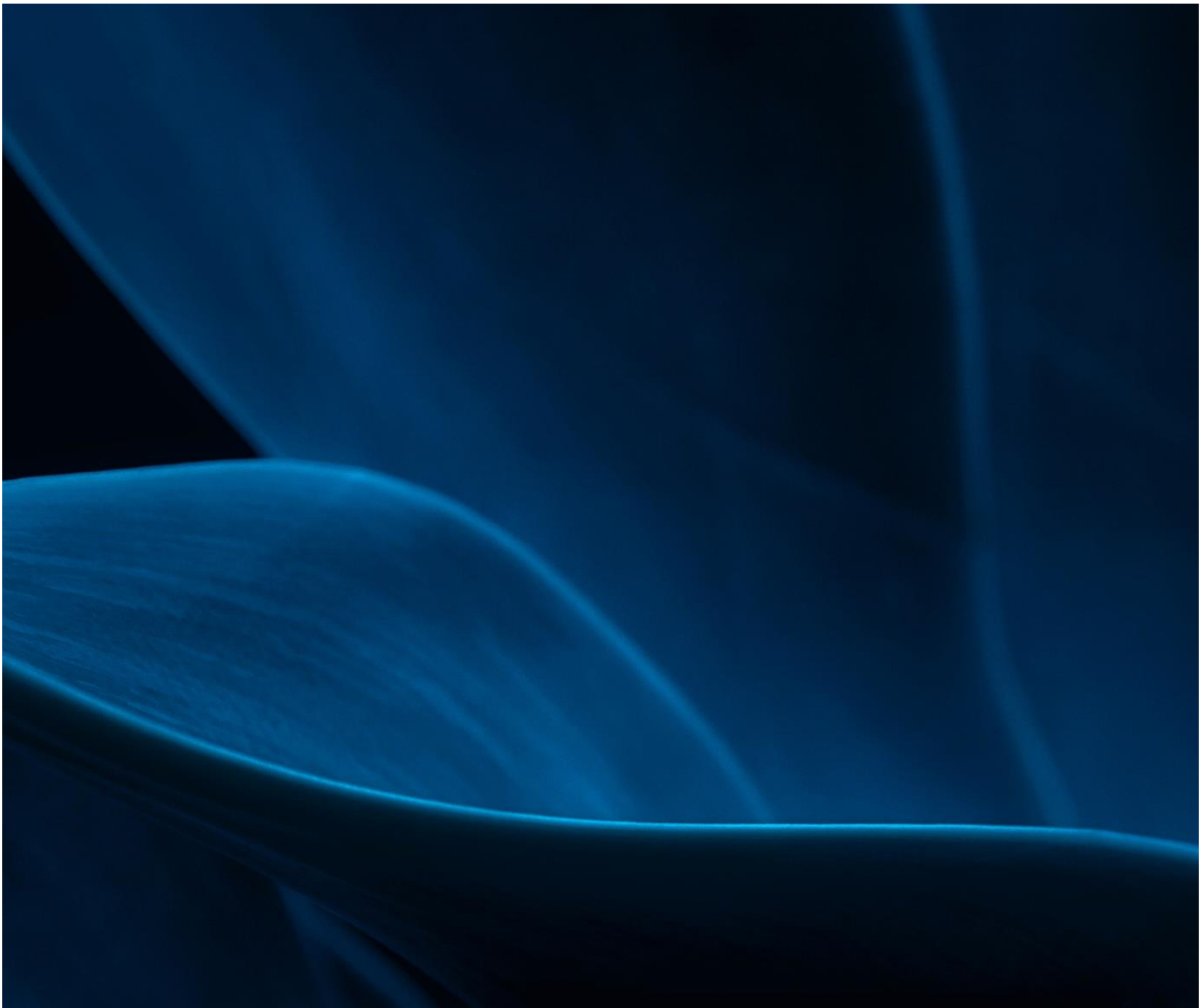

A technology diffusion model for industrial process heating

White paper – June 2024

referee

cambridge econometrics
clarity from complexity

Authors

Isha Dwesar
Pim Vercoulen
Iakov Frizis
Jon Stenning
(Cambridge Econometrics)

Contributors

Freya Gompertz
Sachin Gulati
(Cambridge Econometrics)

Project director

Jon Stennig – js@camecon.com

Contact person

Iakov Frizis – if@camecon.com

Contents page

Appendices

Tables

Figures

A technology diffusion model for industrial process heating

Executive Summary

In this white paper, we present the technology diffusion model for industrial heating process, called FTT:IH (FTT: Future Technology Transformations; IH: Industrial heating). FTT:IH was developed under the REFEREE (real value of energy efficiency) Horizon project funded by the European Commission. The model simulates technology take up of industrial heating processes under the influence of policies. FTT:IH is used to simulate the impact of several explorative policy scenarios on technology diffusion, with the aim at reducing emissions.

1. Introduction

1.1. Background

Industrial processes, that is to say industrial heating and cooling, account for approximately 50% of the European Union's total final energy demand (Fraunhofer ISI, 2024; Rehfeldt, Fleiter, and Worrell, 2018), with industrial high temperature process heat (defined as above 500°C) comprising approximately 1100 TWh (47%), the vast majority of which is provided by fossil fuels (Rehfeldt, Fleiter, and Worrell, 2018; Naegler et al., 2015). Maddedu, et al. (2020), note that fuel combustion provides 70% of the final energy consumed in industry, primarily to supply heat.

The IEA notes that industrial heating constitutes most of the direct industrial CO2 emitted each year and is responsible for almost one fifth of global energy consumption (IEA, 2018). Indeed, SIPA estimates that heavy industry is responsible for approximately 22% of global CO_2 emissions, 40% of which (approximately 10% of total emissions) are the direct result of combustion for the purpose of high-quality heat (SIPA, 2019). McKinsey supports the estimation of heat generation representing 40% of industrial emissions (McKinsey & Company, 2018), and The European Environment Agency notes that the industry sector accounted for 26% of total final energy consumption and about 21% of the GHG emissions (775 Mt of CO2 equivalent) in 2019 (European Environment Agency, 2024; Fraunhofer ISI, 2022). The European Commission notes that heavy industrial processes such as the production of cement, steel, petrochemicals, glass, ceramics, petroleum refining, and others contributed for at least 34% of total CO2 emissions in 2019 (European Commission, 2021).

The high emissions generated by industrial heating is a direct result of the heavy reliance on fossil fuels, which in turn can be attributed to their relative low cost, high availability at large scale, and efficiency in producing the high-quality heat required by industrial processes (SIPA, 2019). These factors make industrial heating a prime target for decarbonisation.

1.2. Decarbonising industrial heating in Europe

Previous attempts to decarbonise the industrial sector have seen success, with the European chemical industry council reporting that process industries in Europe have succeeded in reducing their energy intensity by 47% from 1991 to 2019 (Maghrabi, et al., 2023; Vallejo, et al., 2021; Napp et al., 2014). Fraunhofer ISI also note that the industrial sector reduced their emissions by 35% from 1999 to 2019 by implementing structural changes to the sector, as well as capitalising on energy efficiency measures (Fraunhofer ISI, 2022; European Environment Agency, 2024). Despite these improvements, it is clear that further reductions in energy intensity and emissions must be made in order for the EU to achieve their decarbonisation targets, particularly as the demand on industrial sectors, and thus their energy consumption, is projected to grow and continue to be dominated by fossil fuels (Maghrabi, Song, and Markides, 2023; BP, 2019).

Madeddu et al., (2020) explored potential routes to European industrial electrification, breaking industrial processes down by their heat requirement and proposing three stages of electrification based on the maturity of the technologies used. Her proposed Stage 1, using mature technologies such as heat pumps, mechanical vapour recompression (MVR), electric boilers, infrared heaters, and microwave and radio frequency heaters, was projected to cover 42% of industrial useful energy demand (66% if the energy content in chemical feedstocks which, by nature, cannot be electrified, is ignored). Stage 2 and 3 include presently less mature but more advanced technologies such as induction, resistance, and electric arc furnaces, as well as plasma technology, and were projected to cover 50% and 60% of useful energy demand respectively (78% and 99% if chemical feedstocks are excluded).

1.3. Policy context

The EU is committed to climate neutrality by 2050, noting that all parts of society, including industry, will play a role in achieving this goal (European Commission, 2024). The EU committed €700 million of the estimated €2.6 billion total R&D costs required. The REPowerEU Plan, announced in 2022, focussed on Russian fossil fuels as a target for reduction due to the disruption to the global energy market caused by Russia's invasion of Ukraine. It noted that at that time the EU imported 90% of its gas, 45% of which was provided by Russia, and proposed complete independence from Russian fossil fuels well before 2030 (European Commission, 2022). The plan identified the reduction of fossil fuel consumption by industry as a key strategy for achieving this goal, alongside smart investment into decarbonisation and green transition projects (European Commission, 2022; European Commission, 2022). It proposed to increase the headline 2030 target for renewables from 40% to 45% under the Fit for 55 package, aiming to use this increased target as a framework for other packages, including the increase of renewable hydrogen-based production processes in industry and increased solar photovoltaic capacity (European Commission, 2022; European Commission, 2022).

1.4. Modelling industrial heat decarbonisation

Various models have been developed to assess decarbonisation of industrial heat (in some form). Among the most prominent models are PRIMES (E3Modelling, 2018), REMIND (Baumstark et al., 2021), and GEC (International Energy Agency, 2023). Other smaller scale models exist as well, such as IESA-Opt (West et al., 2024) and FORECAST (Fleiter et al., 2018). There is variety in the approach these models use to assess industrial (heating) processes, ranging from optimisation (e.g. IESA-Opt, PRIMES, REMIND) to simulation (e.g. FORECAST), or a combination of the two (e.g. GEC). Optimisation models seek to minimise (system) costs or maximise a production function and optimises decision-making accordingly. Simulation models include responses to the economic environment and internal feedback loops, without abiding to an objective function. We refer to Mercure et al. (2019) for a detailed discussion on the dichotomy of modelling approaches.

Most of the models mentioned above include optimising behaviour towards decision-making on technologies. Optimisation of decision-making ignores fundamental uncertainty and potentially irrational expectations of decision-makers. Many bottom-up technology models optimise towards a certain constraint, which in most cases is an emission reduction pathway. While such models are useful for energy planning purposes, and agenda setting, their utility dwindles when it comes to policy appraisal exercises as accounting for uncertainty is vital (Grubb et al., 2021).

The Future Technology Transformations (FTT) family of models seeks to simulate technology diffusion in a given sector. The methodology was conceived by Jean-Francois Mercure and applied to the power sector (Mercure, 2012). Since then, additional models were developed to describe technological decision-making for the private road transport sector (Mercure and Lam, 2015), the residential heating sector (Knobloch et al., 2021), and the iron & steel sector (Vercoulen et al., 2023). The mathematical background of FTT is provided by Mercure (2015). Here, we present the latest addition that describes technology uptake in the industrial process heat sector, called FTT:IH.

1.5. Structure of this document

In chapter 2 the core of the FTT:IH is explained by first outlining the main definitions, model scope, mathematical core, assumptions, and policy options available to the model user. A model such as FTT:IH is very data-hungry, so the database that sits in the background of the model is discussed in chapter 3, focussing on the techno-economic data, information on recent historical uptake of industrial process heating technologies, and finally on how the demand projections for industrial process heating are determined. Then, chapter 4 will lay out the explorative scenarios to show-case the model mechanisms. Followed by chapter 5 which describes the results of those scenarios, focussing on technology take-up, and impacts on emissions. Finally, chapter 6 provides a discussion of the results, model limitations, a comparison effort to similar model outcomes, and final key takeaway messages.

2. Model description

2.1. Definitions

A few key definitions are explained in this section to facilitate the understanding of the model logic.

- Industrial process heating: This encompasses all heat applied to facilitate industrial processes, such as but not limited to drying, boiling, providing activation energy for chemical conversion, smelting, pre-heating of materials, etc.
- Indirect heating processes: One of the two modes of process heat application. Industrial processes that are heated through a secondary medium, e.g. a boiler heating a water reservoir, which heats up the process of interest.
- Direct heating processes: One of the two modes of process heat application. Industrial processes where the heat is directly applied. Direct heating processes often involve high temperature processes.
- Useful energy demand: Useful energy demand is the amount of energy that is "put to work". In this context, it is defined as the demand for heating before conversion losses.
- Final energy demand: Final energy demand refers to the energy purchased to provide a certain service. It therefore includes conversion losses during the application of energy.
- Market share: Technology market shares are defined as the share of useful heat demand delivered of the total.

2.2. Model scope

Regions

Due to data availability, this model only covers all member states of the European Union and the United Kingdom as individual regions. The rest of the world is omitted for the time being as no valid data sources have been found. All regions included in FTT:IH also correspond to regions that are individually represented in the macroeconomic E3ME model.

Sectors

FTT:IH simulates uptake of processing heating technologies in 5 sector groups:

- Chemicals (CHI)
- Food, beverages, and tobacco (FBT)
- Non-Ferrous Metals, Transport Equipment, and Machinery (MTM)
- Non-Metallic Minerals (NMM)
- Other Industrial Sectors (OIS)

While the data sources used for development (more information is provided in chapter 3) include representation of the iron & steel sector we have excluded it from FTT:IH, because FTT:Steel (Vercoulen et al., 2023) treats process heating within the iron & steel sector separately.

Technologies

Process heating technologies are extremely diverse (Madeddu et al., 2020; Danish Energy Agency, 2024), and some can only be applied for niche applications. The technology options included in FTT:IH do not account for the specificities of individual process heating technologies that exist in industry as comparisons of individual technologies was not deemed practical given the restrictions imposed by the available data. Instead, FTT:IH considers “umbrella” technologies that align with energy inputs. Then, a distinction is made between direct and indirect process heating technologies as these technology groups are unlikely to overlap.

The technologies included in FTT:IH are displayed in Table 2-1. The technology scope was determined by cross-referencing the descriptive names of processes in the JRC-IDEES dataset (European Commission et al., 2017) together with the supplementary information from Madeddu et al. (2020).

Table 2-1: Overview of technologies included in FTT:IH.

Indirect heating technologies	Direct heating technologies
Indirect Heating Coal	Direct Heating Coal
Indirect Heating Oil	Direct Heating Oil
Indirect Heating Gas	Direct Heating Gas
Indirect Heating Biomass	Direct Heating Biomass
Indirect Heating Electric	Direct Heating Electric
Indirect Heating Steam Distributed	Direct Heating Steam Distributed
Heat Pumps (Electricity)	

Steam Distributed heating is enabled in the model but treated as an exogenous input. Distributed heating depends on the available heat networks in a region, and the availability of heat networks depends on decisions made by other industries that face large amounts of residual heat streams. Such decision-making sits outside the decision-making for onsite process heating technologies and is therefore not included in the endogenous decision-making core of FTT:IH. This treatment is similar to that of district heating in FTT:Residential Heating for space and water heating in residential buildings (Knobloch et al., 2021).

