Multi-sectoral interactions in low-carbon transitions: simulating the co-evolution of energy production and end-use sectors

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Abstract: An effective mitigation of climate change requires the parallel large-scale diffusion of sustainable technologies in energy production and end-use sectors. The whole-system transition towards a low-carbon economy thus unfolds in a co-evolutionary way, driven by sector-specific policies and social and industrial dynamics. A new low-carbon socio-technical system across sectors is likely to self-organise as decarbonisation unfolds, partly driven, partly made complex by multi-sectoral interactions. However, little is known on the quantitative implications of multi-sectoral transitions, and how future technology pathways may dynamically interact with each other. Many important questions arise, such as: How will electricity generation, transport and household fuel-use co-evolve as it transitions towards a low-carbon state? Are there possible mismatches in transition paces between sectors? Are there pitfalls and cautionary tales to be learned? For investigating these questions, we use a novel type of simulation-based integrated assessment model (IAM), the E3ME-FTT-GENIE model. It is arguably the IAM with a theoretical underpinning closest to a transitions perspective, integrating bottom-up representations of Future Technology Transitions (FTT) in power generation, road transport and residential heating into an econometric whole-systems model with global coverage (E3ME). This approach enables a detailed quantitative investigation of the unfolding pace and interactions of socio-technical transitions from a whole-systems perspective. For each respective sector, we first simulate their current trend trajectories, and identify policy mixes which drive a transition consistent with limiting global warming to 2°C. We then simulate alternative scenarios of policy failure or sectoral ‘drop outs’, in which the low-carbon transition does take place in some sectors, but not in others. The simulation results form the basis for investigating the dynamical coevolution between sectors.

Keywords: Technology Diffusion; Sectoral Transitions; Multi-sectoral Interactions; Climate Change Mitigation; Simulation-based Modelling

1. Introduction and background

In 2015, the Paris Agreement was adopted under the United Nations Framework Convention on Climate Change (UNFCCC). The overarching climate goal of the Paris Agreement is to hold 'the increase in the global average temperature to well below 2°C above the pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels'. To achieve the goals, all parties are required to undertake efforts towards reaching global peaking of Greenhouse Gas (GHG) emissions as soon as possible.

An effective mitigation of climate change requires the parallel large-scale diffusion of sustainable technologies in energy production and end-use sectors. Electricity generation, the transport sector and the heating sector account for over 60% of global primary energy demand [1]. To reduce emissions, the reliance on oil imports, and improve energy security, governments are laying out policies aimed at increasing the numbers of low emissions cars. Likewise, in the heating sector, technological solutions include the reduction of heat demand by improving the thermal insulation of houses and the shift to renewable and efficient heating technologies, with potential synergies between both [2]. Simultaneously, under various policy incentives, renewable energy is being deployed for electricity generation, reducing GHG emissions from the energy production side. The integration of the transport sector, the heating sector and the power sector offers the potential to significantly reduce GHG and world dependence on fossil fuel resources.

The whole-system transition towards a low-carbon economy thus unfolds in a co-evolutionary way, driven by interdependent policies and social dynamics. For example, GHG emissions from electric driving depend directly on the fuel type used in the generation of electricity charging. Moreover, introducing many EVs poses new challenges such as building infrastructure for charging and improving electricity grid [3].

While socio-technical transitions literature has gained significance in addressing the long-term transition pathways in different energy sectors, few transitions or modelling studies quantitatively model the interactions between different energy sectors over time and how policy incentives would affect the decarbonisation pathways in a holistic approach. In particular, previous modelling studies predominantly utilise an optimization approach in which it would be particularly challenging to explicitly model system mismatch in technological transitions pathways as a result of different policies and pace in the power sector, transport sector and the heating sector.

This study presents the analysis of indirect emissions from the transport and heating sector as a result of technological diffusion in the transport sector and the heating sector. It brings together three recently developed sub-components of the E3ME-FTT model, namely the FTT-Power [5], the FTT-Transport [6] and the FTT-Heat [7]. The detailed modelling approach of the E3ME-FTT model is given in [8]. These models of the diffusion process are inherently dynamical, and therefore, by combining them, we are able to diagnose how different sectors interact.

We contribute to the existing literature by i) modelling the dynamic interactions between the transport, heating and power sectors across the globe, ii) assessing overall reductions in direct and indirect CO_2 emissions as a result of technological transitions and policy incentives, iii) bridging scales by discussing both the global and individual countries, with a spatial resolution of 59 world regions.

Our research finds that although the direct emissions from the road transport (RT) and the household heating (HH) sectors decline by 2050 in a 2°C scenario, the projected 2050 levels of indirect electricity emissions could become four to five times larger both in HH and RT (around twice as large when compared to current trends), depending on how coordinated or uncoordinated the transitions are in each sector. In case of such a transitions mismatch, we find that a mismatch of sectoral decarbonisation paces may partly counteract the targeted emission reductions. However, they would not lead to emission increases.

The paper is structured as follows: Section 2 summarises the existing literature and identify the gaps. Section 3 describes the key methodology and assumptions of the E3ME-FTT model. Section 4 presents the policy assumptions for the scenario analysis. Section 5 presents our results, and section 6 concludes.

