	1.17	EC (2013b)
Heat pump - air/air	cold	1.97	EC (2013b)
	average	1.77	EC (2013b)
	warm	1.20	EC (2013b)

Here, capacity factors are calculated based on the European Commission’s reference values for annual active mode hours of heating systems in colder, average and warmer climate conditions (European Commission, 2013a). Capacity factors are larger for Member States with a relatively cold climate, and smaller for Member States with a relatively warm climate (which implies that households have a relatively shorter heating period). Furthermore, capacity factors are different between heat pump categories, with air source heat pumps having lower capacity factors due to their reliance on supplementary heaters (as described in the guidelines for Member States on calculating renewable energy from heat pumps, see European Commission, 2013b)

For solar thermal heating systems, the capacity factor is defined as the solar yield: given a country's level of solar irradiation, how much heat is produced for every unit of installed capacity? The factor for each Member State was calculated based on the thermal capacities and heat production as reported by the IEA, and can be seen in Table 23 (in the Appendix).

It is important to note that the capacity factor can only give an estimate for the *necessary* capacity of a household's heating equipment, given a country's *average* climatic conditions and level of housing insulation. The *observed* capacity of an individual household may deviate from the *necessary* capacity, for example if a) boilers are only sold in predefined sizes (which typically leads to oversized boilers for many households), b) the climatic conditions deviate from the mean value for cold/average/warm climate, or c) the boiler's size is larger/smaller than necessary without any good reason. From a conceptual point of view, household-specific differences in capacity factors imply a variation in upfront investment cost (defined as €/kW_{th}), which is represented by the respective cost distributions (see 8.1).

8.7 Learning rates

Learning rates are defined as the relative reduction in a technology's mean upfront investment costs (in %) which is expected for each successive doubling of the installed capacity, summed over all countries. The assumed learning rates in FTT:Heat are presented in Table 10. No further cost reductions are expected for well-established technologies.

Table 10: Assumed learning rates for residential heating technologies (relative reduction in mean upfront investment costs for each successive doubling of the cumulative installed capacities, combined for all countries).

	Investment cost (€/kW$_{th}$)	**Source**
Oil boiler	—	—
Oil condensing boiler	- 6%	Weiss et al. (Weiss *et al.*, 2010)
Gas boilers	—	—
Gas condensing boiler	- 6%	Weiss et al. (2010)
Biomass stove	—	—
Biomass boiler	- 7%	Henkel (2012)
Coal boiler	—	—
District heating	—	—
Electric heating	—	—
Heat pump - ground source	- 35%	Weiss et al. (2010)
Heat pump - air/water	- 35%	Weiss et al. (2010)
Heat pump - air/air	- 35%	Weiss et al. (2010)
Solar thermal	- 20%	Henkel (2012)

Part IV. Scenario simulations

This section assesses the impacts of several scenarios simulations: a current technology and policy trends scenario as a baseline projection, and three scenarios aiming at an increased uptake of renewable heating technologies by households.

9 Definition of scenarios and assumptions

9.1 Assumptions

The simulations carried out for this report are based on the following set of assumptions, all of which need be specified for running FTT:Heat.

The useful energy demand for heating per Member State (UD_{tot}) is calibrated to the European Commission's EUCO30 scenario (E3MLab and IIASA, 2016), which models the achievement of 2030 climate and energy targets of at least 40% greenhouse gas emission reductions, 27% renewable energy share and 30% improvement in energy efficiency, and provides estimates for levels of useful energy demand for heating up to 2050. On average, this implies a reduction of UD_{tot} by around -1% in 2030, and by -30% in 2050 (relative to the 2014 starting values), mainly due to increased levels of building insulation. Also taken from the EUCO30 scenario are the assumptions regarding the future development of fuel prices within the EU until 2030, which are depicted in Figure 4.[17] Due to the large uncertainty regarding future fuel prices in a context of decarbonisation policies, we do not assume any further increases between 2030-2050. The relative trends are applied to each country's historical fuel prices at the start of the simulation.

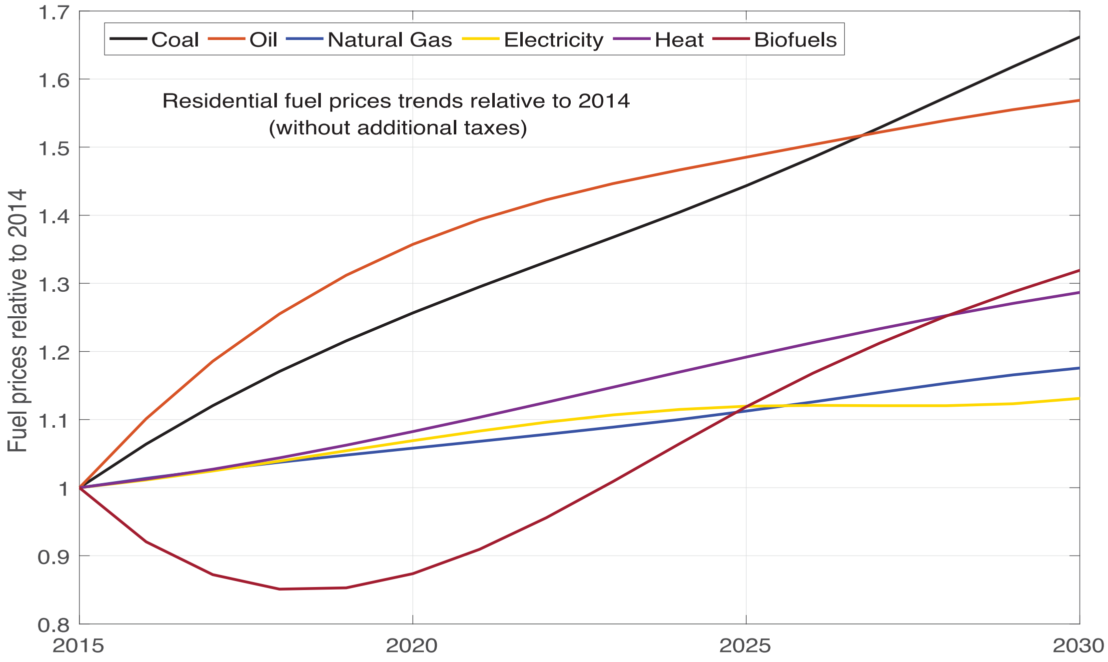

Figure 4: Assumptions for future development of fuel prices faced by households in the EU (exclusive of additional taxes), relative to 2015. Source: own illustration, based on fuel price projections from the European Commission's EUCO30 scenario.

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[17] Relative price trends for district heat were calculated as the weighted average of all other fuel price trends.

A behavioural discount rate r of 10% is assumed for households in all countries and technologies. The useful lifetime (the time after which households make end-of-lifetime investment decisions) is set to 20 years for all technologies, which implies that 5% of the heating stock needs to be replaced within any given year. The payback threshold b for premature replacement investments is set to a mean of 3 years (standard deviation 1 year) for all countries and technologies (Olsthoorn *et al.*, 2017).

Within the matrix of exogenous restrictions, A, it is assumed that households do not change to heating systems that provide a significantly lower comfort level or degree of automation than their existing system. Specifically, the flow between technologies is restricted so that coal boilers and traditional biomass stoves can only be chosen if either of the two is the household's existing heating system (adapted from Kranzl et al. 2013).

As an assumption for all scenarios, the market share of district heating within each Member State is limited to 10 percentage points above the largest observed share between 1990-2014. While this allows for some level of dynamic growth in district heating networks, the assumption reflects the fact that district heating is not available to all households, but depends on the construction of heat networks. Furthermore, the market share of solar heating is limited to the share of water heating within each Member State, reflecting that the technology is mainly used for water heating, and only as a supplementary source for space heating.[18]

As a macroeconomic assumption in E3ME, it is specified that additional government revenues from newly introduced taxes are used to finance newly introduced subsidy payments (if any are included within the scenario). If the tax revenues exceed the subsidy payments, the surplus is used to reduce the employers' contribution to social security payments.[19]

9.2 Scenario definitions

All scenarios include a regulatory phase-out of non-condensing oil and gas boilers, in line with current energy efficiency regulations. The other policy assumptions for the simulations are as follows.

9.2.1 Current technology and policy trends scenario (baseline scenario)

The current technology and policy trends scenario serves as a baseline projection. The policy scenarios then estimate the effect of additional policies for the residential heating sector relative to that baseline. For this purpose, we assume that historical trends in technology diffusion are maintained, implicitly including the impact of existing policies, because their impact on technology choices is captured by the historical data (up to 2014). The baseline scenario also includes policies for a decarbonisation of the power sector (see text box below) and an increased level of housing insulation (in line with the EUCO30 scenario), which affects useful heating demand over time. No additional policies or regulations for the heating sector are imposed.

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[18] In practice, this is only relevant for Member States with high levels of solar irradiation (Cyprus, Malta, Greece, Portugal, Spain), which implies a potentially high economic attractiveness of solar thermal heating when taking into account future cost decreases and policy incentives.

[19] From a macroeconomic perspective (and in E3ME), employers' contributions to social security payments have a similar effect than a tax on labour, so that their reduction can potentially stimulate employment.

Net emission effects of electrified heating

An increased electrification of residential heating, such as a more widespread installation of direct electric heating or heat pumps, results in reduced CO_2 emissions on site, as no fossil fuels are burnt by households using these technologies. At the same time, overall electricity demand increases, which may lead to higher CO_2 emissions by power plants. The net effect of heating electrification therefore strongly depends on the electricity sector's current and future carbon intensity.

Based on its technology composition in 2015, the EU's electricity sector has an average carbon intensity of around 330gCO_2 per kWh of electricity produced (with large variations between Member States). This compares to carbon contents of around 200 and 350gCO_2 per kWh of energy content for natural gas and hard coal, respectively. Given average conversion efficiencies, residential heating with fossil fuels therefore causes direct emissions of 220 (condensing gas boiler) and 500 (coal boiler) gCO_2 per kWh of useful heat produced. Given the current technology composition, a substitution of fossil fuels by electric heating may therefore increase or decrease overall emissions, depending on the respective technologies and the electricity system. In case of heat pumps, one unit of electricity input allows to produce around 2.5-3.5 units of heat. This implies additional emissions by the electricity sector of around 95-130gCO_2 per kWh of useful heat produced, on average, and a net reduction of emissions in all but the most carbon intensive electricity systems.

Regarding the electricity sector's future emissions intensity, we assume a decarbonisation trajectory consistent with the EU's Energy Roadmap 2050, which suggests a reduction of overall GHG emissions by 80-95% until 2050 (relative to 1990). Specifically, the EU power sector is here simulated by the E3ME sub-model FTT:Power. We assume policies that result in an absolute emission reduction of -70% by 2030, and -90% by 2050 (relative to 1990) (see Figure 6). The average emission intensity decreases to 130gCO_2/kWh by 2030, and 45gCO_2/kWh by 2050. This would allow a gradual electrification of heating with relatively minor induced emission increases in the power sector.

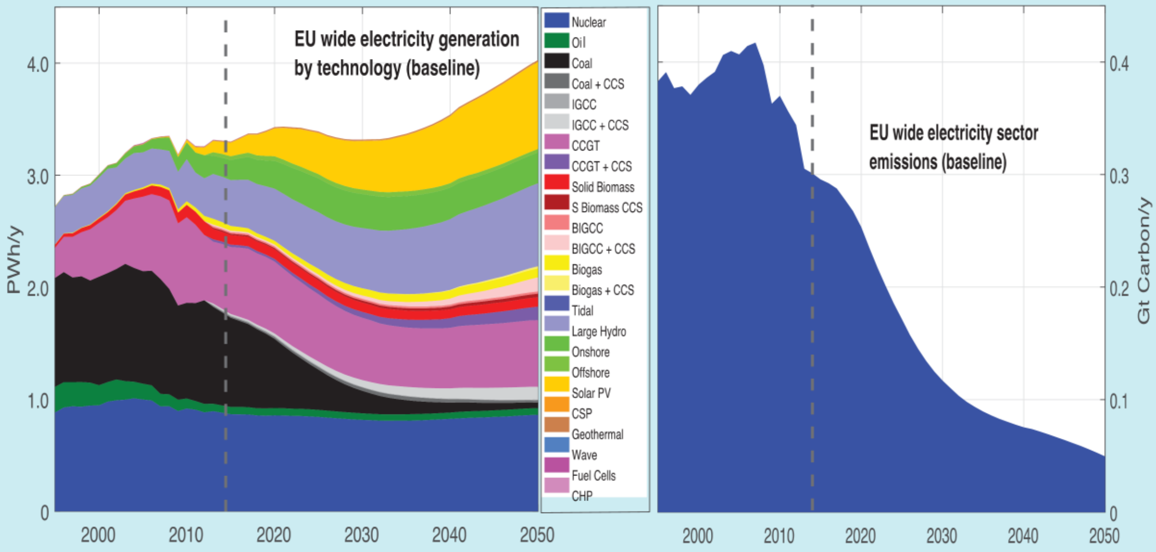

Figure 5: EU wide electricity generation by technology (left side) and resulting carbon emissions (right side), in the current trends baseline scenario without additional heating sector policies. The dashed line indicates the start of the simulation by E3ME-FTT:Power, in which we assume a trajectory towards a -90% emission reduction by 2050.

9.2.2 Additional policies scenarios

The policy scenarios aim at reaching specified decarbonisation objectives for the residential heating sector within all Member States in 2030 and 2050.

Scenario 1: Share of renewables increase by +10pp until 2030

A set of policies is defined for each Member State which aims at increasing the share of renewables in residential heating (%RE) in final energy demand[20] by at least 10 percentage points in each Member State between 2018 and 2030. The objective is loosely based on the European Commission's recent RES directive proposal (European Commission, 2016b), which aims at achieving a higher penetration of renewable heating in all Member States (in the period 2020-2030), where the policy instruments should be flexibly chosen by each Member State. For each Member State which is not projected to reach the 2030 objective in the current trends baseline scenario, one or more of the following policies are simulated:

i. A new *carbon tax* of 50 €/tCO_2 on the residential use of coal, oil and gas is introduced from 2018 onwards (levied until 2030), leading to the following effective tax rates and price increases per type of fuel: +0,01 €/kWh for gas, +0,013 €/kWh for oil, and +0,018 €/kWh for coal. It is assumed that each year until 2030, the tax increases linearly by 10% of its respective starting value (i.e., each year by +5 €/tCO_2). In scenario 1, the tax is set to zero from 2030 onwards.
ii. *Upfront capital subsidies* for the purchase of renewable heating technologies. From 2018 until 2030, the purchase and installation of all renewable-based heating systems (biomass boilers, heat pumps, solar thermal) is subsidized by 30% of the pre-subsidy cost. In scenario 1, the subsidy is completely phased out (set to zero) from 2030 onwards.
iii. *'Kick start'/procurement policies* for renewables-based heating technologies are introduced for a period of five years (from 2018-2022). It is assumed that within each year, the policy scheme replaces between 0.25 and 1 percentage point of the dominant technology's market share in the respective Member State by a combination of renewable heating technologies (biomass boilers, heat pumps, and solar thermal). The policy targets the tendency (and model property) for take-up of a new technology to be greater when its existing market share is greater (due to greater familiarity and lower perceived risk).

Importantly, heterogeneous energy and heating systems across Member States imply that different policy mixes may be required to reach the same objective within in each country. Therefore, not all policies are applied to all Member States. Instead, each country is assigned to one of four groups (labelled as A, B, C and D; see Table 13), based on the following stepwise procedure:

1. *Group A* consists of all Member States which are projected to fulfill the 2030 objective in the baseline scenario, without any additional policies. No further policies are applied in scenario 1.

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[20] The share of renewable residential heating (%RE) per Member State is here defined as the share of renewable technologies (biomass, heat pumps and solar thermal) in total final energy demand for residential heating, excluding electricity (both in the numerator and the denominator). In the case of heat pumps, only the renewable component (and not the electricity input) is counted. This definition is based on, but not identical to the renewable heating and cooling share (RES H&C) as calculated by Eurostat (2015) (which also covers cooling, and accounts for renewable components in the supply of gas, oil and district heat).

2. *Group B* consists of Member States which are projected to fulfill the 2030 objective by introducing the new carbon tax. Apart from the tax, no further policies are applied in scenario 1.
3. *Group C* consists of Member States which are projected to reach the 2030 objective by a combination of the carbon tax and new upfront subsidies.
4. *Group D* consists of Member States which are projected to stay below the 2030 objective, even after introducing price-based incentives for an increased uptake of renewables. For these Member States, *'kick start'/procurement policies* are introduced as an additional policy instrument.

In sum, scenario 1 applies the respective policy mixes to the individual Member States, so that each of them fulfills the objective of increasing the share of renewable heating by at least 10 percentage points over 2018-2030.

Table 11: Overview of scenarios 1-3 and simulated policies by group of Member States, from 2018-30 and 2030-50. Green indicates that a policy is implemented for a group of Member States in the given period, red indicates that a policy is not implemented.

	Time period:	**2018-2030**				**2030-2050**			
	Member States:	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
Scenario 1	Carbon tax	🟥	X	X	X	🟥	🟥	🟥	🟥
	Upfront subsidy	🟥	🟥	X	X	🟥	🟥	🟥	🟥
	'Kick start' policies	🟥	🟥	🟥	X	🟥	🟥	🟥	🟥
Scenario 2	Carbon tax	🟥	X	X	X	X	X	X	X
	Upfront subsidy	🟥	🟥	X	X	X	X	X	X
	'Kick start' policies	🟥	🟥	🟥	X	🟥	🟥	🟥	🟥
Scenario 3	Carbon tax	X	X	X	X	X	X	X	X
	Upfront subsidy	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	'Kick start' policies	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥

Scenario 2: deep decarbonisation by 2050

In this scenario, the defined objective is a virtually complete decarbonisation of the EU's residential heating sector by 2050 (at least 95% reduction in residential heating's on-site CO_2 emissions, relative to 2005). Up to 2030, the policy assumptions in scenario 2 are identical to the description of scenario 1 (with group-wise policy mixes applied to individual Member States). From 2030 onwards, the following policies are introduced in all Member States (independently of their policy-mix up to 2030):

i. From 2030 onwards, the *carbon tax* on the residential use of coal, oil and gas is introduced in all Member States. The carbon tax' starting value in 2030 is set to 110 €/tCO_2, identical to its 2030 end value in scenario 1. As in scenario1, the tax increases linearly by +5 €/tCO_2, eventually reaching 210 €/tCO_2 by 2050.
ii. *Upfront capital subsidies* on the purchase of renewable heating technologies. From 2030 onwards, the purchase and installation of all renewable-based heating systems (biomass, heat pumps, solar thermal) is subsidized by 30% of the capital cost in all Member States. The subsidy rate decreases linearly by 3 percentage points each year, reaching zero by 2040.

Scenario 3: EU wide carbon tax

In this scenario, we simulate the EU wide introduction of a *carbon tax* on the residential use of fossil fuels in all Member States, from 2018 onwards, as the only new policy instrument. As in scenarios 1 and 2, the tax starts at 50 €/tCO_2, and linearly increases by +5 €/tCO_2, eventually reaching 210 €/tCO_2 by 2050. The focus here is not on reaching a specific policy objective, but on the analysis of induced effects. Different to scenarios 1 and 2, no subsidies for renewable technologies are paid to households. Instead, it is assumed that all revenues from the new carbon tax are recycled into the labour market. Specifically, we assume that they would be used to lower the employer's contributions to social security payments, thereby creating incentives for increased employment. Alternatively, carbon tax revenues could be redistributed to households by reducing other taxes (such as on income), or in form of direct payments.

10 Identification of country groups for scenarios 1 and 2

The projected increases in Member States' renewable heating share until 2030 are summarised in Table 12, both for the baseline projection and the policy scenarios. The four country groups, based on how many policies were added for achieving the 2030 objective, can be seen in Table 13.

In the baseline scenario projection, no further policies are introduced for any Member State. As illustrated by figure 5, eight Member States are currently on a trajectory which may allow them to increase their renewable heating share by at least 10 percentage points until 2030 without additional policies: Greece, Spain, France, Ireland, Portugal, Estonia, Cyprus, and Malta. These states constitute country group A, for which no additional policies are simulated before 2030.

The remaining 20 Member States are projected to have an increase in their renewable heating share up to 2030 of less than the objective of 10 percentage points. For these 20 countries, the effect of additional policies is simulated prior to 2030, all designed to promote an increased uptake of renewable heating technologies.

To find a policy mix that meets the objective in each country, a carbon tax, upfront cost subsidies for renewables, and 'kick start' policies for renewables are successively added until the renewable heating share in 2030 is projected to increase by at least 10 percentage points. Countries are grouped accordingly, and the analysis of simulation results focuses on the respective country groups.

Thirteen Member States are projected to fulfil their 2030 objective for renewable heating by introducing new market-based policies to influence purchasing decisions ('market pull policies'). In case of Belgium, Italy, Czech Republic, Poland and Bulgaria, it is projected that the introduction of a carbon tax from 2018 onwards would be sufficient on its own. Therefore, these five Member States constitute country group B. For Denmark, Germany, Austria, Finland, Sweden, Latvia, Lithuania and Hungary, it is projected that a combination of carbon taxes and supplementary upfront capital subsidies would allow them to reach the objective. They constitute country group C.

In the remaining seven Member States, purely price-based policies of the assumed magnitude are projected not to be sufficient to increase their renewable heating share by at least 10 percentage points until 2030: Luxembourg, Netherlands, UK, Slovenia, Slovakia, Romania and Croatia. Historically, decentralised renewable heating technologies (other than traditional biomass) have only very low market shares in all seven countries. Therefore, to fulfil the objective, they require additional 'kick start' policies ('technology push policies') in addition to taxes and subsidies ('market pull policies').

Table 12: Residential heat demand (UD, in TWh_{th}) and shares of renewables in residential heating (%RE) by Member State. Last historical observation for %RE (2014) and projected increases between 2018-2030 (in percentage points), in the FTT:Heat baseline projection and in policy scenarios 1-3**.** Red indicates a projected increase by less than 10pp until 2030, green indicates a projected increase of at least 10pp.

	Group	**Heat demand**	**%RE**	**Projected increase in %RE, 2018-2030**		
		2014	2014	**Baseline**	**Scenario 1+2**	**Scenario 3**
1 Belgium	B	64 TWh/y	9%	+6	+10	+9
2 Denmark	C	38 TWh/y	31%	+4	+10	+5
3 Germany	C	460 TWh/y	16%	+4	+13	+7
4 Greece	A	30 TWh/y	42%	+22	+22	+26
5 Spain	A	83 TWh/y	34%	+15	+15	+23
6 France	A	309 TWh/y	33%	+12	+12	+17
7 Ireland	A	21 TWh/y	5%	+11	+11	+19
8 Italy	B	210 TWh/y	34%	+9	+15	+14
9 Luxembourg	D	2 TWh/y	1%	+2	+11	+3
10 Netherlands	D	87 TWh/y	6%	+2	+11	+3
11 Austria	C	52 TWh/y	49%	+6	+14	+8
12 Portugal	A	11 TWh/y	58%	+21	+21	+23
13 Finland	C	49 TWh/y	49%	+7	+13	+7
14 Sweden	C	66 TWh/y	45%	+5	+13	+5
15 UK	D	309 TWh/y	6%	+1	+12	+2
16 Czech Republic	B	49 TWh/y	29%	+8	+13	+13
17 Estonia	A	8 TWh/y	52%	+10	+10	+11
18 Cyprus	A	2 TWh/y	59%	+15	+15	+19
19 Latvia	C	11 TWh/y	55%	+3	+10	+4
20 Lithuania	C	11 TWh/y	48%	+4	+10	+6
21 Hungary	C	39 TWh/y	19%	+4	+13	+8
22 Malta	A	0,4 TWh/y	25%	+30	+31	+39
23 Poland	B	131 TWh/y	18%	+9	+27	+27
24 Slovenia	D	9 TWh/y	63%	+2	+10	+4
25 Slovakia	D	17 TWh/y	3%	+2	+13	+3
26 Bulgaria	B	16 TWh/y	59%	+9	+10	+10
27 Romania	D	43 TWh/y	61%	+/-0	+12	+1
28 Croatia	D	17 TWh/y	60%	+1	+11	+2

Table 13: Overview of country groups A to D, grouped by the policy mixes applied 2018-2030 in scenarios 1+2. Each Member State's increase in renewables in residential heating (%RE) in the baseline projection (in percentage points) can be seen next to its name. The bottom rows show each group's initial aggregated annual heat demand (in TWh_{th}), on-site direct CO_2 emissions (in Mt) and on-site direct emission intensity (in gCO_2/kWh_{th}) (values for 2014).