2.3. Model core

Economic performance of technologies

The FTT methodology seeks to mimic investor decision-making when it comes to industrial process heating technology choices based on feedbacks with energy prices and reinforcing feedbacks on technology learning-by-doing. The decision-making takes place under bounded rationality which is represented by distributed techno-economic parameters. At the basis of FTT lies the Lotka-Volterra equation (or predator-prey equation – herein after called market share dynamics) which describes competition between technologies for market share. Market share dynamics are estimated by comparing all technologies on the basis of the economic performance (e.g. upfront purchase costs, fuel costs, etc.), diffusion rate dynamics (to represent how quickly one technology can replace another), and the status quo of the technology composition to represent (e.g.) network effects (mimicking behaviour / decision-making).

The economic performance of power generation technologies is evaluated by calculating the levelised costs of industrial heat (LCOIH). The LCOIH describes the break-even point of the net present value of the expenses versus the net present value of the benefits. Both NPV estimates are normalized to describe the costs or benefits of one unit of process heat delivered. If the break-even cost per unit is assumed to be constant over the project's lifetime. This means that ratio between the NPV of the expenses and the benefits can be set equal to 1 (break-even point) and the equation can be re-written to extract the break-even cost from the ratio which then gives us the LCOIH. LCOIH generalizes the lifetime costs of various expense sources, both upfront and during the operational phase of a project. It includes various policy impacts that the user can use to influence the LCOIH and therefore decision-making. Equations 2-1 to 2-3 show the steps taken to estimate the LCOIH and 2-4 displays the final calculation.

$$NPV_{expenses} = \sum_{0}^{\tau} \frac{{IC(t)}/{CF} + OM(t) + FC(t) + CO2Tax(t)}{(1+r)^t} \tag{2-1}$$

$$NPV_{benefits} = \sum_{bt}^{\tau} \frac{P(t) * Use(t)}{(1+r)^t} \approx P * \sum_{bt}^{\tau} \frac{1}{(1+r)^t} \tag{2-2}$$

$$\frac{NPV_{expenses}}{NPV_{benefits}} = 1 \tag{2-3}$$

$$LCOIH = P = \frac{\sum_{0}^{\tau} \frac{{IC(t)}/{CF} + OM(t) + FC(t) + CO2Tax(t)}{(1+r)^t}}{\sum_{bt}^{\tau} \frac{1}{(1+r)^t}} \tag{2-4}$$

Variable declaration: $NPV_{expenses}$ is the net present value of the expenses; $NPV_{benefits}$ is the net present value of the benefits; IC is the upfront investment costs; FC is the fuel costs; OM is the maintenance costs; $CO2Tax$ is the carbon costs as a function of the carbon price or tax and emission intensity per unit of generation; r represents the discount rate; t represents year; and τ represents the expected lifetime of the technology; $\mathbf{P}$ represents the break-even costs, or levelised cost; $\mathbf{Use}$ represents the delivery of 1 MWh of process heat; $LCOIH$ is the levelised cost of industrial heat (estimated for each technology and region, but subscripts are omitted for brevity).

Bounded rationality of the investing agent is represented by accounting for the uncertainty ranges found for relevant cost components. Through a process of error propagation, the standard deviation of the LCOIH can be estimated based on the standard deviation of the individual relevant cost components. See equation

.

$$sdLCOIH = \frac{\sum_0^\tau \frac{\sqrt{\left(\frac{sdIC(t)}{CF}\right)^2 + sdFC(t)^2 + sdOM(t)^2}}{(1+r)^t}}{\sum_0^\tau \frac{1}{(1+r)^t}} \qquad 2\text{-}5$$

Variable declaration: sd$\boldsymbol{LCOIH}$ is the standard deviation of the levelised cost of industrial heat (estimated for each technology and region, but subscripts are omitted for brevity); *sd*$\boldsymbol{IC}$ is the standard deviation of upfront investment costs; *sd*$\boldsymbol{FC}$ is the standard deviation of the fuel costs; sdOM is the standard deviation of the operation and maintenance costs; the other variables are the same as previously declared.

Investor preferences

To determine investor preferences, all technology options are compared on a pair-wise basis using the LCOE and sdLCOIH to yield a binary logit. The sdLCOIH of both options are combined via another round of error propagation (see equation). The sdF_{ij} represents the width of the binary logit. The investor preference is then a function of the difference of the average LCOIH values. The greater the difference the more likely one of the technology options is preferred over the other. Equation displays the investor preference calculation between two technology options.

$$sdF_{ij} = \sqrt{2(sdLCOIH_i^2 + sdLCOIH_j^2)} \qquad 2\text{-}6$$

$$F_{ij} = \frac{1}{1 + e^{\Delta C_{ij}/sdF_{ij}}};\ F_{ji} = 1 - F_{ij} \qquad 2\text{-}7$$

Variable declaration: F_{ij} represents the investor preference for technology i over j; ΔC_{ij} represents the average levelised cost difference between two technologies $(LCOIH_j - LCOIH_i)$; and sdF_{ij} represents the combined standard deviation of both technology's LCOIH distributions. Note that $F_{ij} + F_{ji} = 1$.

Figure 2-1 displays a generic example of cost distribution of two technologies and how that translates to the binary logit to determine the investor preferences. It shows that while one technology option may appear to be more cost-effective compared to another, there is still a lot of overlap between the distributions. This is an indicator of uncertainty around cost-effectiveness of both options and this uncertainty can have various sources. For one, there could be local variability in conditions leading to different cost expectations for the same by technology by different agents. Additionally, if agents are bounded by limited information and foresight, then they may make imperfect decisions. Ultimately, the greater the uncertainty, the wider the binary logit to determine preferences becomes, which makes the decision between two technologies less clear cut.

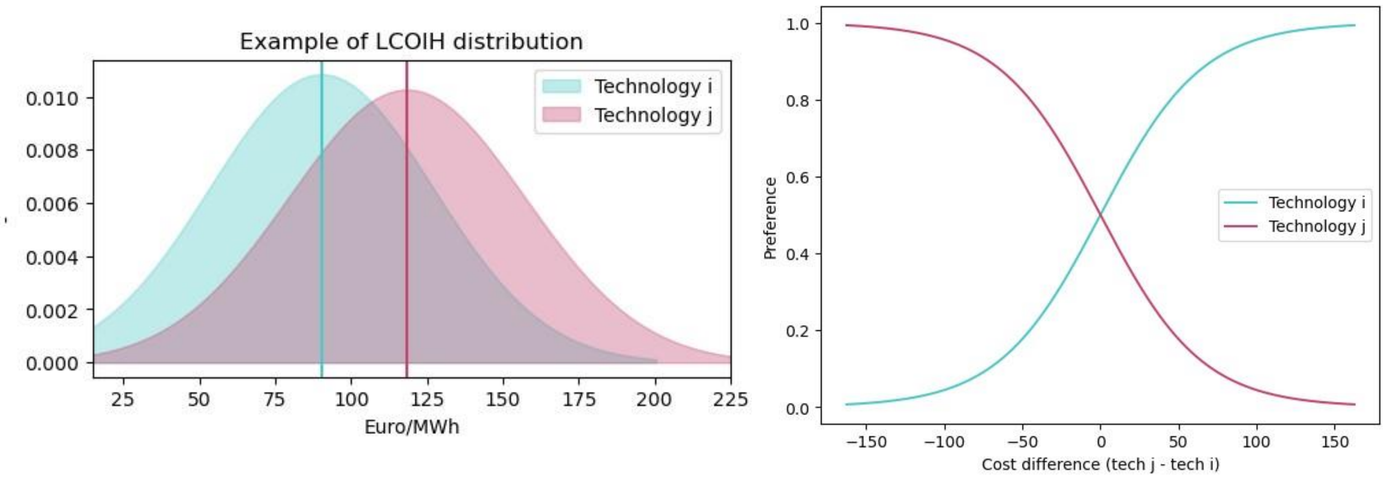

Figure 2-1: Illustration of determining preferences between two generic technologies. The left panel shows the cost distributions, and the right panel shows how those distributions translate to a binary logit to represent preferences.

Substitution dynamics

For every timestep, all agents make new decisions with respect to new process heating capacity based on updated LCOIH expectations that include responses to the wider economic landscape. These new additions replace incumbent capacity that has reached its end-of-life. Technologies approximately decay exponentially, the exponent of which would be proportional to the inverse of its lifetime. The market share decay would therefore be in line with the market share of the incumbent technology over its lifetime. Similarly, new capacity of an alternative technology can become online at the rate proportional to its pre-existing market share over its build time. Combing this with the investor preference for the alternative technology over the incumbent technology, we can develop an estimation of market share substitution from the incumbent technology to the alternative (see equation), and vice versa (see equation).

While these equations track the direction of travel, they misrepresent the rate of travel. Therefore, the substitution frequency matrix is introduced. Its formulation is intuitive; however, its origin is more complicated and for a complete explanation we refer to Mercure (2015). In brief, building on convolutions of probabilistic descriptions of the “death rate” of incumbent technologies and the “birth rate” of alternative technologies, one can determine substitution frequencies that still build on the inverse of the incumbent technology’s lifetime and the alternative technology’s build time in addition to a sector specific constant. This is depicted in equation .

Finally, combining all of the above, we can formulate an adaptation of the Lotka-Volterra equation that describes competition for market share between technologies, rather than competition for e.g. food between species. This is achieved by summating over all substitution interactions a technology can have with all other technologies available in the system. See equation . Note that it includes a correction term to prevent technologies to breach a certain ceiling. This calculation is explained in the next section.

$$\Delta S_{j\rightarrow i} \propto \frac{S_i}{BT_i} \cdot \frac{S_j}{LT_j} \cdot F_{ij} \cdot \Delta t \quad \text{2-8}$$

$$\Delta S_{i\rightarrow j} \propto \frac{S_j}{BT_j} \cdot \frac{S_i}{LT_i} \cdot F_{ji} \cdot \Delta t \quad \text{2-9}$$

$$A_{ij} = \delta_{ij} \frac{\kappa}{BT_i \cdot LT_j} \quad \text{2-10}$$

$$\sum_j \Delta S_{j\rightarrow i} = \Delta S_i = \sum_j S_i S_j \cdot \left(F_{ij} A_{ij} G_i^{max} - F_{ji} A_{ji} G_j^{max}\right) \cdot \Delta t \quad \text{2-11}$$

Variable declaration: $\Delta S_{j\rightarrow i}$ describes the market share change from technology j to technology i, and $\Delta S_{i\rightarrow j}$ describes the opposite movement; S is the market share; BT is the "build time"; ΔS_i is the total market share change; LT is the lifetime; κ represents a time constant specific to the sector it applies to and describes how quickly transitions can happen in general; F is the consumer preference; A represents the substitution frequency matrix; δ_{ij} represents the exclusion matrix that allows and disallows specific substitution interactions (e.g. it is 0 for all direct and indirect process heating technologies); G_i^{max} represents a correction term to prevent technologies breaching a certain maximum share. This is explained in the next section.

Technology constraints

The specificity of technologies included in FTT:IH (see section 2.2) is limited. The technologies are defined in broad terms and are mostly aligned with the fuel input and mode of heat application (direct or indirect). For each sector included in FTT:IH, we assume that the split of market segments between direct and indirect heating per sector remains constant over time, i.e. no substitution is possible between the two. Typically, direct heating is applied to processes that require higher temperatures, while the opposite is true for indirect heating processes. This limits – depending on the sector – the number of technology options available to the industry.

Table 2-2: Market share caps by technology and sector in %. These caps apply within the direct and indirect market segments.

	CHI	FBT	NMT	NMM	OIS
Indirect Heating Coal	100	100	100	100	100
Indirect Heating Oil	100	100	100	100	100
Indirect Heating Gas	100	100	100	100	100
Indirect Heating Biomass	100	100	100	100	100
Indirect Heating Electric	100	100	100	100	100
Indirect Heating Steam Distributed	100	100	100	100	32
Heat Pumps (Electricity)	17	24	18	17	100
Direct Heating Coal	1	1	5	100	100
Direct Heating Oil	100	100	100	100	100
Direct Heating Gas	100	100	100	100	100
Direct Heating Biomass	1	1	1	100	100
Direct Heating Electric	100	100	100	50	100
Direct Heating Steam Distributed	100	100	100	100	100

Model-wise, the constraints as presented in Table 2-2 are adjusted to account for the split in demand for direct and indirect heating processes. Then, the adjusted upper limit of the market share is used to determine a correction term which prevents uptake of technologies beyond this upper limit. See equation .

$$G_i^{max} = \frac{1}{1 + e^{(S_i - S_i^{UL})/0.1}} \qquad \text{2-12}$$

Variable declaration: S_i represents the market share of technology i; S_i^{UL} represents the upper limit of the market shares; and G_i^{max} is the correction term applied within equation .

Calibration

By design, FTT models always simulate and therefore are not calibrated to an exogenous forecast to represent a view of the baseline. However, FTT models are data hungry which makes it very susceptible to data availability and quality. To that end, a calibration process is put in place to mitigate data quality issues. Calibration of the FTT models seeks to align the increment of market shares of the first few years of simulation with the increment of market shares of the last few years of historical data. The rationale is that it is very unlikely that substitution dynamics change in the short term. Market share increments are aligned by adding or subtracting values from the endogenous LCOIH estimates to reflect missing and/or incorrect data.

Integration with E3ME

FTT:IH can be integrated with the E3ME macroeconomic model. The E3ME model is described in detail by Mercure et al. (2019) and in the E3ME model manual (Cambridge Econometrics, 2022). In brief, E3ME is an economy-environment-energy demand-driven simulation model that establishes relationships between variables using timeseries econometrics. In its economic core sits the system of national accounts to track channels of economic effects. It covers the globe (subdivided in 71 regions), and it provides a detailed sectoral granularity (70 sectors in European regions, and 43 sectors in the rest of the world).

Integration of both models allows for important feedback flows between them. Technology decision-making in FTT:IH depends on the economic landscape provided by E3ME. This can be due to changes in fuel prices or changes in gross output for products produced by the chemical industry. Similarly, once technology decisions have been made FTT:IH feeds back the investments required and the energy consumed by the technologies operational. Both direct effects can cascade through the channels of the economic structure within E3ME.

In this explorative study, we focused on displaying the mechanisms within FTT:IH, hence why we used the stand-alone version of FTT:IH without the feedbacks between E3ME and FTT:IH.

2.4. Assumptions

Indirect and direct heating split

The FTT:IH lacks information on the demand for specific industrial processes. Therefore, the model cannot account for a change in the demand of specific products that require a different mode of process heat application. We assume that the split between the modes of process heat application within a sector remains constant over time. However, the demand for process heating between sectors does not remain constant and depends on projections provided by the E3ME model (see section 3.3).

