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DISCUSSION PAPER

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A simulation of decarbonisation policies aiming at residential heating with FTT:Heat model

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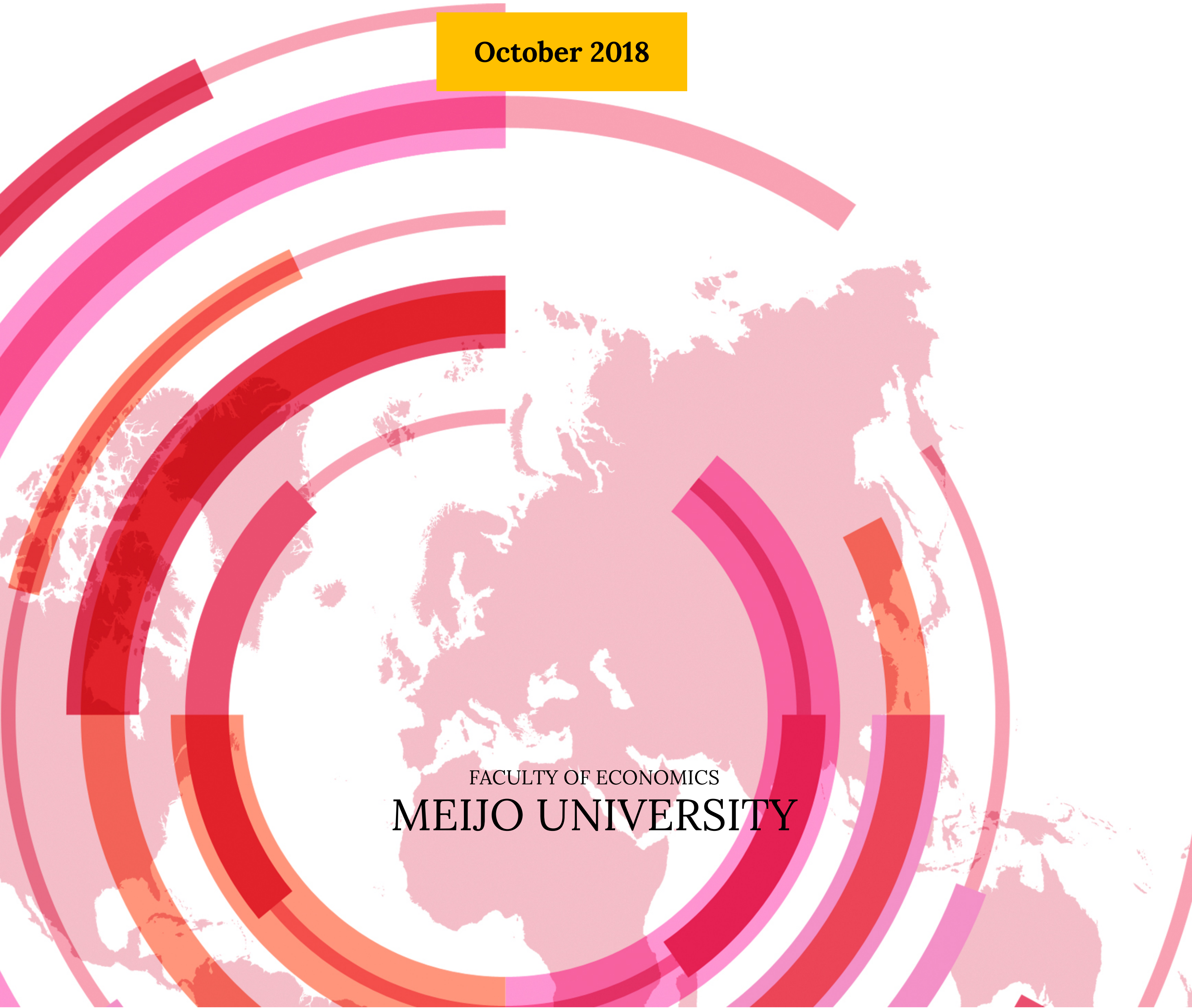

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Reducing the environmental impact of buildings in East Asia: A simulation of decarbonisation policies aiming at residential heating with FTT:Heat

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Abstract:

The main objective of our research is to use a model of technology uptake to study the diffusion of renewable and efficient heating technologies in East Asia. Under which conditions and behavioural assumptions could policies induce a sufficiently fast transition towards renewable heating, and how long would it take? To this end, we performed a series of scenario simulations for different policy instruments in East Asian countries, considering household diversity and bounded rationality of household decisions. In our policy scenarios, we find that an (increasing) fuel tax of 50-200€/tCO2 would be required for reducing direct emissions by around 80% (relative to 2014). Meanwhile, policy mixes are projected to be more effective than a carbon tax on its own for driving the market of low-carbon technologies, involving lower net emissions and reduced cost burdens for households.

Key Wards:

East Asia, Heating Technologies, E3ME-FTT, Fuel Tax, Carbon Tax

1 Introduction

The residential building sector's annual direct emissions were estimated at 2.18GtCO_2 in 2010 (Lucon et al., 2014), equivalent to 7% of the worldwide total CO_2 emissions from fossil fuel combustion and industrial processes. Assuming constant levels, these would accumulate to around 185GtCO_2 between 2015-2100, potentially undermining ambitious climate change mitigation. Space and water heating largely dominate fossil fuel use and CO_2 emissions in residential buildings (IEA, 2013a; Ürge-Vorsatz et al., 2015a). Still, residential heating only receives limited attention compared to the electricity and transport sectors (IEA, 2014). It remains unclear if and how the sector can be decarbonised sufficiently fast.

There is a consensus that the global demand for heating can be fulfilled much more energy-efficiently, thereby reducing fuel use and emissions without reducing comfort (Lucon et al., 2014). Heating loads can be reduced by an improved thermal insulation of houses, and the remaining heat demand can be serviced by renewable and energy-efficient technologies. Through their integrated application, building energy use can be reduced by up to 90% compared to conventional buildings (Urge-Vorsatz et al., 2013; Ürge-Vorsatz et al., 2012a). Given that 50% of the current building stock will still be in use by 2050 (75% in OECD countries) (IEA, 2013b), levels of building efficiency in the next decades strongly depend on building shell retrofits of existing houses (Ürge-Vorsatz et al., 2015b, 2012b).

Aside from space heating, over 40% of global heat demand is for water heating, with particularly large shares in warmer world regions. Demand for water heating is less impacted by insulation (Connolly et al., 2014), but mainly depends on available income, and is thus likely to rise with growing income in many world regions (Daioglou et al., 2012). An ambitious decarbonisation is thus unachievable as long as the remaining heat demand is not provided by renewable and efficient electricity-based technologies. Available alternatives to fossil fuel heating systems rely on the use of biomass (traditional or in modern boilers), electricity (e.g., electric resistance or immersion heating), ambient heat (heat pumps) or solar energy (solar thermal panels) (for an overview, see IEA, 2014). While the operation of solar and biomass systems can potentially be carbon-neutral (abstracting from life-cycle considerations), heating with electricity can be a renewable technology once electricity generation is decarbonised, otherwise, electricity-related emissions must be accounted for. A much more efficient use of electricity can be achieved by heat pumps, which upgrade the ambient low-temperature energy of an air, water or ground source into higher-temperature heat for space and water heating, effectively achieving efficiencies of 200-400% (average ratio of heat output to electricity input) (for an overview, see IEA/ETSAP and IRENA, 2013).