Group A		**Group B**		**Group C**		**Group D**	
No new policies		**Market pull policies only**				**Market pull + push policies**	
---		*Carbon tax*		*Carbon tax + upfront subsidies*		*Carbon tax + upfront subsidies + 'kick start' policies*	
MS	*Δ%RE*	*MS*	*Δ%RE*	*MS*	*Δ%RE*	*MS*	*Δ%RE*
Greece	+22	Belgium	+6	Denmark	+4	Luxembourg	+2
Spain	+15	Italy	+9	Germany	+4	Netherlands	+2
France	+12	Czech Republic	+8	Austria	+6	UK	+1
Ireland	+11	Poland	+9	Finland	+7	Slovenia	+2
Estonia	+10	Bulgaria	+9	Sweden	+5	Slovakia	+2
Portugal	+21			Latvia	+3	Romania	+/-0
Cyprus	+15			Lithuania	+4	Croatia	+1
Malta	+30			Hungary	+4		
Total UD/y:	461TWh	Total UD/y:	470TWh	Total UD/y:	725TWh	Total UD/y:	483TWh
Total CO_2/y	69Mt	Total CO_2/y	87Mt	Total CO_2/y:	107Mt	Total CO_2/y	92Mt
gCO_2/kWh:	150	gCO_2/kWh:	185	gCO_2/kWh:	148	gCO_2/kWh:	190

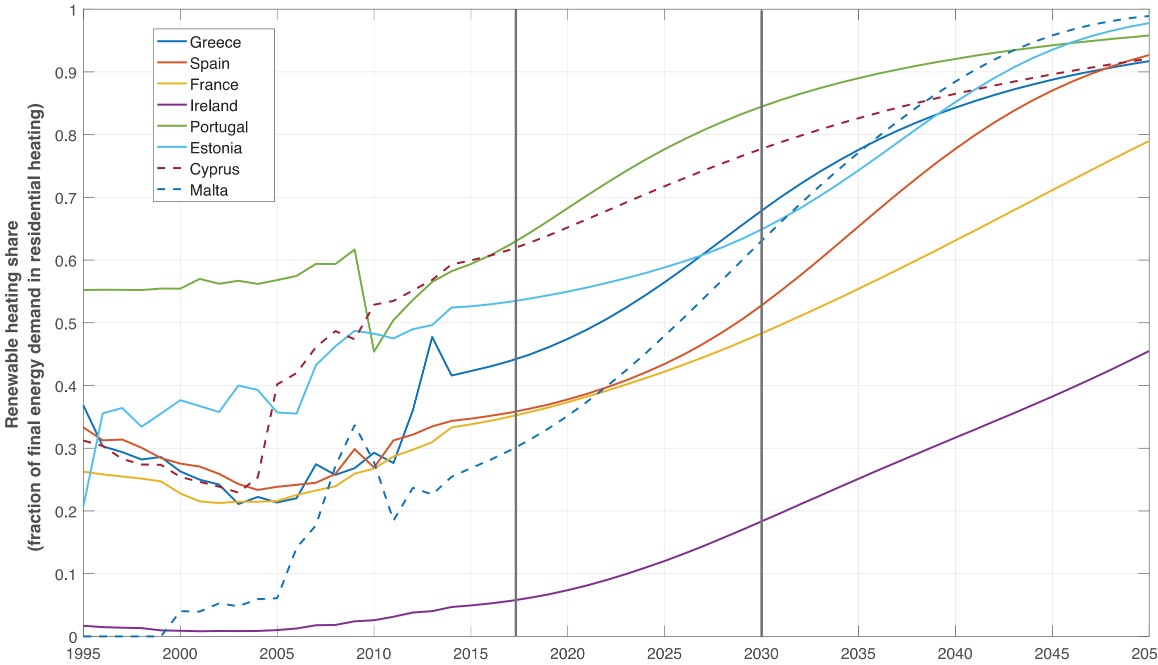

Figure 6: Share of renewables in residential heating over time, historical data and baseline projection by FTT:Heat. Trends for eight Member States which are projected to fulfill the renewable heating objective for 2030 (an increase in the share by 10 pp over 2018-30) without additional policies (country group A).

11 EU wide results

In the following three sections, the results of the scenario simulations are presented. The model simulation by FTT:Heat starts in 2015, while values for 1995-2014 represent historical data. All simulation results are subject to the uncertainties that come along with both the model structure and the data.

In addition to the baseline scenario (assuming current technology and policy trends) and policy scenario 1, which aims at an increased renewable heating share by 2030, we present results for scenario 2, which aims at a complete decarbonisation of the EU's residential heating sector by 2050, and scenario 3, which simulates the EU wide introduction of a carbon tax. Scenarios 1 and 2 include the same policy assumptions for individual Member States up to 2030, and only deviate from each other from 2030 onwards (see section 9.2 for the detailed scenario description). Results until and including 2029 are therefore identical for both scenarios.

Section 11 analyses the implied impacts on the European residential heating system and macro-economy on an aggregated level, summed over all 28 Member States. Simulation results for individual country groups and Member States are presented in sections 12 and 13, focusing on the policy mixes that allow each of them to increase their share in renewable residential heating by at least 10 percentage points until 2030 (scenario 1), and the continuation of such policies until 2050 (scenario 2). We first analyse results for scenarios 1 and 2, before comparing to scenario 3.

11.1 Impacts on heating sector and emissions

Figure 7, Table 14 and Table 15 summarise the EU wide projections for the future development of the residential heating system. Figure 7 illustrates model projections for useful energy demand (heat generation) by technology, fuel use, CO_2 emissions, added heating capacity by technology, and additional spending on heating systems under the baseline scenario and all three policy scenarios. Table 14 shows some key indicators for 2030 and 2050, including the projected share of renewables in residential heating (%RE) and on-site emission intensity of the EU heating system. Table 15 summarises the underlying trends in heating technology diffusion.

Table 14: EU wide residential heating sector total annual heat demand, fuel use, on-site CO_2 emissions, on-site CO_2 intensity, investment[21] in heating appliances, and share of renewables in residential heating (%RE).

	Start	Baseline		Scenario 1		Scenario 2		Scenario 3	
	2014	2030	2050	2030	2050	2030	2050	2030	2050
Heat (TWh/y)	2.142	2.131	1.431	2.131	1.431	2.131	1.431	2.131	1.431
Fuel (TWh/y)	2.517	2.286	1.129	2.158	955	2.141	789	2.225	889
CO_2 (Mt/y)	355	276	110	217	60	211	8	228	24
gCO_2/kWh_{th}	166	130	77	102	42	99	6	107	17
Investment[22] (€2005bn/y)	23	20	8	24	8	28	7	22	10
Renewables	25%	33%	56%	41%	73%	42%	92%	37%	83%

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[21] In the modelling, household expenditure on heating appliances of whatever kind is treated as 'investment'. In the national accounts, purchases of appliances are treated as consumers' expenditure rather than investment, but spending on property is treated as investment.

[22] Annual investment in the year shown.

As an exogenous projection in all scenarios, EU wide useful energy demand would remain more or less constant 2030, and decrease by 33% until 2050 (relative to 2014). All projections for scenarios 1 and 2 are identical up to 2030, as policy assumptions only differ for the period 2030-2050.

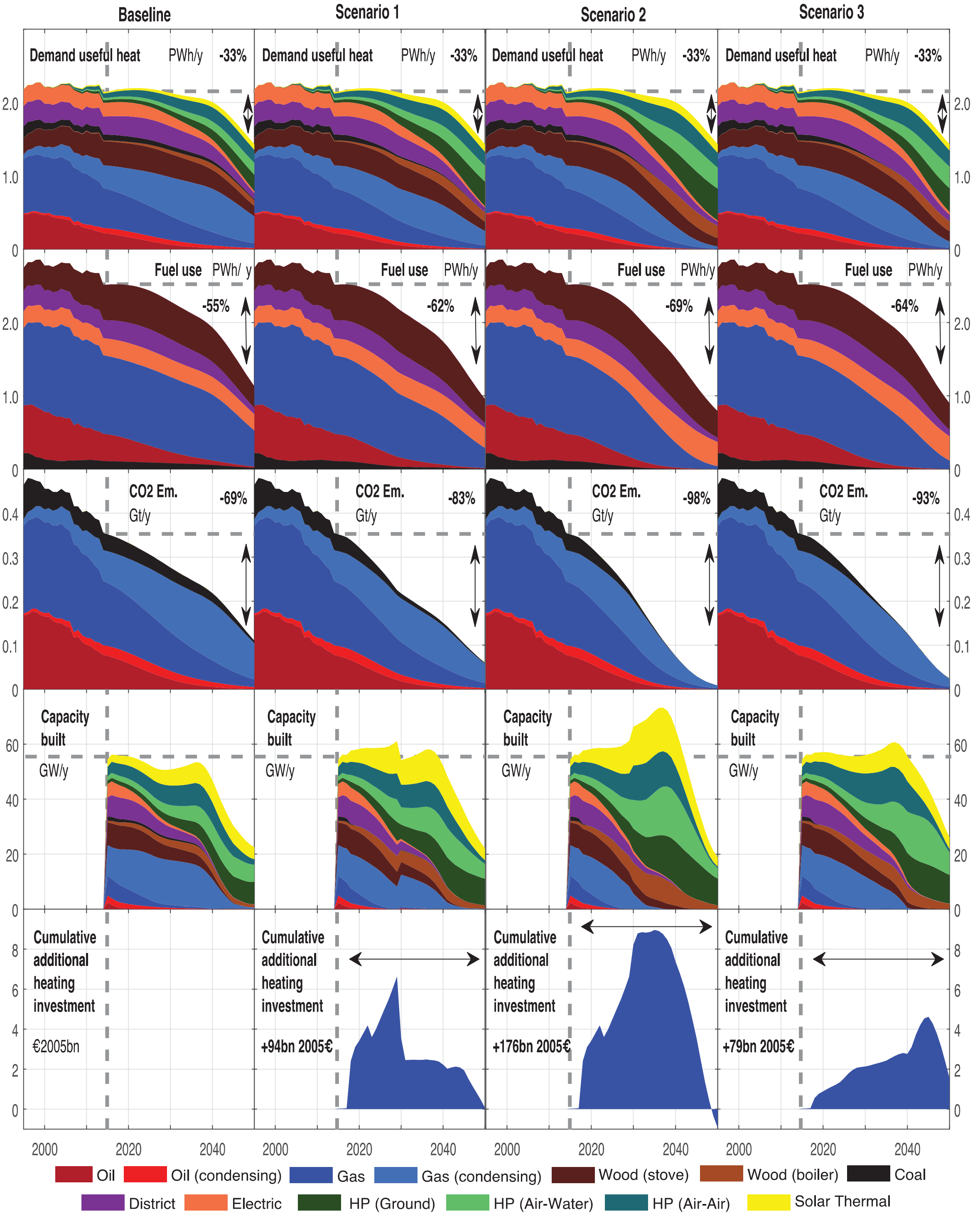


Figure 7: EU wide annual heat generation by technology, fuel use, CO_2 emissions, added heating capacity, and additional heating investments. Model results for baseline and scenarios 1-3. Values from 2015 onwards are projections by FTT:Heat. Bold numbers indicate changes in 2050, relative to 2014 (the last historical data point). Projections for useful energy demand for heating are taken from the EUCO30 scenario.

By 2030, total fuel use for residential heating (incl. biomass, electricity and district heat) is projected to decrease by 9% in the baseline, and by 14% in scenario 1 (relative to 2014). Due to an ongoing shift towards renewables, fossil fuel use would decrease by more than that in both scenarios: by 19% in the baseline, and by 35% in scenario 1. The corresponding emissions reductions by 2030 are projected to be 22% (baseline) and 39% (policy scenario 1). When introducing a carbon tax in all member States from 2018 onwards as the only policy, the resulting emission reduction is slightly smaller (36% by 2030).

Table 15: Technology group market shares in EU wide residential heat demand, in baseline and scenarios 1-3. 2014 shares are calculated from historical data, 2030 and 2050 shares are model projections by FTT:Heat.

	Start	Baseline		Scenario 1		Scenario 2		Scenario 3	
	2014	2030	2050	2030	2050	2030	2050	2030	2050
Oil	13%	6%	1%	5%	1%	4%	0%	5%	0%
Gas	40%	40%	30%	34%	17%	33%	2%	36%	7%
Biomass	16%	17%	15%	20%	18%	20%	20%	19%	19%
Coal	4%	3%	1%	1%	0%	1%	0%	1%	0%
District heat	11%	13%	6%	13%	5%	13%	4%	14%	6%
Electric	9%	7%	2%	7%	1%	7%	1%	8%	3%
Heat pumps	6%	13%	39%	18%	52%	19%	65%	15%	59%
Solar	1%	2%	5%	3%	7%	3%	8%	2%	6%

In 2050, total fuel use for residential heating (incl. biomass, electricity and district heat) is projected to decrease by 55% in the baseline, and by up to 69% in the policy scenarios (relative to 2014, see Figure 7). Fossil fuel use for residential heating in 2050 is projected to decrease by 66% in the baseline, by 82% in policy scenario 1, by 97% in policy scenario 2, and by 92% in scenario 3. The corresponding emissions reductions by 2050 are projected to be 69% (baseline), 83% (scenario 1), 98% (scenario 2) and 93% (scenario 3).

In scenario 1, the policies implemented to reach the renewable heating objectives for 2030 in each Member State are projected to cause a renewable heating transition with such a strong momentum in technology diffusion that it shows large relative impacts up to 2050: emission levels remain constantly lower, renewables would keep on dominating sales, and hardly any new investments into fossil-fuel based heating systems are projected from 2040 onwards, resulting in a -83% emissions reduction by 2050 (relative to 2014, compared to -69% in the baseline). This is despite the fact that subsidies for renewables and the carbon tax are assumed to be discontinued after 2030. In scenario 2, continuing the simulated policies and extending them to all Member States after 2030 would set the EU residential heating system on track for a deep decarbonisation until 2050, resulting in a 98% emission reduction in 2050, according to the model estimates. In scenario 3, a carbon tax on its own (with the rates chosen here) would result in a 5 percentage points lower emission reduction.

The reason for the larger reductions in fossil fuel use and emissions in scenarios 1-3 is a change in household choices of heating technologies, which is induced by the simulated introduction of additional policies. The underlying dynamics can be seen in the bottom panels of Figure 7, which depict the annual additions of heating capacity by households: in the baseline, the combined share of all renewable technologies in sales is projected to increase from 33% of the newly installed capacity in 2015 to 53%

in 2030, and close to 100% by 2050. In the policy scenario 1, the projected share of renewables in the yearly installed capacity is 77% by 2030. In scenarios 2 and 3, no new fossil fuel based heating capacity would be installed after 2040.

Why don't we see faster reactions to policies?

1. **Slow turnover:** only 5% of the stock of heating systems need to be replaced within each year, meaning that a complete turnover would take at least 20 years. Premature replacements can accelerate this process, but require large price differences between technologies.
2. **Diverse preferences:** even if a policy makes one technology cheaper than fossil fuel alternatives on average, it does not necessarily become more attractive for all households. In some cases, heating with fossil fuel may still remain the preferred option.
3. **Inertia:** even if all households would hypothetically *prefer* a new technology over others in a direct comparison, not all households would immediately *choose* the new technology, both due to
   a) *Imperfect information:* not all households know the new technology, and may lack first-hand experience for evaluating its true performance.
   b) *Industry constraints:* there is only a limited capacity for producing and installing the new technology, which cannot be scaled up indefinitely fast.

   Both a) and b) are related to a technology's current market share ('*temporal autocorrelation*'): the more widespread it already is, the faster it can grow in absolute terms. So introducing monetary incentives (such as a carbon tax) in a Member State with low initial market shares of modern renewables is like raising the interest rate on a bank account with low balance: although it changes its *relative* growth trend (and interest payments will accumulate eventually), the interest rate change would not lead to large *absolute* balance increases immediately.

These policy-induced changes in household choices gradually change the overall technology composition. Under current trends, the overall share of gas in residential heat production would remain stable at 40% until 2030, and decrease to 30% by 2050, while oil and coal almost completely vanish from the technology mix. Heat pumps and solar would continue their ongoing growth, roughly doubling their respective 2014 market shares by 2030. In scenario 1, all renewable technologies are projected to increase their future market shares compared to baseline: heat pumps and solar are projected to gain a 18% and 3% market share by 2030, respectively (compared to 13% and 2% under current trends), while the uptake of modern biomass systems would result in a growth of biomass by 3 percentage points, relative to baseline. This comes at the expense of fossil fuels, which would lose 9 percentage points, compared to the baseline projection. Electric and district heating would remain stable until 2030, and decrease in market share afterwards.

Figure 8 shows the resulting changes in EU wide residential fuel use and sectoral CO_2 emissions for scenario 1-3, relative to the baseline projection. The substitution of fossil fuel technologies by renewables leads to large reductions in fossil fuel use in all three scenarios, up to -100% for coal, -90% for oil, and -80% for gas (where the remaining share is partly attributable to other household end-uses, foremost cooking). Meanwhile, the residential demand for biofuels and electricity is projected to increase by up to 20%, relative to baseline. Overall, the fuel switching by households leads to reduced residential emissions (up to around -150MtCO_2 per year), while emissions in the power sector would slightly increase (by not more than +15MtCO$_2$ per year) (due to additional electricity demand, which would partly be generated by fossil fuel plants). Compared to the current trends scenario, the absolute emission decreases post-2040 are relatively smaller, due to the projected decrease in heat demand in this period (which results in decreasing baseline emissions). In sum, EU wide total emissions by 2050 are projected to be lower by up to -100MtCO$_2$ per year (in scenario 2), compared to the baseline.

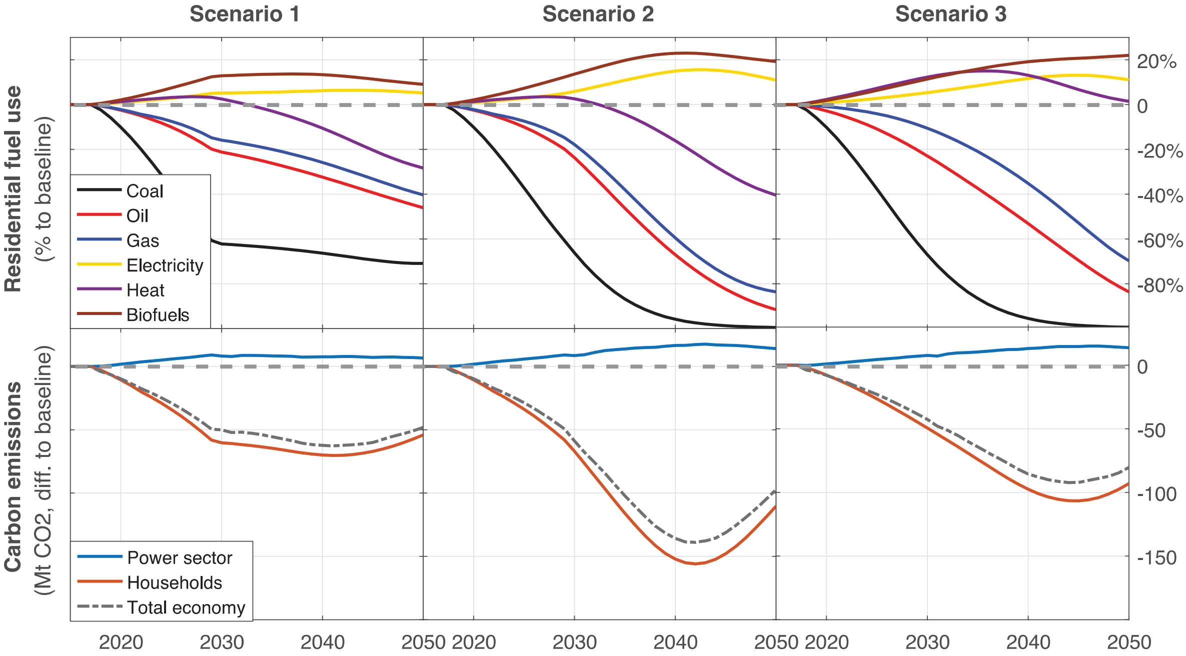
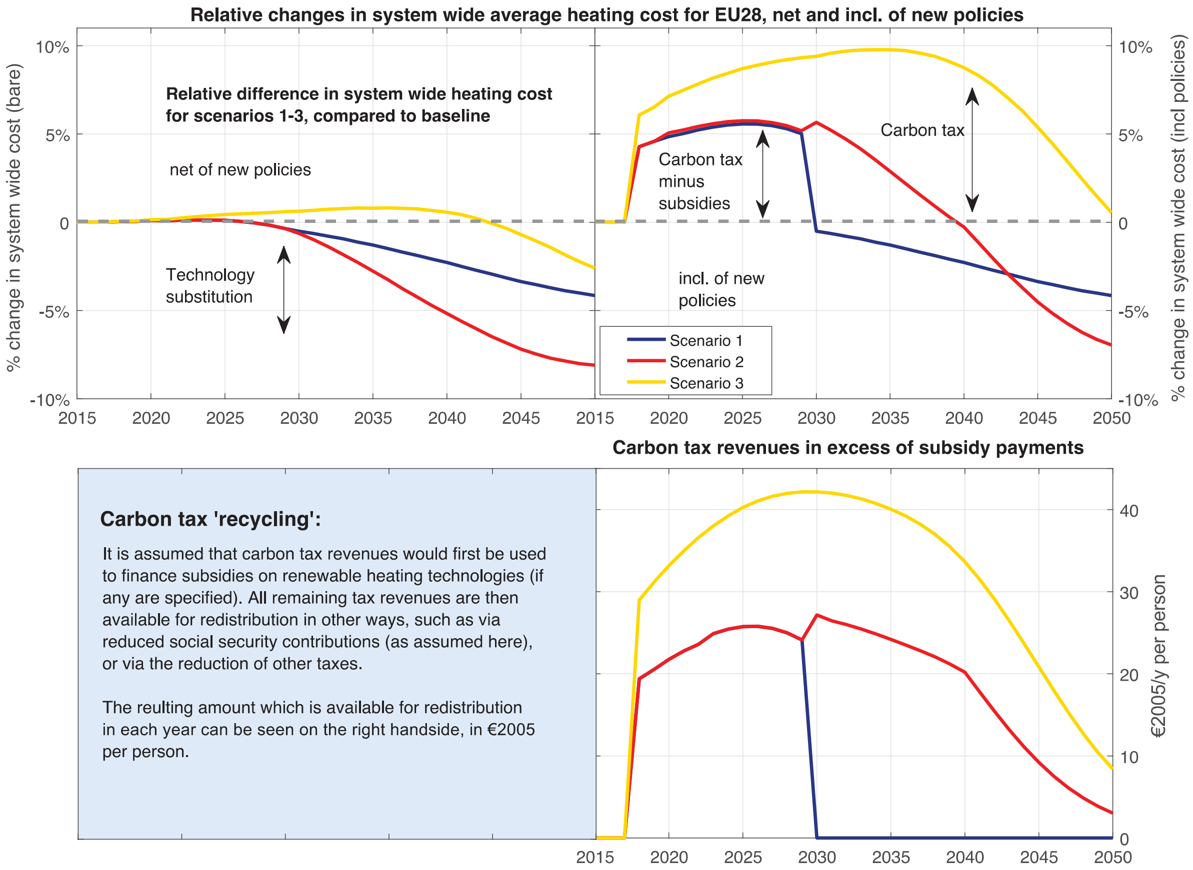


Figure 8: EU wide relative changes in residential fuel use and carbon emissions (all policies until 2030), scenarios 1-3 compared to baseline projections. The upper panels show the relative changes in residential fuel use by fuel type, the bottom panels show absolute changes in sectoral CO$_2$ emissions.

