

FTT:Heat — A simulation model for technological change in the European residential heating sector

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ABSTRACT

We introduce a new bottom-up model for simulating Future Technology Transformations in the European residential heating sector, FTT:Heat. The model simulates the uptake and replacement of heating technologies by households in all individual Member States up to 2050, and allows to simulate the potential effect of real-world policy instruments aiming at an increased uptake of low-carbon technologies. It features an explicit representation of households' technology choices, based on observed preferences and non-linear diffusion dynamics. Decision-makers are modelled as individual households, which are subject to limited information and bounded rationality. Their decisions reflect behavioural factors and preferences at the micro level, and may result in sub-optimal outcomes from a macroeconomic perspective. For demonstration, we simulate policy mixes for reaching the EU's 2030 renewable heating targets in each Member State. Under current diffusion trends, some countries are estimated to continue an ongoing transition towards renewable heating, while others would hardly see any decarbonisation. For increasing the share of renewable heating by at least ten percentage points until 2030, 20 Member States need to introduce additional policies, the necessary stringency of which differs between countries. Due to the slow turnover of heating systems, resulting cost increases faced by households could persist over decades.

1. Introduction

Heating accounts for around half of the European Union's (EU) final energy consumption, and for 80% of the average European household's energy demand (European Commission, 2016a). Given the EU's commitment to cut its greenhouse gas emissions by at least 40% until 2030 and 80–95% until 2050 (relative to 1990), the decarbonisation of residential heating plays an important role in the block's long-term energy strategy (European Commission, 2011). Therefore, both the EU and various Member States (MS) have enacted policies aimed at heating (Connor et al., 2013; European Commission, 2014). Perhaps most prominently, the recent 'Clean Energy for All Europeans' package aims at a zero emission building stock by 2050, which should be realised by national decarbonisation roadmaps (as part of the energy performance of buildings directive, see European Commission, 2017a).

Substantial reductions in residential demand for space heating are expected to result from improved levels of building insulation (Ürge-Vorsatz et al., 2012, 2013; Lucon et al., 2014). Meanwhile, 75% of current buildings in the EU will still be in use in 2050 (IEA, 2013), and demand for water heating is less impacted by insulation measures (Daiglou et al., 2012). Therefore, overall heat demand will likely remain high, even when the building stock would undergo thermal retrofitting at an ambitious pace (Connolly et al., 2014). Further decarbonisation needs to originate from technological change, both by replacing existing heating systems by more efficient ones, and by replacing fossil fuel based boilers by renewable and electricity-based heating technologies, such as solar thermal systems and heat pumps (see e.g. IEA, 2014).

To this end, MS want to commit themselves to increase the share of renewables in final energy demand for heating (excluding electricity,

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including ambient heat) by one percentage point (p.p.) each year until 2030, whereby the specific measures are chosen on a national level (as part of the revised renewables directive, see Council of the EU, 2017; European Commission, 2016b). However, it remains unclear how such an ambitious transition towards renewables can be realised, and which specific policy instruments are necessary within each MS (European Commission, 2016a).

The design of effective strategies to reach such targets requires to more accurately simulate the outcome of different policy instruments (Li, 2017; Mercure et al., 2016b), a requirement which is also stressed in IPCC-AR5 (Kolstad et al., 2014). This, in turn, requires energy-economy models with non-idealised representations of household behaviour and dynamics of technology uptake (Clayton et al., 2015; Rai and Henry, 2016; Clarke et al., 2014). Most energy models for policy-analysis are of the cost-minimising type, aiming to identify optimal policy pathways from the normative perspective of a social planner (for reviews, see Mundaca et al., 2010; Li et al., 2015; Mercure et al., 2016a). While this is a powerful analytical approach for identifying policy targets which are technically feasible or socially desirable (to answer the question what *should* happen), it is less suited for an ex-ante simulation of policy effects (what *would* happen), since it abstracts from many real-world imperfections for the example of behavioural loss aversion, see (Knobloch et al., 2019).

Household decisions for using a certain heating technology are not necessarily identical to what is considered cost-optimal from a societal perspective. Under conditions of limited information and bounded rationality (Simon, 1955), it is unlikely that all households would immediately choose the same cost-optimal solution, immediately after it gets introduced into the market (Rogers, 2010). On a micro-level, individual decisions are heterogeneous, depending on preferences and dynamic effects of social influence (Wilson et al., 2015; Kastner and Stern, 2015; Achtnicht and Madlener, 2014; Michelsen and Madlener, 2012; Lillemo et al., 2013; Hecher et al., 2017), as well as on norms, attitudes and values (Abrahamse and Steg, 2009; Abrahamse et al., 2005; Steg, 2008; Dietz et al., 2009; Clayton et al., 2015; Stern, 1986). On a macro-level, the speed with which heating technologies can diffuse depends on the ability of industry to restructure its production and installation capacities, leading to industrial inertia and the structural resilience of dominant technologies (see Grubb (2014); Geels (2004) for general discussions, and Johansson (2017); Karytsas and Chorapanitis (2017) for the specific case of heating).

Other models of heating technology uptake in Europe have included some representation of household behaviour and preferences, mostly focusing on one or several regions. Examples for the modelling of non-idealised household behaviour for heating technology choice are the BLUE model for the UK by Li (2017) and the incorporation of household preferences into the UK TIMES model by Li et al. (2018). For the case of France, Giraudet et al. (2012) include investment barriers into a bottom-up model for space heating which is linked to IMACLIM-R, and Cayla and Maïzi (2015) represent household heterogeneity within the TIMES-Households model. Typically, such approaches aim at the inclusion of household behaviour into an otherwise still normative optimisation-framework. An alternative is the development of bottom-up models of technology choice, such as the Invert/EE-Lab model for several EU countries (Kranzl et al., 2013; Stadler et al., 2007), which is perhaps closest to our work. It represents heterogeneous household choices by means of multinomial logit functions, and includes empirically calibrated investment barriers. Further alternatives are agent-based models, such as Sopha et al. (2011) for the uptake of wood-pellet heating in Norway, and system dynamics models, such as Romagnoli et al. (2014) and Ziemele et al. (2016) for technological change within district heating networks in Latvia. Both approaches can represent the dynamic behaviour of complex feedback systems over time, and can be rich in their behavioural resolution. Due to enormous data requirements for their calibration, however, they typically focus on one region.

For the case of multi-regional energy-economy models, it has been argued that the behavioural and socio-technical elements which were identified as being relevant for technology transitions are so complex that their detailed representation in such frameworks may remain unfeasible (Li et al., 2015; Geels et al., 2016). However, we argue that at least a conceptual representation is possible, and present FTT:Heat as a new bottom-up non-optimisation model of intermediate complexity, which is at least closer to reality. To the best of our knowledge, it is the first model of this type for residential heating which covers all 28 EU countries (for an extension of the model to 59 world regions, see Knobloch et al., 2019).¹

FTT:Heat does not calculate cost-optimal pathways. Instead, it simulates likely trajectories of technology diffusion in individual countries, and possible outcomes of policies, given observed recent technological trajectories and households' decisions on technology uptake. It can be used for an ex-ante simulation of market-based and regulatory policies (as well as combinations thereof), and to assess which impacts they would have on the technology composition, fuel use, emissions, and investments. This makes FTT:Heat well-suited for an ex-ante impact assessment of policies, while remaining tractable in a larger modelling framework. It is hard-linked to the global macro-econometric model E3ME (through fuel use, energy prices and investments) (Cambridge Econometrics, 2014), which allows for economic feedbacks between the heating sector and the wider economy, and is part of the simulation-based Integrated Assessment Model E3ME-FTT-GENIE (Mercure et al., 2018b).

Conceptually, FTT:Heat is based on a stylised representation of heterogeneous household behaviour, observed choice preferences, and the non-linear characteristics of self-reinforcing technology transitions. We model households' decisions between different heating technologies based on statistically distributed parameters, which implies a diversity of choices. Non-linearities in technology growth are mathematically modelled by means of dynamic shares equations (derived in Mercure, 2015, 2012), which endogenously reproduce the typical S-shaped dynamics of technology diffusion (Wilson and Grubler, 2011; Rogers, 2010). In combination with endogenous technological learning (Grübler et al., 1999), this leads to path-dependence and potential 'lock-ins' of simulated technological trajectories (Arthur, 1989), which makes the model much more consistent with a transitions theory perspective than standard engineering-based tools (see e.g. Geels, 2002). Unlike in equilibrium models, reactions to policy changes are not fully instantaneous, so that it takes some time to steer the system towards a new direction. Inertia keeps the model in a trajectory that has momentum, and policies are used to alter the direction of the trajectory, which is henceforth maintained even if policies are removed.

For demonstration, we apply FTT:Heat for simulating policy scenarios consistent with reaching the EU's objective of increasing the renewables share in residential heating by 10p.p. until 2030, and achieving a zero emissions building stock by 2050. In a baseline scenario, we analyse the current trends of heating technology diffusion in all MS, revealing large discrepancies between countries: while some MS are on a trajectory which may allow them to achieve their 2030 objective without additional policies, others wouldn't see any substantial decarbonisation. In a next step, a mix of policies is defined which is projected to increase the share of renewables to the envisioned extent in each individual MS. Results show that the necessary policy effort hugely differs across the EU.

Section 2 describes the model and data. Section 3 introduces the simulated policy scenarios and discusses the results. Section 4 concludes. Additional information and results on the level of individual countries are provided in the Supplementary Information (SI).

¹ Note that at the time of model development, the UK was still part of the EU.