In this paper, we focus on the latter: the diffusion of renewable heating technologies in East Asia. Assuming reasonable improvements in building insulation, will it be possible to decarbonise the sector by 2050? Residential heat generation is overwhelmingly small scale and distributed, taking place on site within homes. The uptake of new heating equipment depends on the individual decision-making by heterogeneous households, each with subjective preferences and perceptions, and only limited information. The sum of such decisions inevitably deviates from the least-cost optimum as it would be determined by models that assume a single, fully rational agent or social planner (Kirman, 1992). Avoiding costly policy-design failures requires an upfront simulation of policy effects, based on an analysis of people's actual behaviour, and accounting for nonlinear diffusion dynamics (Mercure et al., 2016; Rai and Henry, 2016). A behavioural modelling of decision-making is particularly relevant for policies aiming at a premature replacement of existing systems, which will likely be necessary for deep decarbonisation (Geels et al., 2017), and for which households are found to apply very strict payback thresholds (Olsthoorn et al., 2017).

Here, we take a simulation-based approach for modelling different policy scenarios, aiming at near-zero global CO_2 emissions by 2050 in the residential heating sector. Each scenario focuses on different combinations of policy instruments. Specifically, we use the ‘Future Technology Transformations’ model FTT:Heat (Knobloch et al., 2017, 2018). As a non-equilibrium bottom-up simulation model, it allows to analyse the dynamics behind policy-induced technology transitions, accounting for limited information and bounded rationality by consumers. The model is designed to explicitly simulate the potential effects of policy instruments in 59 world regions covering the globe, projecting technology diffusion and resulting CO_2 emissions up to 2050. Furthermore, the integration with the global Integrated Assessment Model E3ME-FTT-GENIE allows for the analysis of feedback effects with other sectors and the wider economy, as well as a simulation if the CO_2 emission trajectory reaches the climate target (Mercure et al., 2018).

The paper is structures as follows. Section 2 gives some background information on the policy context. In section 3 we present our model and data. Policy scenarios and results of the model simulations are presented and discussed in section 4. Section 5 concludes.

2 Background

2.1 China

Residential energy demand in China in 2015 was around 4.100TWh in 2015 (11% of the country’s total energy consumption): around 1.600TWh in urban residential buildings, 1.700TWh in rural residential buildings and 800TWh of biomass consumption in rural buildings. Between 2001 and 2014, the country saw steady increases for all types of residential energy demand: space heating and cooling, water heating, and appliance use. The total energy consumption of urban residential buildings (excluding northern urban heating) increased by around 40% in this time.

In 2006, the Chinese government began to treat resource conservation as a fundamental national policy in its overall economic and social development strategy. Since that year, energy conservation in the residential sector has been included as a binding indicator in China’s National Economic and Social Development Outline within the Five‑Year Plans. The policies for energy conservation in residential sector include the following policies.

In December 2017, eight ministries and commissions including the National Development and Reform Commission and the National Energy Administration jointly issued the Clean Winter Heating Plan for Regions in Northern China (2017-2021) with the aim to improve the level of clean heating and reduce the emission of air pollutants. To this end, it is planned that natural gas and renewables should rapidly replace coal boilers for heat generation. The work will focus on the “2+26” cities, accelerating the construction of supporting facilities for urban natural gas pipeline networks. In September 2006, “Opinions on promoting application of renewable energy in buildings’” and “A tentative management method of special funds for renewable energy development” were issued by the Ministry of Housing and Urban-Rural Development, cooperating with the Ministry of Finance. In these two documents, four of the eight technologies which are subsidized by the government are different types of ground source heat pump systems (GSHP) (such as water source heat pump systems, seawater source heat pump systems and sewage source heat pump systems). After that, a series of policies was established to promote GSHP on the city and town level: at the end of 2010, 47 cities and 98 towns got the funding from the central government to promote GSHP. Each city got 50-80 million RMB (8-13 million Euro) and each town got 15-20 million RMB to promote this technology. By 2021, the new floor supply area heated by GSHP technologies in northern China is planned to reach 10 billion square meters. In addition, subsidies are paid for the installation of solar water heating systems.

2.2 Japan

In 2015, the residential sector accounted for around 13.8% of Japan’s total energy consumption. The share of energy use for space heating in residential energy demand was 22% in 2015, and 29% for water heating. The share of space cooling was at 2%. In the 1960s, coal accounted for more than one-third of household energy consumption. Then oil, mainly kerosene, replaced coal, which decreased to a share of only 6% in 1973. With the diffusion of all-electric homes, the share of electricity in residential energy demand (including all end-uses, not just heating) increased to 51% in 2015.

The government of Japan promotes thorough energy management and the introduction of energy efficient equipment. The Act on the Improvement of Energy Consumption Performance of Buildings has been introduced in 2015. The Act stipulates mandatory compliance with energy efficiency standards for large construction projects. The compliance with energy efficiency standards will gradually become a requirement for new construction projects by 2020.

Also, the Introduction of highly energy efficient equipment and devices is promoted. The top runner program was established in 1998, and the number of targeted equipment and devices has gradually increased since then. Today, electric heat pumps for water heating are also included. The introduction of energy efficient water heaters is subsidized by Ministry of Economy, Trade and Industry. Local governments also support the introduction of energy efficient water heaters, such as solar water heaters and heat pump water heaters.

2.3 Korea

In 2015, the residential sector accounted for around 9% of Korea’s total energy consumption. The share of heating in total energy use in the residential sector has decreased from 77% in 2000 to 67% in 2015, partly due to the diffusion of insulation and efficient heating technologies. At the same time, energy use for space cooling grows rapidly. In the 1990s and 2000s, the main energy source for newly constructed towns shifted from coal and oil to natural gas and district heating systems, partly caused by high oil prices.

The government of Korea established standards for building insulation in 1976. Since 1985, regulations for envelope insulation and energy efficient design were implemented for large and high energy consuming buildings. In addition to the strengthened insulation standards, the government has been requiring higher permission standards for buildings to expand their efforts in using high-efficiency lighting, boilers, freezers, etc. Also, the Energy-saving Building Design Standard has been introduced in order to enforce regulations on the total energy consumption of the building sector. It requires 10% improvement every five years. The government of Korea has proceeded to lead a program to strategically expand the distribution of energy efficient appliances. Energy efficiency standards and labelling programs were implemented in 1992.

The government of Korea has supported the introduction of electric heat pump systems and solar water heater by subsidy. However, it is considered that the progressive electricity charge scheme for households is impeding the further diffusion of electric heat pumps. Also, there have been disputes whether the electric heat pumps may increase the peak load in winter.

2.4 Taiwan

In 2015, the residential sector accounted for around 11% of Taiwan's total energy consumption and CO_2 emissions. In response to the United Nations Framework Convention on Climate Change, the Bureau of Energy, Ministry of Economic Affairs (BOE, MOEA) has been positively promoting the research and development of renewable energy technologies, including solar thermal and heat pump systems.

Due to the country's hot climate, air conditioners consume 13% of total energy consumption in Taiwan. Ground source heat pumps have the potential to increase the efficiency of air conditioning, thereby reducing energy demand. However, although GSHPs are used in more and more areas around the world, they are rarely seen in Taiwan. The main reason is seen in the large imbalance between cooling and heating loads in Taiwanese buildings.