In all policy scenarios, households increasingly choose heating systems which are less fuel, but more capital intensive, thereby increasing the overall household spending on heating systems. Additional spending reaches around 6 Billion 2005€ per year by 2030 in scenario 1 (+12€/y per person, or around +480€ every 20 years for a two-person household replacing its heating system), and would increase to around 9 Billion 2005€ per year during the 2030s in scenario 2 (+45% relative to baseline) (+17€/y per person, or around +680€ every 20 years for a two-person household replacing its heating system). Overall, the additional expenditures between 2018-2050 accumulate to +94 and +176 Billion 2005€ in scenarios 1 and 2, respectively. Additional expenses under a carbon tax as the only policy instrument are significantly lower, summing up to +79 Billion 2005€. As households do not receive any subsidies on upfront costs in this scenario, they tend to choose less capital intensive technologies, reflected in relatively lower market shares for heat pumps and solar thermal (while gas still has a 7% market share by 2050). This also explains the relatively higher market share of district heating, which is not subject to the residential carbon tax.

The induced substitution of fossil fuel based technologies does not occur instantaneously, however. Both due to the long technical lifetimes of heating systems (which mean that only around 5% of the stock needs to be replaced each year) and the inertia of technology transitions, substantial changes in market shares can only be observed after several years (or even decades). Even when relative costs change dramatically, many households will be ‘locked’ into their existing heating systems for a considerable time. During this transition period, all households could benefit from the redistribution of carbon tax revenues, but households which keep on operating their old, carbon-intensive heating technologies would face higher heating costs.



Carbon tax 'recycling':

It is assumed that carbon tax revenues would first be used to finance subsidies on renewable heating technologies (if any are specified). All remaining tax revenues are then available for redistribution in other ways, such as via reduced social security contributions (as assumed here), or via the reduction of other taxes.

The reulting amount which is available for redistribution in each year can be seen on the right handside, in €2005 per person.

Figure 9: EU wide relative changes in total heating system costs per country, compared to baseline projection. The top left panel shows the changes in real costs (fuel and capital), the top right panel the changes in the prices faced by households (incl. of new taxes and subsidies). The bottom panel shows the carbon tax revenues in excess of subsidy payments (in 2005€/y per person), which can be used for the benefit of households in various ways.

The projected impacts on the cost of residential heating can be seen in Figure 9, which shows the relative differences in EU wide average levelised cost of heating for scenario 1-3, relative to baseline. In terms of bare levelised cost (net of carbon taxes and subsidy payments, shown in the upper left panel), the gradual technology substitution induced by policies in scenarios 1 and 2 and would result in small relative cost reductions by 2030 (less than -1%), increasing to -4% and -8% by 2050, respectively. Despite these technological efficiency increases, the introduction of carbon taxes means that the average household would effectively face higher heating costs (while benefiting from the redistribution of carbon-tax revenues), at least until 2030. In scenario 1, the combination of the tax with subsidies results in average cost increases of around +5% during the 2030s. When the policies are discontinued after 2029 (scenario 1), households' effective heating costs become lower than in the baseline from 2030 onwards. In case of a policy continuation (and expansion to more Member States), households would not benefit from cost reductions until 2040, on average (scenario 2). The largest cost increases would result from the EU wide application of a carbon tax in scenario 3, which would add up to 10% on average system wide heating cost, with no effective cost reduction before 2050. At the same time, the introduction of a carbon tax without a parallel subsidy scheme leads to the largest amount of excess carbon tax revenues, which can be redistributed to households (see lower panels of Figure 9).

11.2 Macroeconomic impacts

Figure 10 shows the EU wide carbon tax revenues and subsidy payments for the simulated policies in case of all three scenarios. Under scenario 1, EU wide revenues from the new carbon tax would peak at around 17 Billion 2005€/y in 2029 (around 35 €/y per person), after which the policy is phased out. Under scenario 2, the overall tax revenues would peak at 20 Billion 2005€/y in 2030 (41 €/y per person), when the tax is extended to all Member States. Afterwards, the fuel-switching effect (due to the induced technology substitution away from fossil fuels) would exceed the effect of increasing tax rates (+5 €/tCO$_2$ per year), resulting in a gradual decrease of overall revenues (to 1,6 Billion 2005€/y in 2050).

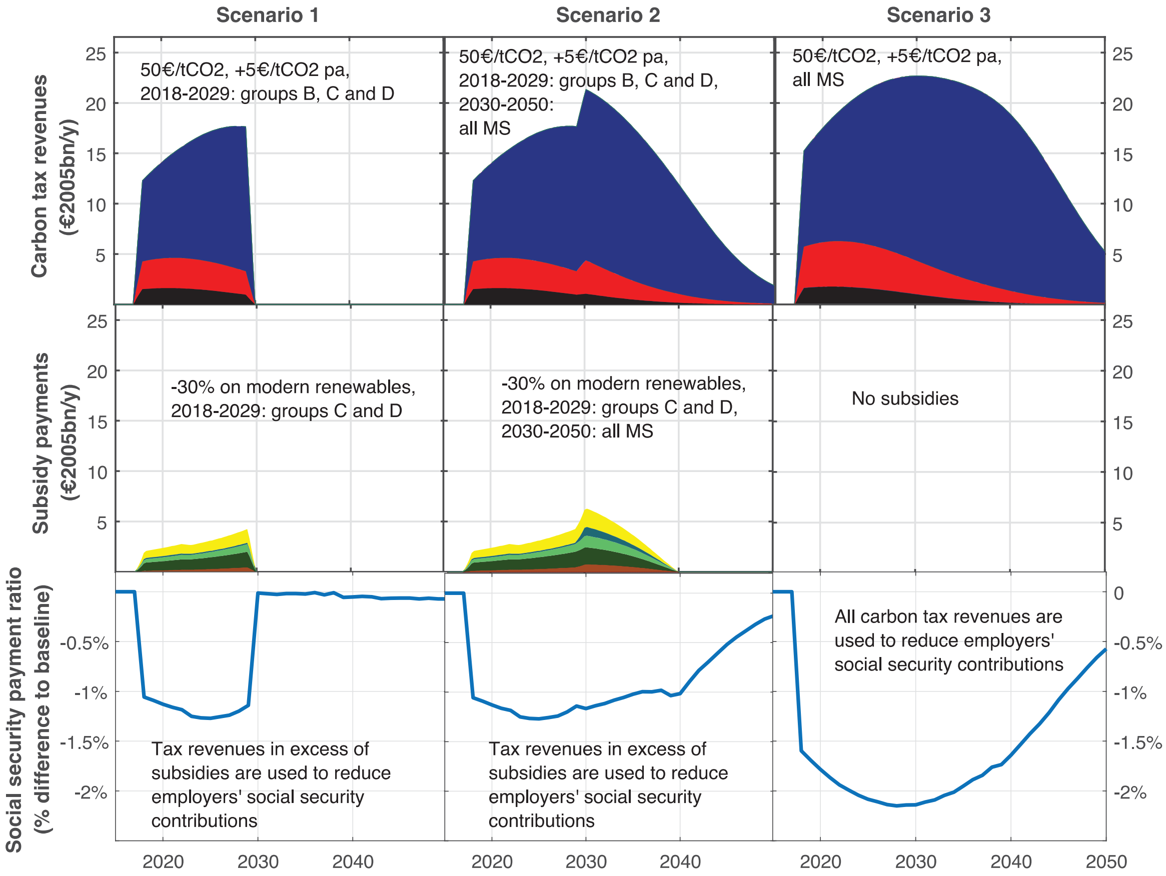


Figure 10: EU wide tax revenues from the simulated carbon tax in €2005bn per year (top panels), and upfront payments for the simulated capital subsidy in €2005bn per year (middle panels), for scenarios 1-3. Carbon tax revenues which exceed subsidy payments are assumed to be used for reducing employers' social security contributions (relative changes to baseline shown in the bottom panels).

The largest carbon tax revenues are projected for scenario 3, in which the policy is applied to all Member States from 2018 onwards without any supporting policies. Peak revenues would then be around 22 Billion 2005€/y by 2030 (44 €/y per person). As in scenario 2, revenues would decrease afterwards, but to a lower extent.

Subsidy payments in scenario 1 would peak around 4 Billion 2005€/y in 2030, being zero afterwards. In scenario 2, which assumes an extension of the subsidy scheme to all Member States from 2030 onwards (with annually decreasing subsidy rates), subsidy payments would reach their maximum of 6 Billion 2005€/y by 2030, decreasing to zero by 2040, when the subsidy scheme is assumed to end. As defined in the scenario assumptions, no subsidies are paid in scenario 3. Instead, all carbon tax revenues are available for lowering employers' contributions to social security payments (as assumed here), or could alternatively be redistributed to households in other ways.

In all scenarios, overall carbon tax revenues are projected to exceed overall subsidy payments at all times. The resulting relative reductions in employers' contribution to social security payments can be seen in the bottom panels of Figure 10: around -1% in scenarios 1 and 2, and up to -2% in scenario 3. In all three cases, the reductions are an exact mirror image of excess revenues, so that they would either abruptly become zero in 2030 (scenario 3), or would gradually decrease towards 2050.

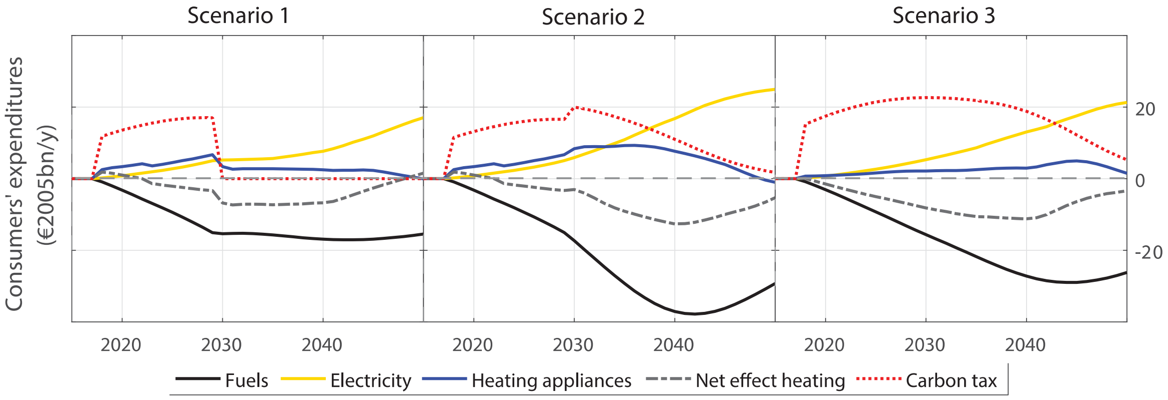


Figure 11: EU wide changes in consumers' expenditures (in €2005bn), scenarios 1-3, relative to baseline. Solid lines represent heating related expenditure changes, the dashed line the net change in heating related expenditures. The dotted red line shows the carbon tax payments in comparison.

The simulated decarbonisation of residential heating leads to several shifts in household expenditures, all of which are summarised in Figure 11. In all scenarios, reduced household expenditures for fuels constitute the largest absolute change: EU wide fuel savings (net of the new carbon tax) range between -15-17 Billion 2005€ per year by 2030 (29-33 €/y per person), and reach up to -29 Billion 2005€ per year by 2050 (56 €/y per person) (scenario 2). At the same time, household expenditures on electricity would increase by around +5 Billion 2005€ per year by 2030 (in all scenarios), and by +17-25 Billion 2005€ per year by 2050. In addition, expenditures on heating systems would increase by up to +9 Billion 2005€ per year (17 €/y per person) during the 2030s (see section 11.1). Fuel savings exceed these increased expenditures on electricity and appliances at almost all times in all scenarios, so that households' net expenditures on heating decrease by up to -11 Billion 2005€/y (21 €/y per person). Net savings on heating would exceed residential carbon tax payments around 2030 in scenario 1 (when the tax is phased out), around 2040 in scenario 2, and around 2050 in scenario 3. Although the tax revenues can be redistributed to households in various ways (such as subsidies for renewables), many households would likely face increases in direct heating-related costs, as long as they don't replace their heating system.

The induced shifts in household demand and expenditure have direct consequences for several economic sectors. Figure 12 compares the resulting changes in employment for sectors which are directly related to heating, relative to baseline. On the plus side, gradual electrification of residential heating increases the overall electricity demand by +2-4% (+60-120TWh/y) by 2050 (see Figure 13), which implies additional power sector investments of a similar relative magnitude (up to +3,7 Billion 2005€ per year), and creates 27,000-36,000 new jobs by 2050 (7,000-10,000 by 2030). Furthermore, the additional spending on heating systems would increase overall household spending on appliances by up to +10%, which induces additional investments (up to +0,5%, see Figure 13) and employment (up to +4,900 in the 2030s) by the machinery and equipment sector.

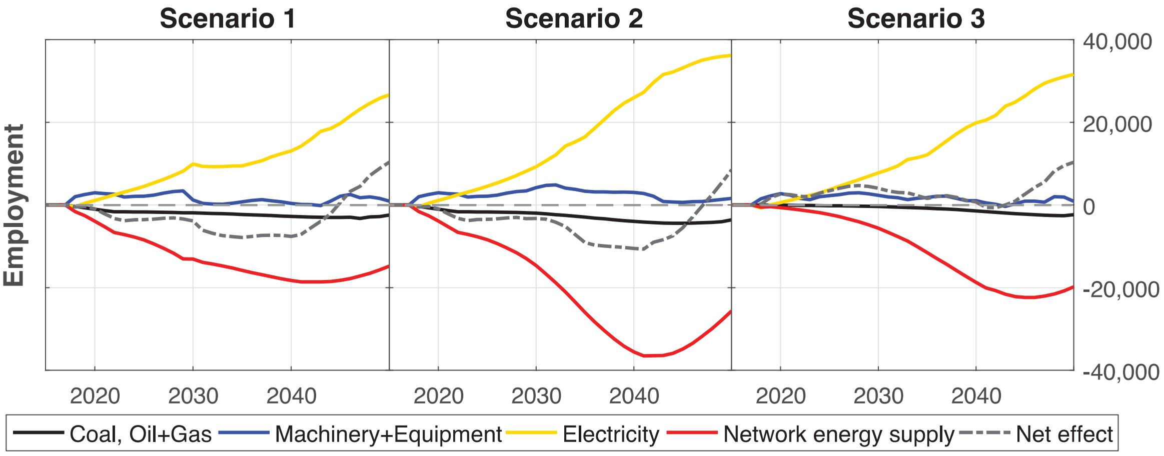


Figure 12: EU wide employment changes in energy and heating related economic sectors, in scenarios 1-3, relative to baseline. Solid lines represent heating related sectors, the dashed line the net change in heating related employment.

On the minus side, decreased demand for fossil fuels would cause comparably small job losses in the coal, oil and gas producing industries, not exceeding 4,400 in any scenario. More is at stake in the network energy supply industry (which is operating gas networks, for example): projected job losses in this sector are up to -13,000 by 2030 (scenarios 1 and 2), and up to -26,000 by 2050 (scenario 2). However, long-term impacts on the network energy supply may well be different if the existing networks are used for the provision of renewable energy, such as biogas (which was not considered within this analysis). Summing over all these sectors, the net employment effect is scenario dependent. In scenarios 1 and 2, the net effect is partly negative (up to -11,000 in scenarios 1 and 2), and job creation only exceeds job losses after around 2045. In scenario 3, which causes less substitution of fossil fuels and therefore less job losses in network energy supply, the employment effects are consistently positive throughout the entire simulation period (+4,000 by 2030, and +10,000 by 2050).

The overall relative changes in EU wide macro-economic indicators can be seen in Figure 13. While most indicators follow a similar pattern in all three scenarios, the relative magnitude and timing of their changes reflects the differences in scenario assumptions. This is especially evident in case of scenario 1, which assumes a discontinuation of new policies from 2030 onwards: after 2030, energy-related indicators stabilise, while other macroeconomic indicators revert to their baseline trends. In all scenarios, consumers' expenditures are relatively smaller (around -0,2%) while a carbon tax is applied, since the tax payments exceed the induced cost savings. It is projected that EU wide electricity demand increases by +60-120TWh/y, or +2-4% (compared to a baseline which already includes some degree of electrification in the residential and transport sector).

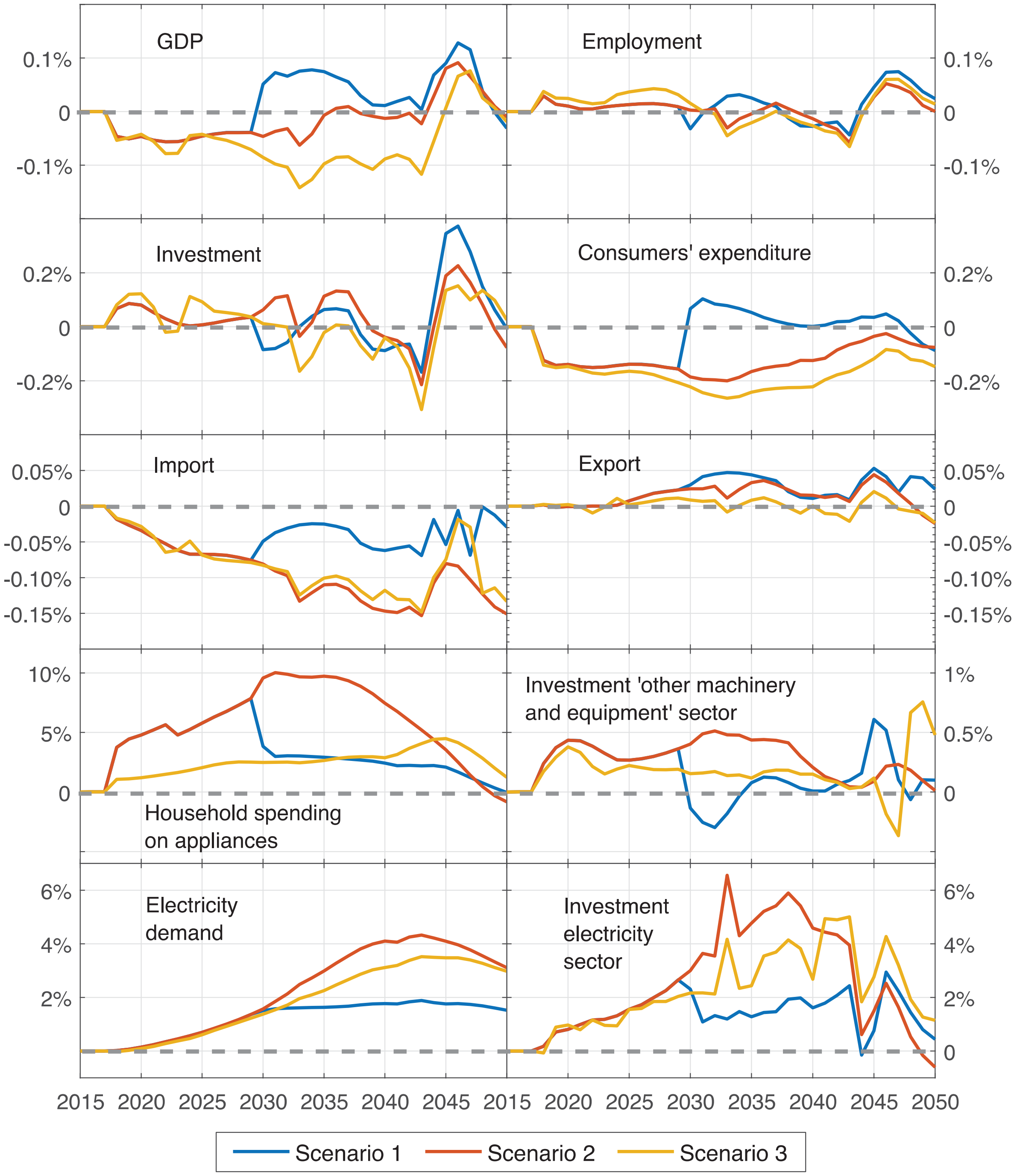


Figure 13: EU wide relative changes in macroeconomic indicators in scenarios 1-3, compared to baseline projections (which already include some degree of decarbonisation, see Figure 7).

Investments by the electricity sector increase in line with electricity demand, and investments by the machinery and equipment sector in line with household spending on heating systems (although on a much smaller scale as in the electricity sector, as heating systems only constitute a minor part of the sector's overall demand structure).

EU wide imports largely follow the decreasing trends in residential fossil fuel demand: oil and gas imports from outside the EU fall by up to -5 Billion 2005€ per year (compared to a baseline which already includes some degree of decarbonisation), and overall product imports by up to -0,15%. Meanwhile, exports to non-EU regions increase by up to +0,05% (in scenarios 1 and 2). Additional exports mainly consist of electrical appliances and coal, each in the value of up to +0,5 Billion 2005€ per year.

The decreases in consumers' expenditures initially tend to exceed the increases in investments. In all scenarios, the EU wide GDP would therefore be around -0,05% smaller until 2030, compared to baseline. In scenario 1, GDP effects are projected to be positive immediately after 2030 (up to +0,1%): households would still benefit from the induced efficiency improvements, but would not have to pay the carbon tax any longer. In case of scenario 2, GDP effects would become positive once the benefits of more efficient heating start exceeding the carbon tax payments, which would be around 2035. For similar reasons, GDP in scenario 3 would stay lower than in baseline until 2045 (see Figure 11 for the underlying trends of tax payments and cost savings).

Other than GDP, EU wide employment is projected to remain relatively stable around its baseline level in all scenarios, despite small job losses in heating related sectors (see Figure 12). The reduction of employers' contributions to social security payments (using carbon tax revenues) makes labour relatively less expensive, leading to slightly increased employment in all other sectors. This mechanism is illustrated by scenario 3, which generates the most carbon tax revenues: the relative reduction of labour costs decouples the trends in employment (which shows marginal increases) and GDP (the scenario has the largest projected GDP decrease).

12 Impacts by country group: heating sector and emissions

This section analysis the policy-induced changes in Member States' residential heating systems for each country group.

12.1 Country group A

Country group A's combined demand for heating as an energy service was around 461TWh/y in 2014 (equivalent to 22% of the EU28 residential heating demand). Based on the EUCO30 scenario, this demand for heat is projected to decrease by -8% until 2030, and by -40% until 2050 (relative to 2014), because of improved building insulation and behavioural change.

Key projections for country group A's residential heating system under baseline trends and scenarios 1-3 are summarised in Figure 14. FTT:Heat projects that the heat demand will be provided by a less carbon intensive technology mix. According to the model baseline projections, the residential heating sector's CO_2 emissions would decrease by -43% in 2030 (compared to -22% for the entire EU28), and by -89% in 2050.

Table 16: Residential heat demand (UD, in TWh_{th}) and share of renewables in residential heating (%RE) by Member State for country group A. Last historical observation for RES (2014) and projected increases between 2018-2030 (in percentage points), in the FTT:Heat baseline projection and in policy scenarios 1-3**.** Red indicates a projected increase by less than 10pp until 2030, green indicates a projected increase of at least 10pp.

Group A	**Heat demand**	**%RE**	**Projected increase in %RE, 2018-2030**		
	2014	2014	**Baseline**	**Scenario 1+2**	**Scenario 3**
4 Greece	30 TWh/y	42%	+22	+22	+26
5 Spain	83 TWh/y	34%	+15	+15	+23
6 France	309 TWh/y	33%	+12	+12	+17
7 Ireland	21 TWh/y	5%	+11	+11	+19
12 Portugal	11 TWh/y	58%	+21	+21	+23
17 Estonia	8 TWh/y	52%	+10	+10	+11
18 Cyprus	2 TWh/y	59%	+15	+15	+19
22 Malta	0,4 TWh/y	25%	+30	+31	+39

The eight Member States in group A are projected to reach the renewable heating objectives for 2030 without additional policies (see Table 16). In the appendix, additional figures depict their individual historical and projected heat generation mix by technology. Greece, Portugal, Spain, Cyprus and Malta are projected to further increase heat generation by solar thermal heat: in all four Member States, the technology had relatively high market shares in 2014 (the last historical data point), ranging from 3% in Spain to 32% in Cyprus.