2. Methodology and data

FTT:Heat is a simulation model of technological change. It does not minimise/maximise some objective function — neither on the macro level (the social planning approach), nor on the micro level (utility maximisation of rational agents). Instead, the model simulates the diverse decisions of households: which technologies would they choose in a context of bounded rationality, and which effects could policies have? Conceptually, it is similar to other models for the power (Mercure, 2012; Mercure et al., 2014) and transport sector (Mercure et al., 2018a), using the same dynamic shares equation at its core.

Fig. 1 depicts a schematic representation of the FTT:Heat model and its integration with E3ME. Table 1 presents descriptions of the variables and abbreviations used in the model description throughout the text.

2.1. Key elements

The model is driven by the exogenous demand of households for space and water heating as an energy service, $UD_{tot,t}$, in the form of time series of useful heat demand per country. Future demand foremost depends on climatic conditions, building stock characteristics (such as levels of insulation), floor space per person, income, and individual temperature preferences (Isaac and Van Vuuren, 2009; Daioglou et al., 2012). Importantly, overall heat demand is not modelled by FTT:Heat. Instead, the model can be soft-linked to other models, from which UD_{tot} is taken as an exogenous input. In case of this paper, future trends are

Table 1

Nomenclature used in the model description.

Name	Description
%RE	Share of renewables in residential heating (in %)
b_i	Payback threshold (in years)
CE_i	Conversion efficiency (kWh of heat per kWh)
CF_i	Capacity factor (hours per year)
D_i	Final energy demand (in kWh per year)
F_{ij}	Choice-based matrix of household preferences
F(C)	Cumulative cost distribution function
f(C)	Cost distribution density
FC_i	Fuel costs (in Euro per kWh)
$GCOH_i$	Generalised cost of heating (in Euro per kWh)
γ_i	Intangible household preferences
IC_i	Upfront investment costs (in Euro per kW)
LR_i	Learning rate
MR_i	Maintenance-repair costs (in Euro per kW)
MS	Member States
p.p.	percentage point
r_i	Discount rate (in %)
S_i	Technology market share (in %)
t	Simulation period (in years)
UD_i	Useful heat demand (in kWh of heat)
τ_i	Technical life expectancy (in years)

taken from the European Commission’s EUCO30 scenario, which projects improved levels of future building insulation (see section 3.2).

The role of FTT:Heat is to simulate the technology composition over time: which heating technologies (such as oil boiler or heat pumps, see Table A4) will supply which fraction of UD_{tot} ? Initial market shares, $S_i(t = 0)$, are calculated from historical data. The model then projects their future development in each period, $S_i(t)$, based on the decision-making of households and the dynamic shares equations (see section 2.2).

The model’s core is a representation of technology diffusion, which is based on three key elements (described in more detail in the following sections):

- 1 *Distributed decision-making*: households make decisions regarding buying and replacing heating systems, choosing between available technologies. Households have diverse preferences, which we represent by means of statistically distributed parameters of technology characteristics, leading to distributed choices.
- 2 *Dynamic shares equation*: technology uptake is subject to inertia, due to bounded rationality of households, and limited production capacities of industries. There is thus an endogenous, dynamic constraint on the potential speed with which technologies can grow, resulting in the bottom-up emergence of S-shaped diffusion curves.
- 3 *Technological learning*: costs of technologies endogenously decrease with cumulative investment due to learning by doing, further amplifying the path-dependency of technology uptake over time.

In each simulation period (1/4 year), FTT:Heat first simulates the changes in market shares per technology. The new level of useful heat demand which is serviced by technology i , $UD_i(t)$, is then calculated as:

$$UD_i(t) = S_i(t) * UD_{tot}(t) \tag{1}$$

UD_i can change for two independent reasons: when the overall heat demand (UD_{tot}) changes, and when the technology composition (S_i) changes. For any heating technology i , its installed capacity is then estimated based on UD_i . Positive changes can result from an increase in its market share, and/or an increase in UD_{tot} . Negative changes either correspond to decreasing market shares, and/or an decrease in UD_{tot} .

Finally, the model calculates the resulting levels of final energy demand, fuel demand, and CO₂ emissions, based on technology-specific

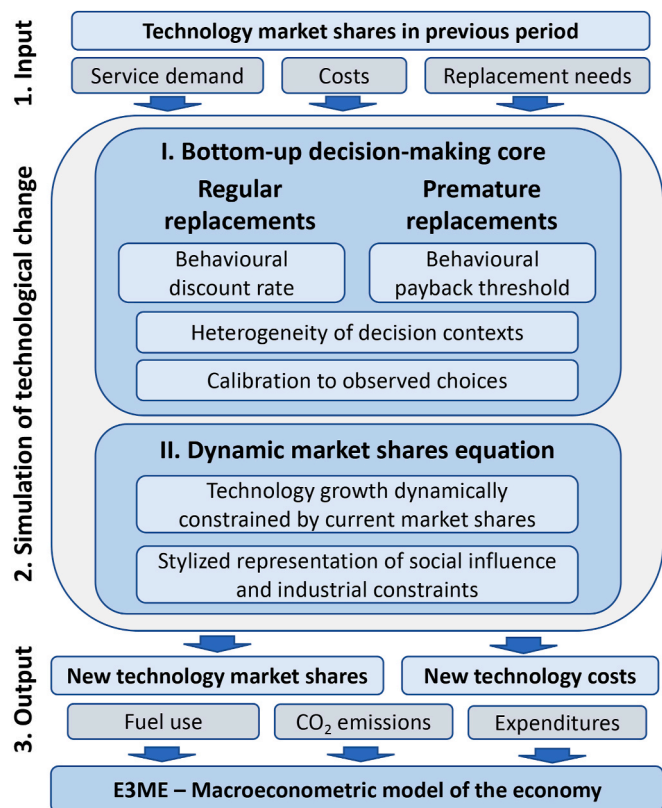


Fig. 1. Schematic representation of the FTT:Heat model and its integration with E3ME. Based on input assumptions and historic data, the decision-making core of FTT:Heat simulates technology choices by heterogeneous households from a bottom-up perspective, based on distributed technology costs and empirically observed preferences. Simulated choices result in updated technology market shares and costs (via technological learning). Projected fuel use, CO₂ emissions and household expenditures per country are fed back to the macroeconomic model E3ME, which integrates the data into its simulations of economic feedbacks.

conversion efficiencies and fuel-specific emission factors.

2.2. The decision-making model core

2.2.1. Diversity of household preferences

Households are assumed to decide in the context of different individual situations and perceptions, related to the variety of households' characteristics and preferences. In the model, we represent this diversity by means of statistically distributed technology parameters on which choices are made (e.g., upfront costs for gas heating may be lower than this technology's mean cost for one household, but larger than the mean for another household). Due to such heterogeneity, households' preferences for heating technologies are also distributed (e.g., solar thermal may be less attractive than gas on average, but still be more attractive for some households). Such diversity stems from the variability of technologies as such (e.g., varying characteristics of boilers), and the diversity of households' individual situations (such as heating behavior, building properties or available income).

Mathematically, we represent the comparison of two technologies based on heterogeneous household preferences as a comparison of two frequency distributions with unequal means (conceptually identical to a binary logit). When the mean cost difference between heating technologies starts to decrease, an increasing share of households may start to prefer the alternative technology. Because all households slightly differ in their individual characteristics and perspectives, they make different decisions at different points in time for different reasons. Distributed choices in combination with gradual cost decreases partly explain how the model projects gradual profiles of technology adoption, similar to the S-shaped trajectories which have been empirically described for a wide range of technologies (Rogers, 2010). This approach enables us to avoid using a normative optimisation algorithm to represent the decision-making process, and its conceptual limitations. A gradual substitution between technologies can also take place when costs remain constant, driven by the self-reinforcing dynamics of the dynamic shares equation (see section 2.3.1).

2.2.2. The generalised cost of heating

In each period, a subset of households is assumed to evaluate a subset of technology options (the ones they know of and have access to, see section 2.3.1), based on their respective generalised cost of heating ($GCOH_i$). It is defined as the present value cost of operating a heating system of technology i throughout its technical lifetime, normalised for the production of one unit of heat per year, including non-monetary preferences:

$$GCOH_i = \sum_t \frac{IC_{i,t} + \frac{MR_{i,t}}{CF_i} + \frac{FC_{i,t}}{CE_i}}{(1+r)^t} \Bigg/ \sum_t \frac{1}{(1+r)^t} + \gamma_i \quad (2)$$

IC_i , MR_i and FC_i are upfront investment costs, maintenance-repair costs, and fuel costs. CF_i is a technology's capacity factor, and CE_i its conversion efficiency. γ_i is an empirical parameter which captures 'intangible' cost components and households preferences (see section 2.2.3). r is a discount factor. Importantly, it is not an implicit discount rate (such as estimated by Hausman, 1979; Train, 1985, based on observed market outcomes), and not meant as a cumulative representation of investment barriers (for a discussion of conceptual differences, see Schleich et al., 2016). Instead, it expresses the relative importance of future compared to present costs, as measured in choice experiments (e.g. Rivers and Jaccard, 2006). Policies can be added on top of the basic cost components of $GCOH_i$, such as subsidies on a technology's investment costs, or a fuel tax.