3 Methods and data

3.1 Methods

FTT:Heat is a simulation model of technological change, which aims at a realistic representation of how the residential heating systems in 59 world regions[1] may develop until 2050, given households' individual decisions in a context of bounded rationality and limited information. A detailed description of the methodology and model is given in Knobloch et al. (2017, 2018). Table 1 presents an overview of how behavioural features are represented by the modelling, based on categories for improving the behavioural realism of global integrated assessment models as suggested by McCollum et al. (2017).

Table 1 Integration of behavioural realism into FTT:Heat. Categories and their description are adapted from McCollum et al. (2017).

Behavioural feature	**Description**	**Modelling in FTT:Heat**
Heterogeneity	Differences in decision maker characteristics	Statistically distributed technology and choice parameters, resulting in a distribution of preferences and choices
Social influence	Imitation (herding, bandwagon) effects, distinction (status-seeking), or neighbourhood effects	All decisions are linked to technologies' current market shares as a proxy for their visibility and trialability, assuming that households gather information from their peers, leading to inertia Decisions on premature replacements are based on behavioural payback thresholds
Bounded rationality	Costs of searching for and acquiring information	
Non-optimizing heuristics	Decisions in familiar, repeated contexts influenced by past experience (habit, inertia, loyalty)	
Non-monetary preferences	'Intangible' non-monetary costs and benefits	Inclusion of region-specific 'intangible' cost parameters for all technologies, estimated based on empirical diffusion trends
Non-market discount rates	Implicit discount rates estimated from market behaviour	Behavioural discount rate of 9%, based on choice experiments
Contextual conditions	Behaviour is influenced, constrained, or determined by infrastructure, the physical environment, or other contextual factors	Region-specific capacity and efficiency factors, constraints on the maximum diffusion of district heating

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[1] A list of all regions can be found in the E3ME manual (Cambridge Econometrics, 2014).

Political and social institutions	Institutions and culture shape decisions and behaviour	Not explicitly modelled

The model simulates likely pathways, and how different policies may impact the future trajectory. The choice of households between different technologies is modelled based on statistically distributed choice parameters, which leads to a diversity of choices, and reproduces the typical dynamics of technology transitions. The theoretical framework is derived in Mercure (2015), and has previously been applied to the power and transport sectors (Mercure, 2012; Mercure et al., 2017, 2014). A detailed model description of FTT:Heat can be found in Knobloch et al. (2017, 2018), of which the key elements are summarised here.

For each country, the starting point is an exogenous level of total annual demand for residential heating as an energy service, expressed in terms of useful energy demand. Individual heating technologies (e.g., gas boilers, heat pumps) compete for market shares of the total demand. At every time step Δt (set to 1/4 year), FTT:Heat simulates which technologies supply which share, along with the resulting level of fuel use and emissions.

3.1.1 Decision-making by diverse households

At the core is an aggregate representation of decision-making by diverse households, based on cost and decision parameters that have statistical variations. The decision-making determines the composition of new heating units purchased.

If it comes to the point that a household decides between heating systems, FTT:Heat performs a pairwise comparison of all available heating technologies based on a single quantity, the levelised cost of heating (LCOH). It is the present value cost of operating a heating system during its lifetime, including investment, maintenance and fuel costs, which themselves depend on technology- and region-specific conversion efficiencies and capacity factors, according to our model data. In addition, policies can be imposed, such as a subsidy on upfront investment costs or a carbon tax.

Of paramount importance is the diversity of households, which stems from different individual contexts and perceptions when they take a decision, which may originate from a large set of individual characteristics (of the household, the technology or the dwelling), preferences and constraints. This diversity is represented by statistical distributions of cost-parameters, which implies a heterogeneity of households' choices: a technology may be less attractive than an alternative on average, but more attractive for some households. This implies that the LCOH is not treated as a unique value, but rather, as a distribution, derived from distributed underlying cost parameters.

Many additional aspects may be valued by households, on which little information is available, such as the perceived inconvenience of a technology (e.g., for pellet heating, see Sopha et al., 2010), or possible co-benefits (e.g., using a heat pump for cooling purposes). In FTT:Heat, these missing components are defined as intangibles. The value of the intangibles is a technology- and region-specific empirical parameter, which is derived by a calibration with historical diffusion data: it is the set that makes the rate of diffusion continuous at the cross-over between historical data and the model projection, in each region. It implicitly captures any existing policies that have influenced the historical trend of technology diffusion, but remain unspecified in the model. The intangibles are added as a constant to the LCOH, resulting in the *perceived* levelised cost of heating.

In a heterogeneous group of agents, choices are often unanimous. A representation of heterogeneous agents comparing two technologies, based on the distribution of perceived costs, implies a comparison of frequency distributions: the fraction of households preferring technology *i* over technology *j* is the fraction of households for which the perceived cost of heating with technology *i* is less than with technology *j* (i.e., the model calculates a binary logit). Performed for all possible pairs of technologies, this results in a complete order of distributed household preferences between all pairs of available options.

Diversity of choices implies a differentiation of the market: households take different decisions at different points in time for different reasons, which results in dynamics of technology uptake as described by diffusion theory (Rogers, 2010). If the perceived cost difference between technologies gradually decreases, an increasing fraction of households will choose the alternative technology. The resulting profile of adoption is then a very gradual one, the steepness of which depends on the widths of the distributions.

3.1.2 Technology diffusion dynamics

The future development of technology shares is simulated based on a replicator dynamics equation (for a detailed derivation in a technology context, see Mercure, 2015). Combining the choice-based matrix of household preferences (F_{ij}) with current technology market shares (S_i and S_j) and the fraction of technology *j* which needs to be replaced (based on average technology lifetime τ_j), we can derive the flow of market shares from heating technology *j* to *i* in period Δt:

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

Net flows from technology *j* to technology *i* are obtained by subtracting the reverse flow from technology *j* to *i* (since agents are heterogeneous, reverse decisions always take place). The overall net flow of market shares to technology *i* is the sum of all such pair-wise comparisons over all competing technologies *j*, which yields the non-linear *replicator dynamics* equation of evolutionary theory (Hofbauer and Sigmund, 1998):

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

Each single flow from a technology *j* to an alternative technology *i* is determined by three interacting elements:

I. Preferences (*F*): which fraction of households would prefer which technology, given that they were to buy a heating system within period Δt? These preferences are determined by the decision-making core that compares perceived costs.
II. Replacement needs ($S_j \tau_j^{-1}$): how many heating systems of technology *j* need replacement in period Δt? This depends on the market share of technology *j* and the annual fraction of deaths within its population, which is approximated as the inverse of *j*'s technical life expectancy, τ_j.
III. Flow restrictions (S_i): given preferences and replacement needs, which fraction of flows can be realised? The flow is restricted for two reasons: (a) restricted access to information by households, and (b) limited production capacities in industry. Both restrictions can be approximated as proportional to the market share of the alternative technology *i* in the previous period (S_i), based on Mercure (2015, 2017).

Without flow restrictions, one would implicitly assume that (a) all households have perfect information on all technologies at all times, and (b) that technologies can be obtained everywhere on demand, the industry assumed to be able to instantaneously scale up its production of any technology, without any limits. Instead, by introducing the dynamic share restrictions, the trajectory of technology uptake resembles s-shapes diffusion curves. This is an improvement in comparison to exogenous growth constraints in standard optimization models, since here the constraint is fully *endogenous*. As a central implication, technology transitions in FTT:Heat become subject to inertia, as technological change cannot occur instantaneously: it possesses autocorrelation in time (i.e. it is strongly path-dependent).