Based on JRC-IDEES, the CHI, FBT, and OIS sectors are mainly reliant on indirect process heat, while MTM and NMM are mostly reliant on direct heating processes (Mantzos et al., 2018).

Temperature bands of industrial processes

Industrial demand for process heating is not a uniform service. We have already discussed the split between the mode of heat application. However, a multitude of processes fall within each mode and different temperatures are required to facilitate different processes. In general, indirect heating is used for processes that have lower temperature requirements, while direct heating is typically used for processes that have higher temperature requirements. This is reflected in the technology constraints (refer back to section 2.3) and based on the potential of application as reported in datasheets provided by the Danish Energy Agency (2022). However, the model lacks information on how the demand for processes by temperature bands develop over time. In essence, due to the combination of fixed splits between the direct and indirect heating segments and the fixed technology constraints, we are also implicitly assuming that the split in demand for processes by temperature bands remains fixed.

Process heating capacities

A technology model ideally distinguishes between investors choosing to add new capacities and operators using the capacity available to meet demand. However, this requires detailed information on the capacity available and its use for a reasonable number of years of history. Such information is not freely available for industrial heating processes and therefore capacity factors are assumed to remain constant. This means that capacities always track with the market share in terms of useful heat demand delivered.

2.5. Policy options

The FTT models allow for a multitude of real-world policies that can be implemented. The policy options range from technology support to penalising policies and they can interact through three interactions:

- through the cost components within the LCOIH calculation
- through investor preferences
- and directly with the substitution dynamics

Table 2-3: Overview of policy options available in FTT:IH.

Policy	Policy type	Definition	Effect	Dimensions
Subsidies on upfront investment	Market-based	Reduces the upfront investment costs	Changes the LCOIH estimation, and therefore decision-making	By region and technology
Fuel tax	Market-based	Increases the operational costs	Changes the LCOIH estimation, and therefore decision-making	By region and fuel
Fuel rebate	Market-based	Reduces the operational costs	Changes the LCOIH estimation, and therefore decision-making	By region and fuel
Carbon tax or price	Market-based	Increases the operational costs depending on the carbon intensity of each technology option	Changes the LCOIH estimation and therefore decision-making	By region and sector

Regulatory market caps	Regulation-based	Prevents uptake of technologies above a predefined cap	Changes investor preferences	By region and technology
Phase-out of new additions	Regulation-based	Prevents uptake of new additions and therefore a technology is faced out at its natural decline rate	Changes investor preferences	By region and technology
Government procurement / strategic investment	Regulation-based	Seeds the system with additional capacity of a technology	Changes market share dynamics	By region and technology

3. Database

3.1. Cost components

As section 2.3 alluded to, in order to produce an accurate estimate of economic performance of technologies on which they can be compared the model requires accurate techno-economic data inputs. Here, we relied predominantly on datasets produced by the Danish Energy Agency (2022). We mapped the broad technology categories as interpreted from the JRC-IDEES dataset (Mantzos et al., 2018) to the techno-economic data of each individual technology as provided by the Danish Energy Agency (2022). See Table A-1 in the appendix for an overview of the collected techno-economic data used in FTT:IH.

3.2. Historical uptake of process heating technologies

Useful energy demand, final energy demand, and emissions for the period 2000 to 2015 were obtained from the JRC-IDEES dataset (Mantzos et al., 2018). The dataset does so by recognising various process heating and non-process heating processes. Table 3-1 displays which processes we included in our description of the sectors included in FTT:IH.

Table 3-1: Mapping of sectors in the JRC-IDEES dataset to the FTT:IH classification, including heating (sub)processes.

JRC-IDEES sectors	FTT:IH sectors	(sub)processes included
Alumina production	NMT	High enthalpy heat processing; refining
Aluminium - primary production	NMT	Processing; finishing
Aluminium - secondary production	NMT	Pre-treatment; processing; finishing
Other non-ferrous metals	NMT	Thermal production; processing; finishing
Basic chemicals	CHI	Processing; thermal furnaces
Pharmaceutical products etc.	CHI	High enthalpy heat processing
Other chemicals	CHI	High enthalpy heat processing; thermal furnaces
Cement	NMM	Pre-processing; clinker production
Ceramics & other NMM	NMM	Drying & sintering; processing
Glass production	NMM	Melting; Annealing
Pulp production	NMM	Pulping thermal
Paper production	NMM	Stock preparation; paper machine (steam use); finishing
Printing and media reproduction	n.a.	n.a.
Food, beverages and tobacco	FBT	Direct heating; specific heating; steam processing; drying
Transport Equipment	NMT	Foundries; connection techniques; heat treatment; steam processing
Machinery Equipment	NMT	Foundries; connection techniques; heat treatment; steam processing
Textiles and leather	OIS	Pre-treatment with steam; wet-processing with steam; drying
Wood and wood products	OIS	Steam processing; drying
Other Industrial Sectors	OIS	Steam processing; process heating; drying

3.3. Demand projections

The starting point is the sum of all useful energy demand by heating processes as provided by the JRC-IDEES dataset (Mantzos et al., 2018). To estimate future demand, we used growth rates of final energy demand of the relevant corresponding sector provided by IEA's World Energy Outlook. The year-on-year growth rates are then applied to the historical estimate to project forward the demand for useful energy demand for process heating. The integrated version of FTT:IH within E3ME includes responses to gross output estimates of the relevant industrial sectors.

4. Explorative scenarios

4.1. Scenario overview

In order to display the mechanisms within FTT:IH and to explore the model's solution power, we considered four scenarios. Table 4-1 provides an overview of the simulated scenarios. The reference scenario can be seen as being akin to a "current policies" scenario. It will show continued diffusion trajectories without the influence of (additional) policies. The second scenario focuses on promoting low-carbon alternatives (all electric and bio-based options) via subsidies on upfront investments in order to increase their cost-competitiveness. Cost-competitiveness is further promoted in the third scenario by adding a carbon tax to the policy mix. Finally, we add phase-out regulations on new capacities of fossil-fuelled technology options in the fourth scenario.

We used the stand-alone model version of FTT:IH in order to avoid interference from feedbacks with E3ME. This makes the results less suitable for policy evaluation, but more suitable to understand the underlying mechanisms of the model.

Table 4-1: Overview of model scenarios.

#	Scenario	Scenario short	Column title
1	Reference	ref	In line with current policies
2	Subsidies	subs	Includes upfront subsidies on low-carbon process heating technologies of 50% of the upfront investment and it is applied between 2025 and 2050.
3	Subsidies + carbon tax	subs_ct	As above, plus the inclusion of a carbon tax that increases linearly from 0 in 2025 to 100 Euro(2020)/tCO_2.
4	Subsidies + carbon tax + phase out regulations	subs_ct_reg	As above, plus the inclusion of phase-out regulations on fossil fuelled technologies which is applied between 2025 and 2050.

4.2. Key assumptions

The FTT methodology does not at the moment include a mechanism that allows for the introduction of presently non-existent technologies. The user has to seed the system by forcing a small amount of such technologies in. This is called the "kick-starting" of novel technologies. In each of the above scenarios, we add 0.1% of market share to all technologies that are not in the system from the start. The substitution dynamics as described in section 2.3 require a non-zero entry for technologies to be part of the decision-making core. However, FTT:IH is a path-dependent model and therefore the amount of seeding matters for the long-run.

Section 1.3 already referred to the ongoing war in Ukraine and the impact it had on gas prices in relation to Russian gas imports. Such external impacts are likely to affect decision-making with respect to new technologies and therefore need to be reflected in the model. In all of the scenarios, we apply an energy price index of each fuel. These price indices were taken from E3ME, which include the gas price shock, ETS impact on fuel prices in accordance with their carbon contents, and supply and demand interactions and their impact on fossil fuel prices. Electricity prices respond to the fossil fuel prices depending on the technology configuration in the power sector, which is determined by FTT:Power. Figure A-1 in the appendix illustrates the energy price indices used in this study.

5. Results

5.1. Process heat delivered by technology

Europe's process heat is mostly delivered by gas-based processes. This finding applies to both the direct and indirect heating segments (see Figure 5-1). Without additional policies to support low carbon alternatives or penalise carbon intensive incumbents, a small shift towards electricity-based direct process heating is observed. Gas-based direct heating is slowly phased out at its expense. In the indirect heating market segment, gas-based process heating decreases to a lesser extent.

Applying subsidies on upfront investment does little to promote additional low-carbon process heating technologies in Europe's industrial system. A minute amount of low-carbon processes are added to the industrial systems. The subsidies are fairly ineffective because most of the costs occur in the operational phase for most technologies. Subsidies on upfront investments therefore have limited effect in changing the decisions.

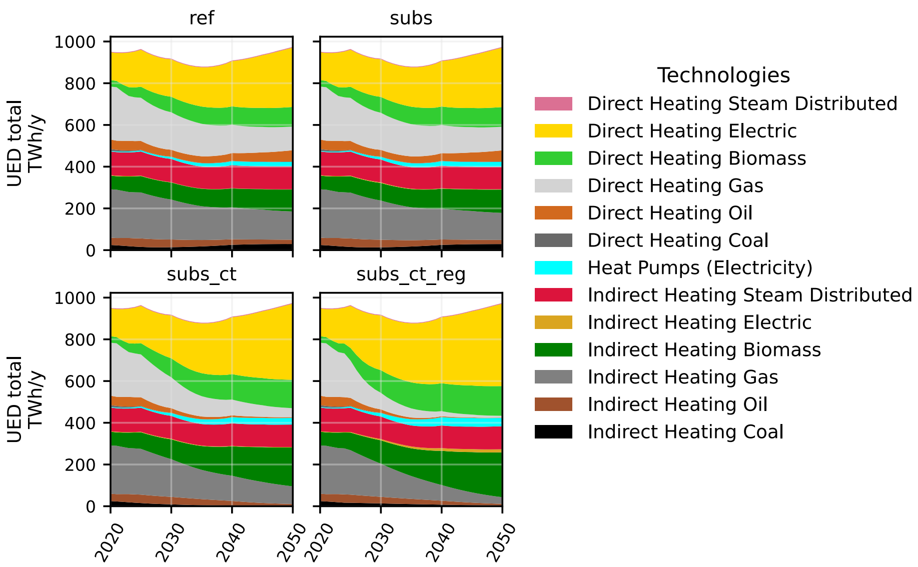

Figure 5-1: Process heat delivered by technology across all sectors (excl. iron & steel) and across all member states of EU27 and the UK.

Carbon taxes penalise technologies in accordance with their emission intensity. Together with subsidies, it provides larger disparity between the LCOIH of low-carbon and high-carbon processes. A minor shift towards heat pumps is observed in the indirect heating segment, but more so a shift to indirect bio-based heating is observed. In the direct process heating segment, we note a shift to additional electric and bio-based processes, which almost completely remove indirect gas-based heating. A similar shift occurs in the direct heating segment, but it is less pronounced. Adding phase-out regulations, in addition to the implementation of a carbon tax and subsidies, a further shift away from fossil-fuel based technologies is observed.

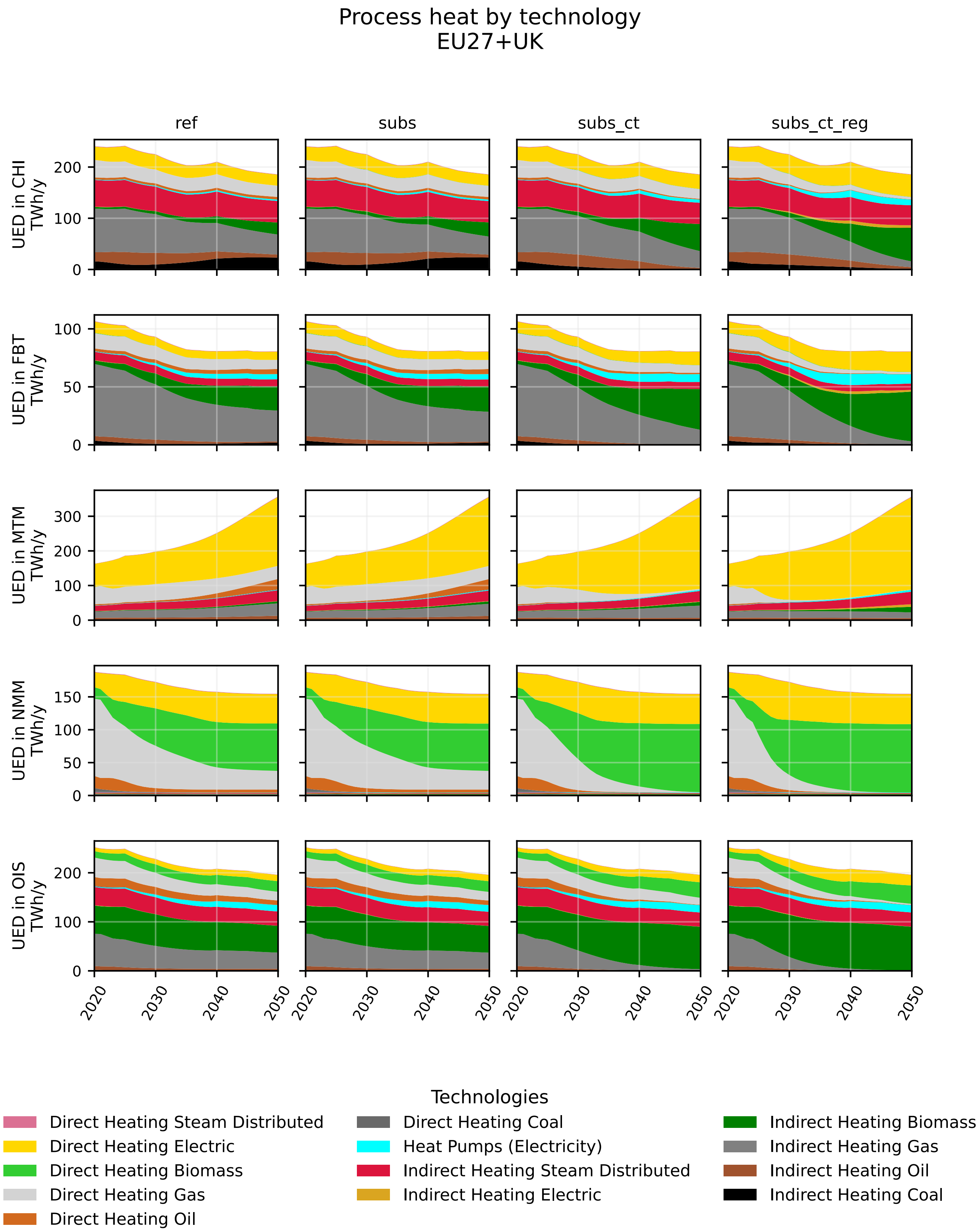

Figure 5-2: Process heat delivered by technology in each sector and scenario; summed across all EU27 member states and the UK.