$GCOH_i$ is not meant to be a factual description of how households evaluate the costs and benefits of different technologies. Rather, it is a conceptual representation which allows to incorporate the relevant (known or estimated) decision parameters, and to make them compa-

table across technologies. To account for the heterogeneity with which households perceive and evaluate such characteristics, several terms in $GCOH_i$ are distributed. The variation of investment costs reflects the diverse individual characteristics of different buildings and households, such as different installation and replacement costs, or costs of adaptive measures when switching between technologies. The cost distributions of FC_i and MR_i reflect the volatility of (expected) energy prices and maintenance costs. The overall standard deviation, $dGCOH_i$, is obtained by combining all standard deviations of individual parameters, as the root of the sum of their squares (the standard error propagation method):

$$dGCOH_i = \sqrt{\frac{dIC_i^2}{CF_i^2} + \frac{dMR_i^2}{CF_i^2} + \frac{FC_i^2}{CE_i^2}} \quad (3)$$

2.2.3. Intangible household preferences

Households' preferences for heating technologies can be influenced by a wider set of factors, not all of which are explicitly specified in $GCOH_i$. People may perceive certain technologies as less/more convenient or attractive than other technologies, for various reasons, not necessarily related to pure costs.

In FTT:Heat, we define such components as 'intangibles'. Their technology- and country-specific value is an empirical parameter, γ_i , which we derive from historical data on technology uptake. The parameter captures the difference between the observed diffusion in historical data, and diffusion as projected by the model from the available data. It ensures that at the beginning of the simulation, the projected rates of technology diffusion are consistent with the historical rates.

We estimate γ_i by means of a two-step calibration process: first, FTT:Heat is run with $\gamma_i = 0$ for all technologies, solely based on the engineering cost components. For each MS, we then compare the projected future growth of all technologies with their respective historic diffusion trend in the data, using a graphical interface. In case of deviations, the values of γ_i are adjusted iteratively, until the empirical trend (from historic data) is consistent with the projected trend at the simulation start (as modelled by FTT:Heat). The approach is roughly similar to the empirical estimation of monetary equivalents for 'soft barriers' by Stalder et al. (2007).

The resulting parameter, γ_i , is an empirical estimate of household preferences which are not covered by the basic cost components. It is technology- and country-specific, and added as a cost-equivalent constant value to a technology's levelised cost of heating (see section 2.2.2). Due to their empirical estimation from recent diffusion trends, the 'intangibles' also implicitly include any policies which are unspecified in the explicit model assumptions, but had an impact on the historically observed uptake of technologies.

Typically, our results suggest that oil, gas, district and electric heating are more attractive to households than suggested by the pure costs, resulting in negative values of γ_i (around -10% to -15%, relative to the pure cost, up to -30% for electricity). Meanwhile, the data suggest that biomass and coal are perceived as less convenient, with typical values of γ_i between +40% to +80%.

The estimated values of 'intangibles' are not necessarily static, but may well change over time, due to changing preferences or policy frameworks. However, as a re-estimation is impossible before new data becomes available, we assume that the historically calibrated 'intangibles' remain constant over the whole simulation period. This implies that our model projections are relatively more uncertain for the longer term, if 'intangibles' should be subject to change under different future conditions.

2.2.4. Pairwise comparisons

Decision-making by households is represented as a pairwise comparison of all available heating technologies, similar to discrete choice

theory (Ben-Akiva and Lerman, 1985). Within each simulation period, for each pair of technologies within a region, the model compares the distributions of their generalised cost of heating ($GCOH_i$). The share of households that – in this period – prefers technology i over technology j is equal to the share of households for which the generalised cost of heating with technology i is less than the generalised cost of heating with technology j . Mathematically, this fraction equals an integral, which can be calculated as

$$F_{ij}(\Delta C_{ij}) = \int_{-\infty}^{\infty} F_j(C) f_i(C - \Delta C_{ij}) dC, \quad (4)$$

where ΔC_{ij} is mean difference in generalised cost and ‘intangible’ preferences between two technologies:

$$\Delta C_{ij} = GCOH_i - GCOH_j. \quad (5)$$

$F(C)$ and $f(C)$ are the cumulative cost distribution function and the cost distribution density, respectively. Evaluating the integral yields the classic binary logit. The standard deviation can be treated using the standard error propagation method:

$$F_{ij} = \frac{1}{1 + \exp(\Delta C_{ij}/\sigma_{ij})}, \quad \sigma_{ij} = \sqrt{\sigma_i^2 + \sigma_j^2}. \quad (6)$$

The resulting choice is stored in the probabilistic choice-based matrix of household preferences, F_{ij} . For example, if 20% of households prefer technology i over j in a pair, then $F_{ij} = 0.2$ and $F_{ji} = 0.8$. The model performs this comparison of frequency distributions for all possible pairs of heating technologies, which results in a complete order of distributed household preferences between all heating technologies.

2.3. Diffusion dynamics as a result of decision-making

Mean agent preferences and actual diffusion are related but not necessarily equal, due to technical lifetimes, limited information and bounded rationality on part of households, and due to limited production capacity for new technologies.

Fundamentally, the potential speed of changes in the technology composition depends on the useful lifetimes of heating systems — for how many years they ‘survive’.

In the model, households can replace their heating system for two different reasons:

1. End-of-lifetime replacements: a heating system needs replacement when it comes to the end of its technical lifetime.
2. Premature replacements: a household may perceive it as uneconomical to continue the operation of a system that is still in working condition, and may therefore decide to replace the system prematurely.

2.3.1. End-of-lifetime replacements

In case of end-of-lifetime replacements, the annual fraction of ‘break downs’ for any technology of category j can be approximated by dividing its total population (S_j) by its average technical life expectancy, τ_j . For each year of the simulation, the replacement need for any technology j is thus estimated as $S_j \tau_j^{-1}$.

When it comes to the point that technology j ‘breaks down’ and a household needs to choose between competing technologies, the fraction of households who would prefer the (competing) technology i over the (incumbent) technology j equals F_{ij} (resulting from pair-wise technology comparisons under distributed choice characteristics, see section 2.2.4) — assuming that the household has the necessary information on and access to technology i . Thus, in any simulation period Δt , the *hypothetical* substitution of technology j by an alternative technology i is given by:

$$\Delta S_{ij} = F_{ij} S_j \tau_j^{-1} \Delta t \quad (7)$$

However, households only choose what they know of and have access to, which is a subset of all technology options. In empirical studies, it is found that household choices are informed by their peers and what they see being used (Rogers, 2010; Abrahamse and Steg, 2013; McShane et al., 2012; Frederiks et al., 2015; Mahapatra and Gustavsson, 2008), while industry growth coevolves with the growth in demand (Grubb, 2014; Johansson, 2017; Karytsas and Chorapanitis, 2017). Both the available first-hand information (obtained from peers) and capacity (built out of an industry’s previous profits and experience) tends to be larger for dominant incumbent technologies, while new entrants compete from a position where only few people have the necessary experience for evaluating, producing and setting up the new technology. We approximate these dynamics in stylised form, as being proportional to the competing technology i ’s current market share, S_i (derived in Mercure, 2015). Therefore, the *realised* substitution of technology j by an alternative technology i is smaller than the *hypothetical* substitution, and given by:

$$\Delta S_{ij} = S_i F_{ij} S_j \tau_j^{-1} \Delta t \quad (8)$$

The introduction of S_i acts as a *dynamic* growth constraint, which evolves fully endogenously during the model simulation, resulting in the bottom-up emergence of S-shaped diffusion profiles which are so typical for the uptake and growth of new technologies (Rogers, 2010). This is an important difference to most other bottom-up energy models, where growth-constraints tend to be imposed ad-hoc on a case-by-case basis (to avoid abrupt changes in technology uptake), often at the (subjective) discretion of the modeller.

To obtain the net change in the market share of any technology i , we sum over all possible pairs of substitutions between two technologies j and i , and obtain the dynamic shares equation:

$$\Delta S_i = \sum_j S_i S_j (F_{ij} \tau_j^{-1} - F_{ji} \tau_i^{-1}) \Delta t \quad (9)$$

Here, the net change of market shares of technology i is regulated by the matrix F_{ij} , minus its transpose. It is a standard representation of the process of selection (similar to the replicator dynamics equation of evolutionary game theory, see Hofbauer and Sigmund, 1998), identically used in evolutionary biology and economics. Three key elements determine the dynamics behind every substitution of a technology j by an alternative technology i :

1. Replacement needs: which fraction of technology j ’s stock needs to be replaced within period Δt , based on its average lifetime ($S_j \tau_j^{-1}$)?
2. Household preferences: if households need to choose a heating system within period Δt , how many of them would hypothetically prefer technology i over technology j (given by F_{ij}), given the context and policies?
3. Share dynamics: which fraction of hypothetical technology substitutions can be realised (dynamically constrained by S_i)?

The third element above is a key difference between FTT:Heat and normative optimisation models. Without the share dynamics, there would be an implicit assumption that (i) households always have all the necessary information on all heating technologies, and that (ii) the production and installation of any technology could be immediately scaled up, without any supply constraints. In reality, however, some households may not have (trustworthy first-hand) information on technology i , while the technology may be completely unavailable to other households (due to a lack of industry capacity for producing and setting up the technology). Therefore, new technologies can only grow gradually. Over time, their changes in relative market shares follow the typical S-shaped trajectory of technology diffusion (Grübler et al., 1999; Sovacool, 2016). This property is reflected in the mathematical

formalism given here, which ensures that growth of technologies is proportional to their current market share, and the shares of other technologies.

Accordingly, technological change in the model simulations cannot occur instantaneously, but the *trajectory of technological change* is subject to inertia. On the one side, this implies that the full effects of changing prices or policies cannot be observed immediately, since it takes time to change the trajectory. On the other side, the inertia of the technology trajectory means that the technology composition can keep on changing, even when all prices are held constant. As a simulation model with such properties, FTT:Heat can therefore not identify ‘optimal’ technology portfolios (from a normative planning perspective). Instead, it aims at projecting the evolution of the market, which is particularly important for evaluating the potential effects of different policies (from the perspective of an impact assessment).