Additionally, for all scenarios in this paper, we assume that households do not switch to technologies with a much lower comfort level (based on Kranzl et al., 2013). Coal and traditional biomass can only be chosen if one of both is the existing heating system. Furthermore, solar thermal heating is limited to the demand of water heating in each country. Finally, the new levels of heat production per technology are obtained by multiplying the resulting shares by the (exogenous) level of a region's total heat demand in the new period, which includes potential demand increases or decreases.

3.1.3 Premature replacements

Households may consider to replace a functioning heating system ahead of its rated end-of-life date, based on economic considerations. By definition, for a household with perfect information and without risk-aversion, this would be beneficial once the marginal running costs of operating the current system exceed the full levelised costs of buying and operating an alternative technology. In practice, households may apply much stricter criteria, and only consider a premature replacement if the potential savings exceed the initial investment in a limited period of time - the so-called *payback threshold*. While it remains debated if such behaviour is an expression of bounded rationality or of neglected economic factors (Gillingham and Palmer, 2014), it accurately describes household behaviour. We here model premature replacements based on results by Olsthoorn et al. (2017), who find that the mean *payback threshold* for a premature replacement of heating systems is 3 ± 1 years.

The resulting preferences and share flows are modelled in the conceptually same way as for regular household decisions (see sections 3.1.1 and 3.1.2), performing pairwise comparisons between all technology pairs, and finally applying the replicator dynamics equation. For the same reasons as described in section 3.1.2, the *realised* flows due to premature replacements are thus smaller than the hypothetical ones, due to limited information and capacity constraints.

3.1.4 Learning by doing

Cost reductions in upfront investment costs are endogenously calculated based on learning curves. They are not a function of time, but of the cumulative global capacity production of a technology, based on technology-specific learning rates. The process of cost reductions due to accumulated knowledge and experience increases path dependence in technology diffusion (Arthur, 1989), with increasing returns to scale for growing technologies. We take learning rates from the literature (Henkel, 2012; Weiss et al., 2010), between 10% (for advanced gas, oil and biomass boilers and solar thermal) and 30% (for heat pumps). These percentage values refer to the relative reduction in a technology's upfront investment costs which is assumed to take place for every additional doubling of a technology's global cumulative capacity. For example, if the global capacity of heat pumps should double until 2030, investment costs for this technology in 2030 are projected to be 30% below their current value.

3.1.5 Economic feedbacks

FTT:Heat is hard-linked to the macroeconometric global simulation model E3ME (Cambridge Econometrics, 2014), and part of the integrated assessment model E3ME-FTT-GENIE, in a similar way to its sister models FTT:Transport and FTT:Power (Mercure et al., 2018). This allows an analysis of the wider macroeconomic effects of policies which are primarily targeted at the residential heating sector.

3.2 Data

3.2.1 Energy demand

Only limited data is available on the specific demand for residential heating, the related fuel consumption and technology composition (IEA, 2014; Lucon et al., 2014). We therefore compiled a new database with time series of final and useful energy demand by technology for 59 world regions, which is described in Knobloch et al. (2018).

The IEA energy statistics report final residential energy demand by fuel type, but do not differentiate by end use application (IEA, 2017). We calculate the shares of heating based on estimates in IEA (2013a). Where such estimates are not available, the heating share is approximated based on heating degree days (given the average relationship in world regions with available data).

Residential heat generation by solar thermal installations for most world regions is available in the IEA energy statistics, which we amended by data from the IEA Solar Heating Programme (Mauthner et al., 2016). No standardised global data exists on heat generation by heat pumps. Data on heat generation by ground-source heat pumps is taken from Lund and Boyd (2016). Data on the use of air-source heat pumps is taken from country-specific sources where available (China Heat Pump Committee of China Energy Conservation Association, 2015 for China; EIA, 2017 for USA; Japan Refrigeration and Air Conditioning Industry Association (JRAIA), 2017 for Japan; Kegel et al., 2014 for Canada; Lapsa et al., 2017 for the USA).

Data on final energy demand was transformed into useful energy demand according to technology-specific conversion efficiencies (see エラー! 参照元が見つかりません。). The electricity demand of heat pumps is calculated based on their (region-specific) seasonal performance factors.

3.2.2 Technology data

Cost and performance data for the 13 different kinds of heating technologies is summarised in Table 2. Mean investment costs (incl. of installation) are taken from Fleiter et al. (2016) and Connolly (2014), which we extrapolated to different world regions based on available household income. A standard deviation equivalent to 1/3 of the mean cost is assumed for all technologies (Danish Energy Agency, 2016, based on cost ranges reported by 2013; NREL, 2016). Residential fuel prices are taken from the IEA (2016), with an assumed standard deviation of 15% (30% for biomass, based on NREL, 2016).

Conversion efficiencies refer to the ratio of thermal energy 'leaving' the heating system, relative to the necessary energy input, covering both space and water heating. For heat pumps, efficiency values are defined as their seasonal performance factor (the annual average ratio of delivered heat to electricity input), which differs by climate region. For solar thermal, local productivity differences are expressed as region-specific capacity factors, calculated from data by the IEA Solar Heat Programme (Mauthner et al., 2016). A useful lifetime of 20 years is assumed for all technologies.

Table 2 Model assumptions for residential heating technologies. Costs refer to mean values. (Data sources: Fleiter et al. (2016), IEA/ETSAP (2012), Danish Energy Agency (2013), EHPA (2016)).

	Upfront cost (€/kW$_{th}$)	**O&M cost** (€/kW$_{th}$ pa)	**Efficiency** (kWh$_{th}$/kWh)	**Learning rate** (%)
Oil	471	19	0.75	---
Oil condensing	512	20	0.86	-10%
Gas	391	8	0.75	---
Gas condensing	434	9	0.9	-10%
Biomass stove	440	0.1	0.1-0.7	---
Biomass boiler	523	2	0.85	-10%
Coal	247	5	0.75	---
District heating	265	16	0.98	---
Direct electric	538	0.5	1.00	---
HP- ground source	1400	14	3.50	-30%
HP- air/water	750	15	2.50-2.70	-30%
HP- air/air	510	51	2.50-2.70	-30%
Solar thermal	773	8	Not applicable	-10%

3.2.3 Heat demand

The demand for useful heat per region is an exogenous parameter, which can be calibrated to different assumptions. For scenarios in this study, we use projections of future changes in heat demand (UE_{tot}) from the IMAGE-REMG model, directly after the methodology described in Isaac and van Vuuren (2009) and Daioglou et al. (2012), resulting in the demand trends as described in Knobloch et al. (2018). Demand levels are projected for (i) a baseline scenario, (ii) a mitigation scenario, involving increased efficiency of new buildings and increased retrofitting of existing houses.

IMAGE-REMG projects UE_{tot} as the sum of demand for space and water heating. For water heating, future demand per person is modelled as a function of income, converging to a maximum saturation value which depends on heating degree days (HDD) (Daioglou et al., 2012). For space heating, demand is modelled as a function of population, floor space per person (*m2/cap*), heating degree days (*HDD*), and the useful energy heating intensity ($UE/m^2/HDD$) (Isaac and van Vuuren, 2009). Future changes in population, climate and income are exogenous drivers, based on the SSP (Shared Socioeconomic Pathway) 2 ('middle of the road') (see Riahi et al., 2017). All relevant data is publicly available via the IMAGE website (PBL, 2018).