Breaking down the energy delivered by sector (see Figure 5-2), we note that certain sectors struggle more to transition away from carbon intensive processes than others. The chemical (CHI), food, beverages, and tobacco (FBT), and Non-Ferrous Metals, Transport Equipment, and Machinery (MTM) sectors show lingering gas-based indirect heating processes in even the most stringent scenario (subs_ct_reg). While there are no technology constraints in the indirect heating market segment of these sectors (see Table 2-2), there is a technology lock-in of gas-based processes which is difficult to unlock, even with a stringent set of policies.

Gas-based processes are replaced by a combination of biobased and electric processes. While the technology constraints do not allow for uptake of bio-based processes in the direct heating segments of CHI, FBT, and MTM sectors, electricity-based processes start off with a critical mass and the most stringent policy scenario allows for an increase of such processes due to path dependency.

Ultimately, we find that electrification of industrial process heat can be propelled with targeted policies (see Table 5-1). The highest shares of electrification are found in the direct heating segment, for which bio-based heating has limited application. The share of electrification of direct heating processes across all sectors by 2030 increases to 56% in the subs_ct_reg scenario which is an increase of 18% compared the reference scenario in 2030. By 2050, this share increases further to 76%, which is 24% higher than the reference scenario in the same year. Electrification of indirect heating processes lags behind the direct heating segment with only a 6% and 28% electrification rate by 2030 and 2050 respectively in the most stringent scenario. The reference scenario only shows 2.5% by 2030 and 5% by 2050. There is a greater competition with bio-based processes to replace gas-based technologies and the bulk of non-electrified process heat is delivered by bio-based technologies.

Table 5-1: Share of electrification of industrial heat delivered by market segment (direct and indirect) for 2030 and 2050 (in %).

		CHI		FBT		MTM		NMM		OIS	
		Direct heating	Indirect heating	Direct heating	Indirect heating	Direct heating	Indirect heating	Direct heating	Indirect heating	Direct heating	Indirect heating
2030	ref	47%	1%	32%	3%	64%	2%	24%	20%	14%	3%
	subs	47%	2%	33%	4%	64%	4%	24%	31%	15%	4%
	subs_ct	48%	2%	34%	5%	69%	5%	25%	31%	16%	6%
	subs_ct_reg	60%	4%	56%	7%	95%	6%	34%	31%	26%	7%
2050	ref	44%	2%	36%	7%	74%	2%	30%	19%	20%	10%
	subs	44%	2%	36%	7%	74%	3%	30%	30%	20%	10%
	subs_ct	48%	13%	49%	24%	90%	7%	29%	30%	22%	31%
	subs_ct_reg	88%	22%	89%	41%	99%	17%	30%	30%	72%	35%

5.2. Emission profiles

Building on the diffusion of industrial process heat technologies and their conversion efficiencies (see Table A-1 of the appendix) in the respective scenarios, final energy demand can be estimated (see Figure C-1 of the appendix). From final energy demand, emissions can be estimated. Figure 5-3 illustrates the emission profiles by technology across all EU27 member states plus the UK and for each scenario.

A decrease of emissions is observed in the reference scenario between 2020 and 2050. This is driven by a decrease in overall demand levels of industrial process heat, especially in sectors that are currently dominated by carbon-intensive processes. The exception is the MTM sector where demand is projected to increase, however, most of the process heat is delivered through electricity-based processes and therefore the growth in demand does not contribute much to direct emissions for fuel combustion.

In line with the limited uptake of low-carbon technologies under the “subs” scenario, a negligible reduction in emissions in found. However, combining subsidies with a carbon tax (subs_ct) does invoke a large-scale transition to low-carbon alternatives and therefore a reduction in emissions. Comparing emissions in 2050 to 2020, we find a reduction of 72%. Preventing new additions of fossil-fuelled technologies to industrial systems (subs_ct_reg) leads to a reduction of 89%.

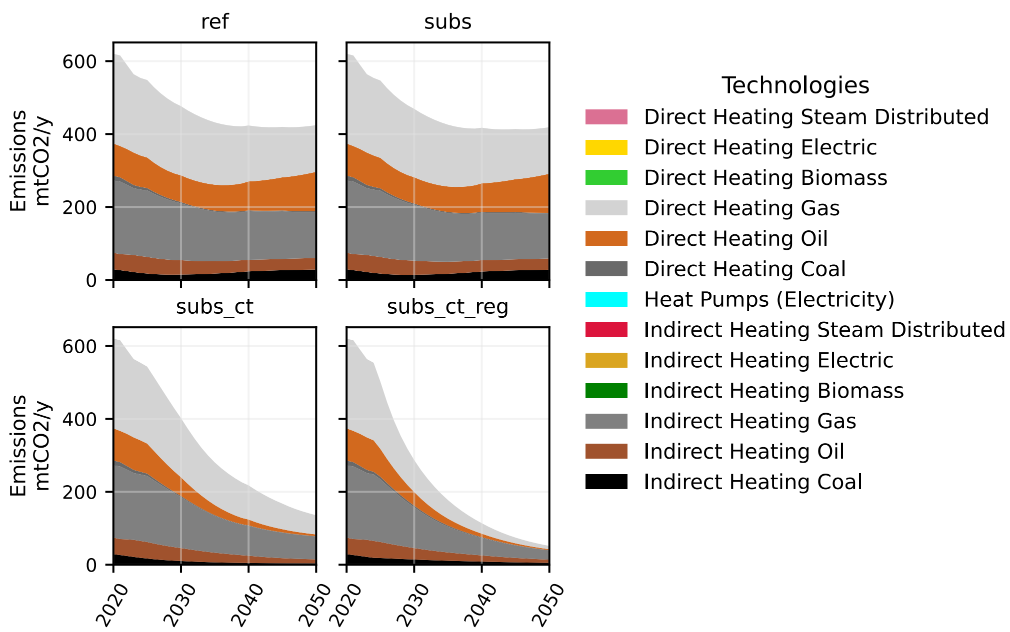

Figure 5-3: Direct CO_2 emissions from process heating by technology across all sectors (excl. iron & steel) and across all member states of EU27 and the UK.

Most of the emissions in the most stringent scenario (subs_ct_reg) are due to the lock-in of gas-based processes in the CHI, FBT, and MTM sectors. Simulations for the NMM and OIS sectors do show a near complete reduction of emissions by 2050. Emissions by sector and technology across all EU27 member states plus the UK are displayed in Figure 5-4.

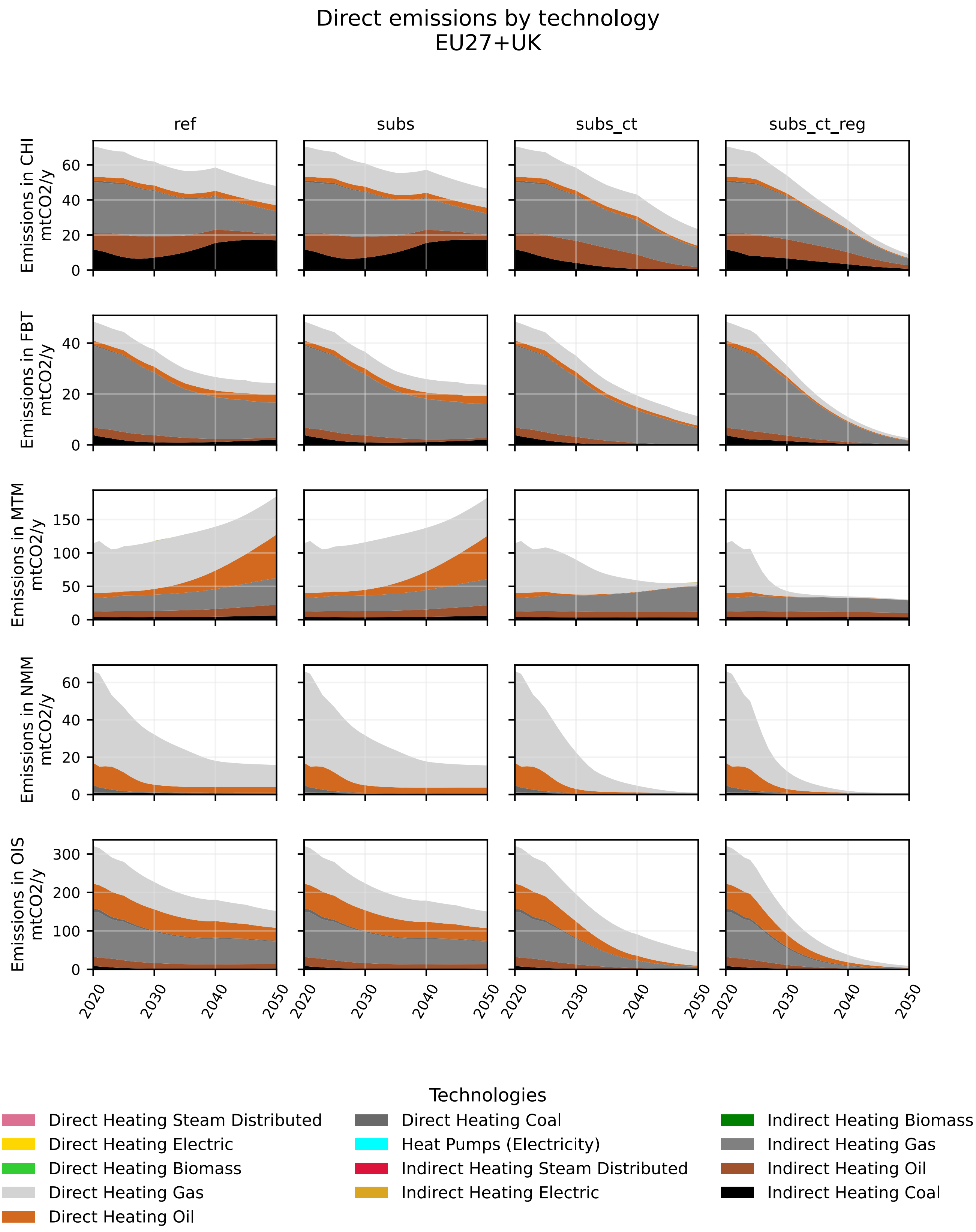

Figure 5-4: Direct emissions by technology in each sector and scenario; summed across all EU27 member states and the UK.

6. Discussion & Conclusion

6.1. Key takeaways

In this study, we have introduced FTT:IH as the latest addition to the FTT family of bottom-up technology models. We have explained the model core, the main data inputs, and assumptions used. On top of that, we have illustrated the model logic behind FTT:IH and shown explorative scenarios with respect to technology diffusion under different policy environments. In combination with other FTT models, the addition of FTT:IH increases the analytical power with regards to technological decision-making. It further allows us to investigate more detailed policy formulations to evaluate its effect on e.g. climate change mitigation.

We used FTT:IH to explore policy-induced diffusion of industrial process heat technologies. The results of the explorative scenarios show that large-scale emission reductions can be incentivised through a set of stringent policies. However, relying solely on policy support for low-carbon processes is not sufficient; penalising policies targeting carbon intensive processes are necessary as well to increase the competitive position of low-carbon alternatives relative to high-carbon processes. Adding restrictive policies – while generally unpopular – further reduces emissions.

6.2. Model limitations

Data availability and quality are always the greatest challenge of detailed bottom-up technology models. In section 2.2, the scope of the FTT:IH model was discussed. We explained that the technology options included are broad categories focussing on the energy input and the process heat segment it applies to. Therefore, FTT:IH lacks some of the technological granularity and prevents analysis of specific uptake of technologies. Whereas Madeddu et al. (2020) considered specific technologies focussed on electrification potentials, our study cannot replicate electrification to the same degree of granularity. This limitation is imposed by the data available. As a minimum, the model requires representation of recent technological take up and techno-economic cost components, and the broadest technology resolution of the two determines the technology resolution applied in the model. In addition, completely novel technologies, such as hydrogen-based process heating, are currently omitted due to lack of sources. Often, hydrogen-based technologies – be it for industrial process heat or for other purposes – is seen as being in direct competition with electrification, which by some is considered to be uncompetitive for many applications (Liebreich, 2020).

On top of availability and quality, data recency is another important component due to the path-dependent character of technology diffusion in FTT:IH. During the development of this model, we relied on the JRC-IDEES-2015 dataset. However, between the inception of the model and the writing of this report, an updated dataset was provided, JRC-IDEES-2021 (European Commission et al., 2024). This updated dataset has not yet been included. A future version of this model will build on the latest data available, which would provide a different point of departure and therefore affect the end results.

7. References

Baumstark, L., N. Bauer, F. Benke, C. Bertram, S. Bi, C.C. Gong, J.P. Dietrich, et al., 'REMIND2.1: Transformation and Innovation Dynamics of the Energy-Economic System within Climate and Sustainability Limits', *Geoscientific Model Development*, Vol. 14, No. 10, 2021, pp. 6571–6603.

BP, 'BP Energy Outlook 2019', 2019.

Cambridge Econometrics, *E3ME Model Manual*, 2022.

Danish Energy Agency, *Datasheet for Industrial Process Heat* , 2022.

———, *Technology Descriptions and Projections for Long-Term Energy System Planning*, 2024.

E3Modelling, *Primes Model Version 2018: Detailed Model Description*, 2018.

European Commission, '2050 Long-Term Strategy', 2024. https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en.

———, 'EU Climate Targets: How to Decarbonise the Steel Industry', 2022. https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/eu-climate-targets-how-decarbonise-steel-industry-2022-06-15_en.

———, *Policy Support for Heating and Cooling Decarbonisation*, 2021.

———, 'REPowerEU: A Plan to Rapidly Reduce Dependence on Russian Fossil Fuels and Fast Forward the Green Transition', May 18, 2022. https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131.

European Commission, Joint Research Centre, M. Rózsai, M. Jaxa-Rozen, R. Salvucci, P. Sikora, J. Tattini, and F. Neuwahl, *JRC-IDEES-2021, the Integrated Database of the European Energy System – Data Update and Technical Documentation*, Publications Office of the European Union, 2024.

European Commission, Joint Research Centre, S. Tchung-Ming, L. Mantzos, T. Wiesenthal, N. Matei, and M. Rozsai, *JRC-IDEES – Integrated Database of the European Energy Sector – Methodological Note*, Publications Office, 2017.

European Environment Agency, 'EEA Greenhouse Gases - Data Viewer', 2024. https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer.

Fleiter, T., M. Rehfeldt, A. Herbst, R. Elsland, A.-L. Klingler, P. Manz, and S. Eidelloth, 'A Methodology for

Bottom-up Modelling of Energy Transitions in the Industry Sector: The FORECAST Model', *Energy Strategy Reviews*, Vol. 22, 2018, pp. 237–254.