2.3.2. The dynamics of premature replacements

Apart from end-of-lifetime replacements, a household may decide to prematurely replace a heating system that is still in working condition – to ‘scrap’ it. Hypothetically, a completely rational decision-maker with perfect information and zero risk-aversion would constantly compare the marginal running costs of his currently installed technology with the full costs of buying and operating any alternative heating system. A premature replacement would then be profitable when the former exceed the latter.

In reality, empirical evidence shows that most households only consider such a premature replacement if the potential savings exceed the necessary upfront investment within a relatively short period of time (Newell and Siikamäki, 2015; Olsthoorn et al., 2017). For heating systems, such a ‘payback time’ describes the number of years before which the reduced energy costs would have ‘paid back’ the initial investment. The payback threshold describes the maximum payback time for which a household would still perceive the investment as attractive. Empirical studies regularly find that such thresholds are usually much lower than a technology’s technical lifetime (only a fraction of potential savings is taken into account, see Gillingham and Palmer, 2014; Knobloch and Mercure, 2016; Sorrell, 2004). For the case of prematurely replacing an existing boiler, Olsthoorn et al. (2017) have conducted choice experiments with 15,000 households in eight EU countries.² The reported mean payback threshold is as low as three years, with a standard deviation of one year.

In the model, the premature replacement of a working system is thus only simulated as being sufficiently attractive if the potential savings (from reduced operating costs, MC_i) exceed the necessary investment costs of an alternative technology (inclusive of subsidies) within the defined payback time, b :

$$(MC_j - MC_i) > IC_i / b \quad (10)$$

This is a much stricter condition to fulfil, since the household ignores all savings that occur beyond the considered payback period, b . As for end-of-lifetime replacements, the comparison is performed over all pairs of technologies, yielding the *hypothetical* household preferences for premature replacements. The *realised* premature replacements are calculated based on the dynamic shares equation, and subject to the same constraints (see section 2.3.1).

2.4. Learning and cost reductions

We represent endogenous technological learning as a process of ‘learning by doing’, in which the investment costs of a heating technology (IC_i) decrease with the cumulative installation of such heating systems over time. By permanently changing the cost structure, this

further amplifies the path-dependence of technology transitions (Grübler et al., 1999; Arthur, 1989). Cost reductions are endogenously calculated based on learning curves:

$$IC_i(t) = IC_{0,i} \left(\frac{W_i(t)}{W_{0,i}} \right)^{-\beta_i} \quad (11)$$

$W_i(t)$ is the cumulative produced capacity of technology i at time t . $IC_{0,i}$ and $W_{0,i}$ are initial costs and cumulative technology capacity at the start of the model simulation. β_i is the learning exponent, which is derived from the technology-specific learning rate: $\beta_i = \ln(1 - LR_i) / \ln(2)$, where LR_i is the learning rate (set to values from Weiss et al., 2010; Henkel, 2012, see Table A4).

2.5. Integration with E3ME

FTT:Heat is dynamically integrated with the global macro-econometric model E3ME (Cambridge Econometrics, 2014), which is consistent with FTT:Heat in its underlying philosophy and assumptions (Mercure et al., 2019). Notably, E3ME is a simulation model rather than an optimisation model, and accounts for fundamental uncertainty.³ The dynamic feedbacks between FTT:Heat and E3ME foremost work through fuel use, energy prices and household expenditures (Mercure et al., 2018b). Any changes that occur in residential heating can potentially impact other economic sectors (such as electricity generation or fossil fuel extraction), which are represented in E3ME. When simulating new policies, the integration of both models allows to analyse induced changes throughout the economy, as well as the resulting impact on economic indicators (such as employment).

2.6. Data

2.6.1. Final and useful energy demand by country

For estimating the current trends in technology diffusion, FTT:Heat requires disaggregated historical data on useful heat generation per technology, for each MS. Since such disaggregated time-series on energy end-use are not readily available, we compiled a new database, which is made available as SI.

The main data input is final energy demand for residential heating by fuel type, which is available in the ODYSSEE database (Enerdata, 2017). Data on heat generation by heat pumps over time is taken from the European Heat Pump Association (EHPA) (2016), supplemented by the EurObserv'ER (2017) database. For solar thermal heating, we compiled time-series from the annual reports of the IEA Solar Heating & Cooling Programme (2017).

In the case of oil and gas, the final energy demand per fuel is further sub-divided between conventional and condensing boilers, based on their relative share in the installed capacity (as reported by European Commission, 2017b). For biomass, the final energy demand is sub-divided between conventional biomass systems and modern biomass systems with higher efficiency, such as biomass boilers, based on capacity shares from Fleiter et al. (2016).

The resulting time series of final energy demand per technology ($D_i(t)$) are transformed into time series of estimated useful energy demand ($UD_i(t)$), based on technology-specific conversion efficiencies

³ Fundamental uncertainty is distinguished from pure risk in that uncertainty cannot be quantified using probabilities, while risk can (Knight, 1921; Keynes, 1921). Given the existence of ‘unknown unknowns’, it is not possible to optimise the decision-making process, and agents either make decision errors, or plan ahead for uncertain outcomes. In the model formulation of E3ME, fundamental uncertainty implies that while the identity of supply and demand matching is observed, there is no constraint that demand equals potential supply. It is thus possible for there to be unused resources, for example unemployed workers, unused equipment or financial capital, which can be brought in for production if the demand requires it.

² France, Germany, Italy, Poland, Romania, Spain, Sweden, UK.

(CE_i) (see A.4):

$$UD_i(t) = D_i(t) * CE_i \tag{12}$$

2.6.2. Technology data

Table A4 shows the assumed technology-specific data for all heating technologies: upfront investment costs (including installation costs), maintenance and repair costs, conversion efficiencies, learning rates, and lifetimes.

Cost levels for buying and installing heating systems are different in each MS (for example, due to local variations in building codes or wages). For each country, we converted the stated mean costs to country-specific values based on relative cost differences for buying and installing across countries, taken from Connolly et al. (2013) and Fleiter et al. (2016).

For the representation of distributed costs, a standard deviation of 1/3 of the mean costs is assumed for all technologies, based on the cost ranges given by the Danish Energy Agency (2013, 2016) and the National Renewable Energy Laboratory (2016).

Capacity factors are constant and calculated based on the European Commission's (EC) reference values for annual active mode hours of heating systems in colder, average and warmer climate conditions (European Commission, 2013). The capacity factor of solar thermal heating systems is defined as the country-specific solar yield: the amount of useful heat generated by every unit of installed capacity, which is influenced by different levels of solar irradiation. For each MS, we calculated the respective factors based on data from the IEA Solar Heating & Cooling Programme (2017).

3. Results and discussion

3.1. Policy scenarios

This section introduces several scenarios: a current technology and policy trends scenario, and three policy scenarios aiming at the increased uptake of renewable heating technologies by households (see Table 2).

3.1.1. Current technology trends

In the current technology and policy trends scenario, we assume that historical trends in technology diffusion are maintained, implicitly including the impact of existing policies (the impact of which on technology choices is implicitly captured by the 'intangible' cost parameters, which were derived from the recent diffusion data). Importantly, due to the ongoing diffusion, some MS may therefore see increasing shares of renewables without the implementation of additional policies.

Table 2

Overview of scenarios 1–3 and simulated policies by group of Member States, from 2018–30 and 2030–50. 'X' indicates that a policy is implemented for a group of Member States in the given period.

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 (until 2022)				X				
Scenario 2	Carbon tax		X	X	X	X	X	X	X
	Upfront subsidy (until 2040)			X	X	X	X	X	X
	Kick start policies (until 2022)				X				
Scenario 3	Carbon tax	X	X	X	X	X	X	X	X
	Upfront subsidy								
	Kick start policies								

Furthermore, projections on future levels of residential heat demand take into account improved levels of building insulation, as projected in the EC's EUCO30 scenario (see section 3.2).

3.1.2. Scenario 1: increasing the share of renewables until 2030

For each MS, we simulate a policy mix which aims at increasing the share of renewables in residential heating (%RE) by at least 10p.p. until 2030. This policy objective is loosely based on the EC's recent RES directive proposal (European Commission, 2016b), which aims at a higher penetration of renewable heating in all MS. The policy instruments for reaching the target can be flexibly chosen by each country. %RE is defined here as the share of renewable heating technologies (solar thermal, biomass and heat pumps) in a MS's final energy demand for residential heating, excluding electricity (both in the numerator and the denominator).⁴

For each MS which is not projected to reach the 2030 objective in the current trends scenario, we impose one or more of the policies below. These were identified as being relevant in discussions with policy-analysts from the EC,⁵ based on what already exists and is described in the literature (Connor et al., 2013; Cansino et al., 2011; European Commission, 2014):

1. A new carbon tax of 50€/tCO₂ on the residential use of coal, oil and gas is introduced from 2018 onwards. The value is well within the range of carbon price estimates for 2020 in IPCC-AR5 scenarios for limiting CO₂ concentrations to 450ppm (Clarke et al., 2014), and similar to residential carbon taxes in place to date.⁶ In each year until 2030, the tax increases linearly by 10% (by +5€/tCO₂). In scenario 1, the tax is discontinued from 2030 onwards (in order to analyse which long-term impacts the policy may induce post-2030).
2. A 30% upfront capital subsidy on renewable heating technologies. Between 2018 until 2030, the purchase and installation of solar thermal, modern biomass and heat pump systems is subsidized by 30% of the mean pre-subsidy cost. In scenario 1, the subsidy ends in 2030.
3. 'Kick start' procurement policies for renewables-based heating technologies are introduced in MS in which such technologies currently have very low market shares (or are entirely absent). It is assumed that for a period of five years (2018–2022), each year the government (local or national) in the respective country replaces between 0.25–1p.p. of the dominant technology's market share by a mix of renewables.⁷ The policy targets the tendency that a new technology's take-up tends to be faster when its current market share is larger (see section 2.3.1), and thus nucleates a diffusion process by promoting the expansion of a whole supply chain (e.g. local dealers, maintenance firms), itself improving the availability of these technologies where previously unavailable.