3.3 Scenario definition

We created five model scenarios (labeled **a-e**) aiming at a decarbonisation of residential heating until 2050, all of which use a different set of policies, implemented from 2020 onwards. Scenario **a** assumes increased levels of thermal insulation for new houses, compared to the baseline trend in heat demand: we assume that the space heating intensity converges to 60 kJUE/m2/HDD by 2100 (from current values ranging from 50–150 kJUE/m2/HDD), consistent with the assumption that aggregate insulation efficiency increases (e.g. in reaction to more stringent building regulations) (for more details on the estimation of heat demand trends, see Knobloch et al., 2018). In addition to improved insulation, scenario **a** includes a continuation of current policies for technology uptake, the effect of which is implicitly included in the intangible parameters.

In scenarios **b-e**, we explore two policy instruments and combinations thereof: a residential carbon tax and technology subsidies for renewable heating technologies, being implemented in addition to the improved levels of building insulation. These policy instruments were chosen based on their successful previous implementation in at least some countries (for an overview, see Connor et al., 2013).

I. The (sectoral) *carbon tax* is specified as an absolute increase in the household price of fossil fuels, relative to their respective carbon content (we do not assume an inclusion of households into emissions trading).[2] We simulate carbon taxes of (i) 25€/tCO_2, linearly increasing to 100€/tCO_2 in 2100 (scenario **b**), and (ii) 50€/tCO_2, linearly increasing to 200€/tCO_2 in 2100 (scenario **c**).

II. *Technology subsidies* are defined as a relative reduction in a renewable heating technology's mean upfront investment cost. Eligible are solar thermal, heat pumps, and modern biomass. We simulate a subsidy rate of -25% (scenario **d**), which is assumed to remain constant from 2020 until 2030, and linearly phased out afterwards, reaching zero in 2050.

Scenarios **b-d** focus on single policy instruments, while scenario **e** simulates a policy mix involving both a carbon tax (of 50€/tCO_2) and a technology subsidy (of -25%).

Table 3 Overview of policy assumptions in the modelled scenarios.

Scenario	Policies targeted at technology uptake	Insulation policies
A		Improved thermal insulation of buildings, lowering the demand for space heating to kJ_{UE}/m2/HDD by 2100
B	Carbon tax of 25Euro/tCO_2 (from 2020 onwards), linearly increasing to 100Euro/tCO_2 in 2050	Improved thermal insulation
C	Carbon tax of 50Euro/tCO_2 (from 2020 onwards), linearly increasing to 200Euro/tCO_2 in 2050	Improved thermal insulation
D	Subsidy payments of -25% on the upfront investment costs of modern renewables, paid from 2020-30, phased out afterwards	Improved thermal insulation
E	Carbon tax of 50Euro/tCO_2 and -25% subsidy	Improved thermal insulation

For all scenarios, we assume constant energy prices, for two reasons: first, future energy prices are highly uncertain, especially in a context of global deep decarbonisation. Effectively, this makes constant prices as likely as any other scenario. Second, it allows for a clearer identification of policy effects, which may otherwise be convoluted with the effects of a change in energy prices. Indirect CO_2 emissions from electricity use are projected by FTT:Power, assuming a power sector decarbonisation scenario consistent with limiting global warming to 2C°, as described in Mercure et al. (2018)

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[2] The specific carbon tax is only applied to the residential sector, and not assumed to be linked to other sectors, such as the power sector, which is subject to a separate set of policies.

4 Results

4.1 Policies for decarbonisation

The main results for policy scenarios **a-e** are illustrated by Figure 1 and Figure 3, which show the projected technology composition (left) and CO_2 emissions (right) in China, Japan, South Korea and Taiwan until 2050.

Values from 1995-2014 are estimates based on historical data, while the model simulation starts in 2015 (indicated by the dashed vertical line). 2014 values for total heat demand and emissions are represented as horizontal dashed lines. Dashed curves indicate the baseline demand trend without improved building insulation. Percentage values refer to changes in demand and total annual CO_2 emissions by 2050, relative to 2014. Values in brackets refer to the respective changes in direct CO_2 emissions, without counting emission by electricity generation.

4.1.1 China

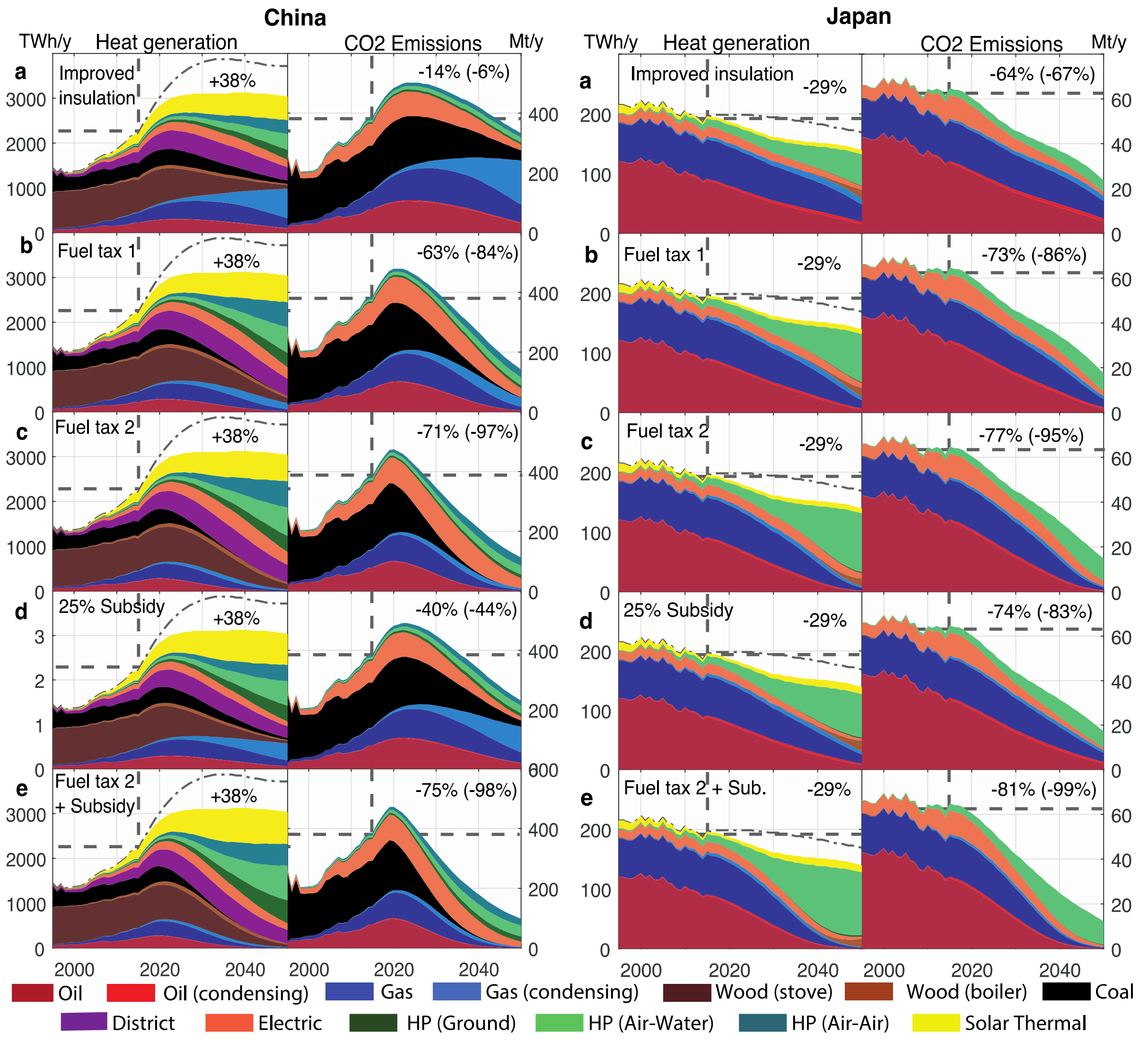
Of all four analysed countries, China shows the most dynamic development in its residential heating sector – both in terms of projected changes in heat demand, and in terms of projected changes in the heating sector's technology composition.