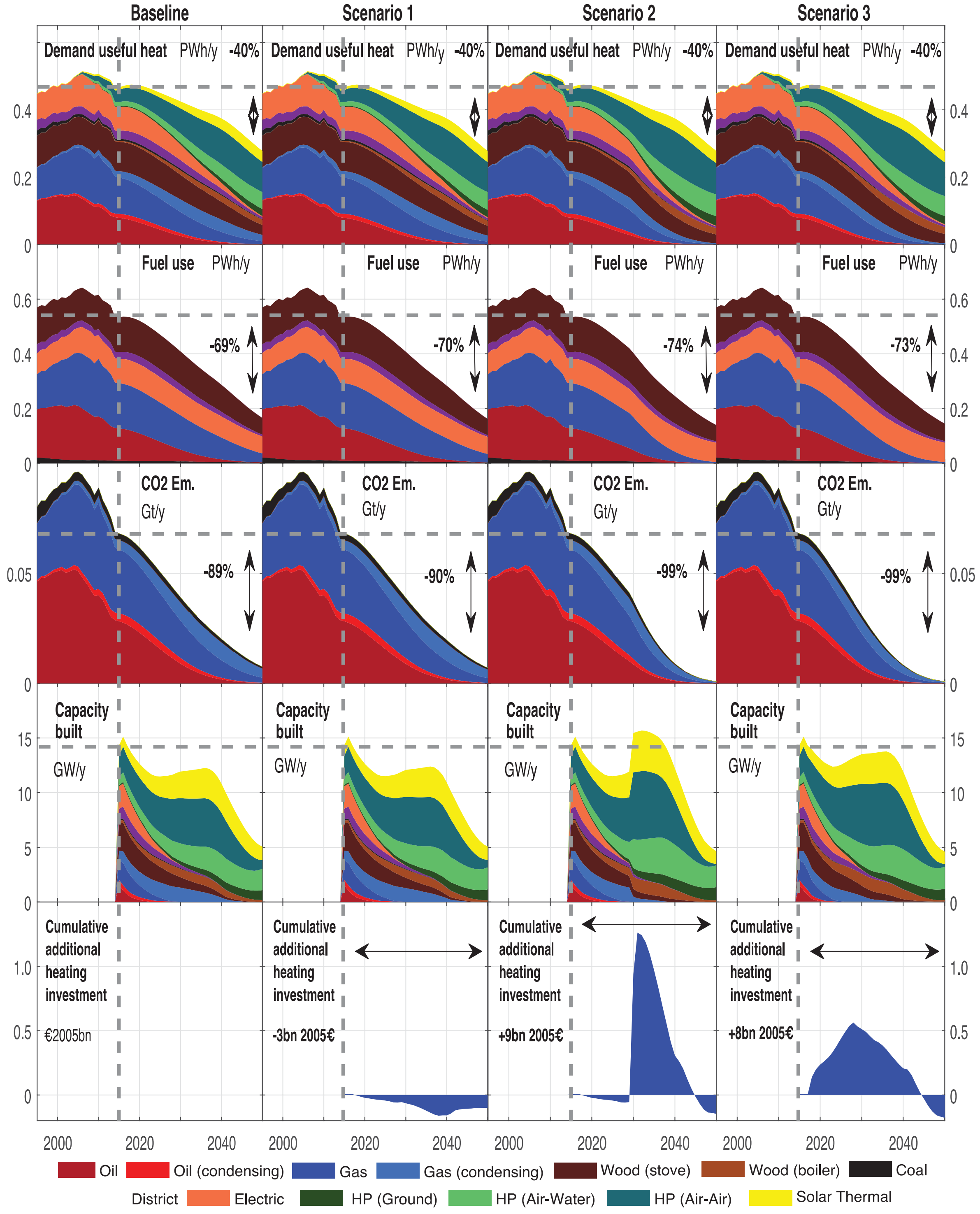


Figure 14: Country group A projections for annual heat generation by technology, fuel use, CO_2 emissions, added heating capacity, and household investments in heating systems. Model results for baseline and scenarios 1-3. Values from 2015 onwards are projections by FTT:Heat. Bold numbers indicate changes in 2050, relative to 2014 (the last historical data point). Projections for useful energy demand for heating are taken from the EUCO30 scenario.

By 2030, these shares are projected to grow by +7-15 percentage points per Member State. Meanwhile, the projected growth of renewable heating in France and Estonia is mainly due to a continued diffusion of heat pumps. In 2014, the technology had a relatively high market share in both Member States: 14% in France, and 16% in Estonia. In Ireland, the strong baseline growth in the country's renewable share is mainly due to an ongoing shift away from coal and oil-based heating, predominantly towards modern biomass systems, combined with some growth in heat pumps and solar thermal.

Because no additional policies are implemented in scenario 1, there are only minor differences compared to the baseline projection. These differences originate in the policies implemented in other Member States, which would result in gradual cost reductions for renewable technologies with increasing total capacities. Over the entire period 2018-2050, household spending on heating systems in country group A would therefore be -3 Billion 2005€ lower than in the baseline. By 2050, fuel use and emissions would be one percentage point lower. In scenario 2, a carbon tax and subsidies on renewables are implemented from 2030 onwards. The policy mix leads to a steep increase in new installations of renewable heating capacity, accumulating to +9 Billion 2005€ until 2050. Consequently, the country group would be on a pathway to complete decarbonisation by 2050, achieving a projected reduction in direct CO_2 emissions by -99%. In scenario 3, the same degree of decarbonisation would be achieved. Different than in scenario 2, the additional installation of renewable capacity would be spread out more evenly, starting with the introduction of the carbon tax in 2018.

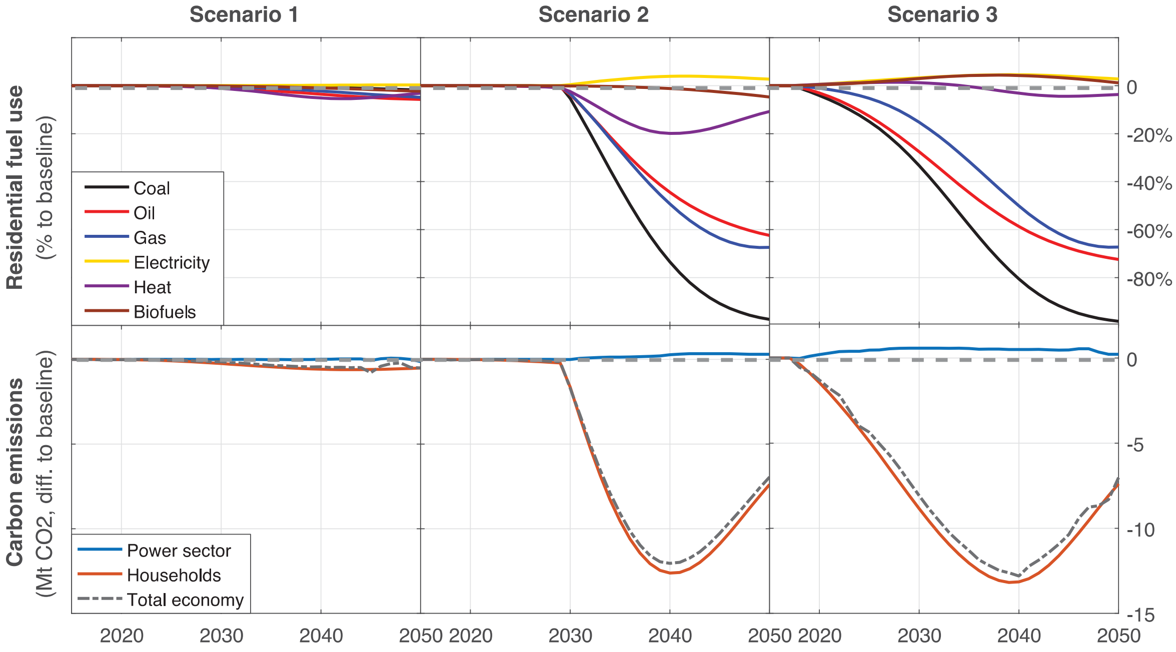


Figure 15: Policy effects in case of country group A, all changes relative to baseline. Upper panels: relative changes in total residential fuel use, by fuel type. Bottom panels: absolute changes in sectoral CO_2 emissions, by households and the power sector.

Figure 15 illustrates the relative policy impacts on residential fuel demand and sectoral CO_2 emissions. Only very minor changes are projected for scenario 1, which assumes no new policies for country group A. In scenario 2, changes relative to baseline start after the introduction of new policies 2030. It is projected that by 2050, group-wide residential demand for coal, oil and gas would decrease by -97%, -67% and -62% (compared to baseline), respectively. These fuels are substituted by electricity, demand for which is projected to increase by up to +4% (electricity). As a result, total residential CO_2 emissions in 2050 would be lower by -7$MtCO_2$, while emissions in the power sector would increase by +0,4$MtCO_2$. Overall, this implies reduced total emissions by around -6,6$MtCO_2$ per year. Per country, the economy-wide emission reductions are by far the largest in France (-4,8 $MtCO_2$ in 2050), which has the group's largest demand for residential heating (see in the appendix, which shows the trends of heat generation by technology per country).

Carbon tax 'recycling':

It is assumed that carbon tax revenues would first be used to finance subsidies on renewable heating technologies (if any are specified). All remaining tax revenues are then available for redistribution in other ways, such as via reduced social security contributions (as assumed here), or via the reduction of other taxes.

The reulting amount which is available for redistribution in each year can be seen on the right handside, in €2005 per person.

Figure 16: Country group A relative changes in levelised heating system costs per country, compared to baseline projection. The top left panel shows the changes in real costs (fuel and capital), the top right panel the changes in the prices faced by households (incl. of new taxes and subsidies). The bottom panel shows the carbon tax revenues in excess of subsidy payments (in 2005€/y per person), which can be used for the benefit of households in various ways.

Figure 16 shows the projected changes in total system costs for residential heating per Member State in case of scenario 2, with and without the costs of new policies for households. Without accounting for the additional tax expenses, system wide costs remain at baseline level until 2030, and start decreasing afterwards in all eight countries (by 2050 between -3% in Spain and -10% in Cyprus). When including the additional carbon tax and subsidies, system wide costs immediately increase in 2030 in four Member States, depending on their shares of fossil-fuel based heating (between +1% in Greece and +13% in Ireland). At the same time, these Member States would see the largest amounts of carbon tax revenues in excess of subsidy payments (per person), which can be redistributed to households. In all countries but Ireland, households' effective heating costs would become lower than in the baseline projection before 2035 (2045 in Ireland). By 2050, households would benefit from the efficiency increases without paying any more carbon taxes (as no more fossil fuel is used any longer), so that cost decreases would be similar to the projections net of policies.

12.2 Country group B

Country group B's combined demand for residential heating was around 470TWh/y in 2014 (around 22% of the total EU28 demand). In the EUCO30 scenario, it is assumed to slightly increase by +5% until 2030, followed by a decrease by around -33% until 2050 (relative to 2014).

For all five Member States in group B, the introduction of a new tax on the residential use of fossil fuels is projected to be a sufficient instrument for reaching the 2030 renewable heating objective.

Figure 17 shows country group B's projected annual heat generation, fuel use, CO_2 emissions, and capacity additions until 2050, both in the baseline projection (assuming current trends) and the policy projections. In the FTT:Heat baseline projection, the country group's residential heating system would already undergo some decarbonisation without further policies: the group's combined CO_2 emissions by residential heating are projected to decrease by around 22% until 2030 and by 81% until 2050, respectively. However, the individual country's projected increases in their shares of renewable heating would all fall short of 10 percentage points, ranging from 6 percentage points (in Belgium) to 9 percentage points (in Italy) (see Table 17).

In scenario 1, the carbon tax is projected to raise all individual increases above 10 percentage points: to exactly +10 percentage points in Belgium and Bulgaria, and to as much as +27 percentage points in Poland, where households are projected to rapidly move away from coal, which would be subject to the largest relative price increases (see in the appendix, which shows the trends of heat generation by technology per country). The technology transition towards renewables would thereby reduce direct emissions from residential heating by -49% in 2030 (relative to 2014, compared to -22% in the baseline), and by -90% in 2050 (compared to -81%). In scenario 2, the continuation of the carbon tax beyond 2030 (plus the introduction of subsidies until 2040) results in a -99% reduction of CO_2 emissions in 2050.

Table 17: Residential heat demand (UD, in TWh_{th}) and share of renewables in residential heating (%RE) by Member State for country group B. Last historical observation for RES (2014) and projected increases between 2018-2030 (in percentage points), in the FTT:Heat baseline projection and in policy scenarios 1-3. Red indicates a projected increase by less than 10pp until 2030, green indicates a projected increase of at least 10pp.

Group B	**Heat demand**	**%RE**	**Projected increase in %RE, 2018-2030**		
	2014	2014	**Baseline**	**Scenario 1+2**	**Scenario 3**
1 Belgium	64 TWh/y	9%	+6	+10	+9
8 Italy	210 TWh/y	34%	+9	+15	+14
16 Czech Republic	49 TWh/y	29%	+8	+13	+13
23 Poland	131 TWh/y	18%	+9	+27	+27
26 Bulgaria	16 TWh/y	59%	+9	+10	+10

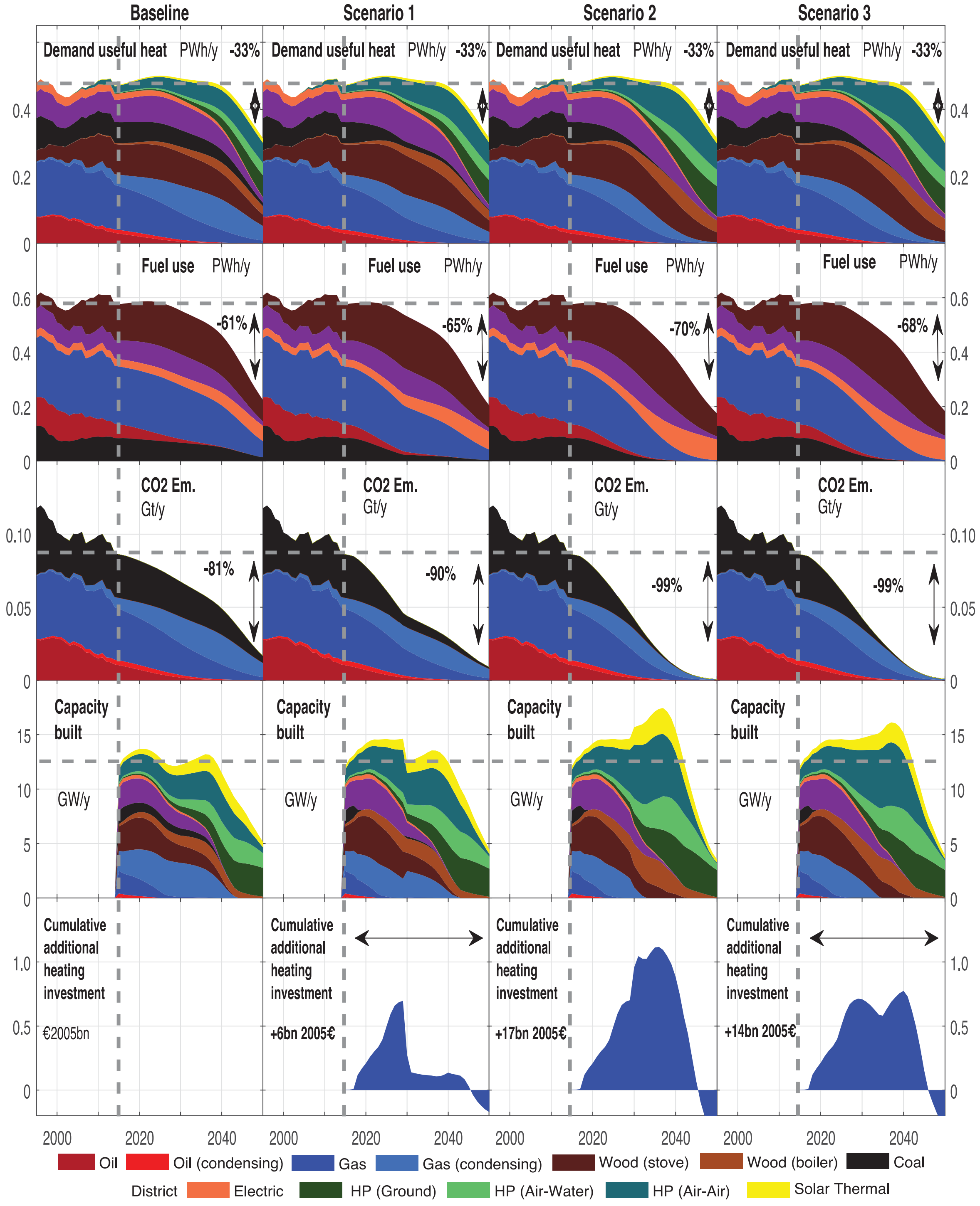


Figure 17: Country group B annual heat generation by technology, fuel use, CO_2 emissions, added heating capacity, and household investments in heating systems. Model results for baseline and scenarios 1-3. Values from 2015 onwards are projections by FTT:Heat. Bold numbers indicate changes in 2050, relative to 2014 (the last historical data point). Projections for useful energy demand for heating are taken from the EUCO30 scenario.

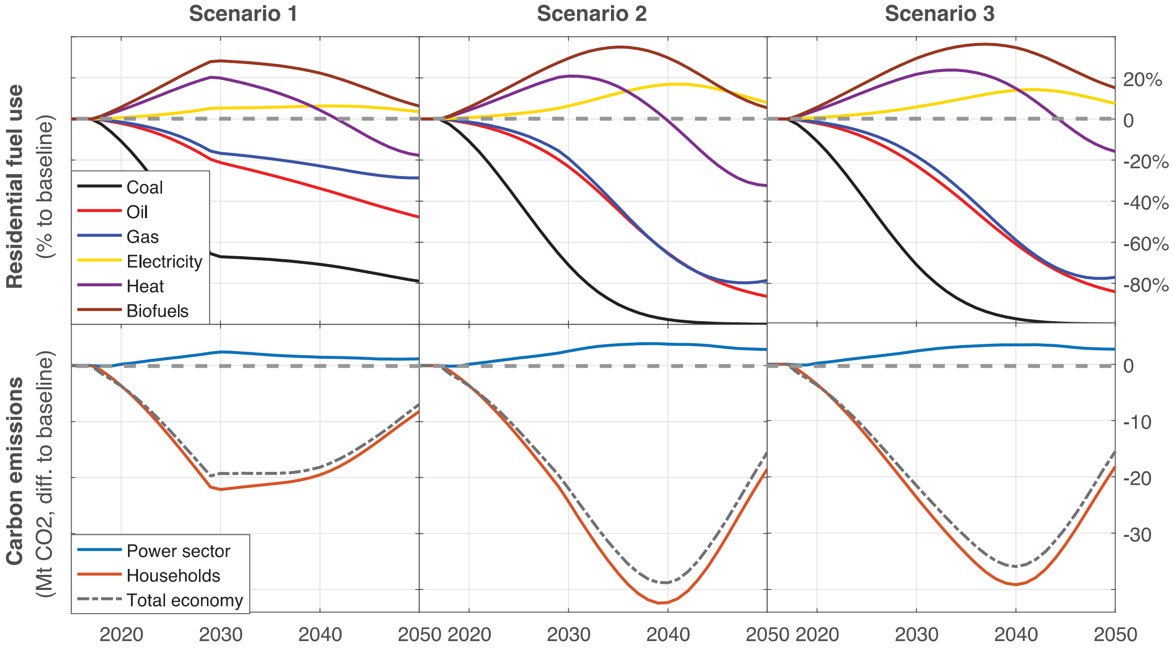
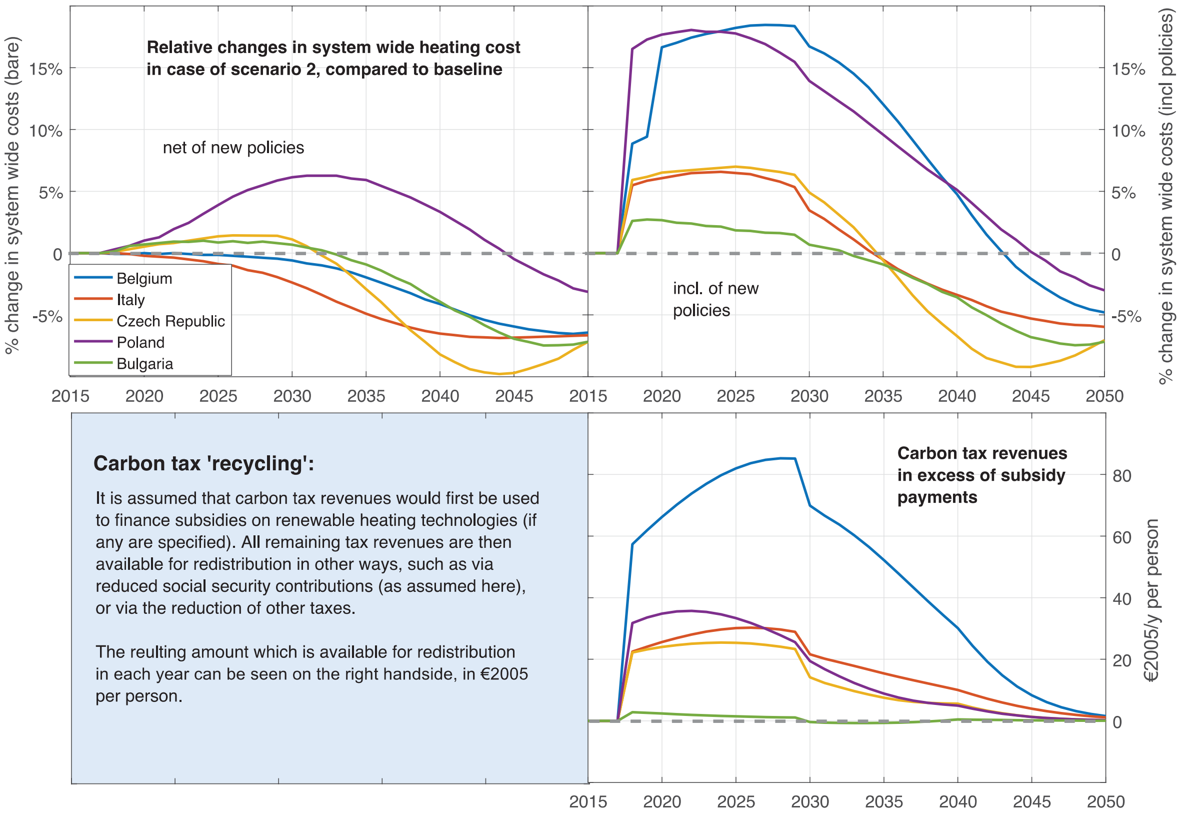


Figure 18: Policy effects in case of country group B, all changes relative to baseline. Upper panels: relative changes in total residential fuel use, by fuel type. Bottom panels: absolute changes in sectoral CO_2 emissions, by households and the power sector.

From an economic perspective, the induced shift towards renewable heating would come along with increased annual household expenditures for heating systems (up to +22%, or +700 M 2005€ per year, in scenario 1). The increase in expenditures is partly due to a temporal shift in household purchases: the carbon tax induces them to shift towards (more capital intensive) renewables earlier than in the baseline, which in turn decreases heating system purchases after 2045. A less capital-intensive decarbonisation would be achieved in scenario 3, which is identical to scenario 2, but does not assume any new subsidies in 2030-2040. Overall additional household expenditures on heating systems would here be +14 Billion 2005€, compared to +17 Billion 2005€ in case of scenario 2.

Figure 18 illustrates the policy's relative impacts on residential fuel demand and sectoral CO_2 emissions, compared to the baseline. In scenario 1, it is projected that group-wide residential demand for coal, oil and gas in 2030 would decrease by -67%, -21% and -17%, respectively. These fuels are substituted by an increased residential demand for biomass (+29%), district heat (+20%) and electricity (+5%), relative to baseline. As a result, total residential CO_2 emissions in 2030 would be lower by -20MtCO_2, while emissions in the power sector would increase by +2,2MtCO_2. Overall, this implies reduced total emissions by around -17,8MtCO_2 per year. Per country, the economy-wide emission reductions are by far the largest in Poland (-12,1MtCO_2 in 2030), where coal would otherwise remain a dominant heating technology in the baseline projection.



Carbon tax 'recycling':

It is assumed that carbon tax revenues would first be used to finance subsidies on renewable heating technologies (if any are specified). All remaining tax revenues are then available for redistribution in other ways, such as via reduced social security contributions (as assumed here), or via the reduction of other taxes.

The reulting amount which is available for redistribution in each year can be seen on the right handside, in €2005 per person.

Figure 19: Country group B relative changes in levelised heating system costs per country, compared to baseline projection. The top left panel shows the changes in real costs (fuel and capital), the top right panel the changes in the prices faced by households (incl. of new taxes and subsidies). The bottom panel shows the carbon tax revenues in excess of subsidy payments (in 2005€/y per person), which can be used for the benefit of households in various ways.