Fraunhofer ISI, *Direct Electrification of Industrial Process Heat. An Assessment of Technologies, Potentials and Future Prospects for the EU Energy Innovation. Study on Behalf of Agora Industry*, 2024.

———, *Modelling Pathways towards a Climate-Neutral EU Industry Sector*, 2022.

Grubb, M., P. Drummond, J.-F. Mercure, and C. Hepburn, 'The New Economics of Innovation and Transition: Evaluating Opportunities and Risks', EEIST: Economics of Energy Innovation and System Transition, 2021. https://eeist.co.uk/eeist-reports/the-new-economics-of-innovation-and-transition-evaluating-opportunities-and-risks/.

IEA, 'Clean and Efficient Heat for Industry', 2018. https://www.iea.org/commentaries/clean-and-efficient-heat-for-industry.

International Energy Agency, *Global Energy and Climate Model Documentation 2023*, 2023.

Knobloch, F., H. Pollitt, U. Chewpreecha, R. Lewney, M.A.J. Huijbregts, and J.F. Mercure, 'FTT:Heat — A Simulation Model for Technological Change in the European Residential Heating Sector', *Energy Policy*, Vol. 153, June 1, 2021, p. 112249.

Liebreich, M., 'Hydrogen Ladder', 2020. https://about.bnef.com/blog/liebreich-separating-hype-from-hydrogen-part-two-the-demand-side/.

Madeddu, S., F. Ueckerdt, M. Pehl, J. Peterseim, M. Lord, K.A. Kumar, C. Krüger, and G. Luderer, 'The CO2 Reduction Potential for the European Industry via Direct Electrification of Heat Supply (Power-to-Heat)', *Environmental Research Letters*, Vol. 15, No. 12, 2020, p. 124004.

———, 'The CO2 Reduction Potential for the European Industry via Direct Electrification of Heat Supply (Power-to-Heat)', *Environmental Research Letters*, Vol. 15, No. 12, December 1, 2020.

Maghrabi, A.M., J. Song, and C.N. Markides, 'How Can Industrial Heat Decarbonisation Be Accelerated through Energy Efficiency?', *Applied Thermal Engineering*, Vol. 233, October 1, 2023.

Mantzos, L., M. Rozsai, N.A. Matei, E. Mulholland, M. Tamba, and T. Wiesenthal, *JRC-IDEES-2015 Dataset*, 2018.

———, *JRC-IDEES-2015 Dataset*, 2018.

McKinsey & Company, *Decarbonization of Industrial Sectors: The next Frontier*, 2018.

Mercure, J.F., and A. Lam, 'The Effectiveness of Policy on Consumer Choices for Private Road Passenger

Transport Emissions Reductions in Six Major Economies', *Environmental Research Letters*, Vol. 10, No. 6, June 1, 2015.

Mercure, J.F., 'FTT:Power A Global Model of the Power Sector with Induced Technological Change and Natural Resource Depletion', *Energy Policy*, Vol. 48, 2012, pp. 799–811.

Mercure, J.-F., 'An Age Structured Demographic Theory of Technological Change', *Journal of Evolutionary Economics*, Vol. 25, No. 4, 2015, pp. 787–820.

Mercure, J.-F., F. Knobloch, H. Pollitt, L. Paroussos, S.S. Scrieciu, and R. Lewney, 'Modelling Innovation and the Macroeconomics of Low-Carbon Transitions: Theory, Perspectives and Practical Use', *Climate Policy*, Vol. 19, No. 8, September 14, 2019, pp. 1019–1037.

Naegler, T., S. Simon, M. Klein, and H.C. Gils, 'Quantification of the European Industrial Heat Demand by Branch and Temperature Level', *International Journal of Energy Research*, Vol. 39, No. 15, 2015.

Napp, T.A., A. Gambhir, T.P. Hills, N. Florin, and P.S. Fennell, 'A Review of the Technologies, Economics and Policy Instruments for Decarbonising Energy-Intensive Manufacturing Industries', *Renewable and Sustainable Energy Reviews*, Vol. 30, 2014, pp. 616–640.

Rehfeldt, M., T. Fleiter, and E. Worrell, 'Inter-Fuel Substitution in European Industry: A Random Utility Approach on Industrial Heat Demand', *Journal of Cleaner Production*, Vol. 187, June 20, 2018, pp. 98–110.

SIPA, *LOW-CARBON HEAT SOLUTIONS FOR HEAVY INDUSTRY: SOURCES, OPTIONS, AND COSTS TODAY*, 2019.

Vallejo, L., and et al., 'Halving Global CO2 Emissions by 2050: Technologies and Costs', *International Energy Journal*, Vol. 21, 2021, pp. 147–158.

Vercoulen, P., S. Lee, X. Han, W. Zhang, Y. Cho, and J. Pang, 'Carbon-Neutral Steel Production and Its Impact on the Economies of China, Japan, and Korea: A Simulation with E3ME-FTT:Steel', *Energies*, Vol. 16, No. 11, June 2, 2023, p. 4498.

West, K., T. van Harmelen, V. Koning, G.J. Kramer, and A. Faaij, 'Detailed Modelling of Basic Industry and Material Flows in a National Energy System Optimization Model', *Resources, Conservation and Recycling*, Vol. 206, 2024, p. 107617.

Appendices

Appendix A - Techno-economic data

Table A-1: Techno-economic data included in FTT:IH for the chemical industry. Similar datasets specific to the other industries

		1 Investment cost mean	2 Investment cost SD	3 O&M cost mea	4 O&M cost SD	5 Lifetime (years)	6 Leadtime (years)	7 Learning rate	8 Discount rate	9 Conversion efficiency	10 Fuel cost mean	11 Fuel cost SD
Region	Technology	(MEuro per MW)	(MEuro per MW)	(Euros/ MJ/s/year)	(Euros/ MJ/s/year)	years	years	-	-	-	(Euros/ MJ/s/year)	(Euros/ MJ/s/year)
BE	Indirect Heating Coal	0.434	0.022	43704	2185	25	1	-0.05	0.05	0.54	131.61	26.32
BE	Indirect Heating Oil	0.048	0.002	9170	459	25	1	-0.05	0.05	0.72	158.70	31.74
BE	Indirect Heating Gas	0.048	0.002	10105	505	25	1	-0.05	0.05	0.76	246.63	49.33
BE	Indirect Heating Biomass	0.536	0.027	43704	2185	25	1	-0.05	0.05	0.65	122.70	24.54
BE	Indirect Heating Electric	0.069	0.003	7776	389	25	1	-0.05	0.05	0.90	484.01	96.80
BE	Indirect Heating Steam Distributed	0.868	0.043	0	0	20	1	-0.05	0.05	0.82	0.00	0.00
BE	Heat Pumps (Electricity)	0.949	0.047	26657	1333	20	1	-0.433	0.05	3.00	145.20	29.04
BE	Direct Heating Coal	0.191	0.010	5462	273	15	1	-0.05	0.05	0.25	288.02	57.60
BE	Direct Heating Oil	0.013	0.001	2288	114	15	1	-0.05	0.05	0.44	256.95	51.39
BE	Direct Heating Gas	0.013	0.001	2288	114	15	1	-0.05	0.05	0.48	390.92	78.18
BE	Direct Heating Biomass	0.191	0.010	5462	273	15	1	-0.05	0.05	0.11	704.86	140.97
BE	Direct Heating Electric	0.052	0.003	1369	68	12.5	1	-0.05	0.05	0.60	730.12	146.02
BE	Direct Heating Steam Distributed	0.868	0.043	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
DK	Indirect Heating Coal	0.458	0.023	46096	2305	25	1	-0.05	0.05	0.62	239.48	47.90
DK	Indirect Heating Oil	0.050	0.003	9672	484	25	1	-0.05	0.05	0.51	294.01	58.80
DK	Indirect Heating Gas	0.050	0.003	10658	533	25	1	-0.05	0.05	0.68	757.08	151.42
DK	Indirect Heating Biomass	0.566	0.028	46096	2305	25	1	-0.05	0.05	0.56	181.97	36.39
DK	Indirect Heating Electric	0.073	0.004	8202	410	25	1	-0.05	0.05	0.90	971.99	194.40
DK	Indirect Heating Steam Distributed	0.915	0.046	0	0	20	1	-0.05	0.05	0.80	0.00	0.00
DK	Heat Pumps (Electricity)	1.001	0.050	28117	1406	20	1	-0.433	0.05	3.00	291.60	58.32
DK	Direct Heating Coal	0.201	0.010	5761	288	15	1	-0.05	0.05	0.25	603.82	120.76
DK	Direct Heating Oil	0.014	0.001	2413	121	15	1	-0.05	0.05	0.43	348.06	69.61
DK	Direct Heating Gas	0.014	0.001	2413	121	15	1	-0.05	0.05	0.46	1102.85	220.57
DK	Direct Heating Biomass	0.201	0.010	5761	288	15	1	-0.05	0.05	0.11	900.85	180.17

DK	Direct Heating Electric	0.055	0.003	1444	72	12.5	1	-0.05	0.05	0.59	1480.85	296.17
DK	Direct Heating Steam Distributed	0.915	0.046	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
DE	Indirect Heating Coal	0.443	0.022	44637	2232	25	1	-0.05	0.05	0.53	124.08	24.82
DE	Indirect Heating Oil	0.049	0.002	9366	468	25	1	-0.05	0.05	0.57	155.85	31.17
DE	Indirect Heating Gas	0.049	0.002	10321	516	25	1	-0.05	0.05	0.67	195.46	39.09
DE	Indirect Heating Biomass	0.548	0.027	44637	2232	25	1	-0.05	0.05	0.57	213.34	42.67
DE	Indirect Heating Electric	0.071	0.004	7942	397	25	1	-0.05	0.05	0.90	1324.03	264.81
DE	Indirect Heating Steam Distributed	0.886	0.044	0	0	20	1	-0.05	0.05	0.71	0.00	0.00
DE	Heat Pumps (Electricity)	0.969	0.048	27227	1361	20	1	-0.433	0.05	3.00	397.21	79.44
DE	Direct Heating Coal	0.195	0.010	5578	279	15	1	-0.05	0.05	0.25	269.24	53.85
DE	Direct Heating Oil	0.013	0.001	2337	117	15	1	-0.05	0.05	0.40	221.74	44.35
DE	Direct Heating Gas	0.013	0.001	2337	117	15	1	-0.05	0.05	0.44	297.81	59.56
DE	Direct Heating Biomass	0.195	0.010	5578	279	15	1	-0.05	0.05	0.11	1070.64	214.13
DE	Direct Heating Electric	0.053	0.003	1399	70	12.5	1	-0.05	0.05	0.54	2187.77	437.55
DE	Direct Heating Steam Distributed	0.886	0.044	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
EL	Indirect Heating Coal	0.517	0.026	52058	2603	25	1	-0.05	0.05	0.54	730.33	146.07
EL	Indirect Heating Oil	0.057	0.003	10923	546	25	1	-0.05	0.05	0.55	875.77	175.15
EL	Indirect Heating Gas	0.057	0.003	12036	602	25	1	-0.05	0.05	0.48	1164.37	232.87
EL	Indirect Heating Biomass	0.639	0.032	52058	2603	25	1	-0.05	0.05	0.54	195.95	39.19
EL	Indirect Heating Electric	0.083	0.004	9262	463	25	1	-0.05	0.05	0.90	1504.47	300.89
EL	Indirect Heating Steam Distributed	1.034	0.052	0	0	20	1	-0.05	0.05	0.69	0.00	0.00
EL	Heat Pumps (Electricity)	1.130	0.056	31753	1588	20	1	-0.433	0.05	3.00	451.34	90.27
EL	Direct Heating Coal	0.227	0.011	6506	325	15	1	-0.05	0.05	0.25	1598.27	319.65
EL	Direct Heating Oil	0.016	0.001	2725	136	15	1	-0.05	0.05	0.39	1228.06	245.61
EL	Direct Heating Gas	0.016	0.001	2725	136	15	1	-0.05	0.05	0.43	1318.83	263.77
EL	Direct Heating Biomass	0.227	0.011	6506	325	15	1	-0.05	0.05	0.11	943.91	188.78
EL	Direct Heating Electric	0.062	0.003	1631	82	12.5	1	-0.05	0.05	0.53	2542.99	508.60
EL	Direct Heating Steam Distributed	1.034	0.052	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
ES	Indirect Heating Coal	0.468	0.023	47149	2357	25	1	-0.05	0.05	0.52	299.72	59.94
ES	Indirect Heating Oil	0.051	0.003	9893	495	25	1	-0.05	0.05	0.56	388.57	77.71
ES	Indirect Heating Gas	0.051	0.003	10901	545	25	1	-0.05	0.05	0.66	420.95	84.19

ES	Indirect Heating Biomass	0.579	0.029	47149	2357	25	1	-0.05	0.05	0.55	212.19	42.44
ES	Indirect Heating Electric	0.075	0.004	8389	419	25	1	-0.05	0.05	0.90	1342.88	268.58
ES	Indirect Heating Steam Distributed	0.936	0.047	0	0	20	1	-0.05	0.05	0.69	0.00	0.00
ES	Heat Pumps (Electricity)	1.023	0.051	28759	1438	20	1	-0.433	0.05	3.00	402.86	80.57
ES	Direct Heating Coal	0.206	0.010	5892	295	15	1	-0.05	0.05	0.25	631.91	126.38
ES	Direct Heating Oil	0.014	0.001	2468	123	15	1	-0.05	0.05	0.42	527.31	105.46
ES	Direct Heating Gas	0.014	0.001	2468	123	15	1	-0.05	0.05	0.45	613.75	122.75
ES	Direct Heating Biomass	0.206	0.010	5892	295	15	1	-0.05	0.05	0.11	1034.59	206.92
ES	Direct Heating Electric	0.056	0.003	1477	74	12.5	1	-0.05	0.05	0.56	2156.47	431.29
ES	Direct Heating Steam Distributed	0.936	0.047	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
FR	Indirect Heating Coal	0.465	0.023	46851	2343	25	1	-0.05	0.05	0.58	458.24	91.65
FR	Indirect Heating Oil	0.051	0.003	9831	492	25	1	-0.05	0.05	0.63	497.71	99.54
FR	Indirect Heating Gas	0.051	0.003	10832	542	25	1	-0.05	0.05	0.73	457.82	91.56
FR	Indirect Heating Biomass	0.575	0.029	46851	2343	25	1	-0.05	0.05	0.62	392.41	78.48
FR	Indirect Heating Electric	0.074	0.004	8336	417	25	1	-0.05	0.05	0.90	1177.34	235.47
FR	Indirect Heating Steam Distributed	0.930	0.047	0	0	20	1	-0.05	0.05	0.69	0.00	0.00
FR	Heat Pumps (Electricity)	1.017	0.051	28577	1429	20	1	-0.433	0.05	3.00	353.20	70.64
FR	Direct Heating Coal	0.205	0.010	5855	293	15	1	-0.05	0.05	0.25	1084.51	216.90
FR	Direct Heating Oil	0.014	0.001	2453	123	15	1	-0.05	0.05	0.45	698.85	139.77
FR	Direct Heating Gas	0.014	0.001	2453	123	15	1	-0.05	0.05	0.49	689.73	137.95
FR	Direct Heating Biomass	0.205	0.010	5855	293	15	1	-0.05	0.05	0.11	2146.97	429.39
FR	Direct Heating Electric	0.056	0.003	1468	73	12.5	1	-0.05	0.05	0.61	1748.91	349.78
FR	Direct Heating Steam Distributed	0.930	0.047	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
IE	Indirect Heating Coal	0.466	0.023	46903	2345	25	1	-0.05	0.05	0.54	302.18	60.44
IE	Indirect Heating Oil	0.051	0.003	9842	492	25	1	-0.05	0.05	0.49	730.11	146.02
IE	Indirect Heating Gas	0.051	0.003	10844	542	25	1	-0.05	0.05	0.52	561.98	112.40
IE	Indirect Heating Biomass	0.576	0.029	46903	2345	25	1	-0.05	0.05	0.56	245.45	49.09
IE	Indirect Heating Electric	0.075	0.004	8345	417	25	1	-0.05	0.05	0.90	1652.33	330.47
IE	Indirect Heating Steam Distributed	0.931	0.047	0	0	20	1	-0.05	0.05	0.69	0.00	0.00
IE	Heat Pumps (Electricity)	1.018	0.051	28609	1430	20	1	-0.433	0.05	3.00	495.70	99.14
IE	Direct Heating Coal	0.205	0.010	5861	293	15	1	-0.05	0.05	0.25	661.29	132.26