2. Literature review

Energy models are valuable mathematical tools that have been applied to aid decision making in energy planning, and to analyse energy policies and implications arising from the introduction of new energy technologies. Formal mathematical models are useful tools for a better understanding of emergent dynamics, since they can be used to represent macro-level dynamics [9] [10]. A variety of modelling techniques have been utilised for energy and emissions projections in various sectors where technological change takes place. The most widely used method for energy systems modelling is cost-optimisation, and one of the most widely used models for energy systems is TIMES/MARKAL and its various strands, used widely across the world. A version of that model is maintained by the Energy Technology Systems Analysis Program (ETSAP) of the IEA, the latter having been used in more than 50 countries [11]. Similar to that, the MESSAGE model (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) is a dynamic linear programming model that calculates cost minimal supply structures over a given time horizon [12], also used internationally, and notably, as one of the main models in the last IPCC report.

While the strength of the optimisation framework is its ability to find cost-minimisation configurations, useful for a normative analyses concerning the most efficient use of available investment and natural resources, it is less robust for the study of technological transitions, as real systems are characterised by strong path-dependence and a reluctance to change, due to embedded social and technological factors [13] [14]. Such aspects cannot easily be represented in such normative frameworks, as they become unsolvable. An optimisation method is thus no appropriate basis for modelling transitions.

As opposed to optimisation, simulation models are run using discretised time steps, using specific exogenous inputs with the goal of generating endogenous outputs. The sustainable transitions community has seen a number of attempts to develop models that capture multi-level dynamics of social technical transitions. For example, the EU MATISSE project [15] [16] [17] aimed to simulate transitions within social systems in the energy sector, following the Multi-Level Perspective framework (Geels), by using an agent-based approach and systems dynamics.

It has been argued in the existing literature that the transitions framework originates from evolutionary theory [19]. Using existing evolutionary models thus makes a good starting point for analysing socio-technical transitions [20]. In the FTT model, the diversity of consumers drives product differentiation and technological transitions for energy technologies. The model represents a new methodology to model consumer decisions using a bounded rational form of discrete choice theory in a technology diffusion framework. The mathematical model describes technological diffusion in the transport, power and heating sectors by linking consumer heterogeneity to technological path dependency, based on evolutionary theory in the form of Lotka-Volterra equations [21] [6]. This approach offers an opportunity to develop representations of multiple policy instruments, which currently amounts to 5 for power generation, 7 for road transport and 5 for household heating, in addition to cross-sectoral policies such as fuel or carbon taxes. These include regulatory, technology push and pecuniary incentives. This policy resolution makes one of the key strengths of the FTT framework, offering a huge policy space.

In the co-evolutionary model of economic development by [22], innovation pathways are determined by the complex interplay between technology, industry structure and institutions. In reality, the decarbonisation challenge lies in the co-evolution of technologies, infrastructures and institutions, the power of incumbents and the complex challenges of rapidly scaling up new technologies [23]. Most past scenario studies for the transport and heating sectors have been primarily focused on their own sectoral effect on emissions, and often use exogenous scenario assumptions for understanding the evolution of the whole energy system [24] [25] [26] [27]. Some studies have examined the impact of EV and heating on power supply without considering the whole energy system [26] [28] [30].

Some energy system optimisation models have taken a systematic view to analyse the effect of the transport sector and the heating sector on the overall global decarbonisation scenario [31] [32] [33]. Although the optimization approach has the advantage of finding a cost-optimal solution and covering the entire energy system, past studies have paid insufficient attention to how future technology pathways in different sectors may dynamically interact with each other. Additionally, there are significant shortcomings in optimizing public policies, especially given the complex nature of contemporary economies and the heterogeneous nature of agents that interact within these economies [34]. Under the optimization framework, it is challenging to carry out a detailed quantitative investigation of the unfolding pace and interactions of socio-technical transitions from a whole-systems perspective. Furthermore, optimisation models have relatively restricted resolution on distinct policy instruments, modelling primarily the system effects of a carbon tax, generally uniform across sectors.

3. Methodology

3.1 Overview of the E3ME-FTT-GENIE integrated assessment model

The FTT models are subcomponents of the E3ME model, the latter representing in a top-down aggregate perspective relationships between macroeconomic quantities through a chosen set of econometric relationships that are regressed on the past 45 years of data and are projected 35 years into the future. The macroeconomics in the model determine total demand and trade for manufactured products, services and energy carriers, output and employment globally in 59 regions (a list is given in the appendix) and over 40 economic sectors. Meanwhile, technology diffusion in the FTT family of technology modules determines changes in the environmental intensity of economic processes, including changes in amounts of energy required for transport, electricity generation and household heating, from a bottom-up perspective.

Figure 1 shows the structure of the model. E3ME exchanges information dynamically with several FTT technology diffusion modules, themselves hard-linked to E3ME. E3ME generates the demand for carbon-intensive products and services to the FTT modules, which feedback prices, investment and the demand for other inputs such as energy carriers. The natural resources modules limit the deployment of renewables, and track the depletion of fossil and nuclear fuels. The models are solved together iteratively within the same computer code.