Figure 19 shows the projected relative impacts of the new carbon tax on levelised system costs for residential heating, with and without the costs of the new policies for households. Without accounting for the additional tax expenses, system wide costs in 2030 remain largely unchanged (between -2% in Italy and +1% in Czech Republic) everywhere but in Poland, where real costs would increase by around +5% (relative to baseline). By 2050, net household costs for heating are projected to be -3% to -7% lower in all Member States, relative to the baseline. Between 2035-2045, households' heating costs would become lower than in the baseline projection even when including all carbon tax payments.

Overall, the results for country group B indicate that a carbon tax can be successful in steering the residential heating sector towards renewable technologies, leading to large reductions in residential fuel use and emissions. At the same time, households could face increased costs for heating. Due to the long lifetimes and slow stock turnover in the heating system, many households would be facing these costs for considerable time, before they may eventually switch to alternative technologies. The political acceptability of such a policy may therefore depend on the way in which carbon tax revenues are redistributed to households.

12.3 Country group C

Country group C’s combined demand for residential heating was around 725TWh/y in 2014 (around 34% of the total EU28 demand), largely dominated by demand in Germany (460TWh/y). In the EUCO30 scenario, group-wide demand is assumed to stay constant until 2030, followed by a 29% decrease until 2050 (relative to 2014).

For countries in group C, the simulated carbon tax on its own is projected to be insufficient for reaching the 2030 renewable heating objective. In combination with upfront capital subsidies for the purchase of renewable heating technologies, however, the ten percentage point increase is projected to be achieved in all Member States (see Table 18).

Figure 20 shows country group C’s projected annual heat generation, fuel use, CO_2 emissions, and capacity additions until 2050, both in the baseline projection (assuming current trends) and the policy projections for scenarios 1-3. As for country group B, the FTT:Heat baseline projects some significant decarbonisation in the group’s residential heating systems, even without the introduction of further policies: the group’s combined CO_2 emissions by residential heating are projected to decrease by around -23% until 2030 and by -63% until 2050, respectively. Projected baseline increases in individual country’s shares of renewable heating until 2030 range from 3 percentage points (Latvia) to 7 percentage points (Finland) (see Table 18).

The new policies in scenarios 1 and 2 are projected to raise all individual increases above 10 percentage points (from +10 points in Denmark to +14 percentage points in Austria), leading to a reduction of CO_2 emissions by -40% in 2030 (relative to 2014, compared to -23% in the baseline), and -77% in 2050 (compared to -63% in the baseline). When continuing all policies post 2030, an almost complete decarbonisation can be achieved (-96% emission reduction by 2050). When applying a carbon tax as the only policy instrument, the respective reduction would by -91%.

Table 18: Residential heat demand (UD, in TWh_{th}) and share of renewables in residential heating (%RE) by Member State in country group C. Last historical observation for RES (2014) and projected increases between 2018-2030 (in percentage points), in the FTT:Heat baseline projection and in policy scenarios 1-3**.** Red indicates a projected increase by less than 10pp until 2030, green indicates a projected increase of at least 10pp.

Group C	**Heat demand**	**%RE**	**Projected increase in %RE, 2018-2030**		
	2014	2014	**Baseline**	**Scenario 1+2**	**Scenario 3**
2 Denmark	38 TWh/y	31%	+4	+10	+5
3 Germany	460 TWh/y	16%	+4	+13	+7
11 Austria	52 TWh/y	49%	+6	+14	+8
13 Finland	49 TWh/y	49%	+7	+13	+7
14 Sweden	66 TWh/y	45%	+5	+13	+5
19 Latvia	11 TWh/y	55%	+3	+10	+4
20 Lithuania	11 TWh/y	48%	+4	+10	+6
21 Hungary	39 TWh/y	19%	+4	+13	+8

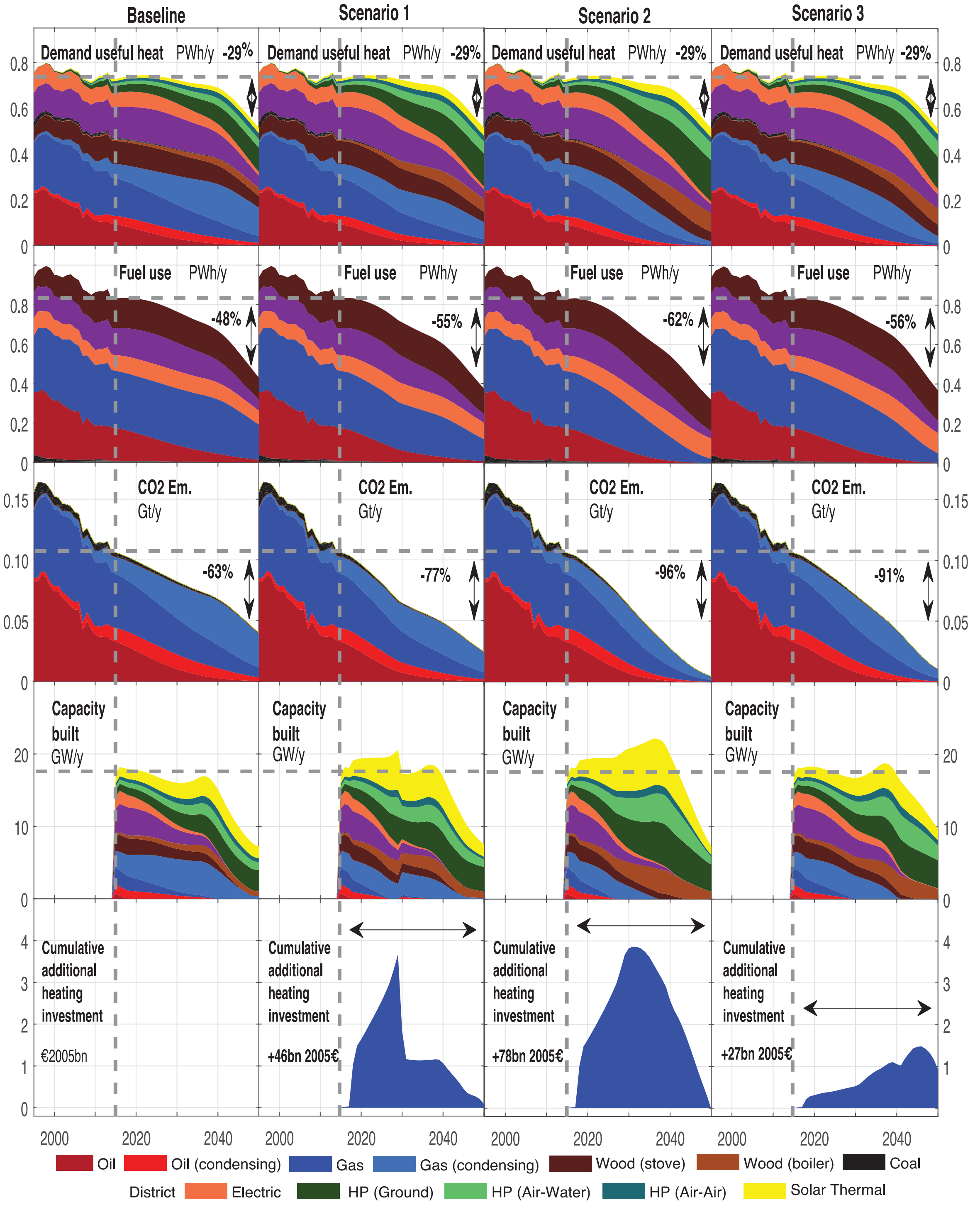


Figure 20: Country group C annual heat generation by technology, fuel use, CO_2 emissions, added heating capacity, and household investments in heating systems. Model results for baseline and scenarios 1-3. Values from 2015 onwards are projections by FTT:Heat. Bold numbers indicate changes in 2050, relative to 2014 (the last historical data point). Projections for useful energy demand for heating are taken from the EUCO30 scenario.

In terms of technology substitutions, the underlying dynamics are quite different across the eight countries. On the one side is Germany, whose residential heating system is largely dominated by oil and gas (see in the appendix for illustrations of each country's heating system over time). In the policy scenarios, both fuels would be increasingly replaced by renewable technologies. In the Scandinavian countries, on the other side, the induced growth of renewables would partly replace historically large district heating systems (which are neither taxed, nor subsidised in this scenario). Instead of incentivising the uptake of decentralised renewable heating technologies, it may therefore be a feasible alternative to increase the use of renewables in centralised heat plants, the fuel and technology use of which are not part of the simulation by FTT:Heat.

With regard to investments, the induced increase in annual household expenditures for heating systems would be much more pronounced than for country group B: the projected increase relative to the baseline is up to +46% (or +3,9 Billion 2005€ per year in total) in 2030, compared to an increase of +22% for country group B. Incentivised by both the carbon tax and the capital subsidy on renewables, households substitute one for the other more quickly. When comparing the three scenarios, overall additional expenditures are by far the largest in case of scenario 2, in which they accumulate to +78 Billion 2005€ in total (compared to +27 Billion 2005€ in total in scenario 3).

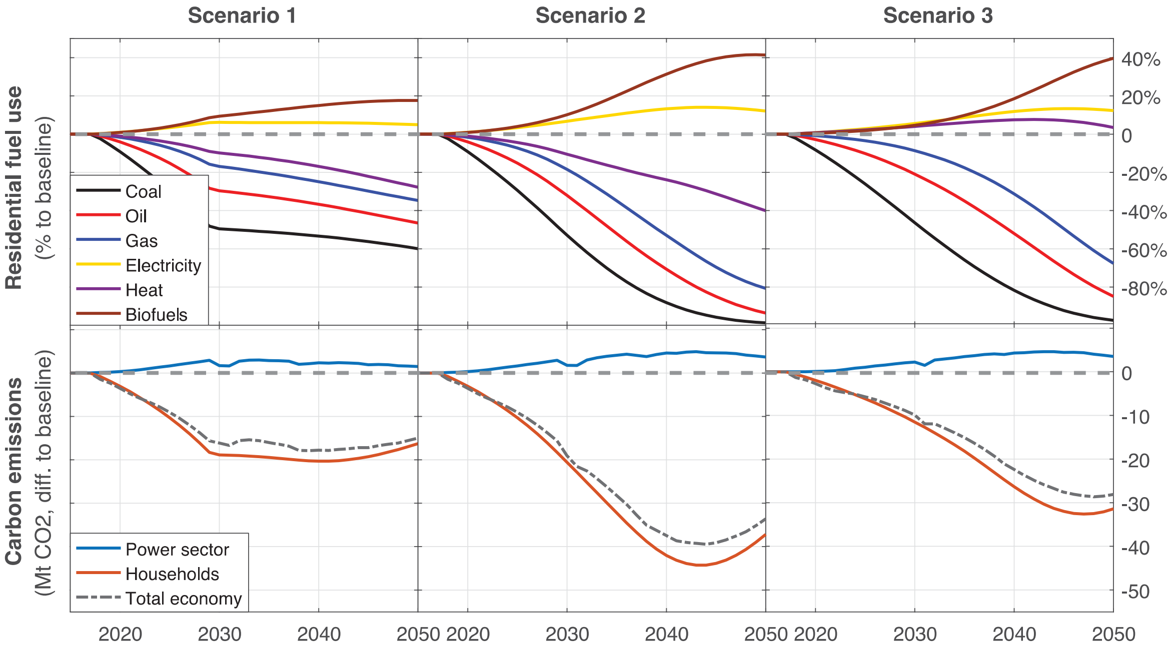
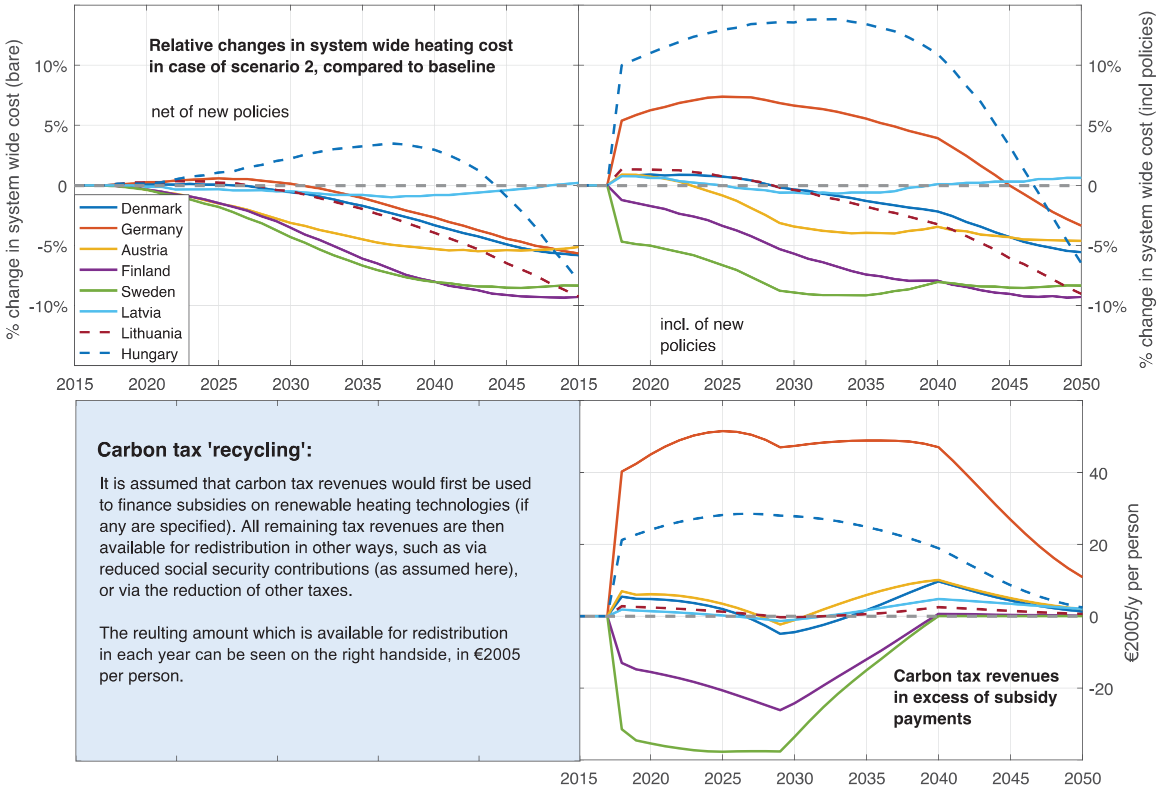


Figure 21: Policy effects in case of country group C, all changes relative to baseline. Upper panels: relative changes in total residential fuel use, by fuel type. Bottom panels: absolute changes in sectoral CO_2 emissions, by households and the power sector.

Figure 21 illustrates the policy combination's relative impacts on residential fuel demand, sectoral CO_2 emissions and investments. For scenario 1, it is projected that compared to the baseline, group-wide residential demand for coal, oil and gas in 2030 would decrease by -50%, -30% and -17%, respectively. These fuels are replaced by a larger use of biomass and electricity, for which demand is projected to increase by +10% and +6% in 2030 (relative to baseline). During the same period, the residential demand for heat is projected to decrease by -10%, relative to baseline trends. As a result, total residential CO_2 emissions in 2030 and 2050 would be lower by -18,3MtCO_2 and -36,7MtCO_2 (in case of scenario 2), while emissions in the power sector would increase by +2,9-3,7MtCO_2. Overall, this implies reduced total emissions by 2030 and 2050 in all Member States. The largest absolute reduction is projected for Germany (-26,8MtCO_2 in 2050), which would keep on having the largest heat demand, which would largely be served by fossil fuels in the baseline. In scenario 3, overall reductions in fossil fuel use and emissions are significantly lower, reaching -28,3MtCO_2 in 2050. Another striking difference is the demand projection for district heating: as renewables are not subsidised in this scenario, households prefer less capital-intensive alternatives, which would here lead to a relative increase in district heat demand.



It is assumed that carbon tax revenues would first be used to finance subsidies on renewable heating technologies (if any are specified). All remaining tax revenues are then available for redistribution in other ways, such as via reduced social security contributions (as assumed here), or via the reduction of other taxes.

The reulting amount which is available for redistribution in each year can be seen on the right handside, in €2005 per person.

Figure 22: Group C relative changes in total heating system costs per country, compared to baseline projection. The top left panel shows the changes in real costs (fuel and capital), the top right panel the changes in the prices faced by households (incl. of new taxes and subsidies). The bottom panel shows the carbon tax revenues in excess of subsidy payments (in 2005€/y per person), which can be used for the benefit of households in various ways.

Relative changes in the projected total system costs for residential heating can be seen in Figure 22. The upper left panel shows the changes in real system costs (without policy costs), the right panel depicts the changes in the heating prices faced by households (which see both a relative increase due to the tax from 2018 onwards, and a relative decrease due to the subsidies from 2018-2030). All countries but Hungary would face constant or slightly decreasing real system costs, with the largest relative reductions being projected from 2030 onwards. System costs in Hungary would increase, partly due to a shift away from relatively cheap gas. In terms of system costs inclusive of policies, historically fossil-fuel dependent Germany and Hungary would see relative increases by +7% and +14% by 2030 (relative to baseline), respectively. The other six Member States have historically less carbon-intensive heating systems, which also explains why a carbon tax on its own does not show much of an effect. They benefit from the capital subsidy scheme while paying only limited overall amounts of carbon taxes, effectively reducing their cost of heating. In case of Finland and Sweden, the carbon tax revenues would therefore be insufficient for financing the assumed subsidy scheme. In Hungary and Germany, on the other side, carbon tax revenues exceed projected subsidy payments by up to 50 2005€ per person and year, and these additional revenues can be redistributed to households.

Like for country group B, the overall results for country group C suggest that households in the analysed countries can be sufficiently incentivised for shifting to renewable heating, so that the objectives for 2030 could be achieved in all cases. The simulated mix of a carbon tax with a subsidy scheme is not only projected to largely reduce the residential demand for fossil fuels, but also projected to substantially increase investments in heating systems and electricity generation. While the subsidy may speed up the transition of households towards renewables (with investments in heating system increasing by around +20% in 2019, the year after the simulated introduction of new policies), a large-scale substitution of fossil fuels would still not take place immediately: additional investments do not peak until 2030. At the same time, the introduced policies may induce long-lasting effects even long after 2030, with the largest changes being projected from 2030 to 2050 (despite the capital subsidy being completely phased out after 2030, and the tax being held constant after 2030).

12.4 Country group D

Country group D's combined demand for residential heating was 483TWh/y in 2014 (around 23% of the total EU28 demand), dominated by demand in the UK (309TWh/y). In the EUCO30 scenario, group-wide heat demand is projected to slightly increase by +2% until 2030, followed by a decrease by around -33% until 2050 (relative to 2014).

Table 19: Residential heat demand (UD, in TWh_{th}) and share of renewables in residential heating (%RE) by Member State in country group D. Last historical observation for %RE (2014) and projected increases between 2018-2030 (in percentage points), in the FTT:Heat baseline projection and in policy scenarios 1-3**.** Red indicates a projected increase by less than 10pp until 2030, green indicates a projected increase of at least 10pp.

Group D	**Heat demand**	**%RE**	**Projected increase in %RE, 2018-2030**		
	2014	2014	**Baseline**	**Scenario 1+2**	**Scenario 3**
9 Luxembourg	2 TWh/y	1%	+2	+11	+3
10 Netherlands	87 TWh/y	6%	+2	+11	+3
15 UK	309 TWh/y	6%	+1	+12	+2
24 Slovenia	9 TWh/y	63%	+2	+10	+4
25 Slovakia	17 TWh/y	3%	+2	+13	+3
27 Romania	43 TWh/y	61%	+/-0	+12	+1
28 Croatia	17 TWh/y	60%	+1	+11	+2

In the case of country group D, it is projected that the 2030 renewable heating objectives are still not achieved after the introduction of both a new tax on the residential use of fossil fuels and capital subsidies for renewable technologies. While these policies do show some impact on technology uptake, the resulting absolute increase in the renewable heating share is not sufficiently large. One reason are the historically low market shares of modern renewable heating technologies in these countries (see in the appendix for on overview), which leaves households with only limited possibilities for the incentivised technology substitutions until 2030 (assuming that households would not switch to traditional biomass for reasons of comfort and convenience). In many Member States in country group D, the so far slow diffusion of modern renewables may be related to the historical dominance of network-based heating technologies, predominantly gas (in Luxembourg, Netherlands, UK, Slovakia).

For achieving the 2030 objective, 'kick start' policies for renewables are introduced as a third element of the policy mix. It is assumed that within a five-year period (2018-2022), active government policies result in the annual replacement of between 0,25-1,0 percentage points of the market-dominating technology's market share by a mix of renewable technologies.

Figure 23 shows the country group's projected annual heat generation, fuel use, CO_2 emissions, and capacity additions until 2050, both in the baseline projection (assuming current trends) and the policy scenarios 1-3. In the FTT:Heat baseline projection, the country group's residential heating system would hardly undergo any decarbonisation until 2030: the group's combined CO_2 emissions by residential heating are projected to decrease by less than -5% (relative to 2014) without further policies. A decoupling of fossil fuel use and heat demand is only projected for after 2030: by 2050, emissions are projected to decrease by -50%, while heat demand is projected to be -33% lower.

In scenario 1, the simulated mix of three policy instruments (carbon tax, subsidies and 'kick start' schemes) is projected to raise all countries' renewable heating share by at least +10 percentage points until 2030. These increases need to be seen relative to the comparably low baseline increases within country group D, which were projected to be smaller than +3 percentage points for all seven countries (see Table 19). The technology transition towards renewables would reduce direct emissions from residential heating by -24% in 2030 (relative to 2014, compared to -5% in the baseline), and by -79% in 2050 (compared to -50%). In scenario 2, the continuation of the carbon tax and subsidies beyond 2030 results in a -97% reduction of CO_2 emissions in 2050. When applying a carbon tax as the only policy instrument (scenario 3), the respective reduction would by -87%.

From an economic perspective, country group D would see the largest relative increases in investments, compared to the other groups: the induced shift towards renewable heating is projected to increase annual household expenditures for heating systems by 60% in 2030 (+2,5 Billion 2005€ per year). Overall additional household expenditures on heating systems would be +45 Billion 2005 € in scenario 1, +71 Billion 2005€ in scenario 2, and +30 Billion 2005€ in scenario 3.

The large policy-induced impacts within this group are illustrated by Figure 24, which shows the relative changes in residential fuel demand and sectoral CO_2 emissions. It is projected that compared to the baseline, group-wide residential demand for coal, oil and gas in 2030 would decrease by -49%, -32% and -20%, respectively. These fuels are substituted by electricity and biomass, whose use for residential heating in 2030 is projected to increase by +11% each (relative to baseline). As a result, total residential CO_2 emissions in 2030 would be lower by -19,1MtCO_2, while emissions in the power sector would increase by +4,0MtCO_2. Overall, this implies a relative reduction in group-wide total emissions by -15,0MtCO_2 in 2030, and by up to -40,0MtCO_2 in 2050 (scenario 2).