Importantly, each MS has different market conditions and technology compositions. Therefore, different country-specific mixes of policy

⁴ The 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). In the case of heat pumps, only the renewable component in the form of ambient heat (and not the electricity input) is counted.

⁵ FTT:Heat was developed as part of a project for the EC, Directorate-General for Energy (DG ENER). The simulated policies and scenarios were hence identified and discussed during multiple meetings with policy-analysts from DG ENER, based on the policies' expected relevance within the European context.

⁶ Such as in France, where the residential carbon tax rate is set to be 44.6€/tCO₂ in 2018, linearly increasing to 100€/tCO₂ in 2030 (Republique Francaise, 2015).

⁷ An example would be the purchase and installation of heat pumps or solar thermal systems in publicly owned residential buildings, initiated by city councils.

instruments can be necessary to reach the same objective in different MS, in line with local conditions. Accordingly, not all policies are applied in the same way to all MS. Instead, we assign each country to one of four groups (A to D), following a stepwise procedure:

1. *Group A*: MS which the model projects to meet the target under current technology diffusion trends, without any additional policies.
2. *Group B*: MS which the model projects to meet the target when introducing the carbon tax as the only new policy.
3. *Group C*: MS which the model projects to meet the target when combining the carbon tax with upfront subsidies.
4. *Group D*: MS which the model projects to stay below the 2030 target, even when combining the carbon tax with upfront subsidies. To increase the availability of renewable heating technologies in such countries, we introduce 'kick start'/procurement policies as an additional instrument.

3.1.3. Scenario 2: deep decarbonisation by 2050

The policy objective is an almost-complete decarbonisation of residential heating in the EU, achieving near-zero on-site CO₂ emissions by 2050, as envisioned in the EU's 'Clean Energy for All Europeans' package (European Commission, 2017a). Until 2030, the policies are identical to scenario 1. From 2030 onwards, both the carbon tax and the upfront capital subsidies are extended to all MS. The carbon tax is set to 110€/tCO₂ in 2030, eventually reaching 210€/tCO₂ by 2050. The subsidy rate linearly decreases to zero in 2040.

3.1.4. Scenario 3: EU-wide carbon tax

We simulate an EU-wide carbon tax on the residential use of fossil fuels as the only new policy instrument in this scenario, in order to contrast other scenarios with policy mixes. In all MS, the tax starts at 50€/tCO₂, and linearly increases by +5€/tCO₂, eventually reaching 210€/tCO₂ by 2050. There is no particular policy objective. Instead, the focus is on the comparative analysis of effects.

3.2. Assumptions

All assumptions are chosen to be consistent with the EU's current climate policy objectives. Future trends of useful heat demand per MS (UD_{tot}) are taken from the EC's EUCO30 scenario (E3mlab/NTUA and IIASA, 2016), which models pathways for achieving the EU's 2030 climate and energy targets. The scenario provides estimates for annual levels of residential heat demand up to 2050 (see SI-Figs. 3–8 for the trends per MS), which we use as an input. On average, the projected reduction of UD_{tot} is around -1% in 2030, and -30% in 2050, foremost due to improved levels of thermal insulation. We also use the EUCO30 scenario projections for future trends in EU fuel prices (depicted in SI-Fig. 1), which are applied to historical fuel prices in each MS. Because future fuel prices are particularly uncertain in a context of decarbonisation policies, we assume constant prices between 2030–2050.

Note that the EUCO30 scenario results from long-run economic projections with the GEM-E3 model and estimates of energy balances using the PRIMES model, which are partly based on different modelling assumptions than the E3ME model (Mercure et al., 2016a). However, both GEM-E3 and E3ME are typically used in tandem for energy policy assessment in the EU, and both were also used for the assessment of the EUCO scenarios. For this, the models are calibrated to generate a consistent baseline, and are thus consistent in their data inputs (Pollitt et al., 2017). This calibration does not influence endogenous model dynamics, and does not cover the FTT models of technology diffusion.

In all scenarios, we model a regulatory phase-out of lower-efficiency oil and gas boilers, reflecting the EU energy efficiency regulations.⁸ For

the electricity sector, we model a decarbonisation trajectory consistent with the EU's Energy Roadmap 2050 (European Commission, 2011): an absolute emission reduction of -70% by 2030, and -90% by 2050 (relative to 1990), simulated by FTT:Power (Mercure et al., 2014).

For all MS, the discount rate is set to 10%. For premature replacements of heating systems, the mean payback threshold is set to three years, with a standard deviation of one year (Olsthoorn et al., 2017).

Following Kranzl et al. (2013), we assume that households would not opt for heating systems with a significantly lower comfort level than their existing system, and would therefore only choose coal or low-efficiency biomass stoves if either of the two is their currently used technology.

Because solar heating is dominantly used for water heating (and only as a supplementary source for space heating), we exogenously restrict its market share in each MS to the share of water heating in its total heat demand.

In E3ME, we specify that new carbon tax revenues are first used to finance the subsidies for renewable heating (within the respective MS). A potential surplus is used to reduce the employers' contribution to social security payments.

3.3. Results

3.3.1. Identification of country groups

Table 3 shows the projections for the share of renewable residential heating (%RE) in all MS, both under current trends, and when introducing additional policies. Fig. 2 provides examples of technology diffusion and heating emissions trends for five countries (two from group A, and one each from groups C–D), which together account for around two thirds of current EU-wide residential heat demand.

In the projection under current trends of technology diffusion, we find that in eight MS, the technology trajectory may lead to an increase in their renewable heating share (%RE) by at least 10p.p. until 2030, without implementing new policies: Greece, Spain, France, Ireland, Portugal, Estonia, Cyprus, and Malta. The projected increases result from the ongoing uptake of renewables in these countries, as reflected in the historical data (see Fig. 2). These MS together form country group A. The reason for these countries to reach the objective without new policies is as follows.

In Greece, Portugal, Spain, Cyprus and Malta, the model projects further increases in heat generation by solar thermal, which benefits from relatively high levels of solar irradiation in these five MS. Until 2030, the technology is projected to grow by 7–15p.p. without additional policy support, starting from market shares between 3% (in Spain) and 32% (in Cyprus) at the begin of the model simulation. In France⁹ and Estonia, meanwhile, the model projects a further diffusion of heat pumps, which have relatively large (and growing) market shares in both countries (around 15%). In Ireland, the projected growth in renewable heating can be explained by an ongoing substitution of coal and oil-based systems by modern biomass systems, and some growth of heat pumps and solar thermal.

Belgium, Italy, Czech Republic, Poland and Bulgaria constitute country group B. Due to the ongoing diffusion trajectory of certain technologies, the five countries would already undergo some decarbonisation under current trends, increasing their projected %RE between 6p.p. (in Belgium) and 9p.p. (in Italy). For achieving a 10p.p. increase, introducing the new carbon tax in 2018 is therefore projected to be a sufficient policy instrument.

Denmark, Germany, Austria, Finland, Sweden, Latvia, Lithuania and Hungary constitute country group C. For different reasons, the carbon

⁸ <https://ec.europa.eu/energy/en/topics/energy-efficiency/energy-efficient-products/heaters>.

⁹ Consistent with this analysis, the French government has recently adapted its renewable heating target to an increase by 20p.p. until 2030 (instead of 10p.p.) (Republique Francaise, 2018).

Table 3

Residential heat demand (UD, in TWh) and shares of renewables in residential heating (%RE) by MS. Last historical observation for %RE (2014) and projected increases between 2018–2030 (in p.p.), in the FTT:Heat current trends projection and in policy scenarios 1–3.

Group	Country	Heat demand		Projected increase in %RE		
		2014 (TWh _{th})	%RE 2014	Current trends	Scenario 1	Scenario 3
A <i>no new policies</i>	Cyprus	2	59%	+15p.p.	+15p.p.	+19p.p.
	Estonia	8	52%	+10p.p.	+10p.p.	+11p.p.
	Ireland	21	5%	+11p.p.	+11p.p.	+19p.p.
	France	309	33%	+12p.p.	+12p.p.	+17p.p.
	Greece	30	42%	+22p.p.	+22p.p.	+26p.p.
	Malta	0,4	25%	+30p.p.	+31p.p.	+39p.p.
	Portugal	11	58%	+21p.p.	+21p.p.	+23p.p.
	Spain	83	34%	+15p.p.	+15p.p.	+23p.p.
B <i>carbon tax</i>	Belgium	64	9%	+6p.p.	+10p.p.	+9p.p.
	Bulgaria	16	59%	+9p.p.	+10p.p.	+10p.p.
	Czech Republic	49	29%	+8p.p.	+13p.p.	+13p.p.
	Italy	210	34%	+9p.p.	+15p.p.	+14p.p.
	Poland	131	18%	+9p.p.	+27p.p.	+27p.p.
C <i>carbon tax + subsidies</i>	Austria	52	49%	+6p.p.	+14p.p.	+8p.p.
	Denmark	38	31%	+4p.p.	+10p.p.	+5p.p.
	Finland	49	49%	+7p.p.	+13p.p.	+7p.p.
	Germany	460	16%	+4p.p.	+13p.p.	+7p.p.
	Hungary	39	19%	+4p.p.	+13p.p.	+8p.p.
	Latvia	11	55%	+3p.p.	+10p.p.	+4p.p.
	Lithuania	11	48%	+4p.p.	+10p.p.	+6p.p.
	Sweden	66	45%	+5p.p.	+13p.p.	+5p.p.
D <i>carbon tax + subsidies + 'kick start'</i>	Croatia	17	60%	+1p.p.	+11p.p.	+2p.p.
	Luxembourg	2	1%	+2p.p.	+11p.p.	+3p.p.
	Netherlands	87	6%	+2p.p.	+11p.p.	+3p.p.
	Romania	43	61%	0p.p.	+12p.p.	+1p.p.
	Slovakia	17	3%	+2p.p.	+13p.p.	+3p.p.
	Slovenia	9	63%	+2p.p.	+10p.p.	+4p.p.
	UK	309	6%	+1p.p.	+12p.p.	+2p.p.