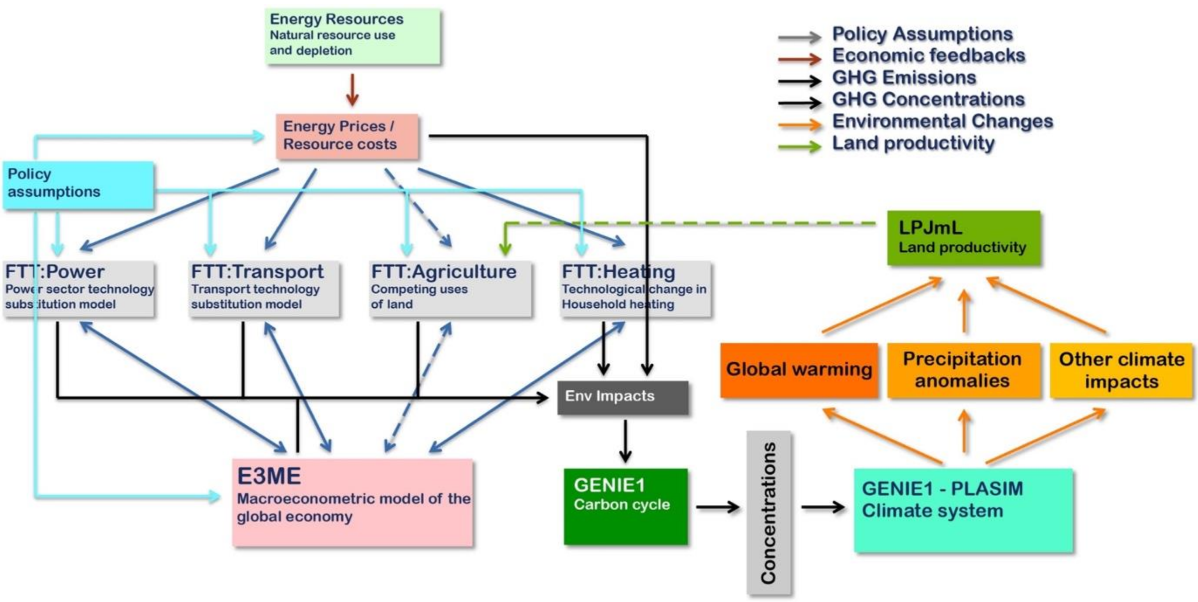

Figure 1 Diagram of the E3ME-FTT-GENIE1 integrated assessment simulation model. Note that the land-use model is under development and not discussed here. Dashed lines refer to sections under development [35] .

The model is path-dependent, such that different policy scenarios generate different techno-economic and environmental trajectories that diverge from each other over time. Using the 'what if' mode of impact assessment, in the present model, policies are chosen, and outcomes are observed in terms of the choice of policies. Meeting policy outcome objectives is obtained by iteratively running the model. The policies included in the model are designed to match as closely as possible real policy instruments, for example energy taxes, vehicle taxes, feed-in tariffs, subsidies, direct regulation, standards and biofuel mandates.

3.2 The FTT family of models

FTT models agents who own or operate technologies that produce certain societal services (e.g. generating electricity, transport, household heating), and who consider replacing such technologies according to lifetimes and contexts. As such, it is both a model of choice and one of technology vintage (or technology fleets). Replacement, or technological change, takes place at rates determined by the survival in time of technology units and/or the financing schedule, when switching from technologies *i* to *j*, denoted A_{ij}. We assume that agents make comparisons between options that they individually see as available in their respective national markets, which we structure by pair-wise comparisons [36]. Bounded rationality is modelled in terms of technology knowledge or access, which we quantify in terms of existing market shares (e.g. if the market shares of certain products are low, many agents do not have access to them). The proportion of agents already using technology *i* is S_i, that technology's market share. The proportion of agents considering the advantages of technology *j* is S_j, the market share of technology *j*. We denote the relative preference of agents for technology *j* over technology *i* with the matrix F_{ij}, a fraction between 0 and 1. If we picture shares of technologies being transferred between technology categories as agents gradually replace the stock, then we obtain the equation:

$$\Delta S_i = \sum_{j=1}^{N} S_i S_j \left[A_{ij} F_{ij} - A_{ji} F_{ji} \right] \Delta t \qquad (1)$$

This equation is famously named the Lotka-Volterra competition equation, a system of non-linear differential equations more often used in ecology to express the competition for resources between species in an ecosystem (e.g. plants competing for space). It is also extensively used in evolutionary game theory [37].

With a replicator equation (the LVC equation), FTT models have a natural representation of path dependence that stems from the self-reinforcing nature of the dynamic system of equations. Based on an approach that describe technological and economic change from a biophysical perspective, the FTT model describes technological transitions as process in an adaptive fitness landscape.

In FTT, we assume that agents individually minimise their own costs and benefits, but due to multi-agent influence (diffusion networks), this does not generally lead to a cost optimum at the system level, and indeed, we do not optimise total system cost. The preference matrix F_{ij} is probabilistic, determined by the use of a binary logit (fig. 2). Discrete choice theory is used to represent the diversity of agent preferences in a group, a diversity that determines elasticities of substitution.[1] Here, substitution is not instantaneous, as opposed to standard multinomial logit models, due to our use of the Lotka-Volterra dynamical system. Thus we use here a binary logit to determine preferences, not substitutions. Logit models take a probabilistic choice mechanism that captures the effects of unobserved variations among decision makers, capturing the inherently probabilistic nature of human behaviour [38]. Rather than assuming perfect rationality, logit models offer an opportunity to understand human choice behaviour under a probabilistic framework. In making a particular choice, individuals are likely to take into account a number of factors, such as geographic, economic, costs and income factors, and the availability to determine the potential success of alternative choices as a substitute.