The demand for heating is projected to continue its ongoing growth, resulting from rising incomes. Therefore, even under ambitious assumptions on the improved insulation of buildings, Chinese residential heat demand in 2050 would be 38% larger then in 2014. At the same time, current trends of technology diffusion suggest that residential heating China is undergoing rapid technological change. Coal and traditional biomass, which are still the dominant technologies in large parts of the country, increasingly get replaced by modern, more convenient heating systems – both by fossil fuel technologies (oil and gas), and by modern renewables. The most striking development is the current growth of solar thermal heating. China is currently the world's largest market for the technology. In our model projections, solar thermal is projected to continue its ongoing growth throughout the next decades, even without further policies.

Due to the ongoing technological change, total CO_2 emissions are projected to peak around 2030, and decrease afterwards – despite the parallel growth in heat demand. The main reason is the gradual phase-out of emission intensive coal systems, combined with a substantial growth in renewables and district heating. This is consistent with the fact that China has recently started to regulate the burning of coal, mainly to limit emissions of PM2.5 and related health impacts.

In the context of the observed growth dynamics in China, we find that the introduction of additional policies could show an effect on the technology composition and emissions relatively quickly. Instead of buying oil and gas heating systems, which are projected to increase their still relatively low market shares under current trends, households would shift towards modern renewables more quickly. As both solar thermal and heat pumps are already present in the Chinese market, their growth could take place at a relatively high pace.

Figure 1 Projected technology composition and CO_2 emissions (direct on-site and indirect emissions from electricity use) in the residential heating sector's of China (left) and Japan (right), under improved levels of building insulation (a), and four policy scenarios aimed at technology uptake (b-e). Model simulations by FTT:Heat start in 2015 (indicated by vertical dashed lines). Horizontal dashed lines represent 2014 levels.



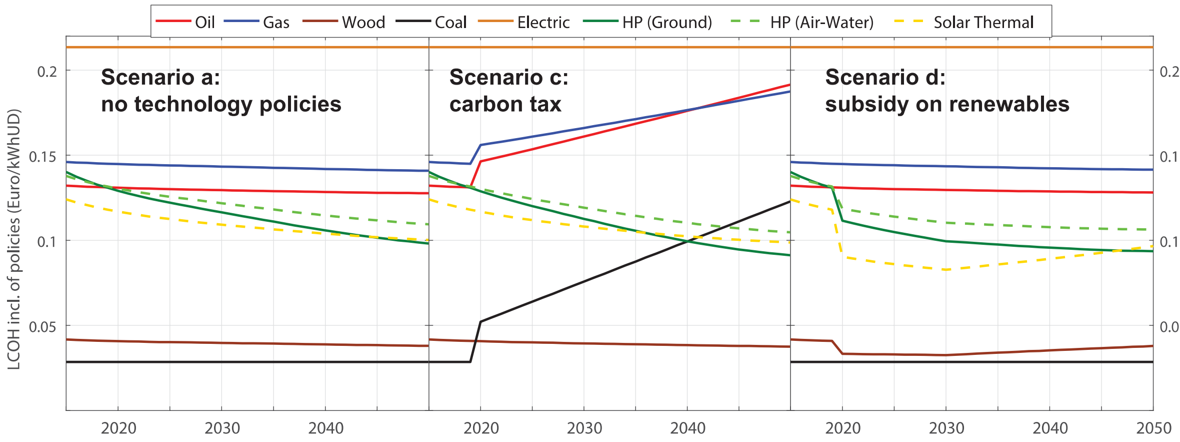
Note: Dashed curves show the baseline demand trends without improved insulation. Percentage values refer to the change by 2050, relative to 2014. For emissions, the first percentage value indicates the reduction in annual total CO_2 emissions (direct + indirect), the values in brackets show the corresponding reduction in direct on-site CO_2 emissions.

As a result, CO_2 emissions would peak around 2020 in all simulated policy scenarios, and quickly decrease afterwards. Direct emissions would decrease by up to 98% in 2050, in case of the higher carbon tax or the policy mix. As for the other countries, remaining emissions would then mostly consist of indirect emissions from electricity use. Given the assumed trajectory in the power sector, the reduction in total emissions would be 71% for the higher carbon tax, and 75% for the policy mix.

4.1.2 Japan

In Japan, the gradual decrease in total heat demand is projected to continue under baseline conditions. With improved insulation, heat demand in 2050 could be decreases by 29%, relative to 2014. The corresponding CO_2 emissions would decrease by more than twice that value, due to (i) an ongoing diffusion of heat pumps, and (ii) the parallel decarbonisation of the power sector, which decreases indirect emissions from electricity use. As a result, total emissions in 2050 would be 64% below their 2014 value, due to the combination of improved insulation levels and gradual improvements in the technological conversion efficiencies of heating systems. The uptake of solar thermal systems would remain limited, however. As evidenced by the decrease in the technology's market share over the last 20 years, solar thermal is associated with relatively high intangible costs in Japan. Under current trends of diffusion, the technology's market share would thus remain relatively stable.

Figure 2 Projected levelised costs of heating (LCOH) with different technologies in Japan (2015-2050), in case of scenario a (without policies aimed at technology uptake), scenario c (carbon tax of 50-200Euro/tCO_2) and scenario d (25% subsidy on renewable heating technologies).



Note: The gradual cost decrease of heat pumps and solar thermal is due to endogenous learning effects: as more capacity of those technologies is being installed over time, their upfront costs are projected to decrease. The carbon tax linearly increases the cost of fossil fuel technologies (middle panel). In case of subsidies for renewables (right panel), the policy leads to an additional steep decrease in levelized costs of renewables in 2020. The subsidies are gradually phased out from 2030 onwards, explaining the flat profile of costs between 2030-50.