tax is projected to be insufficient for reaching the 2030 %RE objective on its own. In MS with strong dominance of fossil fuel technologies (such as Germany and Hungary), their market position is so dominant that additional incentives are needed to break their current 'lock-in'. In most of Scandinavia and the Balticum, fossil fuel technologies only have small shares in the decentralised heating market, which explains the limited potential effect of residential carbon taxes. Effectively, decentralised renewables can only grow in those countries at the cost of district heating, the decarbonisation of which could be a viable alternative (which is not simulated here¹⁰). The combination of the carbon tax with subsidies for renewable heating, however, is able to alter the diffusion trajectory, such that all eight MS are projected to achieve the %RE objective.

In the seven MS of group D, even the combination of price-based policies would be insufficient for reaching the %RE target, according to the model projections: Luxembourg, Netherlands, UK, Slovenia, Slovakia, Romania and Croatia. Apart from traditional biomass, renewable heating technologies have only had very low historical market shares in those countries. This hurdle could be overcome by 'kick start'/procurement policies (as 'technology push policies', in order to make these technologies more widely available), in order to supplement taxes and subsidies (as 'market pull policies', in order to make these technologies economically competitive): by nucleating an initial market by means of procurement schemes (e.g., installing systems in publicly owned residential houses), they help to create the necessary awareness and experience in households, industry and the entire supply-chain (they help to develop the entire socio-technical system surrounding these technologies), thereby making price-based policies more effective.

¹⁰ An accurate representation of technological change within district heating networks would require a separate model of district heat plants, similar to simulating technological change in electricity generation, which is beyond the scope of this model.

The case of group D points to the relevance of policy interactions. On paper, the combination of a carbon tax and subsidy would be sufficient to make renewables sufficiently attractive from a financial perspective. Still, even if all households *should* hypothetically prefer renewable heating technologies in a direct comparison, not all households *would* immediately choose them — both due to *imperfect information* (not all households know the new technology, since they have a small market share,) and limited availability due to *supply constraints* (capacity for technology production and set-up cannot be scaled up instantaneously). Therefore, it is projected that price-based policies could only have limited short-term impacts in countries with small initial market shares of renewables.

3.3.2. Impacts of policies on technology uptake and CO₂ emissions

Fig. 3 illustrates the EU-wide model projections for the technology composition, fuel use, CO₂ emissions, capacity additions, and additional household spending on heating systems, both under current trends and all three policy scenarios. Table B5 shows the underlying market shares of heating technologies over time. Projected trends for all individual MS can be found in the SI (Figs. 3–8). Projections for scenarios 1 and 2 only differ for the period 2030–2050.

Under current trends, the model projects that the market share of gas would remain stable around 40% until 2030, before decreasing to 30% by 2050. Oil and coal would gradually vanish from the technology mix until 2050. Meanwhile, heat pumps and solar thermal are projected to continue their ongoing growth: both technologies would roughly double their market shares until 2030.

In scenarios 1–3, the introduced policies are projected to impact household choices, thereby gradually changing the overall technology composition. In scenario 1, all renewable technologies are projected to increase their respective market shares in 2030, compared to current trends (in brackets): 18% for heat pumps (compared to 13%), 3% for solar thermal (compared to 2%), and an additional 3p.p. for modern biomass systems. These technologies increasingly replace fossil fuels,

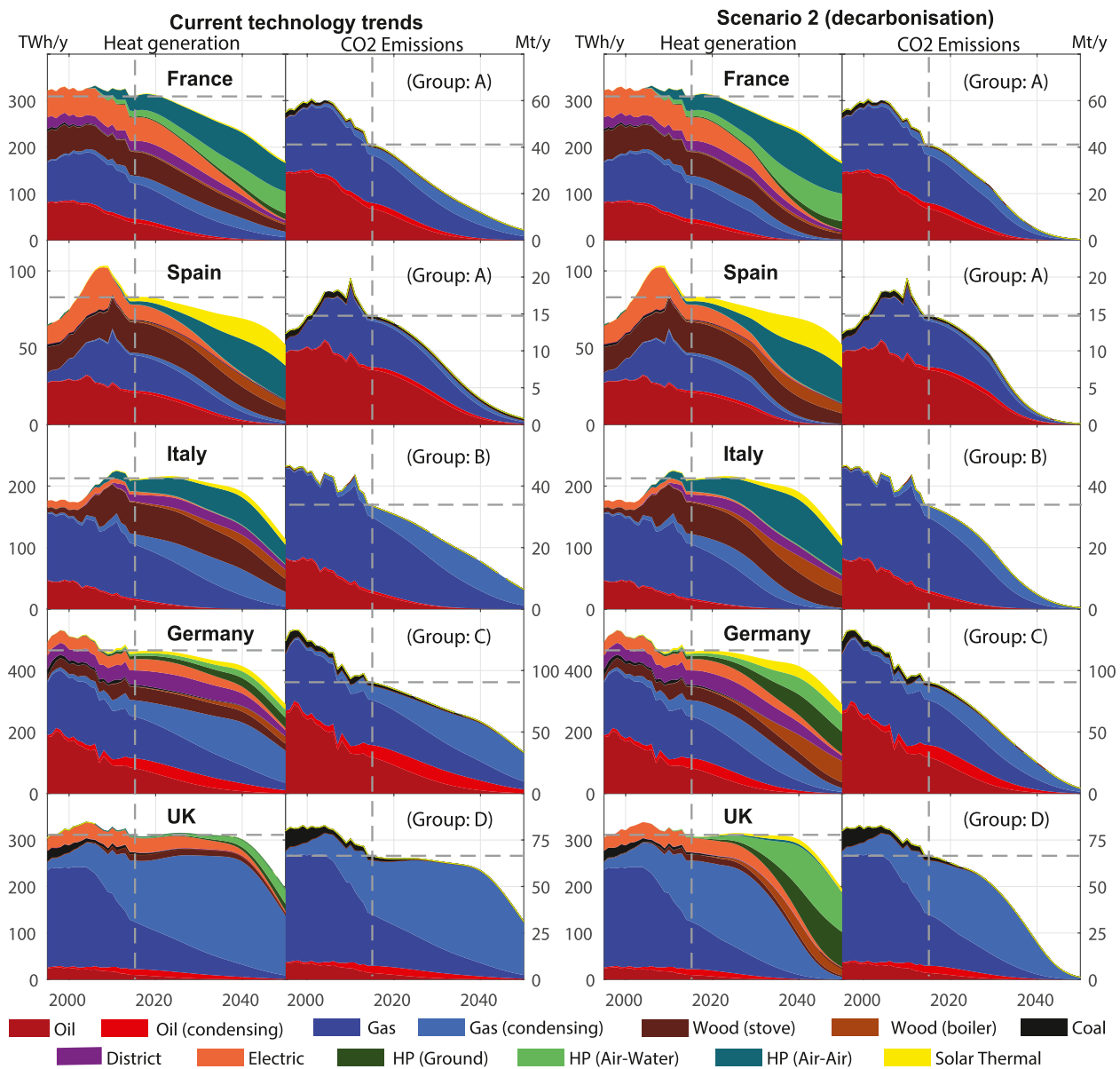


Fig. 2. Annual heat generation by technology and direct CO₂ emissions for five countries, which together account for around two-third of current EU-wide residential heat demand. The left panels show the current trends projections, the right panels the model simulations for scenario 2 (policies for deep decarbonisation). Projections by FTT:Heat start in 2015. Future levels of useful heat demand are an exogenous model input (from the EUCO30 scenario), and include improved levels of future building insulation.

whose market shares would decrease, relative to current trends.

Due to the long technological lifetimes of heating systems and the characteristic non-linear growth patterns of technology diffusion, the induced transition towards renewable heating would not occur instantaneously. Substantial changes can only be expected after several years, or even decades. When monetary incentives are introduced in countries with a small initial market for modern renewables, their potential effect is constrained by the limited local availability of knowledge, first-hand experience and industry know-how with such technologies (see section 2.3.1).

The bottom panels of Fig. 3 illustrate the underlying dynamics, in the form of annual installations of heating capacity by households. Under current trends, the share of renewables in the newly installed capacity is projected to increase from 33% in 2015 to 53% in 2030. In scenario 1, renewables would increase their share to almost 80% of the newly added capacity in 2030. In scenarios 2 and 3, where policies are continued post-2030, households would not buy any new fossil fuel based systems

after 2040. In all scenarios, projected capacity additions decrease after 2035, due to the assumed decrease in residential heat demand, which means that smaller heating systems are sufficient for keeping homes warm (due to improved thermal insulation of buildings). In scenario 2, there is a striking increase in capacity additions of capital-intensive renewable technologies around 2030–2035. The reason is the assumed subsidy on the purchase of renewable heating systems, which is extended to all MS in 2030 and discontinued in 2040. Fossil fuel demand for heating is projected to decrease by -19% under current trends, and -35% in scenario 1. Accordingly, direct CO₂ emissions in 2030 would be lower by -22% (current trends) and -39% (scenario 1), relative to 2014.