IE	Direct Heating Oil	0.014	0.001	2456	123	15	1	-0.05	0.05	0.32	1103.53	220.71
IE	Direct Heating Gas	0.014	0.001	2456	123	15	1	-0.05	0.05	0.35	842.13	168.43
IE	Direct Heating Biomass	0.205	0.010	5861	293	15	1	-0.05	0.05	0.11	1215.13	243.03
IE	Direct Heating Electric	0.056	0.003	1470	73	12.5	1	-0.05	0.05	0.44	3412.46	682.49
IE	Direct Heating Steam Distributed	0.931	0.047	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
IT	Indirect Heating Coal	0.454	0.023	45728	2286	25	1	-0.05	0.05	0.47	726.84	145.37
IT	Indirect Heating Oil	0.050	0.002	9595	480	25	1	-0.05	0.05	0.51	627.95	125.59
IT	Indirect Heating Gas	0.050	0.002	10573	529	25	1	-0.05	0.05	0.59	639.29	127.86
IT	Indirect Heating Biomass	0.561	0.028	45728	2286	25	1	-0.05	0.05	0.50	439.39	87.88
IT	Indirect Heating Electric	0.073	0.004	8136	407	25	1	-0.05	0.05	0.90	3089.81	617.96
IT	Indirect Heating Steam Distributed	0.908	0.045	0	0	20	1	-0.05	0.05	0.63	0.00	0.00
IT	Heat Pumps (Electricity)	0.993	0.050	27892	1395	20	1	-0.433	0.05	3.00	926.94	185.39
IT	Direct Heating Coal	0.200	0.010	5714	286	15	1	-0.05	0.05	0.25	1382.92	276.58
IT	Direct Heating Oil	0.014	0.001	2394	120	15	1	-0.05	0.05	0.37	863.93	172.79
IT	Direct Heating Gas	0.014	0.001	2394	120	15	1	-0.05	0.05	0.40	937.43	187.49
IT	Direct Heating Biomass	0.200	0.010	5714	286	15	1	-0.05	0.05	0.11	1933.36	386.67
IT	Direct Heating Electric	0.054	0.003	1433	72	12.5	1	-0.05	0.05	0.50	5548.31	1109.66
IT	Direct Heating Steam Distributed	0.908	0.045	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
LX	Indirect Heating Coal	0.439	0.022	44195	2210	25	1	-0.05	0.05	0.54	516.83	103.37
LX	Indirect Heating Oil	0.048	0.002	9273	464	25	1	-0.05	0.05	0.59	496.78	99.36
LX	Indirect Heating Gas	0.048	0.002	10218	511	25	1	-0.05	0.05	0.63	587.69	117.54
LX	Indirect Heating Biomass	0.542	0.027	44195	2210	25	1	-0.05	0.05	0.56	158.15	31.63
LX	Indirect Heating Electric	0.070	0.004	7863	393	25	1	-0.05	0.05	0.90	944.46	188.89
LX	Indirect Heating Steam Distributed	0.878	0.044	0	0	20	1	-0.05	0.05	0.69	0.00	0.00
LX	Heat Pumps (Electricity)	0.959	0.048	26957	1348	20	1	-0.433	0.05	3.00	283.34	56.67
LX	Direct Heating Coal	0.193	0.010	5523	276	15	1	-0.05	0.05	0.25	1131.04	226.21
LX	Direct Heating Oil	0.013	0.001	2314	116	15	1	-0.05	0.05	0.39	759.69	151.94
LX	Direct Heating Gas	0.013	0.001	2314	116	15	1	-0.05	0.05	0.42	879.81	175.96
LX	Direct Heating Biomass	0.193	0.010	5523	276	15	1	-0.05	0.05	0.11	782.94	156.59
LX	Direct Heating Electric	0.053	0.003	1385	69	12.5	1	-0.05	0.05	0.52	1632.49	326.50
LX	Direct Heating Steam Distributed	0.878	0.044	0	0	20	1	-0.05	0.05	0.07	0.00	0.00

NL	Indirect Heating Coal	0.445	0.022	44812	2241	25	1	-0.05	0.05	0.54	166.76	33.35
NL	Indirect Heating Oil	0.049	0.002	9403	470	25	1	-0.05	0.05	0.57	311.62	62.32
NL	Indirect Heating Gas	0.049	0.002	10361	518	25	1	-0.05	0.05	0.62	384.41	76.88
NL	Indirect Heating Biomass	0.550	0.027	44812	2241	25	1	-0.05	0.05	0.56	126.57	25.31
NL	Indirect Heating Electric	0.071	0.004	7973	399	25	1	-0.05	0.05	0.90	1107.11	221.42
NL	Indirect Heating Steam Distributed	0.890	0.044	0	0	20	1	-0.05	0.05	0.69	0.00	0.00
NL	Heat Pumps (Electricity)	0.973	0.049	27334	1367	20	1	-0.433	0.05	3.00	332.13	66.43
NL	Direct Heating Coal	0.196	0.010	5600	280	15	1	-0.05	0.05	0.25	364.94	72.99
NL	Direct Heating Oil	0.013	0.001	2346	117	15	1	-0.05	0.05	0.40	447.62	89.52
NL	Direct Heating Gas	0.013	0.001	2346	117	15	1	-0.05	0.05	0.43	550.65	110.13
NL	Direct Heating Biomass	0.196	0.010	5600	280	15	1	-0.05	0.05	0.11	626.58	125.32
NL	Direct Heating Electric	0.053	0.003	1404	70	12.5	1	-0.05	0.05	0.54	1859.96	371.99
NL	Direct Heating Steam Distributed	0.890	0.044	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
AT	Indirect Heating Coal	0.410	0.020	41244	2062	25	1	-0.05	0.05	0.52	450.99	90.20
AT	Indirect Heating Oil	0.045	0.002	8654	433	25	1	-0.05	0.05	0.56	235.83	47.17
AT	Indirect Heating Gas	0.045	0.002	9536	477	25	1	-0.05	0.05	0.65	204.71	40.94
AT	Indirect Heating Biomass	0.506	0.025	41244	2062	25	1	-0.05	0.05	0.55	180.97	36.19
AT	Indirect Heating Electric	0.066	0.003	7338	367	25	1	-0.05	0.05	0.90	1050.08	210.02
AT	Indirect Heating Steam Distributed	0.819	0.041	0	0	20	1	-0.05	0.05	0.70	0.00	0.00
AT	Heat Pumps (Electricity)	0.895	0.045	25157	1258	20	1	-0.433	0.05	3.00	315.03	63.01
AT	Direct Heating Coal	0.180	0.009	5154	258	15	1	-0.05	0.05	0.25	952.27	190.45
AT	Direct Heating Oil	0.012	0.001	2159	108	15	1	-0.05	0.05	0.42	313.63	62.73
AT	Direct Heating Gas	0.012	0.001	2159	108	15	1	-0.05	0.05	0.41	322.91	64.58
AT	Direct Heating Biomass	0.180	0.009	5154	258	15	1	-0.05	0.05	0.11	883.67	176.73
AT	Direct Heating Electric	0.049	0.002	1292	65	12.5	1	-0.05	0.05	0.51	1855.12	371.02
AT	Direct Heating Steam Distributed	0.819	0.041	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
PT	Indirect Heating Coal	0.466	0.023	46903	2345	25	1	-0.05	0.05	0.57	537.96	107.59
PT	Indirect Heating Oil	0.051	0.003	9842	492	25	1	-0.05	0.05	0.63	423.67	84.73
PT	Indirect Heating Gas	0.051	0.003	10844	542	25	1	-0.05	0.05	0.71	498.34	99.67
PT	Indirect Heating Biomass	0.576	0.029	46903	2345	25	1	-0.05	0.05	0.60	804.85	160.97
PT	Indirect Heating Electric	0.075	0.004	8345	417	25	1	-0.05	0.05	0.90	1325.14	265.03

PT	Indirect Heating Steam Distributed	0.931	0.047	0	0	20	1	-0.05	0.05	0.75	0.00	0.00
PT	Heat Pumps (Electricity)	1.018	0.051	28609	1430	20	1	-0.433	0.05	3.00	397.54	79.51
PT	Direct Heating Coal	0.205	0.010	5861	293	15	1	-0.05	0.05	0.25	1241.49	248.30
PT	Direct Heating Oil	0.014	0.001	2456	123	15	1	-0.05	0.05	0.41	648.19	129.64
PT	Direct Heating Gas	0.014	0.001	2456	123	15	1	-0.05	0.05	0.44	801.83	160.37
PT	Direct Heating Biomass	0.205	0.010	5861	293	15	1	-0.05	0.05	0.11	4295.45	859.09
PT	Direct Heating Electric	0.056	0.003	1470	73	12.5	1	-0.05	0.05	0.55	2169.61	433.92
PT	Direct Heating Steam Distributed	0.931	0.047	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
FI	Indirect Heating Coal	0.431	0.022	43455	2173	25	1	-0.05	0.05	0.54	574.70	114.94
FI	Indirect Heating Oil	0.047	0.002	9118	456	25	1	-0.05	0.05	0.50	250.98	50.20
FI	Indirect Heating Gas	0.047	0.002	10047	502	25	1	-0.05	0.05	0.64	421.22	84.24
FI	Indirect Heating Biomass	0.533	0.027	43455	2173	25	1	-0.05	0.05	0.58	680.40	136.08
FI	Indirect Heating Electric	0.069	0.003	7732	387	25	1	-0.05	0.05	0.90	971.85	194.37
FI	Indirect Heating Steam Distributed	0.863	0.043	0	0	20	1	-0.05	0.05	0.71	0.00	0.00
FI	Heat Pumps (Electricity)	0.943	0.047	26506	1325	20	1	-0.433	0.05	3.00	291.55	58.31
FI	Direct Heating Coal	0.190	0.009	5430	272	15	1	-0.05	0.05	0.25	1257.68	251.54
FI	Direct Heating Oil	0.013	0.001	2275	114	15	1	-0.05	0.05	0.38	329.57	65.91
FI	Direct Heating Gas	0.013	0.001	2275	114	15	1	-0.05	0.05	0.42	647.49	129.50
FI	Direct Heating Biomass	0.190	0.009	5430	272	15	1	-0.05	0.05	0.11	3503.78	700.76
FI	Direct Heating Electric	0.052	0.003	1362	68	12.5	1	-0.05	0.05	0.52	1677.82	335.56
FI	Direct Heating Steam Distributed	0.863	0.043	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
SW	Indirect Heating Coal	0.482	0.024	48582	2429	25	1	-0.05	0.05	0.59	437.64	87.53
SW	Indirect Heating Oil	0.053	0.003	10194	510	25	1	-0.05	0.05	0.65	580.84	116.17
SW	Indirect Heating Gas	0.053	0.003	11233	562	25	1	-0.05	0.05	0.73	644.00	128.80
SW	Indirect Heating Biomass	0.596	0.030	48582	2429	25	1	-0.05	0.05	0.63	130.06	26.01
SW	Indirect Heating Electric	0.077	0.004	8644	432	25	1	-0.05	0.05	0.90	944.58	188.92
SW	Indirect Heating Steam Distributed	0.965	0.048	0	0	20	1	-0.05	0.05	0.69	0.00	0.00
SW	Heat Pumps (Electricity)	1.055	0.053	29633	1482	20	1	-0.433	0.05	3.00	283.37	56.67
SW	Direct Heating Coal	0.212	0.011	6071	304	15	1	-0.05	0.05	0.25	1057.38	211.48
SW	Direct Heating Oil	0.014	0.001	2543	127	15	1	-0.05	0.05	0.44	846.19	169.24
SW	Direct Heating Gas	0.014	0.001	2543	127	15	1	-0.05	0.05	0.48	982.70	196.54