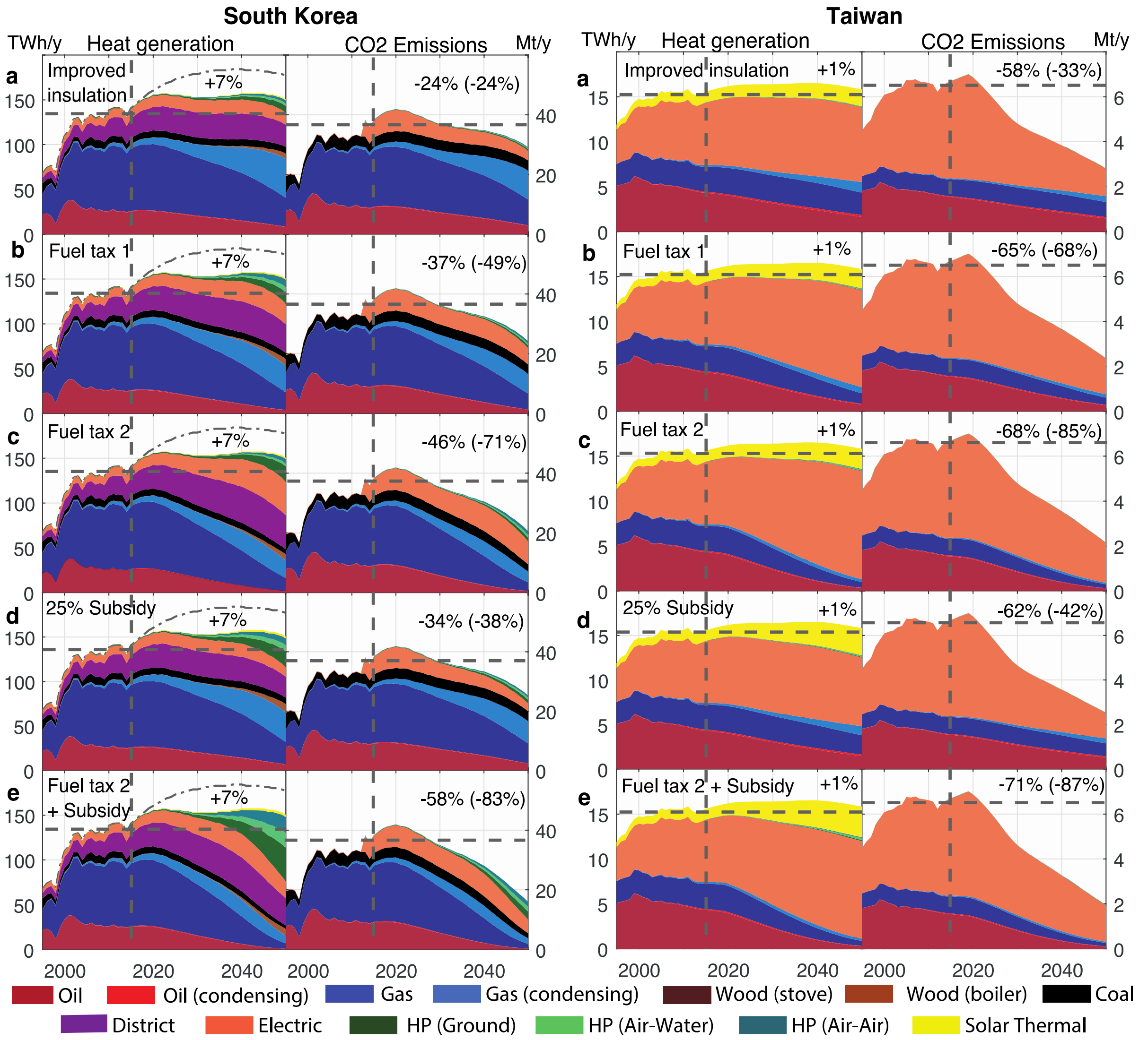
When policies are introduced, the current trends in technology diffusion are intensified. As heat pumps are an already established technology in Japan, they would see the main growth in market shares. In comparison, more efficient gas and oil heating systems are projected to be a less attractive alternative. Due to the availability of heat pumps and solar thermal, households would directly switch to modern low-carbon alternatives, without choosing efficient fossil-fuel technologies as an intermediate solution.

Relative to the simulated carbon taxes, the payment of upfront subsidies for renewables is projected to incentivise the uptake of more capital-intensive and efficient technologies. More households would choose heat pumps and solar thermal, which have higher initial upfront costs, but lower running costs throughout their lifetime. The underlying changes in levelised costs for different heating technologies are illustrated in Figure 2. On the other side, less households would opt for direct electric heating, which is not eligible for the simulated subsidies. Overall, this results in a lower reduction of direct emissions, compared to carbon taxes. However, the higher average efficiency of adopted heating technologies reduces the electricity demand and the induced indirect emissions in the power sector. Therefore, the subsidy scheme could achieve a similar reduction in total emissions.

In our simulations, we find that a combination of subsidies with a carbon tax is most effective in reducing emissions. The policy mix would reduce direct CO_2 emissions to almost zero in 2050. However, as long as electricity generation is not fully decarbonised, indirect emissions would remain. These depend on (i) the efficiency of heating equipment and (ii) the carbon intensity of power generation.

4.1.3 South Korea

Figure 3 Projected technology composition and CO_2 emissions (direct on-site and indirect emissions from electricity use) in the residential heating sector’s of South Korea (left) and Taiwan (right), under improved levels of building insulation (a), and four policy scenarios aimed at technology uptake (b-e).



Note: Model simulations by FTT:Heat start in 2015 (indicated by vertical dashed lines). Horizontal dashed lines represent 2014 levels. Dashed curves show the baseline demand trends without improved insulation. Percentage values refer to the change by 2050, relative to 2014. For emissions, the first percentage value indicates the reduction in annual total CO_2 emissions (direct + indirect), the values in brackets show the corresponding reduction in direct on-site CO_2 emissions.

In South Korea, heat demand is projected to grow under baseline conditions. When the thermal insulation of houses is improved, the demand growth could be limited to 7% in 2050, relative to 2014. Different to Japan, we find that under current trends of technology diffusion, there is hardly any growth of renewable heating technologies. According to our data, the current market shares of both heat pumps and solar thermal are almost negligible. In our projections, they would not gain any significance in the country's technology mix before 2040, if no additional policies are implemented. A continued growth is projected for district heating, which has seen a steady increase over the last 20 years. Overall, the heating market is projected to remain dominated by gas and oil in the coming decades. However, despite that and the growth in demand, CO_2 emissions are projected to decrease under current diffusion trends. The main reason is a shift towards more efficient gas heating systems. As a result, total CO_2 emissions in 2050 are projected to be 24% below their 2014 value.

When a carbon tax is introduced from 2020 onwards, the first effect would be a shift towards direct electric and district heating (the technology composition and emissions of which are not modelled here). Only after that, the policy would also induce a growth of heat pumps. Their growth would start from a low level, and therefore need considerable time before it can gain some momentum. Solar thermal, on the other hand, is both absent from the current mix and more expensive. Its role in the future heating system therefore remains limited in our projections, at least without further policy instruments targeted at the technology's uptake (such as procurement schemes or demonstration projects) . Because the carbon tax would mainly lead to an electrification of residential heating, the policy's net effect on total emissions would depend on the parallel decarbonisation of centralised electricity and heat plants.

Under a subsidy scheme, people would choose more efficient heat pumps, thereby reducing the overall electricity demand and resulting indirect emissions. Again, the largest effect is to be expected from a policy mix, which would reduce direct emissions by 83% in 2050.

4.1.4 Taiwan

Due to its warm climate, heat demand in Taiwan is relatively small, and largely attributable to water heating. The dominant technology is direct electric heating, which is a very convenient technology for low demand, in particular when it is mainly used for water heating. We estimate that the country's demand for water heating is largely saturated, and will therefore remain flat until 2050. At the same time, it cannot be reduced by improved insulation.

Due to the reliance on electric heating, indirect CO_2 emissions from electricity use are much larger than direct emissions from burning fossil fuels on site. Therefore, the most effective way for decarbonising residential buildings in Taiwan is to decarbonise the power sector. In addition, the country's climatic conditions are very favourable for solar thermal heating, which already holds a significant market share (although without much growth dynamics).

We find that under a carbon tax, households would shift towards direct electric heating, which is the most readily available technology. Under a subsidy, solar thermal would become relatively more attractive, and would gain considerable market shares until 2050.