In scenario 1, the implemented policies are projected to have long-lasting impacts even beyond their assumed end-date in 2030. The reason is the momentum and path-dependence in technology uptake: when something new starts to dominate, it becomes increasingly difficult to buy the older systems that are disappearing, since the expertise is disappearing, while new systems become more competitive. Therefore,

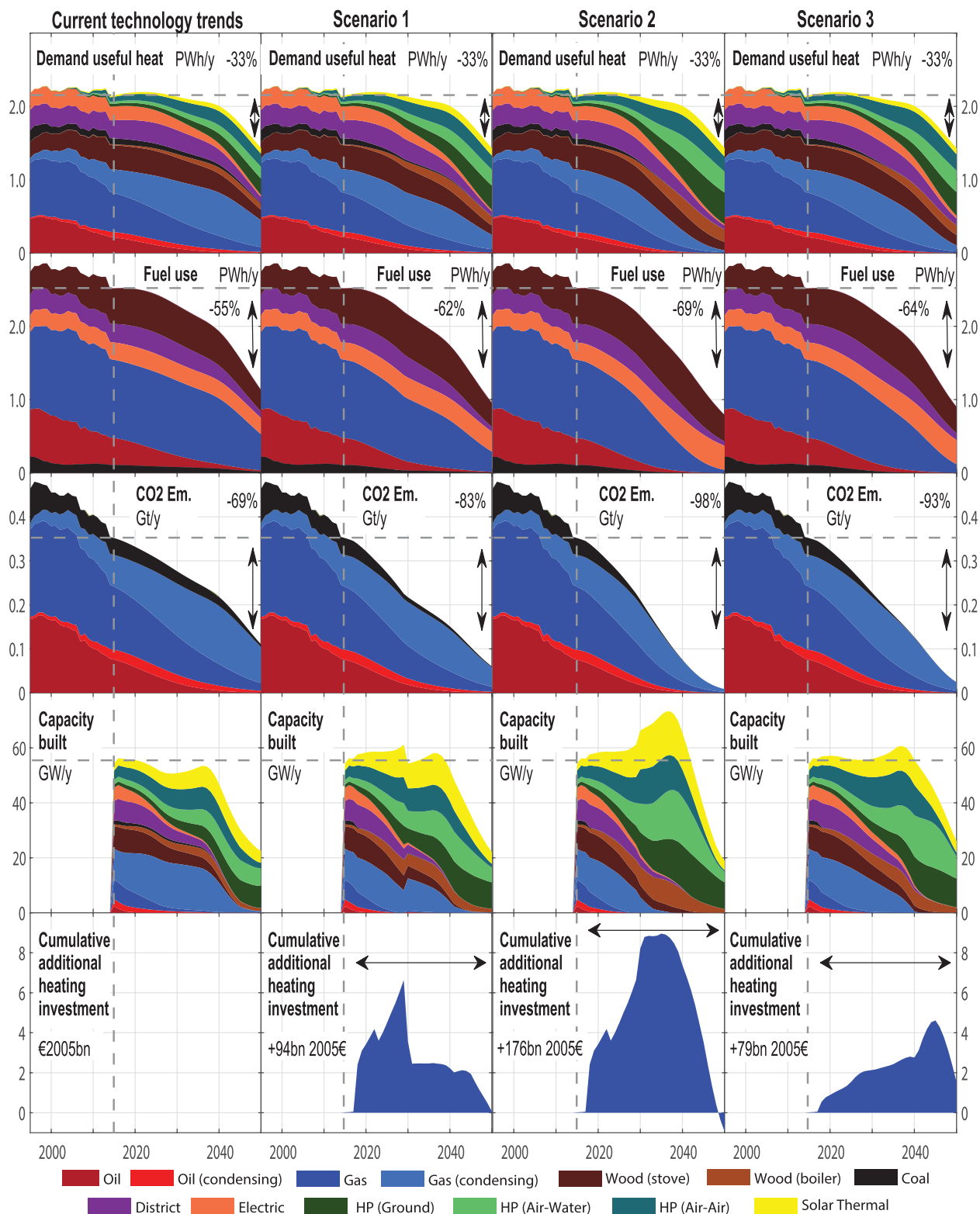


Fig. 3. EU-wide heat generation by technology, fuel use, CO₂ emissions, newly installed heating capacity, and additional household expenditure on heating systems (compared to the ‘current trends’ scenario). Model projections for current technology trends and policy scenarios 1–3. Projections by FTT:Heat start in 2015. Percentage values show changes in 2050, relative to 2014 (the last historical data point). Future levels of useful heat demand are an exogenous model input (from the EUCO30 scenario), and include improved levels of future building insulation.

from 2030 onwards, capacity additions of renewable heating systems only partially revert to their ‘current trends’ level.¹¹ Despite the discontinuation of policies, renewables are projected to keep a relatively stronger position in sales, enabling a -83% reduction in on-site CO₂ emissions by 2050 (partly due to reduced heat demand after 2030). In scenario 2, the policy continuation post-2030 (plus their extension to all MS) would lead to the deep decarbonisation of residential heating, reducing on-site emissions by -98% in 2050. In scenario 3, where the carbon tax is simulated as the only policy, the projected emission reduction is 5p.p. lower.

Heat pumps are projected to play a major role in all scenarios, with a projected EU-wide market share of 39–65% in 2050 (see Table B5). Market shares of different types of heat pumps differ between regions (see Fig. 2), due to regional differences in relative costs, operating conditions and empirically estimated household preferences. The relatively higher upfront investment into a high-efficiency ground-source heat pump tends to be more attractive for households in colder regions (such as Germany or the UK), where heating systems run for more hours per year. Relatively inexpensive air-air heat pumps (which transfer heat from outside air to inside air) are the projected preferred choice in many warmer regions (such as Italy and Spain). Air-water heat pumps are slightly more expensive than air-air systems, but can be used for floor heating and sanitary water heating, which makes them an attractive choice in many countries.

The corresponding changes in residential fuel use and sectoral CO₂ emissions are shown in Fig. 4, relative to current trends. Due to the policy-induced demand reductions for fossil fuels in all scenarios (up to -100% for coal, -90% for oil, and -80% for gas), on-site CO₂ emissions in the residential sector would be reduced by up to -150MtCO₂/y, relative to ‘current trends’. At the same time, the partial electrification of heating would lead to additional electricity demand of +60-120 TWh/y by 2050. If the power sector is decarbonised in line with EU policy targets (see section 3.2), the resulting indirect emission increases would not exceed +15MtCO₂/y at any time, allowing substantial net-reductions on an economy-wide level.

3.3.3. Impacts of policies on residential heating costs

On average, the induced technology substitutions would slightly reduce the EU’s system-wide levelised cost of residential heating (weighted by technology shares) relative to current technology trends, as can be seen in the left panel of Fig. 5 (country-level results are provided in the SI, Figs. 9–12). The bare, average levelised cost of heating (net of carbon taxes and subsidy payments) would be -1% lower than under current trends by 2030, and between -4% and -8% lower by 2050. In case of scenario 3, system-wide costs would initially increase, before falling below their current trend projection in the 2040s.

Households, however, do not face the bare technological cost. They would also need to pay the newly introduced carbon tax, while benefiting from subsidies on renewables (see SI-Fig. 2). Even when policies drastically change the relative cost differences between technologies, many households can be ‘locked’ into using their old heating systems for a long time. During this transition period, the average cost increase faced by households would be between +5-10%, relative to current trends (see right panel of Fig. 5), and up to 20% in individual MS (and can be much higher than national averages for households which are stuck with fossil fuel systems). Households would not benefit from effective cost reductions before 2030 in scenario 1, and not before 2040 in scenario 2, on average. In scenario 3, the average household would face increased heating costs until 2050 (see SI-Fig. 13 for the underlying shifts in households’ expenditures and employment). The carbon tax revenues can be redistributed to households, for example via income tax

¹¹ The projected technology uptake remains relatively close to ‘current trends’ from 2030 onwards, which explains the sudden decrease in ‘additional heating investments’ relative to ‘current trends’.

reductions. Nevertheless, many households would likely face increases in their direct heating expenses, until they replace their heating system.

3.4. Limitations

From a modelling perspective, it is important to keep in mind that the true long-term effect of any policy remains hard to estimate a priori. As the context of technology choices is constantly evolving (such as policies and preferences), it remains uncertain to which extent model structures and parameters (such as technology choice behaviour and empirically determined preferences) might need to be adjusted in the light of new developments. However, while modelling the future features inherent uncertainty, it is nevertheless the only method available to quantitatively inform policy-making. We argue that for the purpose of policy simulation, FTT:Heat provides a clear improvement on optimisation models, as it allows to explore important dynamics of technology uptake in a context of limited information and bounded rationality.

4. Conclusion and policy implications

We introduced FTT:Heat as a new model for simulating technological change and policy instruments in residential heating. By including a bottom-up representation of statistically distributed household decisions, endogenous growth dynamics and technological learning, model simulations allow to reproduce the typical non-linear dynamics of technology transitions, which makes the model well-suited for an ex-ante impact assessment of policies.