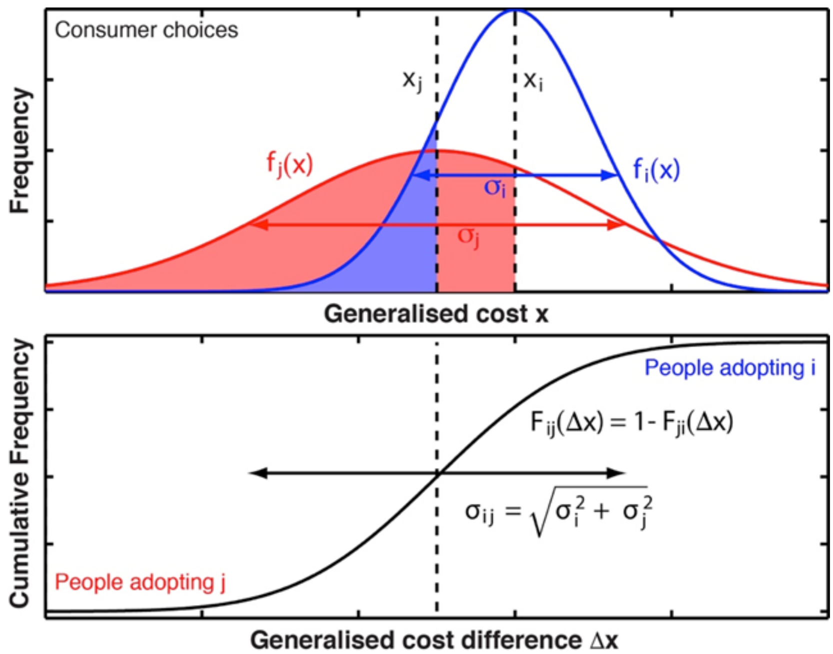

Figure 2 Schematic representation of pair-wise comparison of technological options by heterogeneous agents with varying preferences. *(Top panel)* Preferences vary following distributions in an appropriately chosen space of generalised cost. *(Bottom panel)* The resulting choice matrix follows a series of binary logits, together forming the choice matrix F_{ij}, of which the variations in generalised cost space follows the degree of heterogeneity of agent preferences [39].

Path dependency in energy systems arises from differences in initial conditions, leading to differences in infrastructures and consumption patterns [40]. The importance of historical events is further supported by high irreversibility of technology investments and decision rules that are chained to the environment [41]). In contrast to existing IAMs, the FTT model puts strong emphasis on technological path dependence, consistent with the transitions theory. The FTT framework is thus a good model choice to explore possible mismatches between transitions in sectors.

[1] Diversity/heterogeneity here means all the sources of variations in decisions between different agents, leading to distributed quantities in the model.

3.3 Analysis methodology

We performed a series of scenario analysis using the FTT models to analyse the effectiveness of decarbonisation policies in one of the energy sectors (e.g. transport, heating) when there is a mismatch in the pace of energy transitions between sectors. The analysis was conducted in the following steps:

First, we run a baseline scenario, simulating technology uptake under current trends of technology diffusion, which sets a benchmark. The baseline scenario assumes that no new policies are introduced. However, existing trends are ongoing, and can change the technology composition even without additional policy incentives.

Next, we provide an example of a basket of policies that enables, in the E3ME-FTT model, to achieve emissions reductions consistent with greater than 75% probability of not exceeding 2°C of global warming. We called this scenario the '2°C scenario'. Note that this is not the only basket of policies that can achieve the goals of the Paris Agreement. These policies are added to the baseline case.

Then, assuming the policies that encourage a technological transition in the power sector is absent, we applied the '2°C scenario' policies only to the transport sector and the heating sector. The goal is to find the extent to which we can achieve the sectoral decarbonisation target if transitions pathways are not aligned across sectors.

Based on the scenario analysis, we examined the effect of direct emissions and indirect emissions from the transport sector and the heating sector by the year 2050. The exercise enables us to understand the to what extent emissions could shift from the transport and heating sector to the power sector.

It is clear that both transport and heating interact strongly with the power sector, when technological change leads to a higher use of electricity in these sectors. However, they do not interact strongly with one another, and therefore, we focus on their interaction with electricity generation.

4. Policy assumptions

4.1 Policy instruments in the E3ME-FTT models

In the FTT models, there are four possible sub-types of policies: economic incentives (taxes or subsidies), standards/regulations, public procurement, and monetary instruments. The definitions for these policy types are listed in table 1.

In FTT, economic incentive policies influence the behaviour of the choice model. They come in the form of taxes, subsidies or feed-in tariffs that are used to influence the costs that agents attempt to minimise. For example, capital cost subsidies in power generation influence the cost of generating electricity for a particular technology, which then raises its attractiveness in the discrete choice model that is part of the replicator equation.

Policies in FTT can also be of regulatory form, in which case they restrict what the choice spectrum is for of the investor or consumer. For example, if vehicles of the current petrol engine generation are phased out, they cannot be chosen by agents, and will undergo an exponential decline as a result at a rate that is function of their survival. Vehicles can furthermore be scrapped. New types of vehicles or heating systems can also be introduced in the market, through a purchase program, either funded or enforced by the public authorities, to kick-start a new technology market (e.g. regulating taxi companies with respect to their vehicle efficiency, or installing heat pumps in publicly owned housing). Finally, the content of liquid fuels can be changed by regulation through biofuel mandates.

Table 1 Policy instruments in E3ME-FTT.