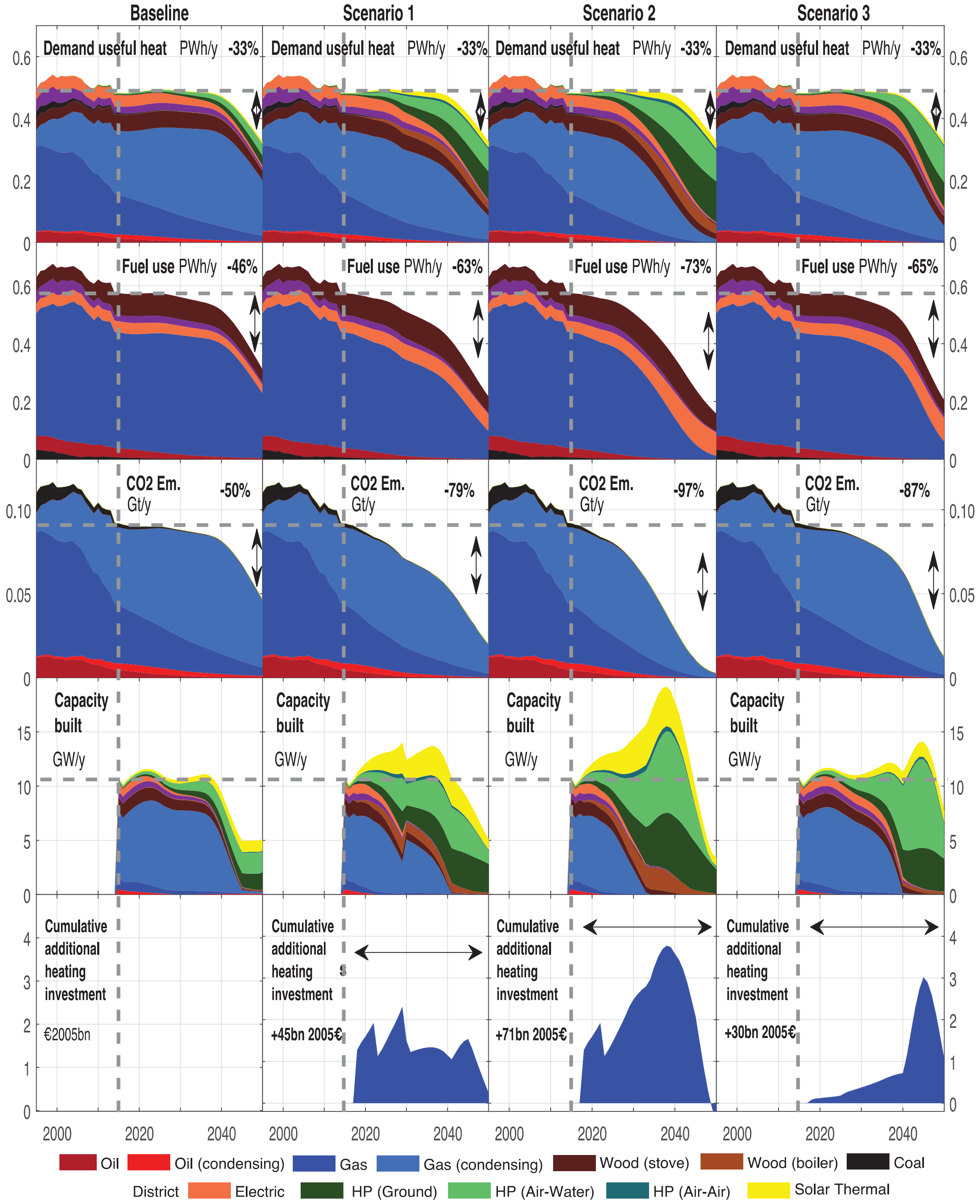


Figure 23: Country group D annual heat generation by technology, fuel use, CO_2 emissions, added heating capacity, and household investments in heating systems. Model results for baseline and scenarios 1-3. Values from 2015 onwards are projections by FTT:Heat. Bold numbers indicate changes in 2050, relative to 2014 (the last historical data point). Projections for useful energy demand for heating are taken from the EUCO30 scenario.

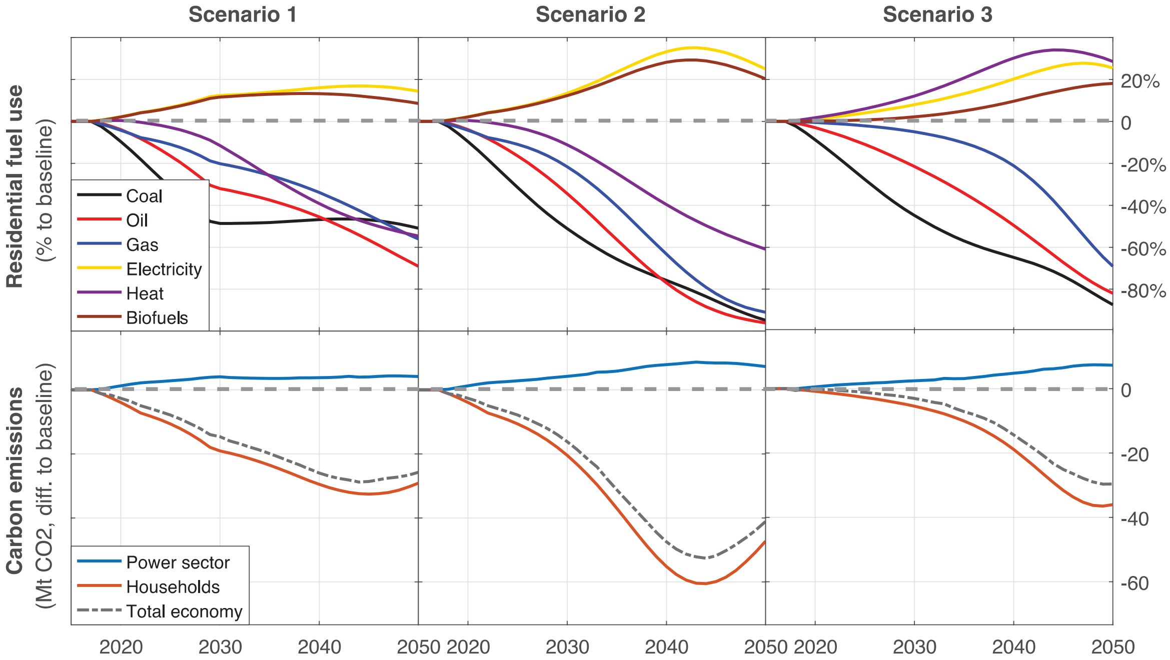
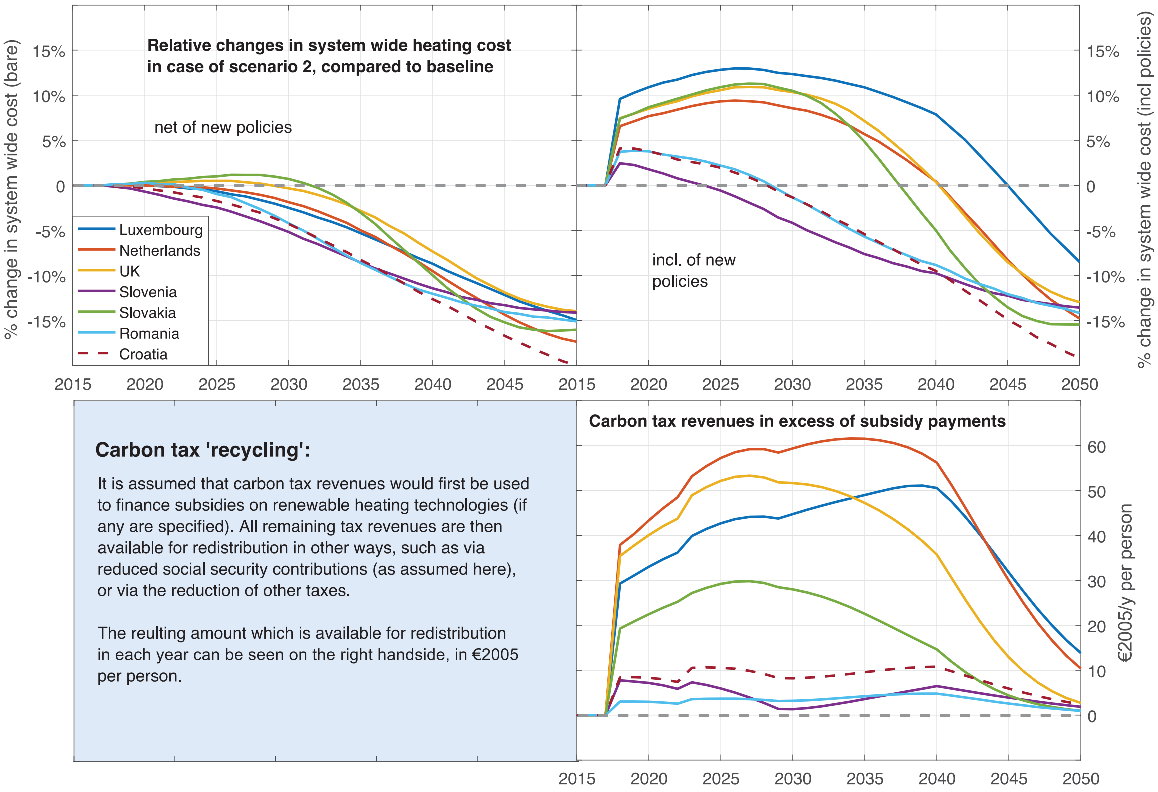


Figure 24: Policy effects in case of group D, all changes relative to baseline. Upper panels: relative changes in total residential fuel use, by fuel type. Bottom panels: absolute changes in sectoral carbon emissions, residential and power sector.

Figure 25 shows the projected relative changes in levelised system costs for residential heating, with and without the costs of new policies for households. Without accounting for the additional tax expenses and subsidies, system wide costs are projected to slightly decrease by (or shortly after) 2030 for all countries (up to -5%), and are projected to be substantially lower in 2050 for all countries (around -15% on average). When including the additional taxes and subsidies faced by households, immediate increases in system wide costs depend on the share of fossil-fuel based heating in the individual countries. For the four Member States with a historically very large reliance on fossil within this group (Luxembourg, UK, Netherlands, Slovakia), households' effective heating costs would stay around +10% above their baseline projection up to the 2040s. At the same time, carbon tax revenues would exceed subsidy payments by up to 60 2005€ per person and year, which can be redistributed to households.

Overall, the results for country group D show that while it may take comparably large efforts, it may be possible to realise a 10 percentage points increase in all analysed countries, even though they show relatively low increases in the baseline scenario. However, the simulated price based policies are projected to be insufficient on their own, given the historically low market shares of renewable heating technologies in all countries. It would therefore need additional 'kick start' policy measures, aiming at actively increasing the diffusion of renewables as early as possible. Practically, this may be achieved by different policy instruments, like procurement schemes (e.g., installing the new heating systems in publicly owned or financed houses), or building code regulations (e.g., prescribing a minimum share of renewables in new houses). As a result, the simulated policy mix could largely reduce the residential consumption of fossil fuels, which remains largely unchanged in the baseline projection. At the same time, country group D is projected to see the largest relative increases in investments, both in heating systems and electricity generation.



Carbon tax 'recycling':

It is assumed that carbon tax revenues would first be used to finance subsidies on renewable heating technologies (if any are specified). All remaining tax revenues are then available for redistribution in other ways, such as via reduced social security contributions (as assumed here), or via the reduction of other taxes.

The reulting amount which is available for redistribution in each year can be seen on the right handside, in €2005 per person.

Figure 25: Country group D relative changes in total heating system costs per country, compared to baseline projection. The top left panel shows the changes in real costs (fuel and capital), the top right panel the changes in the prices faced by households (incl. of new taxes and subsidies). The bottom panel shows the carbon tax revenues in excess of subsidy payments (in 2005€/y per person), which can be used for the benefit of households in various ways.

13 Macroeconomic impacts by country group

In extension of the EU wide analysis of macroeconomic impacts in section 11.2, we here present the relative changes in macroeconomic indicators for each country group. First, we summarise some general trends, which are very similar across country groups. We then focus on some group-specific differences in the respective sub-sections.

As for the EU as a whole, most indicators follow a similar pattern in case of all three scenarios, while the relative magnitude and timing of their changes reflects the differences in scenario assumptions. Scenarios 1 and 2 show identical trends until 2030, and deviate from each other afterwards.

In all country groups, consumers' expenditures are relatively smaller while a carbon tax is applied, as long as the tax payments exceed the induced cost savings. The largest decrease is therefore observable in country group B (up to -0,35%), where a carbon tax is applied as the only policy instrument before 2030. The smallest decreases are projected for group A, where no carbon tax is applied prior to 2030 in scenarios 1 and 2. Even when applying a carbon tax from 2018 onwards (scenario 3), the ongoing decarbonisation means that only small absolute amounts are levied, and consumers' expenditures do not decrease by more than -0,07%.

Investments by the electricity sector always increase in line with electricity demand, and investments by the machinery and equipment sector in line with household spending on heating systems (although on a much smaller scale). These relative increases are smallest for country group A, where no new policies are applied prior to 2030: electricity demand and spending on household appliances increase by not more than +1,3% and +4,7% in all scenarios, relative to the baseline. Relative differences are largest for country group D, which would not see any substantial decarbonisation without new policies: here, electricity demand increases by up to +10%, and household spending on appliances by up to +17%.

As a further similarity between all groups, imports from outside the EU largely follow the decreasing trends in residential fossil fuel demand. Relatively large policy-induced reductions in fossil fuel demand lead to the largest relative changes in country group D, for which imports decrease by up to -0,3%. The smallest relative import reductions are projected for country group A (not more than -0,1% in scenario 3). Exports to outside the EU remain largely unchanged in all country groups, with the exception of group B, where exports are projected to increase by up to +0,15% in the 2030s. These additional exports almost exclusively consist of coal from Poland, demand for which decreases in the country itself when heating is decarbonised.

In all country groups and scenarios, the decreases in consumers' expenditures initially tend to exceed the increases in investments, so that GDP is projected to be -0,1 to -0,2% smaller until around 2030, relative to baseline. There are two noteworthy exemptions from this general pattern: the first is scenario 1, in which policies are discontinued after 2030, leading to GDP increases in all country groups (up to +0,3% in group D). The reason is that households would still benefit from the induced efficiency improvements, but would not have to pay the carbon tax any longer. The second exemption is country group A, where GDP would only significantly decrease in scenarios 2 and 3 (up to -0,05%), and only after 2030. The reason here is that no new policies prior to 2030 are assumed in scenarios 1 and 2.

Projected employment effects are overwhelmingly positive in all scenarios and country groups (up to +0,2%). The respective changes can be related to two main factors: the relative strength of decarbonisation, and the carbon tax revenues available for reducing labour costs (via reduced employers' contributions to social security payments). This can be exemplified by the case of scenario 3, which assumes a carbon tax as the only policy instrument: while model projections for future GDP are almost always smaller than for scenarios 1 and 2, projected employment tends to stay at least at the same level.

13.1 Country group A

For country group A, the macroeconomic impacts of the new policies are summarised in Figure 26, which shows the relative changes in GDP, employment and other indicators relative to their baseline trends, up to 2050. Unlike all other country groups, no new policies are applied prior to 2030 in scenarios 1 and 2, which explains the small changes in this period. Due to the strong decarbonisation trend in the baseline, changes remain comparably smaller even after 2030 and in scenario 3, where a carbon tax is introduced from 2018 onwards.

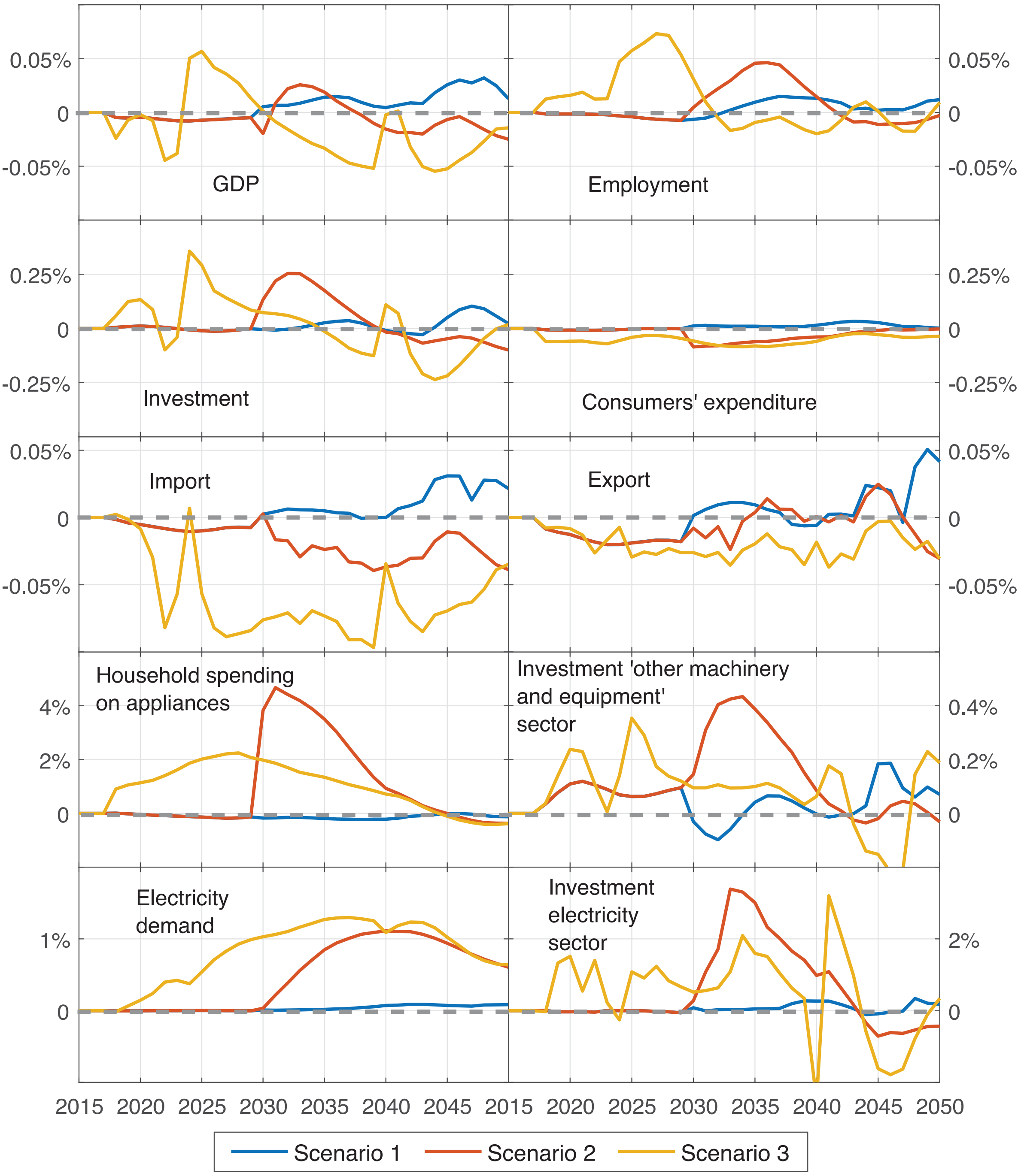


Figure 26: Country group A relative changes in macroeconomic indicators by country, compared to baseline projections.

13.2 Country group B

The macroeconomic impacts of the new policies are summarised in Figure 27, which shows the relative changes in GDP, employment and other indicators relative to their baseline trends, up to 2050. As a carbon tax is the only implemented policy in scenario 1 prior to 2030, projections for scenarios 1-3 are virtually identical for this period. Scenario 2 and 3 only differ by subsidy payments during the 2030s in scenario 2, explaining the small differences between both trends from 2030-2050.

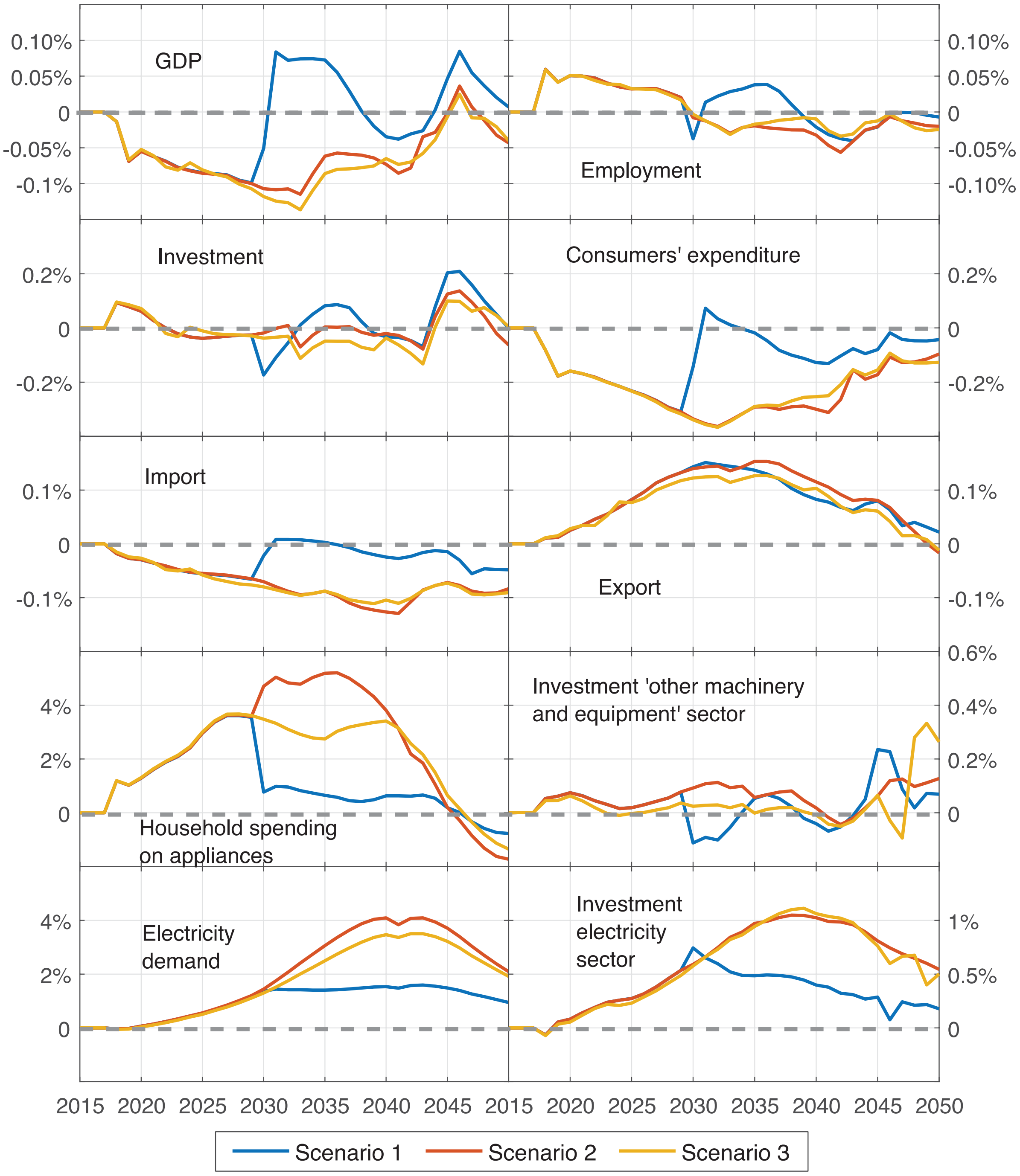


Figure 27: Country group B relative changes in macroeconomic indicators by country, compared to baseline projections.

13.3 Country group C

Figure 28 summarises the relative macroeconomic impacts of the policy mix for country group C, relative to baseline projections. Due to the combination of a carbon tax with subsidies, relative changes in scenarios 1 and 2 are significantly larger than in case of country group B.