We demonstrated the model by simulating several policies and scenarios, inspired by the EU policy objective to increase the share of renewable heating by 10p.p. in each MS until 2030. In our projection under current trends of technology uptake, it became evident that large differences exist between countries’ current trajectories. In eight MS, the renewable heating target could potentially be met without additional policy instruments, due to the continued diffusion of renewables. Meanwhile, other MS would hardly see any changes without new policies. Different degrees of policy effort are required to reach the same policy objective in different places, depending on the national context.

We find that under current trends, without any additional policies, the EU-wide market share of gas would remain relatively stable around 40% until 2030, before decreasing to 30% by 2050. Meanwhile, oil and coal heating systems would gradually vanish from the technology mix. On the other side, heat pumps and solar thermal are projected to continue their ongoing growth: both technologies would roughly double their 2015 market shares until 2030. In the policy simulations, policy mixes of varying stringency would allow all Member States to increase their renewable heating share by at least ten percentage points until 2030, which is projected to reduce on-site CO₂ emissions by residential heating by -39% in 2030 (compared to -22% in the baseline under current trends). Continuing the policies in all Member States after 2030 could eliminate direct emissions almost entirely, according to the model estimates.

Still, even if households *should* hypothetically prefer renewable heating technologies in a direct comparison (from an outside engineering perspective), not all households *would* immediately choose them (from their individual perspective) — both due to *imperfect information*, and limited availability due to *supply constraints*. Therefore, it is projected that price-based policies could only have limited short-term impacts in countries with small initial market shares of renewables. In seven countries, price-based policies on their own are therefore projected to be insufficient for reaching the 2030 renewable heating target, and would need to be supplemented by ‘kick start’/procurement policies, which are aimed at nucleating a market for new technologies. Overall, the results indicate that more policy effort is required to change the technology trajectory in countries with initially low market shares of renewables.

Because of the long technological lifetimes of heating systems and

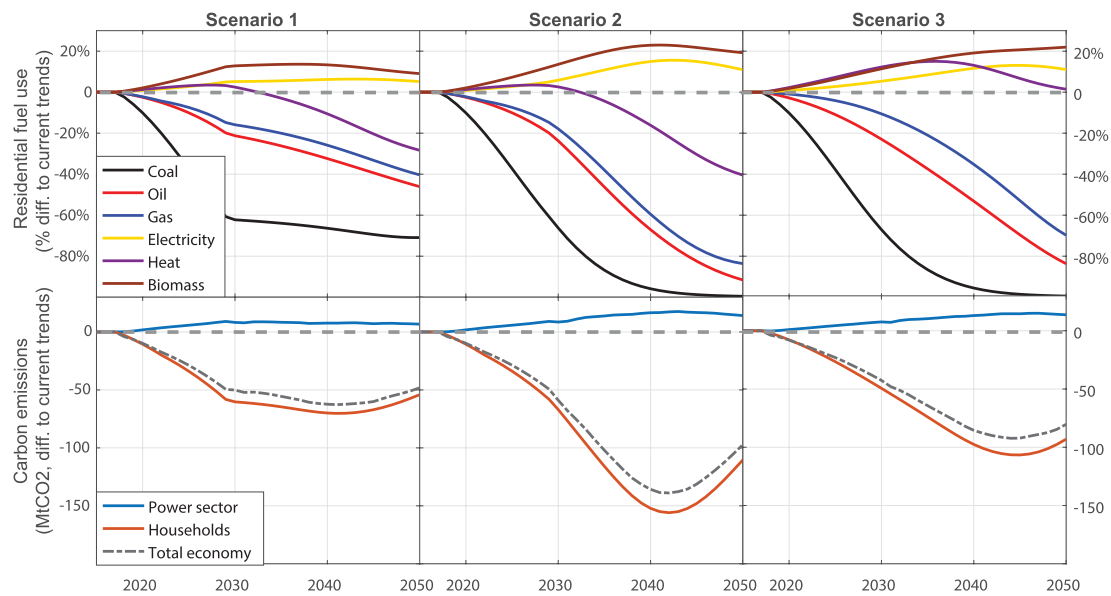


Fig. 4. Changes in EU-wide residential fuel use (upper panels, in %) and CO₂ emissions (bottom panels, in Mt) in scenarios 1–3, compared to the current trends projection.

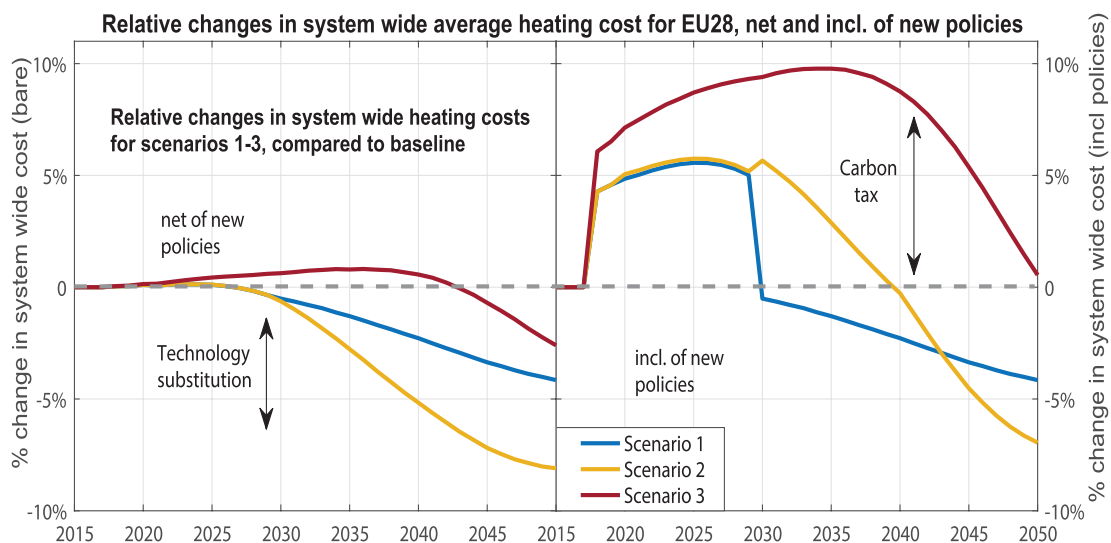


Fig. 5. EU-wide relative changes in system-wide levelised heating costs (weighted by technology shares), compared to the current trends projection. The left panel shows the changes in system-wide bare costs (fuel and capital), the right panel shows the average price changes as they would be effectively faced by households (incl. of carbon tax and subsidies).

the inherent inertia of technological change, a transition towards renewables cannot occur instantaneously. Substantial changes in the technology composition can only be expected several years after the introduction of decarbonisation policies, and may take decades in many cases. Inertia keeps technological change in a trajectory that has momentum, and policies are used to alter the direction of the trajectory, which is henceforth maintained even if policies are removed.

Due to the long timespans involved, policies in the heating sector can have strong distributional impacts: even when relative costs change dramatically (such as under a high carbon tax), many households could be ‘locked’ into using their existing heating systems (and paying carbon taxes) for a considerable time. The political acceptability of a residential carbon tax may therefore depend on the way in which its revenues are redistributed, and if an increase in energy poverty can be avoided.

Code and data availability

The database of heat demand per technology type for each Member State is available as Supplementary Material online. A standalone Matlab version of FTT:Heat is available from the corresponding author on reasonable request.

CRedit authorship contribution statement

Florian Knobloch: Conceptualization, Methodology, Software, Visualization, Writing. **Hector Pollitt:** Methodology, Software, Writing. **Unnada Chewprecha:** Software, Data curation. **Richard Lewney:** Funding acquisition, Project administration. **Mark A.J. Huijbregts:** Supervision, Writing. **Jean-Francois Mercure:** Methodology, Software, Writing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix C. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.enpol.2021.112249>.

Appendix A. Technology assumptions

Table A.4:

Model assumptions for residential heating technologies. All costs refer to mean values. Cost, conversion efficiencies and lifetime assumptions are taken from Fleiter et al. (2016), Danish Energy Agency (2013, 2016), IEA/ETSAP (2012) and European Heat Pump Association (EHPA) (2016), the learning rates from Weiss et al. (2010) and Henkel (2012).

	<i>I</i>		<i>O&M</i>		<i>CE</i>	<i>LR</i>	τ
	Euro/kW _{th}		Euro/kW _{th} pa		kW _{th} /kWh	%	y
	Mean	SD	Mean	SD	Mean	Mean	Mean
Oil	471	157	19	6	0.75	0	20
Oil condensing	512	171	20	7	0.86	-0.06	20
Gas	391	133	8	3	0.75	0	20
Gas condensing	434	145	9	3	0.9	-0.06	20
Biomass stove	440	147	0.1	0.03	0.70	0	20
Biomass boiler	523	174	2	0.7	0.85	-0.07	20
Coal	247	82	5	2	0.75	0	20
District heating	265	88	16	4	0.98	0	20
Direct electric	538	179	0.5	0.2	1.00	0	20
HP- ground source	1400	467	14	5	3.50	-0.35	20
HP- air/water	750	250	15	5	2.50–2.70	-0.35	20
HP- air/air	510	170	51	17	2.50–2.70	-0.35	20
Solar thermal	773	258	8	3	–	-0.20	20

Appendix B. Scenario projections

Table B.5

Technology group market shares in EU-wide residential heat demand, under current technology trends and in policy scenarios 1–3. 2014 shares are calculated from historical data, 2030 and 2050 shares are model projections by FTT:Heat.

	Start	Current trends		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%
Direct electric	9%	7%	2%	7%	1%	7%	1%	8%	3%
Heat pumps	6%	13%	39%	18%	52%	19%	65%	15%	59%
Solar thermal	1%	2%	5%	3%	7%	3%	8%	2%	6%

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