Policy type	**Economy/sector-wide**	**Technology/process-specific**
Economic incentives	Carbon price, carbon tax, income tax	Technology specific subsidies, taxes, feed-in tariffs (power, vehicles, heating)
Standards and regulations	Exogenous* phase-out and efficiency assumptions	Power sector: endogenous* phase-out Road vehicles: efficiency standards, phase out, biofuel mandates Household heating: efficiency standards, phase out, scrapping
Public procurement	Public investment	Public procurement for power generators, vehicles, heating devices, to kick-start diffusion
Monetary	Base interest rates	Lower interest loan programs

4.2 Policy assumptions – scenario for 75% chance 2 °C

We provide here an example of a basket of policies that enables, in the E3ME-FTT model, to achieve emissions reductions consistent with 75% probability of not exceeding 2°C of global warming (see [42] for details on the climate science involved in determining this probability). We note that bioenergy with carbon capture and storage (BECCS) is not a dominant feature of our scenarios, even if the consequence of higher system cost overall. We stress here that all of the policies included play a role in the broader emissions trajectory. We showed elsewhere [4] that policies interact and that the sum of their impacts can be greater than the sum of the impacts of policies applied individually. We do not claim, however, that this is the only basket of policies that can achieve the goals of the Paris Agreement. Note that the policy assumptions in this section are consistent with the assumptions taken in [35].

Electricity sector (FTT:Power)

- **Feed-in-Tariffs** - 100% of the difference between the levelised cost for renewables and the spot price, plus a 10-20% additional incentive to promote renewable uptake (wind and solar only).
- **Direct subsidies** – up to 60% of the investment cost . Phased out by 2050
- **Carbon price** in all regions increasing gradually to 500$/tCO2 in 2050 (2008 dollars)
- **Regulations** are used to phase out or cap coal in some regions

Road transport sector (FTT:Transport)

- **Standards** – more efficient internal combustion engine technologies are introduced as standard in 2017.
- **Regulations** are used to phase out older less efficient combustion engines.
- **Taxes on registration based on rated emissions**, of 100$/(gCO2/km) for every gCO2/km more than the lowest emissions category
- **Taxes on fuel**, increasing up to 0.50$/litre of fuel, in 2012 USD
- **Public procurement** – Electric vehicles introduced in the market in 2020 in all consumer categories
- **Biofuel blend mandate** that increases over time, starting at current levels, reaching 97% in 2050.

Household heating sector (FTT:Heat)

- **Fuel tax** of 50€/tCO_2 in 2020, increasing to 150€/tCO_2 in 2050
- **Subsidies** of 25% of the capital cost for renewable heating systems, linearly phased out after 2030
- **Kick-start** for low-carbon technologies with no presence in various regions

Other sectors (E3ME)

- **Regulations** – Coal phased out in China in non-power applications of heavy industry, replaced by electricity.
- **A biofuel blend** is assumed to increase by 10% per year in aviation
- **Regulations** – Household use of fossil fuels for heating regulated to decrease by 3% per year worldwide.

5. Results

5.1 Trends in global energy technology diffusion

In our model projections, a certain amount of technological change is already taking place under current trends of technology diffusion in all three sectors, even without any additional policies (see Figure 3).

In power generation (PG), a gradual (but relatively slow) decarbonisation is already taking place in most world regions. However, it is more than outpaced by demand increases, so that absolute CO_2 emissions would continue to increase at the global level. In private road travel (RT), an ongoing shift towards higher-efficiency fossil fuel vehicles means that absolute emissions could peak around 2030, despite further demand increases. A larger-scale diffusion of electric vehicles (EVs) takes time to gain momentum, and is not projected before 2035 (hybrid cars ten years earlier). In household heating (space and water) (HH), global demand for useful heat is relatively stable. Due to an increased uptake of heat pumps (HPs) and solar thermal, absolute emissions could see a gradual decline from the 2030s onwards.

In our policy scenario for limiting global warming to 2℃, we see an acceleration of these trends. In PG, additional policies lead to a much faster decarbonisation from 2020 onwards, with steadily decreasing emission intensities, largely driven by a phase-out of coal. In RT and HH, the mix of new policies immediately incentivises a shift towards low-carbon technologies, among them EVs and heat pumps. However, because these electricity-based alternatives currently have very small market shares, substantial additional growth would still be limited in absolute terms ahead of the 2030s.