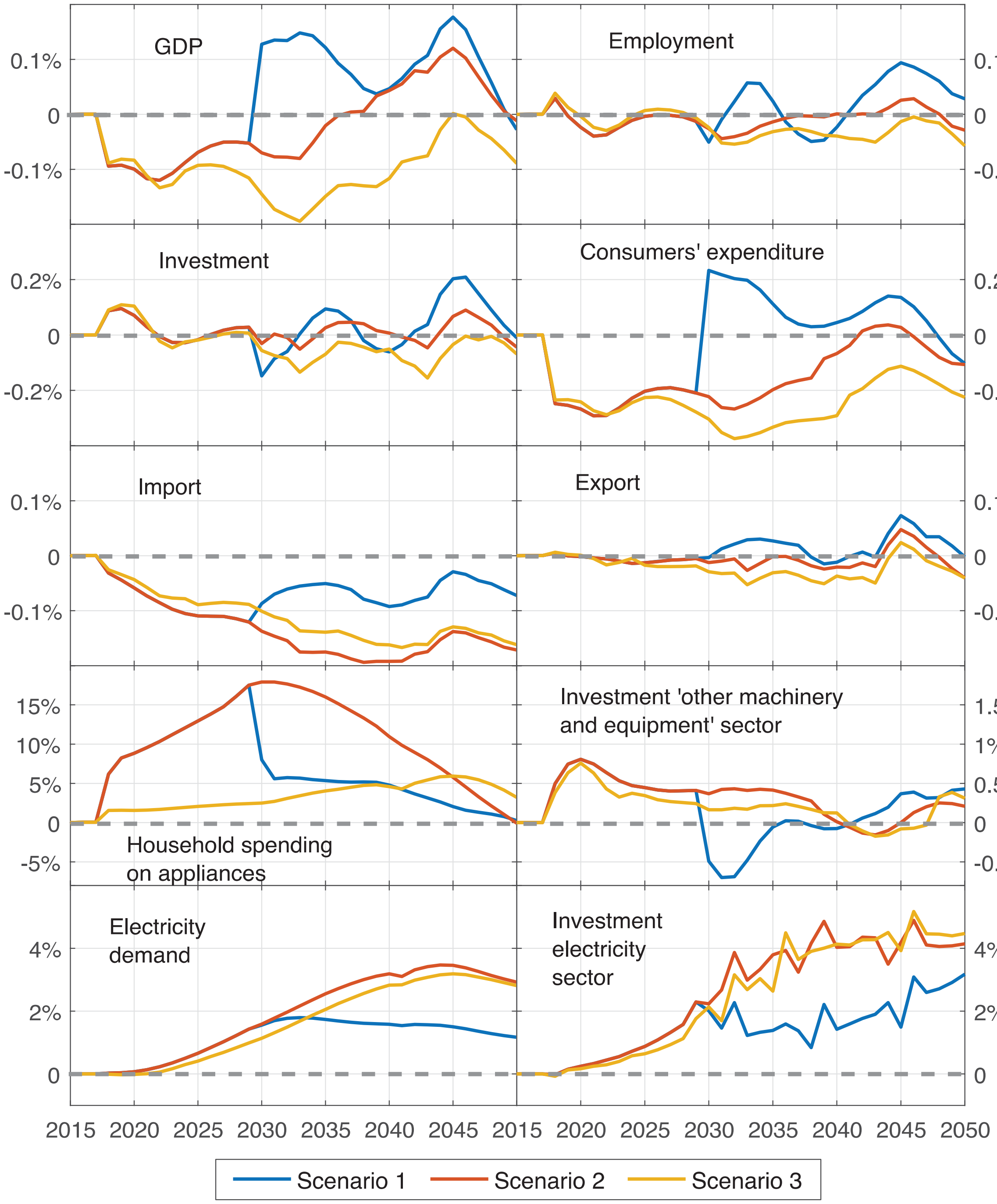


Figure 28: Country group C relative changes in macroeconomic indicators by country, compared to baseline projections.

13.4 Country group D

The macroeconomic impacts of the new policies are summarised in Figure 29, which shows the relative changes in GDP, employment and other indicators relative to their baseline trends, up to 2050. Given that the heating systems in country group D are projected to undergo the largest policy-induced changes compared to the other groups, it also shows the largest relative macroeconomic impacts.

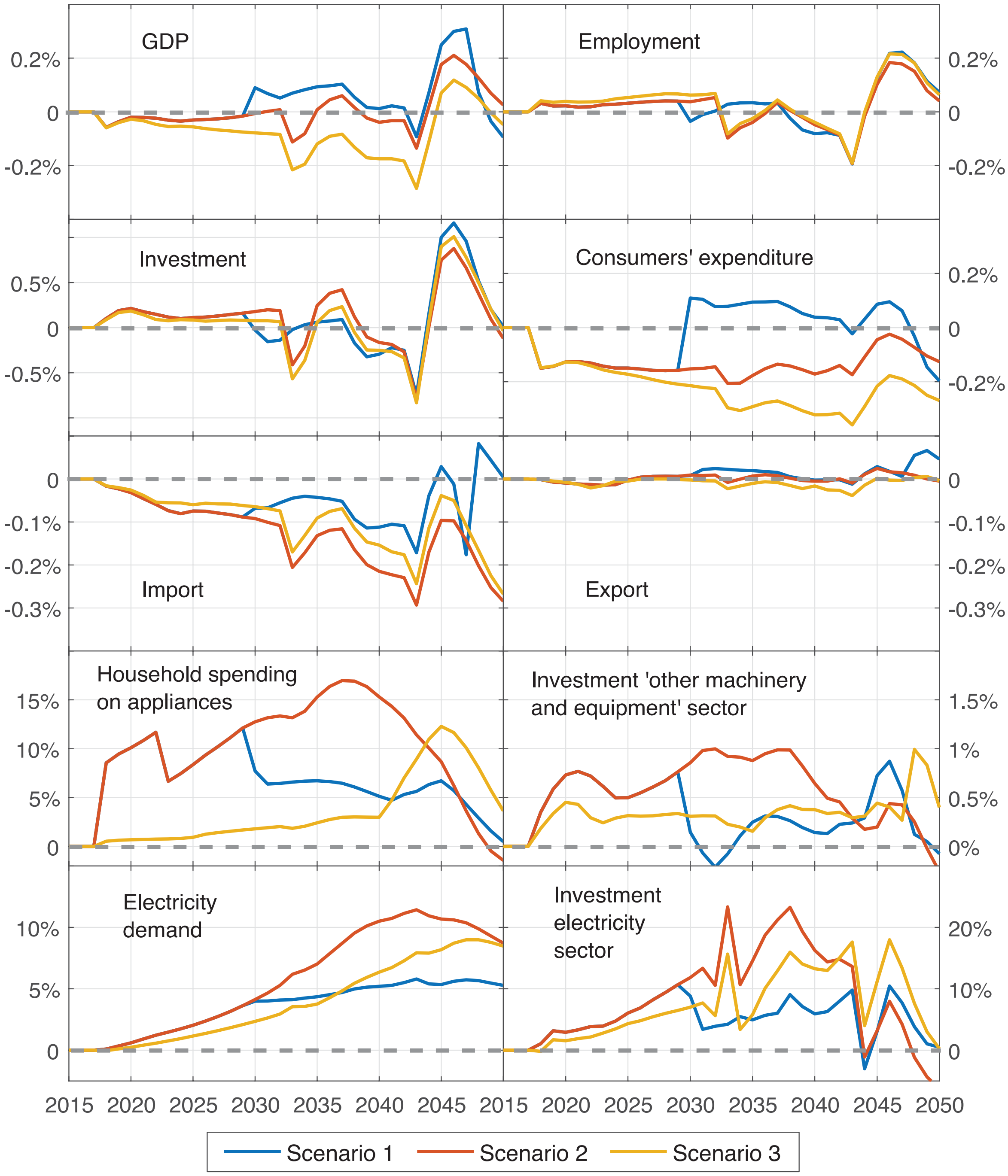


Figure 29: Country group D relative changes in macroeconomic indicators by country, compared to baseline projections.

Part V. Conclusions

In this report, we introduced FTT:Heat as a new dynamic model for simulating *policy-induced technological change* in the residential heating sector. It was shown how technological diversity, household behaviour, social dynamics and industrial constraints can be modelled based on statistically distributed choice parameters and dynamic equations, capturing a diversity of choices, and reproducing the typical dynamics of technology transitions. Instead of identifying cost-minimising solutions from the perspective of a central social planner, FTT:Heat allows the simulation of likely trajectories of heating technology diffusion, based on the bottom-up representation of household decisions. Unlike the optimisation perspective, households are assumed to be subject to limited information and bounded rationality, which implies that their reaction to cost changes (like new taxes and subsidies) is not instantaneous. Accordingly, diverse individual decisions may lead to outcomes which are sub-optimal from a normative perspective, but perhaps closer to reality. It was shown how this framework can be used to simulate the potential effect of various policy instruments on the technology composition, future levels of final energy demand, fuel use, emissions, and investments.

The report also describes how FTT:Heat has been fully integrated into the global macro-econometric model E3ME, which allows simulation of the potential macroeconomic feedbacks between the residential heating sector and the wider economy. Changes in the heating sector can have immediate impacts on other sectors (notably the production of heating equipment, power generation and the extraction and processing of fossil fuels) and macroeconomic developments, both of which are modelled in E3ME. When testing a new policy for the heating sector, the combination of both models makes it possible to analyse the potential relative changes in all economic sectors and world regions, as well as the changes in macroeconomic indicators like household income, employment or GDP.

FTT:Heat was applied for simulating a set of policies and scenarios. A baseline scenario was defined, which assumes the continuation of current policies and technology diffusion trends. Based on the identified trajectories, it was estimated that residential heating within the EU would become less carbon-intensive in the future: CO_2 emissions by residential heating are projected to decrease by around -22% until 2030 (relative to 2014), while household demand for heating would remain stable. A closer look at individual Member States, however, unveils large differences: while some countries are estimated to continue an ongoing transition towards renewable heating, thereby contributing to the EU wide emission reductions, others would hardly see any change in their heating systems under existing policies.

In addition to the current technology and policy trends scenario, several scenarios aiming at an increased share of renewable heating were simulated. We identified policy mixes which would result in an increase in each Member State's share of renewable technologies in residential heating of at least ten percentage points until 2030. For this purpose, different policies were successively added on top of each other, until the ten percentage point increase between 2018 and 2030 was realized within the model simulation. Eight Member States are projected to reach this objective without any additional policies, thanks to an ongoing diffusion of solar thermal systems and heat pumps, combined with the successive substitution of coal heating. For thirteen Member States, the model simulations suggest that the renewable heating objective could be fulfilled by introducing a combination of (additional) market-based policies from 2018 until 2030: a new carbon tax on the residential use of coal, gas and oil (starting at 50 € per ton of CO_2), which would need to be combined with capital subsidies on the upfront cost of renewable technologies in eight Member States (-30% on the installation costs, phased out after 2030). For the remaining group of seven Member States, even the combination of both price instruments is projected to be insufficient for reaching the renewable objective by 2030. In these countries, the current shares of (decentralized) renewable heating are so low that it would require additional ‘kick start’ policies (e.g., procurement policies targeted at publicly owned building) to enable a sufficiently fast growth of the incentivized technologies.[23] The results indicate that the envisioned increase in renewable heating share needs relatively more effort in countries with low starting values.

In the model simulation, the implemented policies would allow all Member States to increase their renewable heating share by at least ten percentage points until 2030, implying a -39% reduction in on-site CO_2 emissions by residential heating (compared to -22% in the baseline). Slightly increased emissions by power plants (due to a +50TWh/y increase in EU wide electricity demand) would be small in absolute comparison, allowing substantial net reductions of EU wide emissions. The induced substitution of fossil fuel based technologies does not occur instantaneously, however. Both due to the long technical lifetimes of heating systems (which mean that only around 5% of the stock needs to be replaced each year) and the inertia of technology transitions, substantial changes in market shares can only be observed after several years (or even decades). Even when costs change dramatically, many households will be ‘locked’ into their existing heating systems for a considerable time. During this transition period, when introducing new carbon taxes, households that still operate the old technologies would therefore face higher heating costs. The political acceptability of such a policy may therefore depend on the way in which carbon tax revenues are redistributed to households.

In addition to reaching the 2030 objectives of increasing renewable heating by ten percentage points, the implemented policies are projected to have large impacts long afterwards: emission levels remain constantly lower, renewables would keep on dominating sales, and hardly any new investments into fossil-fuel based heating systems are projected from 2040 onwards, resulting in a -83% emissions reduction by 2050 (relative to 2014, compared to -69% in the baseline). This is despite the fact that subsidies for renewables and the carbon tax are assumed to be discontinued after 2030. Continuing the simulated policies and extending them to all Member States after 2030 would set the EU residential heating system on track for a deep decarbonisation until 2050, resulting in a -98% emission reduction in 2050, according to the model estimates.

During the simulated policy-induced technology transition, annual household expenditures on heating systems are projected to be up to +45% (or +9 Billion €[24] per year) higher than in the baseline projection, reaching their highest levels between 2030 and 2040 (if policies are continued beyond 2030). Overall additional expenditures between 2018-2050 accumulate to +94 Billion € if polices are discontinued after 2030, and to +176 Billion € if policies are extended up to 2050. In addition, the increased electrification of household heating would increase annual investments by the power sector by up to +6% (or +3,7 Billion € per year). At the same time, households would face additional tax payments on fossil fuels of up to 20 Billion € per year, while receiving capital subsidies on the purchase of renewable heating systems of up to 6 Billion € per year.

From a macro-economic perspective, it is assumed that the additional tax revenues would be used to reduce employers’ contributions to social security payments, thereby incentivizing employment in all sectors. Estimated impacts on total employment are therefore slightly positive over most of the simulation period, despite small net

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[23] In Member States with larges shares of district heating, the renewable objectives may alternatively be achieved by increasing the share of renewables in district heat plants, which are beyond the scope of this study.

[24] In constant 2005 prices, as are all the expenditures described in this section.

reductions in employment in heating related sectors (where induced job creation in the electricity and manufacturing sectors is less than the job losses in the fossil fuel and energy network sectors). The EU wide GDP is projected to be up to +0,1% larger than in the baseline beyond 2030, and up to -0,1% smaller before 2030. The impact of the carbon tax is an important factor influencing GDP outcomes: positive GDP effects are largest in the scenario when the new heating policies are phased out after 2030, allowing consumers' expenditure to rebound, and smallest when applying a carbon tax as the only policy instrument from 2018-2050. From a social perspective, the new policies may not be without distributional impacts, creating both winners and losers: while most households would benefit from lower heating costs in the long term (by around 2040), many face substantial price increases in the short term. Only some households benefit from subsidy payments on heating systems, and only households with fossil fuel heating systems need to shoulder the burden of additional taxes. In particular, households living in rented accommodation, who cannot choose their heating system, could be disadvantaged if their landlord does not invest in a renewable system. The political acceptability of policies targeted at the residential heating sector may therefore depend on the way in which carbon tax revenues are redistributed to households.

References

Cambridge Econometrics (2014) 'E3ME Manual, Version 6'. Available at: https://www.e3me.com.

Connolly, D. *et al.* (2013) *Heat Roadmap Europe 2: Second Pre-Study for the EU27*.

Connolly, D. *et al.* (2014) 'Heat roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system', *Energy Policy*, 65, pp. 475–489. doi: 10.1016/j.enpol.2013.10.035.

Danish Energy Agency (2013) *Technology Data for Energy Plants - Individual Heating Plants and Energy Transport*. Danish Energy Agency.

Danish Energy Agency (2016) *Technology Data for Individual Heating Plants and Energy Transport - Updated chapters, August 2016*. Danish Energy Agency.

E3MLab and IIASA (2016) *Technical report on Member State results of the EUCO policy scenarios*.

Enerdata (2017) *ODYSSEE database*. Available at: www.odyssee-mure.eu.

European Commission (2013a) 'Commission delegated regulation of 18 February 2013 supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to the energy labelling of space heaters, combination heaters, packages of space heater, temperature control a', *Official Journal of the European Union*. European Commission, L 239/1.

European Commission (2013b) *Guidelines for Member States on calculating renewable energy from heat pumps from different heat pump technologies pursuant to Article 5 of Directive 2009/28/EC of the European Parliament and of the Council*.

European Commission (2016a) 'Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on an EU Strategy for Heating and Coolinge', (COM(2016) 51 final).

European Commission (2016b) *Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources (recast)*.

European Heat Pump Association (EHPA) (2016) *Data on heat pump stock, capacities, usable energy production and system costs, 1990-2014*.

Eurostat (1978) *Useful energy balance sheets - 1975*.

Eurostat (2006) 'Statistical aspects of the energy economy in 2004', *Statistics in focus - Environment and energy*.

Eurostat (2015) 'SHARES Tool Manual - Version 2015.70124'.

Fleiter, T., Steinbach, J. and Ragwitz, M. (2016) *Mapping and analyses of the current and future (2020 - 2030) heating/cooling fuel deployment (fossil/renewables)*. European Commission, Directorate-General for Energy.

Gillingham, K. and Palmer, K. (2014) 'Bridging the Energy Efficiency Gap: Policy Insights from Economic Theory and Empirical Evidence', *Review of Environmental Economics and Policy*, 8(1), pp. 18–38.

Grubb, M., Hourcade, J.-C. and Neuhoff, K. (2014) *Planetary economics: energy, climate change and the three domains of sustainable development*. Routledge.

Grübler, A., Nakićenović, N. and Victor, D. G. (1999) 'Dynamics of energy technologies and global change', *Energy policy*, 27(5), pp. 247–280.

Grübler, A. and Wilson, C. (2013) *Energy Technology Innovation*. Cambridge University Press.

Henkel, J. (2012) *Modelling the diffusion of innovative heating systems in Germany -- decision criteria, influence of policy instruments and vintage path dependencies*. TU Berlin.

Hofbauer, J. and Sigmund, K. (1998) *Evolutionary games and population dynamics*. Cambridge University Press.

IEA (2012) *Energy Technology Perspectives 2012*. IEA/OECD.

IEA (2016) *Energy Prices and Taxes, Volume 2016*. International Energy Agency.
IEA/ETSAP (2012a) *Building Shell and Thermal Insulation - Technology Brief R01*. International Energy Agency (IEA) Energy Technology Systems Analysis Program.
IEA/ETSAP (2012b) *Space Heating and Cooling - Technology Brief R02*. International Energy Agency (IEA) Energy Technology Systems Analysis Program.
Jaffe, A. B. and Stavins, R. N. (1994) 'The energy-effincency gap: What does it mean?', *Energy Policy*, 22(10), pp. 804–810. doi: 10.1016/0301-4215(94)90138-4.
Knobloch, F. and Mercure, J.-F. (2016) 'The behavioural aspect of green technology investments: A general positive model in the context of heterogeneous agents', *Environmental Innovation and Societal Transitions*, 21, pp. 39–55. doi: 10.1016/j.eist.2016.03.002.
Madureira, N. L. (2014) *Key concepts in energy*. Springer.
Mercure, J.-F. (2012) 'FTT:Power : A global model of the power sector with induced technological change and natural resource depletion', *Energy Policy*, 48(0), pp. 799–811.
Mercure, J.-F. (2015) 'An age structured demographic theory of technological change', *Journal of Evolutionary Economics*. Springer, 25(4), pp. 787–820.
Mercure, J.-F., Pollitt, H., *et al.* (2016) 'Modelling complex systems of heterogenous agents to better design sustainability transitions policy', *Global Environmental Change*, 37, pp. 102–115. doi: http://dx.doi.org/10.1016/j.gloenvcha.2016.02.003.
Mercure, J.-F., Knobloch, F., *et al.* (2016) 'Policy-induced energy technological innovation and finance for low-carbon economic growth'. European Commission.
Mercure, J.-F. *et al.* (2017) 'Integrated assessment modelling as a positive science: modelling policy impacts in road transport to meet a climate target well below 2C', *arXiv preprint*.
NREL (2016) *Distributed Generation Renewable Energy Estimate of Costs (updated February 2016)*. National Renewable Energy Laboratory (NREL).
Olsthoorn, M. *et al.* (2017) 'Free riding and rebates for residential energy efficiency upgrades: A multi-country contingent valuation experiment', *Energy Economics*, p. in press.
Rogers, E. M. (2010) *Diffusion of Innovations*. Simon and Schuster.
Sorrell, S. *et al.* (2004) *The Economics of Energy Efficiency: Barriers to Cost-Effective Investment*. Edward Elgar Publishing.
Tsikaloudaki, K., Laskos, K. and Bikas, D. (2012) 'On the establishment of climatic zones in Europe with regard to the energy performance of buildings', *Energies*, 5(1), pp. 32–44. doi: 10.3390/en5010032.
Weiss, M. *et al.* (2009) 'Market diffusion, technological learning, and cost-benefit dynamics of condensing gas boilers in the Netherlands', *Energy Policy*. Elsevier, 37(8), pp. 2962–2976.
Weiss, M. *et al.* (2010) 'A review of experience curve analyses for energy demand technologies', *Technological Forecasting and Social Change*. Elsevier Inc., 77(3), pp. 411–428. doi: 10.1016/j.techfore.2009.10.009.
Werner, S. (2016) 'European District Heating Price Series'. Energiforsk.

Appendix

Table 20: Shares of individual heating technologies in buildings, as percentage of total installed capacities per fuel type (dwellings with condensing boiler as percentage of all dwellings with fossil fuel boiler, capacity of biomass boilers as percentage of total biomass heating capacity) (values are for 2012).

	Share of condensing boilers	Share of biomass boilers
Austria	29%	4%
Belgium	31%	3%
Bulgaria	8%	6%
Croatia	4%	1%
Cyprus	40%	11%
Czech Republic	16%	1%
Denmark	61%	2%
Estonia	12%	3%
Finland	1%	6%
France	15%	2%
Germany	24%	2%
Greece	1%	1%
Hungary	8%	15%
Ireland	19%	41%
Italy	13%	2%
Latvia	10%	12%
Lithuania	10%	6%
Luxembourg	—	1%
Malta	—	0%
Netherlands	84%	4%
Poland	20%	6%
Portugal	1%	2%
Romania	4%	0%
Slovakia	19%	7%
Slovenia	9%	0%
Spain	5%	3%
Sweden	5%	4%
United Kingdom	56%	0%
Source:	EU Buildings Observatory	Fleiter et al. 2016

Table 21: Country-specific factors for scaling upfront investment costs to specific price level of each Member State.

	Cost factor
Austria	1.21
Belgium	0.99
Bulgaria	0.45
Croatia	*0.66*
Cyprus	0.75
Czech Republic	0.66
Denmark	1.49
Estonia	0.71
Finland	1.09
France	1.19
Germany	1.2
Greece	0.73
Hungary	0.62
Ireland	1.03
Italy	0.79
Latvia	0.83
Lithuania	0.74
Luxembourg	1.03
Malta	0.65
Netherlands	1.29
Poland	0.71
Portugal	0.59
Romania	0.46
Slovakia	0.7
Slovenia	0.76
Spain	0.82
Sweden	1.45
United Kingdom	1.16
Source:	Calculated based on Connolly et al. (2013)

Table 22: Mean household prices for light fuel oil, natural gas, district heating, and electricity, in €/kWh. All prices for 2014 (heat for 2013).

	Oil	Gas	Heat	Electricity
Austria	0.088	0.090	0.082	0.201
Belgium	0.078	0.073	0.082	0.184
Bulgaria	*0.076*	*0.048*	0.041	0.090
Croatia	*0.075*	*0.048*	0.057	0.132
Cyprus	*0.093*	---	---	0.236
Czech Republic	0.083	0.064	0.081	0.131
Denmark	0.147	0.099	0.13	0.304
Estonia	0.095	0.054	0.046	0.127
Finland	0.101	---	0.073	0.152
France	0.087	0.075	0.071	0.156
Germany	0.075	0.079	0.091	0.298
Greece	0.119	0.079	---	0.178
Hungary	*0.123*	0.041	0.045	0.119
Ireland	0.098	0.084	---	0.23
Italy	0.144	0.095	0.083	0.231
Latvia	0.088	*0.049*	0.06	0.124
Lithuania	*0.066*	*0.050*	0.077	0.132
Luxembourg	0.072	0.058	---	0.166
Malta	0.098	---	---	0.125
Netherlands	0.105	0.086	0.085	0.19
Poland	0.093	0.061	0.054	0.145
Portugal	0.125	0.11	---	0.22
Romania	*0.101*	*0.032*	0.075	0.125
Slovakia	0.101	0.059	0.099	0.161
Slovenia	0.101	0.074	0.072	0.160
Spain	0.083	0.100	---	0.237
Sweden	0.149	0.129	0.091	0.162
United Kingdom	0.076	0.071	0.055	0.193
Source:	IEA, *DG Energy (italics)*	IEA, *Eurostat (italics)*	Werner (2016)	IEA

Table 23: Climatic classifications[25], annual heating degree days (HDD) (average 1970-2015), and annual solar yields (MWh_{th}/kW_{th}) (2014).

	Climate	Heating degree days[26] (per year)	Solar yield MWh_{th}/kW_{th}
Austria	cold	3071	0.58
Belgium	average	1902	0.57
Bulgaria	average	2687	0.70
Croatia	average	2228	0.72
Cyprus	warm	787	1.27
Czech Republic	cold	3571	0.48
Denmark	cold	3131	0.6
Estonia	cold	4445	0.57
Finland	cold	4517	0.59
France	average	1966	0.67
Germany	cold	3713	0.58
Greece	warm	1078	1.00
Hungary	average	2917	0.64
Ireland	average	2083	0.60
Italy	average	1971	0.87
Latvia	cold	4265	0.67
Lithuania	cold	4094	0.57
Luxembourg	cold	3210	0.61
Malta	warm	502	1.14
Netherlands	average	2901	0.57
Poland	cold	3617	0.58
Portugal	warm	1282	1.11
Romania	cold	3129	0.79
Slovakia	cold	3453	0.66
Slovenia	average	2840	0.6
Spain	average	1842	1.00
Sweden	cold	3740	0.52
United Kingdom	cold	3164	0.56
Source:	*classification*	*ODYSSEE*	*IEA*

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[25] Climatic classifications based on heating degree-days: cold — HDD >= 3000, average — 1500 >= HDD < 3000, warm — HDD < 1500 (Tsikaloudaki, Laskos and Bikas, 2012).