SW	Direct Heating Biomass	0.212	0.011	6071	304	15	1	-0.05	0.05	0.11	726.74	145.35
SW	Direct Heating Electric	0.058	0.003	1522	76	12.5	1	-0.05	0.05	0.60	1419.45	283.89
SW	Direct Heating Steam Distributed	0.965	0.048	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
UK	Indirect Heating Coal	0.345	0.017	34704	1735	25	1	-0.05	0.05	0.51	311.12	62.22
UK	Indirect Heating Oil	0.038	0.002	7282	364	25	1	-0.05	0.05	0.59	236.73	47.35
UK	Indirect Heating Gas	0.038	0.002	8024	401	25	1	-0.05	0.05	0.64	260.52	52.10
UK	Indirect Heating Biomass	0.426	0.021	34704	1735	25	1	-0.05	0.05	0.56	180.40	36.08
UK	Indirect Heating Electric	0.055	0.003	6175	309	25	1	-0.05	0.05	0.90	906.78	181.36
UK	Indirect Heating Steam Distributed	0.689	0.034	0	0	20	1	-0.05	0.05	0.67	0.00	0.00
UK	Heat Pumps (Electricity)	0.753	0.038	21168	1058	20	1	-0.433	0.05	3.00	272.03	54.41
UK	Direct Heating Coal	0.152	0.008	4337	217	15	1	-0.05	0.05	0.25	641.21	128.24
UK	Direct Heating Oil	0.010	0.001	1817	91	15	1	-0.05	0.05	0.42	330.39	66.08
UK	Direct Heating Gas	0.010	0.001	1817	91	15	1	-0.05	0.05	0.46	366.25	73.25
UK	Direct Heating Biomass	0.152	0.008	4337	217	15	1	-0.05	0.05	0.11	893.11	178.62
UK	Direct Heating Electric	0.041	0.002	1087	54	12.5	1	-0.05	0.05	0.57	1437.94	287.59
UK	Direct Heating Steam Distributed	0.689	0.034	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
CZ	Indirect Heating Coal	0.471	0.024	47425	2371	25	1	-0.05	0.05	0.45	257.72	51.54
CZ	Indirect Heating Oil	0.052	0.003	9951	498	25	1	-0.05	0.05	0.50	523.01	104.60
CZ	Indirect Heating Gas	0.052	0.003	10965	548	25	1	-0.05	0.05	0.57	573.43	114.69
CZ	Indirect Heating Biomass	0.582	0.029	47425	2371	25	1	-0.05	0.05	0.48	296.74	59.35
CZ	Indirect Heating Electric	0.075	0.004	8438	422	25	1	-0.05	0.05	0.90	1842.33	368.47
CZ	Indirect Heating Steam Distributed	0.942	0.047	0	0	20	1	-0.05	0.05	0.61	0.00	0.00
CZ	Heat Pumps (Electricity)	1.029	0.051	28927	1446	20	1	-0.433	0.05	3.00	552.70	110.54
CZ	Direct Heating Coal	0.207	0.010	5927	296	15	1	-0.05	0.05	0.25	474.96	94.99
CZ	Direct Heating Oil	0.014	0.001	2483	124	15	1	-0.05	0.05	0.33	774.98	155.00
CZ	Direct Heating Gas	0.014	0.001	2483	124	15	1	-0.05	0.05	0.37	881.35	176.27
CZ	Direct Heating Biomass	0.207	0.010	5927	296	15	1	-0.05	0.05	0.11	1264.68	252.94
CZ	Direct Heating Electric	0.057	0.003	1486	74	12.5	1	-0.05	0.05	0.47	3554.06	710.81
CZ	Direct Heating Steam Distributed	0.942	0.047	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
EN	Indirect Heating Coal	0.405	0.020	40741	2037	25	1	-0.05	0.05	0.54	191.35	38.27
EN	Indirect Heating Oil	0.044	0.002	8549	427	25	1	-0.05	0.05	0.40	208.19	41.64

EN	Indirect Heating Gas	0.044	0.002	9420	471	25	1	-0.05	0.05	0.42	230.28	46.06
EN	Indirect Heating Biomass	0.500	0.025	40741	2037	25	1	-0.05	0.05	0.46	169.01	33.80
EN	Indirect Heating Electric	0.065	0.003	7249	362	25	1	-0.05	0.05	0.90	597.75	119.55
EN	Indirect Heating Steam Distributed	0.809	0.040	0	0	20	1	-0.05	0.05	0.58	0.00	0.00
EN	Heat Pumps (Electricity)	0.884	0.044	24850	1243	20	1	-0.433	0.05	3.00	179.32	35.86
EN	Direct Heating Coal	0.178	0.009	5091	255	15	1	-0.05	0.05	0.25	418.75	83.75
EN	Direct Heating Oil	0.012	0.001	2133	107	15	1	-0.05	0.05	0.32	259.27	51.85
EN	Direct Heating Gas	0.012	0.001	2133	107	15	1	-0.05	0.05	0.35	280.76	56.15
EN	Direct Heating Biomass	0.178	0.009	5091	255	15	1	-0.05	0.05	0.11	688.78	137.76
EN	Direct Heating Electric	0.049	0.002	1277	64	12.5	1	-0.05	0.05	0.45	1202.32	240.46
EN	Direct Heating Steam Distributed	0.809	0.040	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
CY	Indirect Heating Coal	0.482	0.024	48498	2425	25	1	-0.05	0.05	0.54	296.71	59.34
CY	Indirect Heating Oil	0.053	0.003	10176	509	25	1	-0.05	0.05	0.44	899.78	179.96
CY	Indirect Heating Gas	0.053	0.003	11213	561	25	1	-0.05	0.05	0.66	362.63	72.53
CY	Indirect Heating Biomass	0.595	0.030	48498	2425	25	1	-0.05	0.05	0.56	172.30	34.46
CY	Indirect Heating Electric	0.077	0.004	8629	431	25	1	-0.05	0.05	0.90	2325.06	465.01
CY	Indirect Heating Steam Distributed	0.963	0.048	0	0	20	1	-0.05	0.05	0.69	0.00	0.00
CY	Heat Pumps (Electricity)	1.053	0.053	29582	1479	20	1	-0.433	0.05	3.00	697.52	139.50
CY	Direct Heating Coal	0.212	0.011	6061	303	15	1	-0.05	0.05	0.25	649.32	129.86
CY	Direct Heating Oil	0.014	0.001	2539	127	15	1	-0.05	0.05	0.30	1301.68	260.34
CY	Direct Heating Gas	0.014	0.001	2539	127	15	1	-0.05	0.05	0.44	547.05	109.41
CY	Direct Heating Biomass	0.212	0.011	6061	303	15	1	-0.05	0.05	0.11	852.99	170.60
CY	Direct Heating Electric	0.058	0.003	1520	76	12.5	1	-0.05	0.05	0.41	5092.74	1018.55
CY	Direct Heating Steam Distributed	0.963	0.048	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
LV	Indirect Heating Coal	0.408	0.020	41120	2056	25	1	-0.05	0.05	0.54	246.99	49.40
LV	Indirect Heating Oil	0.045	0.002	8628	431	25	1	-0.05	0.05	0.57	260.75	52.15
LV	Indirect Heating Gas	0.045	0.002	9507	475	25	1	-0.05	0.05	0.66	152.62	30.52
LV	Indirect Heating Biomass	0.505	0.025	41120	2056	25	1	-0.05	0.05	0.57	145.35	29.07
LV	Indirect Heating Electric	0.065	0.003	7316	366	25	1	-0.05	0.05	0.90	524.37	104.87
LV	Indirect Heating Steam Distributed	0.817	0.041	0	0	20	1	-0.05	0.05	0.72	0.00	0.00
LV	Heat Pumps (Electricity)	0.893	0.045	25081	1254	20	1	-0.433	0.05	3.00	157.31	31.46

LV	Direct Heating Coal	0.180	0.009	5139	257	15	1	-0.05	0.05	0.25	540.52	108.10
LV	Direct Heating Oil	0.012	0.001	2153	108	15	1	-0.05	0.05	0.41	367.49	73.50
LV	Direct Heating Gas	0.012	0.001	2153	108	15	1	-0.05	0.05	0.44	227.25	45.45
LV	Direct Heating Biomass	0.180	0.009	5139	257	15	1	-0.05	0.05	0.11	738.23	147.65
LV	Direct Heating Electric	0.049	0.002	1288	64	12.5	1	-0.05	0.05	0.55	858.42	171.68
LV	Direct Heating Steam Distributed	0.817	0.041	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
LT	Indirect Heating Coal	0.421	0.021	42390	2120	25	1	-0.05	0.05	0.54	246.03	49.21
LT	Indirect Heating Oil	0.046	0.002	8895	445	25	1	-0.05	0.05	0.57	368.87	73.77
LT	Indirect Heating Gas	0.046	0.002	9801	490	25	1	-0.05	0.05	0.63	157.11	31.42
LT	Indirect Heating Biomass	0.520	0.026	42390	2120	25	1	-0.05	0.05	0.56	144.86	28.97
LT	Indirect Heating Electric	0.067	0.003	7542	377	25	1	-0.05	0.05	0.90	512.00	102.40
LT	Indirect Heating Steam Distributed	0.842	0.042	0	0	20	1	-0.05	0.05	0.71	0.00	0.00
LT	Heat Pumps (Electricity)	0.920	0.046	25856	1293	20	1	-0.433	0.05	3.00	153.60	30.72
LT	Direct Heating Coal	0.185	0.009	5297	265	15	1	-0.05	0.05	0.25	538.42	107.68
LT	Direct Heating Oil	0.013	0.001	2219	111	15	1	-0.05	0.05	0.39	538.31	107.66
LT	Direct Heating Gas	0.013	0.001	2219	111	15	1	-0.05	0.05	0.43	233.20	46.64
LT	Direct Heating Biomass	0.185	0.009	5297	265	15	1	-0.05	0.05	0.11	719.84	143.97
LT	Direct Heating Electric	0.051	0.003	1328	66	12.5	1	-0.05	0.05	0.53	867.54	173.51
LT	Direct Heating Steam Distributed	0.842	0.042	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
HU	Indirect Heating Coal	0.361	0.018	36345	1817	25	1	-0.05	0.05	0.54	129.77	25.95
HU	Indirect Heating Oil	0.040	0.002	7626	381	25	1	-0.05	0.05	0.64	133.78	26.76
HU	Indirect Heating Gas	0.040	0.002	8403	420	25	1	-0.05	0.05	0.70	287.97	57.59
HU	Indirect Heating Biomass	0.446	0.022	36345	1817	25	1	-0.05	0.05	0.59	184.51	36.90
HU	Indirect Heating Electric	0.058	0.003	6467	323	25	1	-0.05	0.05	0.90	1038.82	207.76
HU	Indirect Heating Steam Distributed	0.722	0.036	0	0	20	1	-0.05	0.05	0.75	0.00	0.00
HU	Heat Pumps (Electricity)	0.789	0.039	22169	1108	20	1	-0.433	0.05	3.00	311.65	62.33
HU	Direct Heating Coal	0.159	0.008	4542	227	15	1	-0.05	0.05	0.25	284.00	56.80
HU	Direct Heating Oil	0.011	0.001	1903	95	15	1	-0.05	0.05	0.43	197.48	39.50
HU	Direct Heating Gas	0.011	0.001	1903	95	15	1	-0.05	0.05	0.44	455.28	91.06
HU	Direct Heating Biomass	0.159	0.008	4542	227	15	1	-0.05	0.05	0.11	967.92	193.58
HU	Direct Heating Electric	0.043	0.002	1139	57	12.5	1	-0.05	0.05	0.58	1600.89	320.18

HU	Direct Heating Steam Distributed	0.722	0.036	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
MT	Indirect Heating Coal	0.434	0.022	43689	2184	25	1	-0.05	0.05	0.54	153.84	30.77
MT	Indirect Heating Oil	0.048	0.002	9167	458	25	1	-0.05	0.05	0.57	411.09	82.22
MT	Indirect Heating Gas	0.048	0.002	10101	505	25	1	-0.05	0.05	0.66	96.96	19.39
MT	Indirect Heating Biomass	0.536	0.027	43689	2184	25	1	-0.05	0.05	0.56	147.75	29.55
MT	Indirect Heating Electric	0.069	0.003	7773	389	25	1	-0.05	0.05	0.90	455.05	91.01
MT	Indirect Heating Steam Distributed	0.868	0.043	0	0	20	1	-0.05	0.05	0.69	0.00	0.00
MT	Heat Pumps (Electricity)	0.948	0.047	26648	1332	20	1	-0.433	0.05	3.00	136.51	27.30
MT	Direct Heating Coal	0.191	0.010	5460	273	15	1	-0.05	0.05	0.25	336.67	67.33
MT	Direct Heating Oil	0.013	0.001	2287	114	15	1	-0.05	0.05	0.42	565.34	113.07
MT	Direct Heating Gas	0.013	0.001	2287	114	15	1	-0.05	0.05	0.44	146.27	29.25
MT	Direct Heating Biomass	0.191	0.010	5460	273	15	1	-0.05	0.05	0.11	731.43	146.29
MT	Direct Heating Electric	0.052	0.003	1369	68	12.5	1	-0.05	0.05	0.57	723.25	144.65
MT	Direct Heating Steam Distributed	0.868	0.043	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
PL	Indirect Heating Coal	0.462	0.023	46518	2326	25	1	-0.05	0.05	0.55	317.20	63.44
PL	Indirect Heating Oil	0.051	0.003	9761	488	25	1	-0.05	0.05	0.62	651.30	130.26
PL	Indirect Heating Gas	0.051	0.003	10755	538	25	1	-0.05	0.05	0.66	402.22	80.44
PL	Indirect Heating Biomass	0.571	0.029	46518	2326	25	1	-0.05	0.05	0.58	363.85	72.77
PL	Indirect Heating Electric	0.074	0.004	8277	414	25	1	-0.05	0.05	0.90	1123.18	224.64
PL	Indirect Heating Steam Distributed	0.924	0.046	0	0	20	1	-0.05	0.05	0.72	0.00	0.00
PL	Heat Pumps (Electricity)	1.010	0.050	28374	1419	20	1	-0.433	0.05	3.00	336.95	67.39
PL	Direct Heating Coal	0.203	0.010	5813	291	15	1	-0.05	0.05	0.25	711.41	142.28
PL	Direct Heating Oil	0.014	0.001	2435	122	15	1	-0.05	0.05	0.40	997.53	199.51
PL	Direct Heating Gas	0.014	0.001	2435	122	15	1	-0.05	0.05	0.44	605.11	121.02
PL	Direct Heating Biomass	0.203	0.010	5813	291	15	1	-0.05	0.05	0.11	1856.43	371.29
PL	Direct Heating Electric	0.055	0.003	1458	73	12.5	1	-0.05	0.05	0.54	1862.25	372.45
PL	Direct Heating Steam Distributed	0.924	0.046	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
SI	Indirect Heating Coal	0.465	0.023	46842	2342	25	1	-0.05	0.05	0.54	209.36	41.87
SI	Indirect Heating Oil	0.051	0.003	9829	491	25	1	-0.05	0.05	0.61	149.77	29.95
SI	Indirect Heating Gas	0.051	0.003	10830	542	25	1	-0.05	0.05	0.64	549.24	109.85
SI	Indirect Heating Biomass	0.575	0.029	46842	2342	25	1	-0.05	0.05	0.53	170.46	34.09