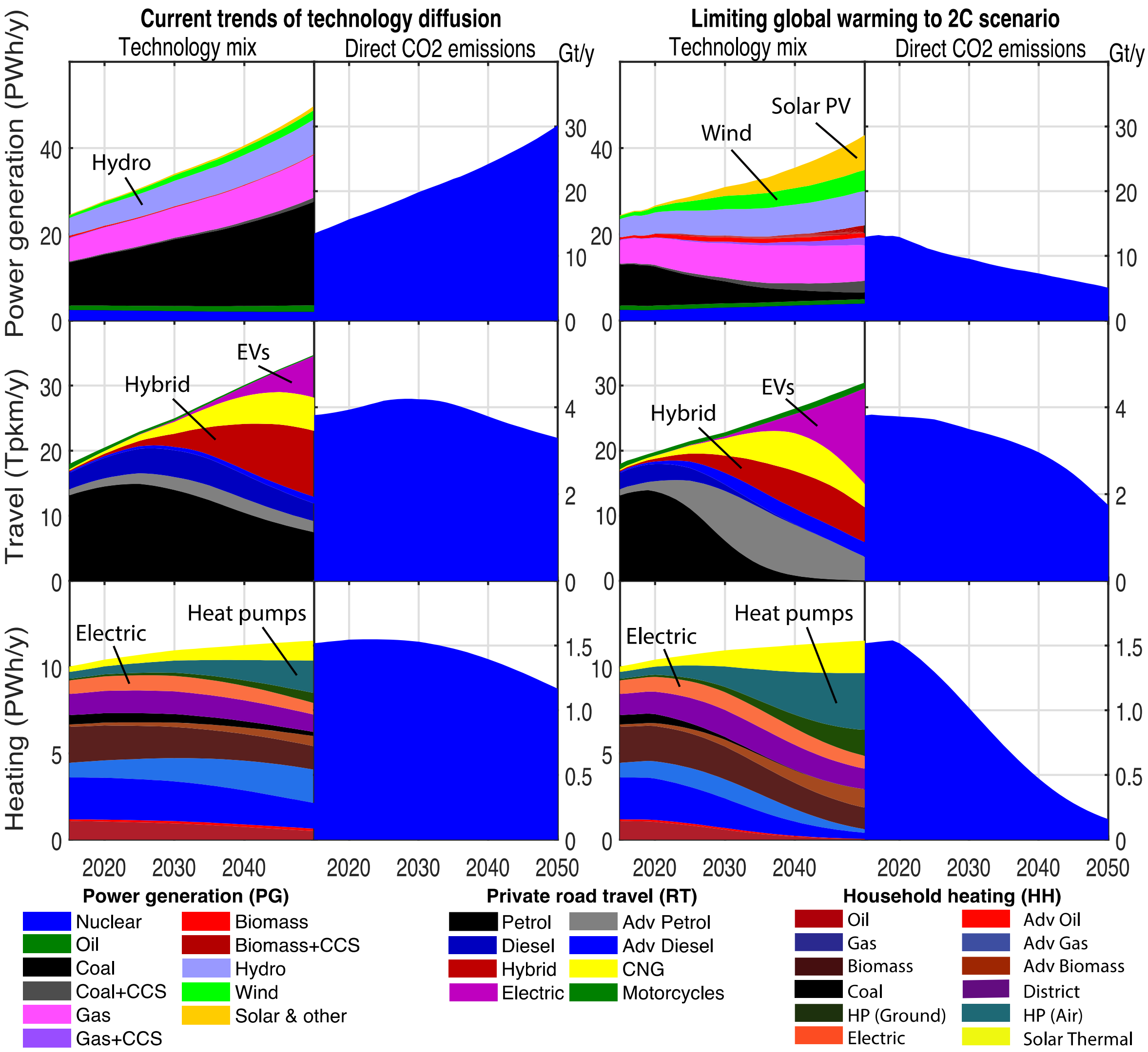

Figure 3 Projections of technology diffusion and direct CO2 emissions from 2015-2050, under the current trajectory of technology diffusion (left panels) and under a set of policies consistent with limiting global warming to 2°C (right panels), shown for (i) power generation (first row), (ii) private road travel (middle row) and (iii) household heating (space and water) (bottom row).

5.2 *Global changes in direct, indirect and total CO_2 emissions from energy end-use in road transport and household heating*

Under current diffusion trends, PG would thus decarbonise sufficiently fast ahead of end-use electrification, so that indirect emission increases are projected to be limited. Figure 4 illustrates the trends in direct, indirect and total CO_2 emissions on the global level, both for RT and HH.

Under current trends, electricity demand in RT would remain close to zero before 2035 and increase to around 1.5PWh/y towards 2050. The resulting indirect emissions remain limited to less than 20% of total RT emissions. In HH, electricity demand is projected to linearly rise under current trends - from around 1PWh/y in 2015, to 1.5PWh/y by 2050. The corresponding share of indirect emissions (in total emissions) would increase from 25% to 40%. Importantly, despite the projected electrification, indirect emission increases in RT and HH would be limited by parallel decarbonisation of PG (as can be seen from the divergence of the power demand (grey dashed lines) and resulting indirect emissions (red lines) in Figure 4).