[26] Heating degree days 'express the severity of the cold in a specific time period taking into consideration outdoor temperature and room temperature' (Eurostat, 2006). It is calculated by adding, for each single day in a year, the difference between the recorded daily temperature and a reference room temperature. Here, the average heating degree days between 1970-2015 are reported.

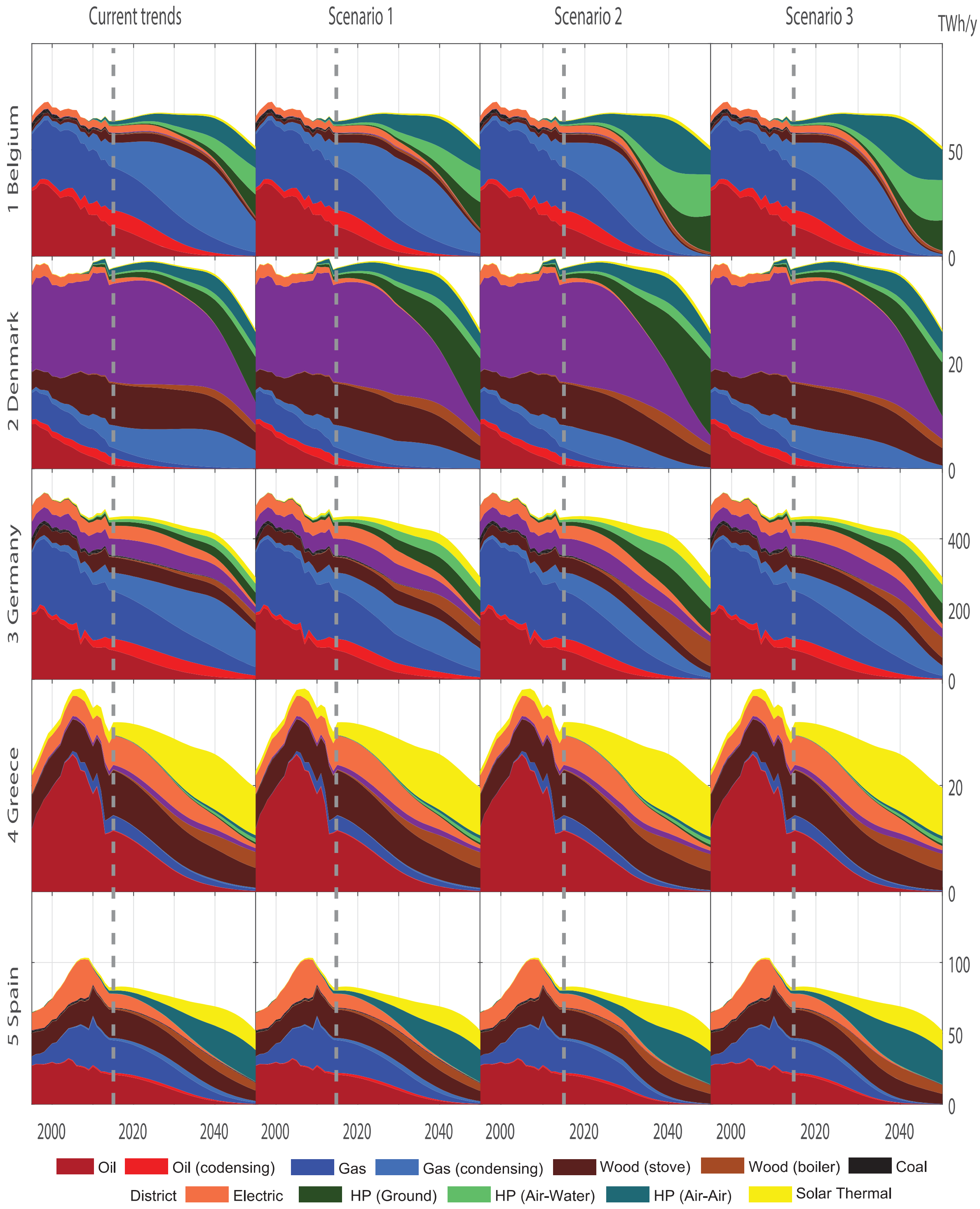

Figure 30: Projections for annual heat generation by technology (in TWh_{th}/y), part 1. Baseline projections under current trends and scenarios 1-3. Values from 2015 onwards are projections by FTT:Heat. Projections for useful energy demand for heating are taken from the EUCO30 scenario.

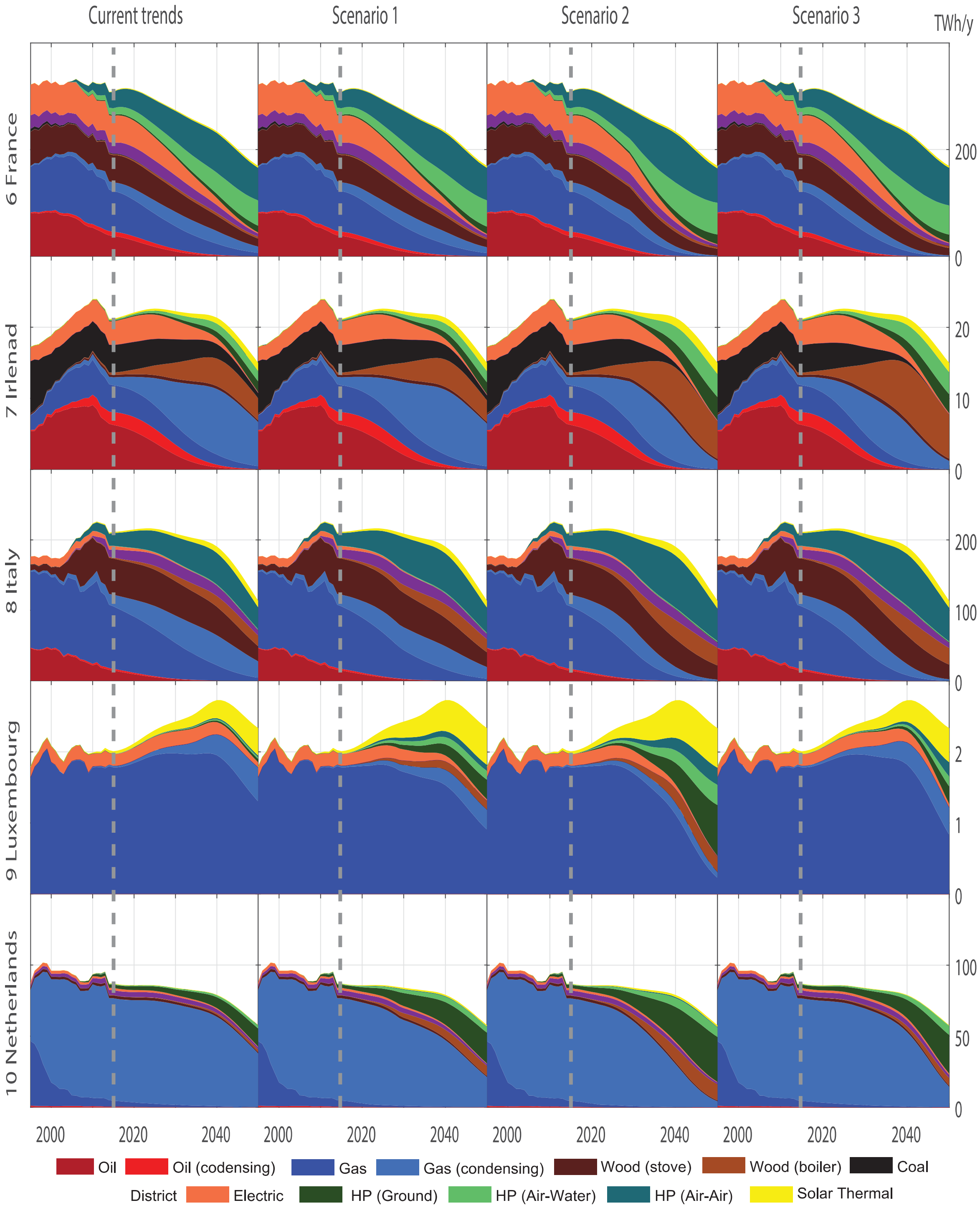

Figure 31: Projections for annual heat generation by technology (in TWh_{th}/y), part 2. Baseline projections under current trends and scenarios 1-3. Values from 2015 onwards are projections by FTT:Heat. Projections for useful energy demand for heating are taken from the EUCO30 scenario.

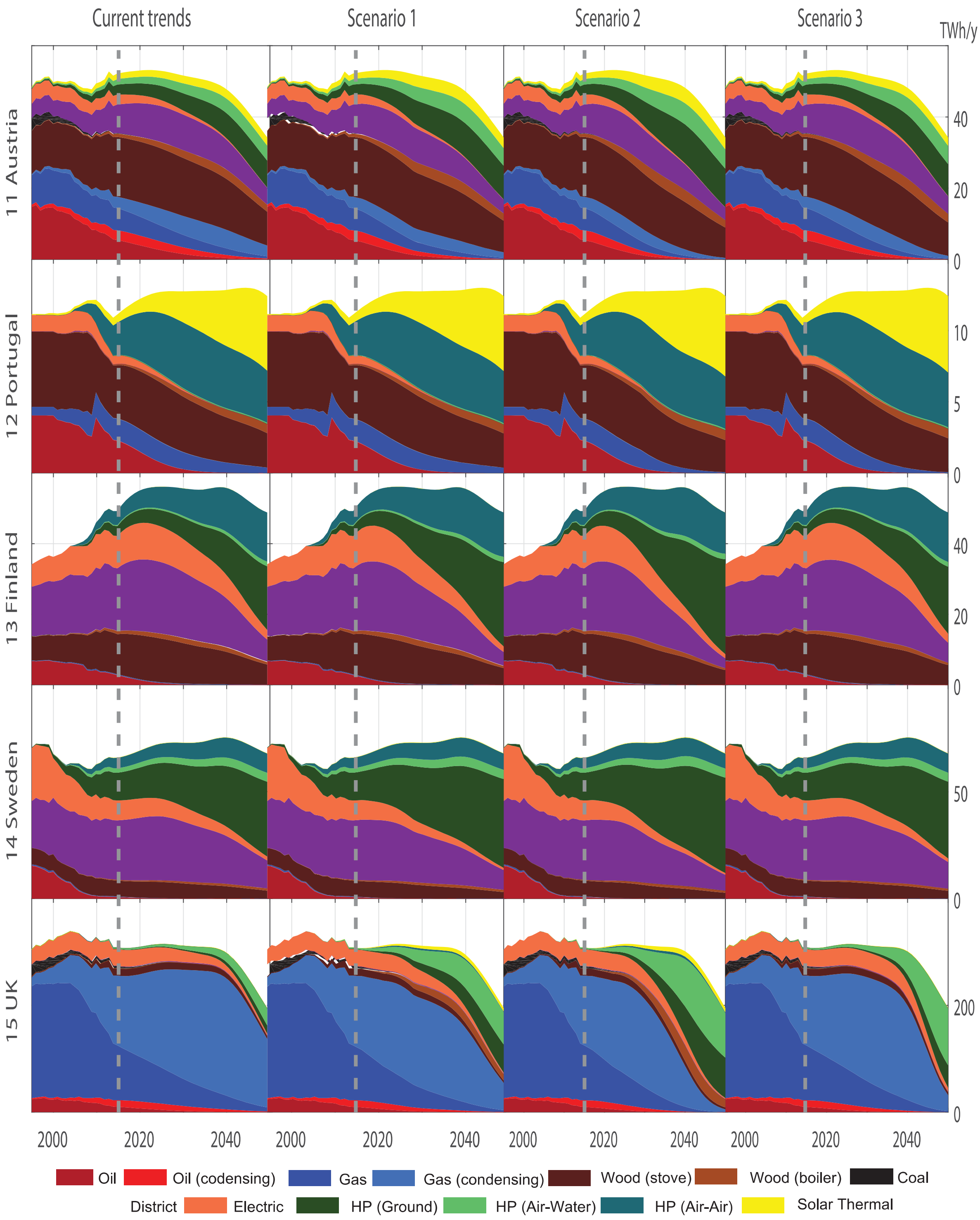

Figure 32: Projections for annual heat generation by technology (in TWh_{th}/y), part 3. Baseline projections under current trends and scenarios 1-3. Values from 2015 onwards are projections by FTT:Heat. Projections for useful energy demand for heating are taken from the EUCO30 scenario.

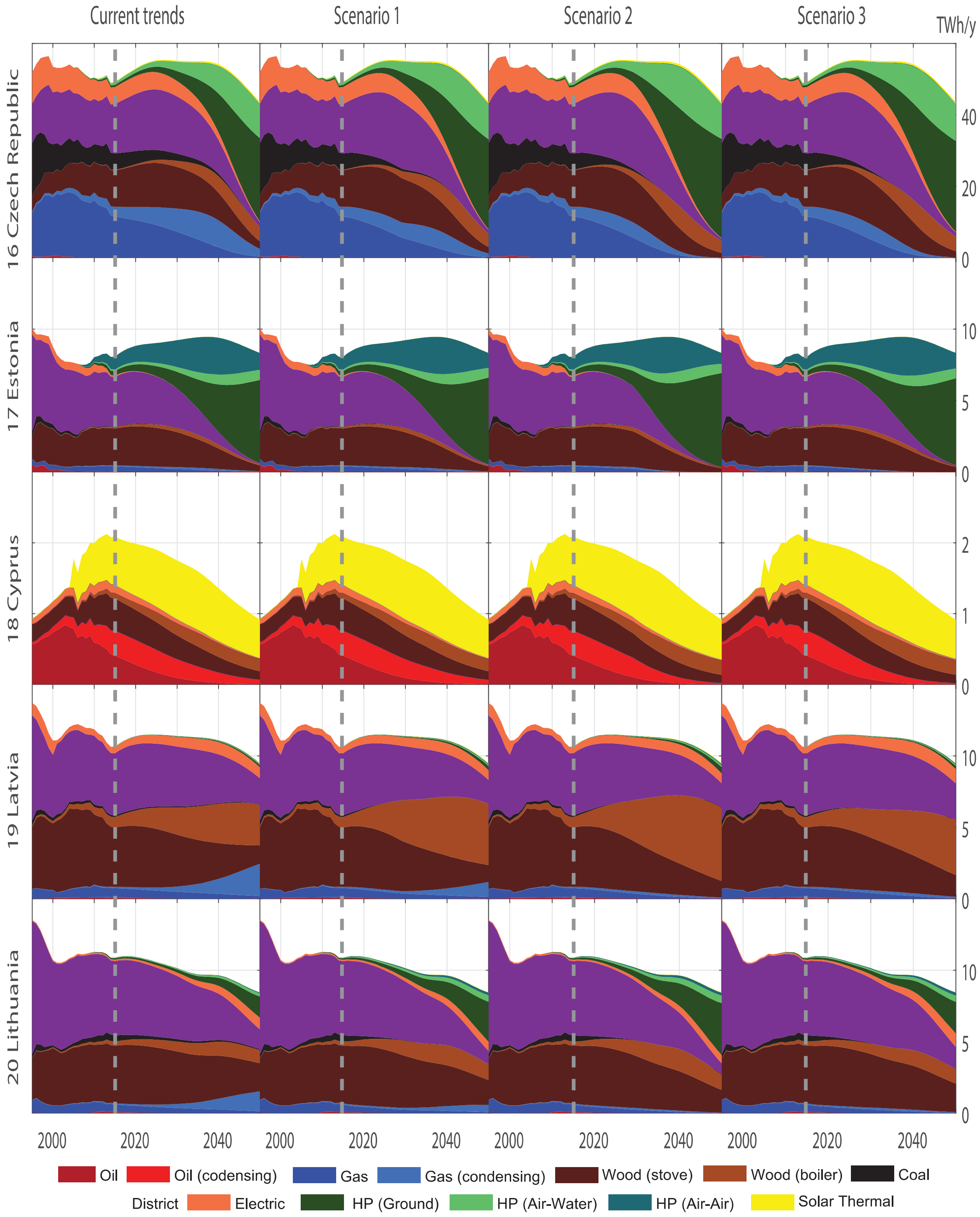

Figure 33: Projections for annual heat generation by technology (in TWh_{th}/y), part 4. Baseline projections under current trends and scenarios 1-3. Values from 2015 onwards are projections by FTT:Heat. Projections for useful energy demand for heating are taken from the EUCO30 scenario.

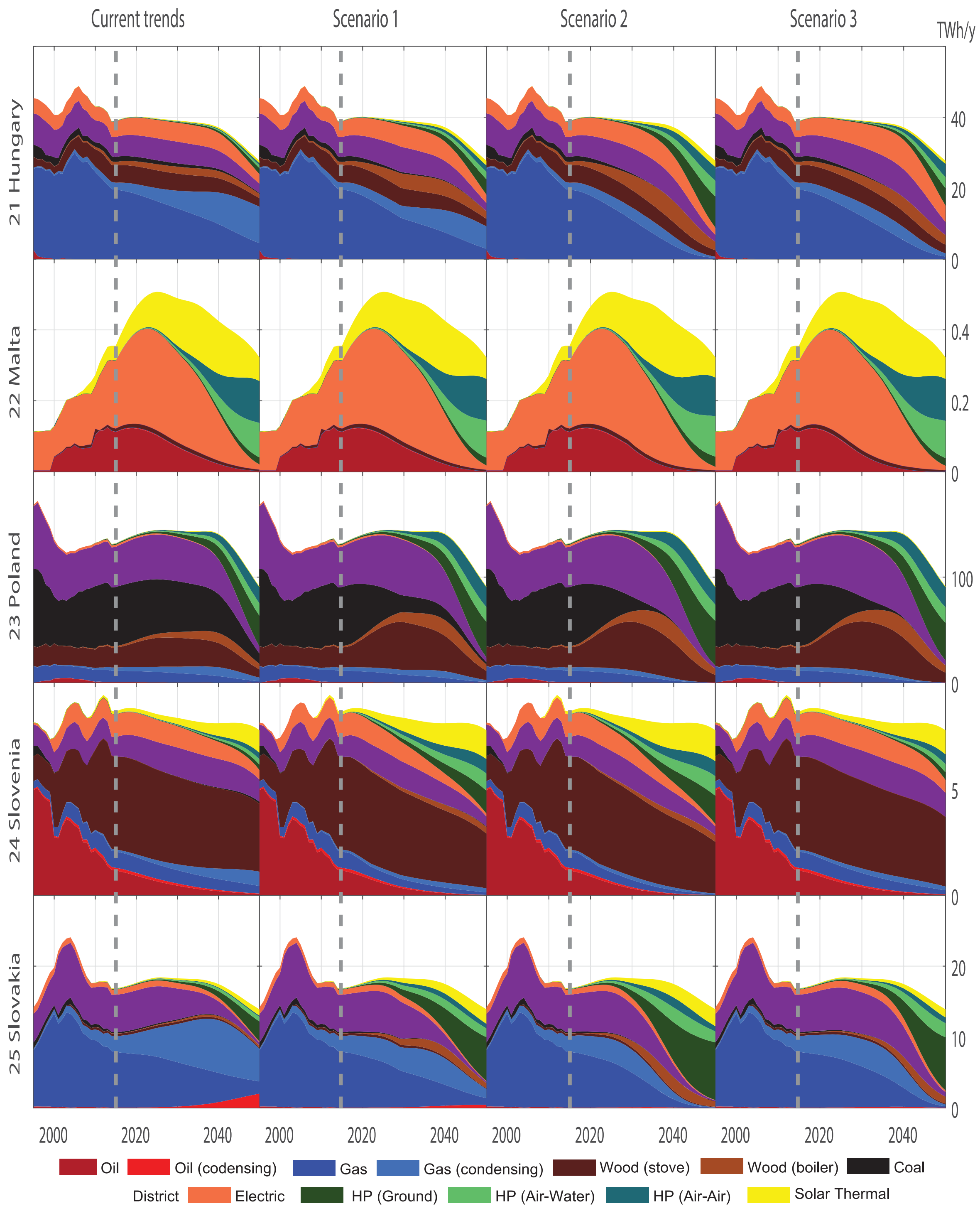

Figure 34: Projections for annual heat generation by technology (in TWh_{th}/y), part 5. Baseline projections under current trends and scenarios 1-3. Values from 2015 onwards are projections by FTT:Heat. Projections for useful energy demand for heating are taken from the EUCO30 scenario.

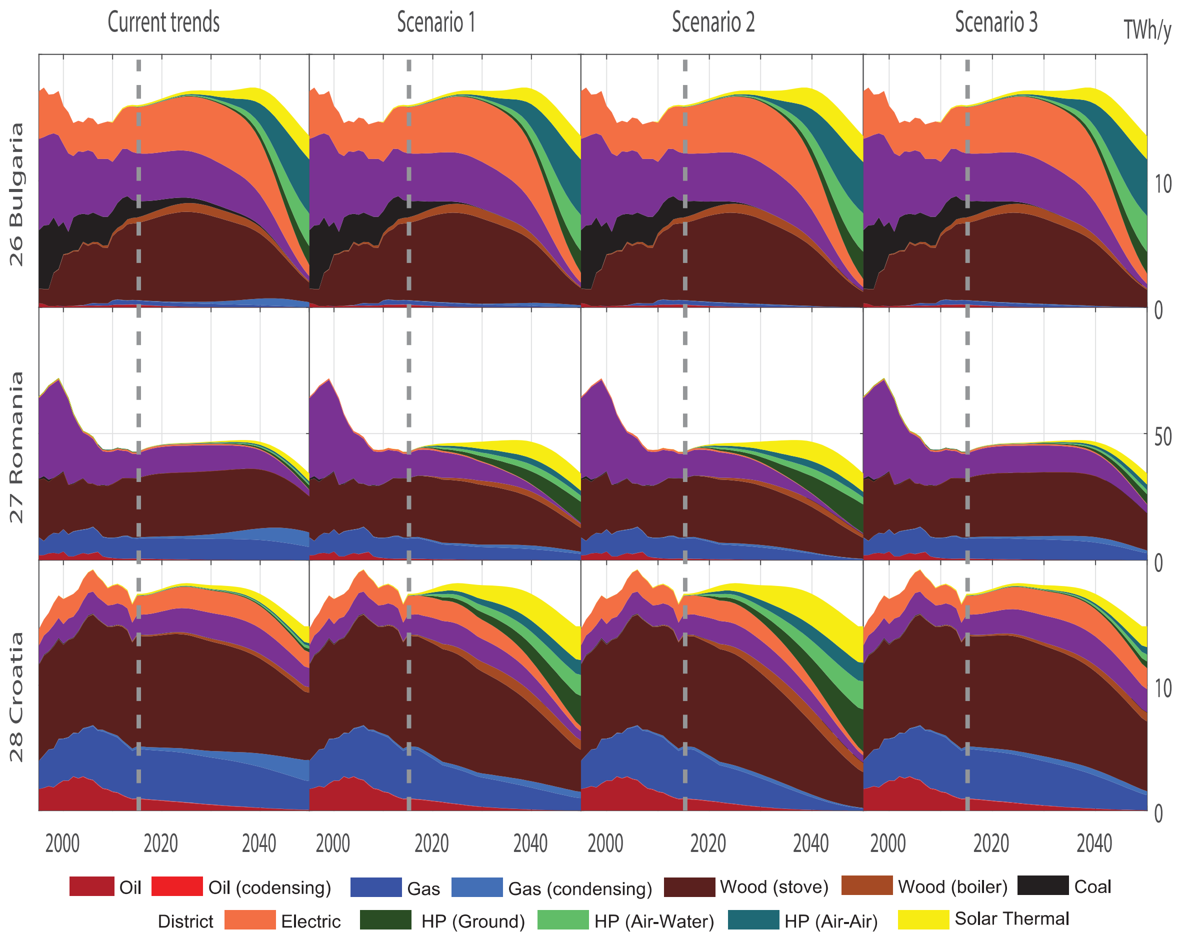

Figure 35: Projections for annual heat generation by technology (in TWh_{th}/y), part 6. Baseline projections under current trends and scenarios 1-3. Values from 2015 onwards are projections by FTT:Heat. Projections for useful energy demand for heating are taken from the EUCO30 scenario.