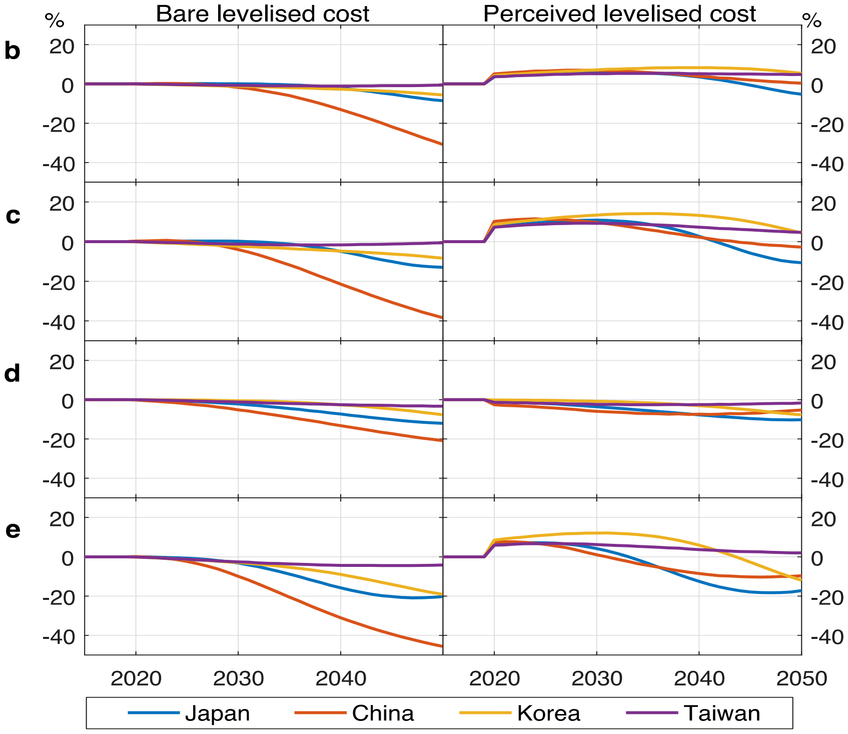
Overall, due to Taiwan's large reliance on electric heating, the effect of policies on total emissions largely relies on indirect emissions from the power sector. When it is decarbonised in line with our 2C scenario, total emissions for residential heating in 2050 would be 58% below their 2014 value, even without any policies in the heating sector.

4.2 Cost-effectiveness of policy mixes

From a public policy perspective, the decarbonisation of heating could not only be beneficial for climate change mitigation, but potentially also enable a more efficient provision of heat in monetary terms. The projected changes in levelised heating costs due to the induced technology transitions (in scenarios **b-e**) are presented in Figure 4, relative to scenario **a** (with improved insulation, but without technology policies). The depicted trends show the average levelised costs of heating per country, which is calculated as the mean value of all technology-specific levelised costs in each respective country, weighted by their market shares at each point in time.

In all simulated scenarios, projected savings from energy expenses exceed the additional costs for the purchase of new heating systems (assuming constant energy prices), leading to reductions in the bare levelised cost of heating in all four countries. The projected cost decreases are largest in China (up to -40%), and between -5% and -20% for South Korea and Japan. Importantly, more stringent policy scenarios (**c** and **e**) are associated with larger net savings. Furthermore, the results indicate that subsidy payments for modern renewables would lead to a more efficient technology composition, leading to lower average heating costs in the medium term.

Figure 4 Changes in levelised costs of residential heating (in %), for policy scenarios b-e (aiming at uptake of low-carbon technologies), relative to scenario a (improved insulation, without technology policies).



Note: The left panels show the changes in bare levelised costs (upfront plus energy costs), the right panels show the changes in levelised costs as perceived by households (including the simulated carbon taxes and subsidy payments).

Table 4 Carbon tax revenues and subsidy payments in scenarios b-e, cumulative from 2020-2050, in billion Euro (constant 2015 price levels).

Scenario		Japan	China	Korea	Taiwan
B	Carbon tax revenues	47	330	49	3
	Subsidy payments	0	0	0	0
C	Carbon tax revenues	75	410	82	4
	Subsidy payments	0	0	0	0
D	Carbon tax revenues	0	0	0	0
	Subsidy payments	-12	-153	-3	-1
E	Carbon tax revenues	35	255	44	2
	Subsidy payments	-14	-171	-4	-1
	Total	21	84	40	2

Households, however, do not directly face the changes in bare levelised costs. They also need to pay for the carbon taxes, and potentially benefit from upfront subsidies. When taxes are used as the only policy instrument, tax payments would exceed the achievable savings in real costs until around 2040 in all scenarios. As a result, the perceived average levelised cost of heating would increase by 5-15% in all scenarios that involve a carbon tax. During this period, net benefits for households would then depend on the way in which tax revenues are redistributed. Table 4 shows the projected tax revenues and subsidy payments per country, for scenarios b-e. In case of the policy mix in scenario e, part of the tax revenues would be recycled into purchase subsidies (equivalent to 9-67% of total tax revenues). The remaining tax revenues would be available for redistribution in other ways, for example by lowering taxes on income.

5 Discussion and Conclusion

Our results show that a decarbonisation of residential heating in Japan, South Korea, China and Taiwan is achievable in 2050, based on existing technologies, and assuming improved insulation of houses. Such a decarbonisation requires substantial policy efforts from 2020 onwards, involving residential carbon taxes and subsidy payments for renewables. Policy mixes are projected to be more effective than a carbon tax on its own for driving the market of new technologies, involving lower cumulative net emissions and reduced cost burdens for households. When combined with subsidies for the purchase of renewable technologies, the decarbonisation can be achieved with a carbon tax of 50-200€/tCO_2 in 2050. In all four countries, the policy-induced technology transition would increase effective heating costs faced by households initially, but lead to net savings in the medium term (through fuel savings and induced reductions in upfront costs of renewables).

Due to long average lifetimes of 20 years for heating equipment, a complete decarbonisation of residential heating needs decades rather than years. Considering the path-dependent diffusion dynamics of technology transitions, the required time scale is even longer than the average lifetime: even if policy incentives for switching to renewables are set in place from 2020 onwards, it is unrealistic that they could immediately gain a 100% market share in sales. It will take time until the diffusion gains momentum: households and installers need to learn about the existence and performance characteristics of new technologies, and industry needs to restructure its production capacities.

The model projections demonstrate that the effectiveness of policies depends on behavioural decision-making by households. Although the net costs of the technology transition are projected to be negative in all analysed countries, we find that these savings would not be realised without additional policy incentives. The reason is that no household faces the system-wide cost over time. Instead, households decide from their individual perspectives, based on what they know and can observe. This leads to trends of technology diffusion which deviate from what would be considered as optimal from a societal perspective.

Other aspects of household decision-making are likely relevant, but still remain unspecified in our modelling - such as split incentives (e.g. in case of rented property), or a limited access to finance (which is one possible reason behind low required payback times). The value of 'intangibles', which we estimate from historical diffusion trends, are not necessarily constant over decades, but may change over time. Furthermore, our results must be interpreted in the light of very limited data availability on energy end-use by households or the stock of heating systems. Overall, there remains a considerable degree of uncertainty regarding behaviour, data and the future development of technology characteristics, under which the true long-term effect of any policy is hard to estimate a priori.

Using a detailed modelling study, we suggest that a decarbonisation of residential heating in 2050 is possible, but is unlikely to happen without stringent policy instruments. While our modelling achieves the target with our set of assumed behavioural features, in reality, policy design must take into account as much additional behavioural knowledge as possible. While the evidence base is still thin, there is little time spare, and therefore further research will need to be carried out in conjunction to the introduction of policies.

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