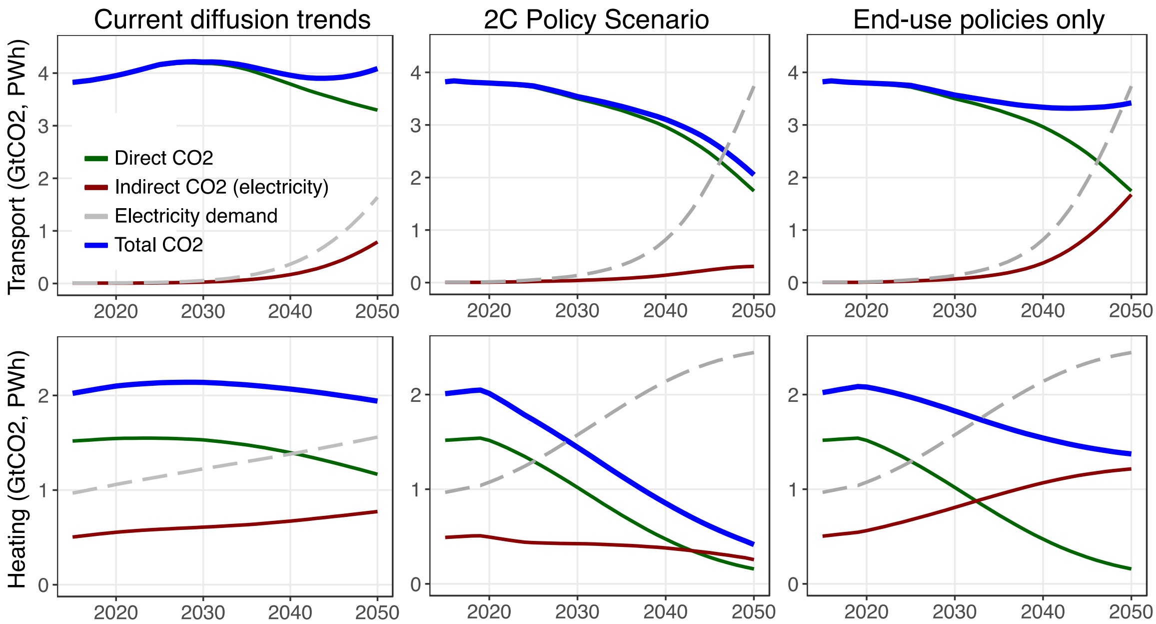

Figure 4 Projections of direct CO2 emissions (green), indirect (use-phase) CO2 emissions from electricity use (red) and combined emissions (blue), 2015-2050, in private RT (first row) and HH (second row). The dashed grey lines depict the corresponding electricity demand in the respective end-use sector. The left column shows the trend under current trajectories of technology diffusion and electrification, the middle column under policies consistent with limiting global warming to 2°C. The right column depicts an 'end-use policies only'-scenario: no further policies are assumed for the power sector, while RT and HH are subject to the same policies as in the 2°C scenario.

In the 2℃ policy scenario, the situation is conceptually similar, but more pronounced. Electricity demand for RT is projected to be around twice as high by 2050 (+2PWh/y), compared to current trends. Still, due to the both faster and deeper decarbonisation of PG, resulting indirect emissions are around 50% lower. In HH, electricity demand in 2050 is projected to be around 1PWh/y higher than under current trends. As in RT, resulting indirect HH emissions would be lower than under current trends, due to the decarbonisation of PG. Still, they would eventually become the dominant source of HHs total emissions, surpassing direct on-site emissions around 2040.

So, what would happen in case of a mismatch between the paces of sectoral transitions? What if RT and/or HH would transition towards electricity-based technologies as incentivised in the 2℃ policy scenario, while technological change in PG would remain on its current trajectory? For both RT and HH, projected 2050 levels of indirect electricity emissions would be four to five times larger compared to the 2℃ policy scenario, and around twice as large as compared to current trends scenario. Indirect emission increases of this magnitude would largely cancel out the projected reductions in direct end-use emissions. In case of such a transitions mismatch, overall end-use emissions (RT and HH) still be reduced compared to current trends, though emission reductions could be three times larger when PG is decarbonised in parallel. Nevertheless, total emissions would be lower than under current trends, both in RT and HH. Overall, this suggests that a mismatch of sectoral decarbonisation paces may partly counteract emission reduction targets, but would not increase total emissions.

5.3 When does electrification reduce end-use emissions?

It is important to acknowledge that the technology composition and carbon intensities of PG, RT and HH hugely differ between world regions. In particular, the risk of sectoral mismatches depends on the carbon intensity of a region's PG system, as it largely determines indirect emissions of RT and HH.

Figure 5 and Figure 6 illustrate the emissions trade-off that is implicitly made in electrifying RT and HH, for each world region. The x-axis shows the indirect CO_2 intensities (from electricity use) when driving an EV or operating an electric heat pump. For each region, this intensity depends on its PG's respective CO_2 intensity at a given point in time (shown here for 2015, 2030 and 2050). For some countries, indirect emission intensities are already close to zero, such as in the cases of Norway (where electricity generation is dominated by hydro) or France (dominated by nuclear). Potential capacity constraints aside, the potential risk of a transitions mismatch is thus very low in such countries. At the opposite end of the spectrum are countries whose power systems still heavily rely on coal, such as India or Poland. Most countries, however, can be found somewhere in between those two extremes.