SI	Indirect Heating Electric	0.074	0.004	8334	417	25	1	-0.05	0.05	0.90	1089.37	217.87
SI	Indirect Heating Steam Distributed	0.930	0.047	0	0	20	1	-0.05	0.05	0.65	0.00	0.00
SI	Heat Pumps (Electricity)	1.017	0.051	28572	1429	20	1	-0.433	0.05	3.00	326.81	65.36
SI	Direct Heating Coal	0.205	0.010	5854	293	15	1	-0.05	0.05	0.25	458.17	91.63
SI	Direct Heating Oil	0.014	0.001	2452	123	15	1	-0.05	0.05	0.39	234.64	46.93
SI	Direct Heating Gas	0.014	0.001	2452	123	15	1	-0.05	0.05	0.42	842.37	168.47
SI	Direct Heating Biomass	0.205	0.010	5854	293	15	1	-0.05	0.05	0.11	801.12	160.22
SI	Direct Heating Electric	0.056	0.003	1468	73	12.5	1	-0.05	0.05	0.52	1875.12	375.02
SI	Direct Heating Steam Distributed	0.930	0.047	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
SK	Indirect Heating Coal	0.540	0.027	54338	2717	25	1	-0.05	0.05	0.54	146.66	29.33
SK	Indirect Heating Oil	0.059	0.003	11402	570	25	1	-0.05	0.05	0.57	180.70	36.14
SK	Indirect Heating Gas	0.059	0.003	12564	628	25	1	-0.05	0.05	0.59	545.05	109.01
SK	Indirect Heating Biomass	0.667	0.033	54338	2717	25	1	-0.05	0.05	0.52	203.83	40.77
SK	Indirect Heating Electric	0.086	0.004	9668	483	25	1	-0.05	0.05	0.90	2285.83	457.17
SK	Indirect Heating Steam Distributed	1.079	0.054	0	0	20	1	-0.05	0.05	0.64	0.00	0.00
SK	Heat Pumps (Electricity)	1.179	0.059	33144	1657	20	1	-0.433	0.05	3.00	685.75	137.15
SK	Direct Heating Coal	0.237	0.012	6791	340	15	1	-0.05	0.05	0.25	320.95	64.19
SK	Direct Heating Oil	0.016	0.001	2845	142	15	1	-0.05	0.05	0.42	248.51	49.70
SK	Direct Heating Gas	0.016	0.001	2845	142	15	1	-0.05	0.05	0.42	764.44	152.89
SK	Direct Heating Biomass	0.237	0.012	6791	340	15	1	-0.05	0.05	0.11	940.01	188.00
SK	Direct Heating Electric	0.065	0.003	1703	85	12.5	1	-0.05	0.05	0.52	3919.99	784.00
SK	Direct Heating Steam Distributed	1.079	0.054	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
BG	Indirect Heating Coal	0.435	0.022	43783	2189	25	1	-0.05	0.05	0.52	153.34	30.67
BG	Indirect Heating Oil	0.048	0.002	9187	459	25	1	-0.05	0.05	0.57	435.00	87.00
BG	Indirect Heating Gas	0.048	0.002	10123	506	25	1	-0.05	0.05	0.65	91.22	18.24
BG	Indirect Heating Biomass	0.537	0.027	43783	2189	25	1	-0.05	0.05	0.53	0.00	0.00
BG	Indirect Heating Electric	0.070	0.003	7790	390	25	1	-0.05	0.05	0.90	623.50	124.70
BG	Indirect Heating Steam Distributed	0.869	0.043	0	0	20	1	-0.05	0.05	0.67	0.00	0.00
BG	Heat Pumps (Electricity)	0.950	0.048	26706	1335	20	1	-0.433	0.05	3.00	187.05	37.41
BG	Direct Heating Coal	0.191	0.010	5472	274	15	1	-0.05	0.05	0.25	323.08	64.62
BG	Direct Heating Oil	0.013	0.001	2292	115	15	1	-0.05	0.05	0.42	590.84	118.17

BG	Direct Heating Gas	0.013	0.001	2292	115	15	1	-0.05	0.05	0.41	143.40	28.68
BG	Direct Heating Biomass	0.191	0.010	5472	274	15	1	-0.05	0.05	0.11	0.00	0.00
BG	Direct Heating Electric	0.052	0.003	1372	69	12.5	1	-0.05	0.05	0.52	1084.93	216.99
BG	Direct Heating Steam Distributed	0.869	0.043	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
RO	Indirect Heating Coal	0.354	0.018	35683	1784	25	1	-0.05	0.05	0.49	143.72	28.74
RO	Indirect Heating Oil	0.039	0.002	7487	374	25	1	-0.05	0.05	0.54	127.35	25.47
RO	Indirect Heating Gas	0.039	0.002	8250	413	25	1	-0.05	0.05	0.60	87.03	17.41
RO	Indirect Heating Biomass	0.438	0.022	35683	1784	25	1	-0.05	0.05	0.52	162.23	32.45
RO	Indirect Heating Electric	0.057	0.003	6349	317	25	1	-0.05	0.05	0.90	960.99	192.20
RO	Indirect Heating Steam Distributed	0.709	0.035	0	0	20	1	-0.05	0.05	0.65	0.00	0.00
RO	Heat Pumps (Electricity)	0.775	0.039	21765	1088	20	1	-0.433	0.05	3.00	288.30	57.66
RO	Direct Heating Coal	0.156	0.008	4459	223	15	1	-0.05	0.05	0.25	287.93	57.59
RO	Direct Heating Oil	0.011	0.001	1868	93	15	1	-0.05	0.05	0.37	187.20	37.44
RO	Direct Heating Gas	0.011	0.001	1868	93	15	1	-0.05	0.05	0.40	130.48	26.10
RO	Direct Heating Biomass	0.156	0.008	4459	223	15	1	-0.05	0.05	0.11	751.61	150.32
RO	Direct Heating Electric	0.043	0.002	1118	56	12.5	1	-0.05	0.05	0.50	1747.05	349.41
RO	Direct Heating Steam Distributed	0.709	0.035	0	0	20	1	-0.05	0.05	0.07	0.00	0.00
HR	Indirect Heating Coal	0.470	0.023	47304	2365	25	1	-0.05	0.05	0.54	352.93	70.59
HR	Indirect Heating Oil	0.052	0.003	9926	496	25	1	-0.05	0.05	0.57	110.40	22.08
HR	Indirect Heating Gas	0.052	0.003	10937	547	25	1	-0.05	0.05	0.64	363.17	72.63
HR	Indirect Heating Biomass	0.581	0.029	47304	2365	25	1	-0.05	0.05	0.56	2.14	0.43
HR	Indirect Heating Electric	0.075	0.004	8417	421	25	1	-0.05	0.05	0.90	854.77	170.95
HR	Indirect Heating Steam Distributed	0.939	0.047	0	0	20	1	-0.05	0.05	0.69	0.00	0.00
HR	Heat Pumps (Electricity)	1.027	0.051	28854	1443	20	1	-0.433	0.05	3.00	256.43	51.29
HR	Direct Heating Coal	0.207	0.010	5911	296	15	1	-0.05	0.05	0.25	772.37	154.47
HR	Direct Heating Oil	0.014	0.001	2477	124	15	1	-0.05	0.05	0.39	161.08	32.22
HR	Direct Heating Gas	0.014	0.001	2477	124	15	1	-0.05	0.05	0.42	555.04	111.01
HR	Direct Heating Biomass	0.207	0.010	5911	296	15	1	-0.05	0.05	0.11	10.61	2.12
HR	Direct Heating Electric	0.056	0.003	1482	74	12.5	1	-0.05	0.05	0.53	1464.11	292.82
HR	Direct Heating Steam Distributed	0.939	0.047	0	0	20	1	-0.05	0.05	0.07	0.00	0.00

Appendix B - Energy price projections

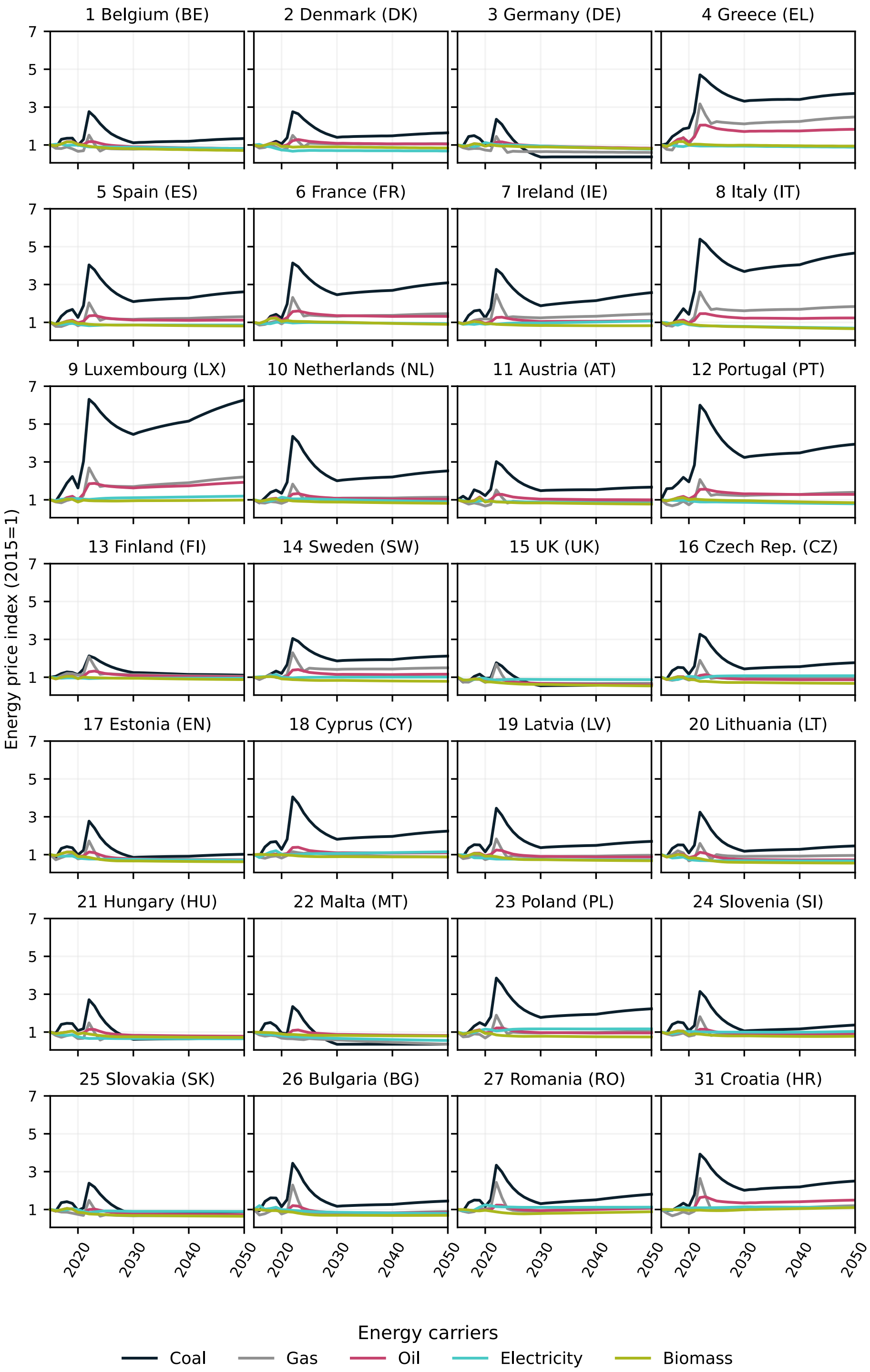

Figure B-1: Energy price index (2015=1) over the simulation period (2015-2050).

Appendix C - Final energy demand by technology

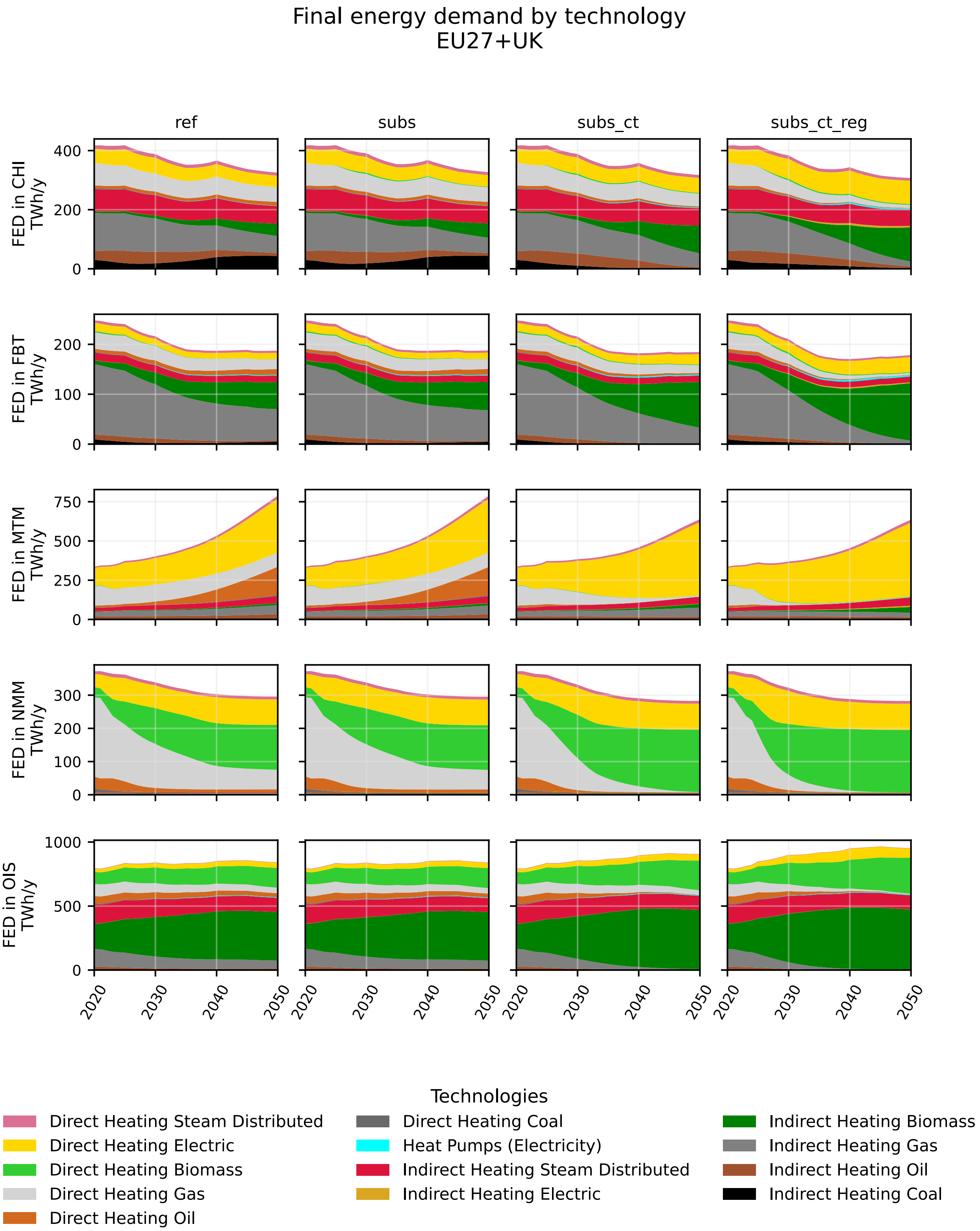

Figure C-1: Final energy demand by technology in each sector and scenario; summed across all EU27 member states and the UK.