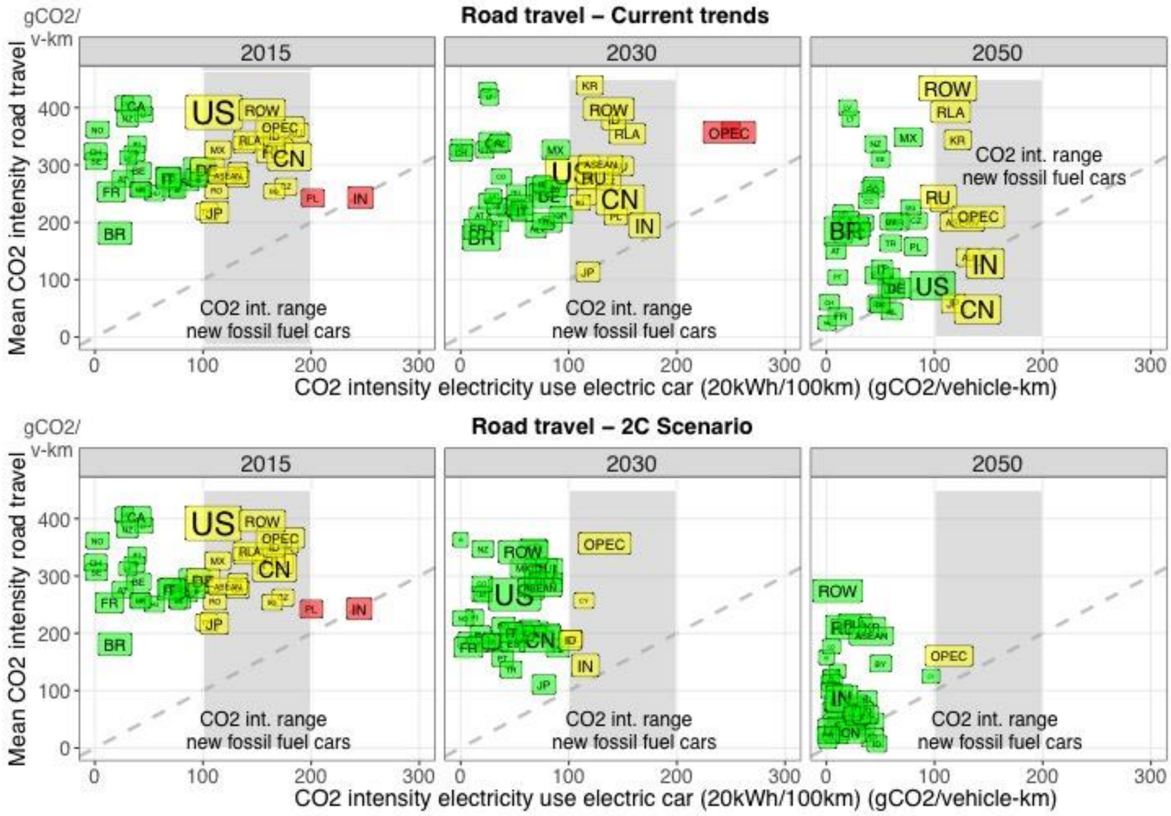

Figure 5 Current (2015) and projected (2030 and 2050) use-phase CO_2 intensities in RT (in gCO_2/v-km), under current trends of technology uptake (upper panels) and in the 2°C policy scenario (bottom panels). Label sizes indicate total CO_2 emissions from RT in a region (direct plus indirect from electricity use). The x-axis shows the indirect CO_2 intensity from electricity use for driving an electric car (with a fuel economy of 20kWh/100km), which depends on the power sector's respective CO_2 intensity in different world regions. For comparison, the grey bar illustrates the range of CO_2 intensities of new fossil-fuel powered cars. When a region's label is left of the bar (indicated in green), indirect electricity emissions from driving electric are lower than the direct emissions from driving the most efficient fossil fuel car. The opposite holds for regions located right of the bar (indicated in red). The y-axis corresponds to a region's mean CO_2 intensity in RT (direct emissions only), averaged over the entire car fleet. For regions above the dashed line, indirect emissions from driving electric are below its car fleet's mean CO_2 intensity.

Emission reductions of RT and HH through electrification depend on the reference point used, which is either (i) the respective end-use sector's average CO_2 intensity at a given point in time, or (ii) the CO_2 intensity of state-of-the art fossil fuel-based alternatives (fuel-efficient new cars/heating systems).

(i) In Figure 5, each region's average CO_2 intensity of RT or HH is shown on the y-axis. The grey dashed lines indicate where these are equal to indirect emissions from electricity use in RT or HH, given each region's PG system. For all regions whose label is located above the dashed line, average emission intensities exceed the expected emission intensities from the depicted electric alternatives (a 20kWh/100km electric vehicle, or COP=3 heat pump, respectively). In these cases, electrification could decrease total use-phase emissions.

(ii) Grey bars indicate the ranges of CO_2 intensities of new fossil fuel-based technologies. When a region's label is left of the bar (indicated in green), indirect electricity emissions from driving/heating electric are lower than the direct emissions from using the most efficient fossil fuel technology and electrification would lead to emission reduction. The opposite holds for regions located right of the bar (indicated in red). For regions within the bar (indicated in yellow), electrification could either be more or less CO_2 intensive, depending on the specific fossil fuel-based technology which would be chosen alternatively.

The horizontal distance between a region's label and the dashed grey line indicates how much a sector's electrification could reduce its average emission intensity. The distance towards the grey bar indicates the difference in the emission intensity of new technologies. Regardless of the reference used, the further right a region is located on the x-axis, the larger the risk that mismatches in sectoral transition speeds in PG and end-use sectors could result in absolute emission increases.

5.4 When would EVs reduce CO_2 emissions in road travel?

For RT in 2015, it can be seen that replacing an average car with an EV would reduce the sector's total emissions in all modelled world regions. Only in two cases (India and Poland), the indirect emissions from driving an EV would currently exceed the direct emissions of driving most state-of-the-art fossil fuel cars. In all other world regions, driving electric is either less emission intensive in almost all cases (green regions), or at least on par with fossil fuel cars (depending on its specific fuel economy, yellow regions).

Under current trends, the emission intensities of PG are projected to decrease over time in almost all world regions, even without additional policies. Accordingly, electric driving would become increasingly less emission intensive. By the time that EVs are projected to gain significant market shares (2030 onwards), the power sector would already be decarbonised to such an extent that the uptake of EVs would not lead to emission increases. Still, PG decarbonisation remains limited. Therefore, in many world regions the indirect emissions from driving EVs would still not be lower than the direct emissions from driving a new fossil fuel car.

In the 2°C scenario, the power sector would be decarbonised much quicker. By 2030, EVs would therefore be less CO_2 intensive than new fossil fuel cars in all but four regions (OPEC, India, Indonesia, Cyprus). By 2050, the CO_2 savings from driving an electric car would become even larger, as PG becomes even less CO_2 intensive.

5.5 When would heat pumps reduce CO_2 emissions in household heating?

For HH, similar observations can be made. Only in one world region (India), the indirect emissions from using a heat pump would currently exceed the direct emissions of heating with oil (but would still be lower than heating with coal). In all other world regions, an average heat pump is either less emission intensive than state-of-the-art gas condensing boilers (green regions), or at least on par with an average gas or oil heating (depending on its specific conversion efficiency, yellow regions).

Different than in RT, however, many regions already have a relatively high market share of technologies with zero or low direct CO_2 emissions (foremost biomass, electric resistance or district heating). This means that the average CO_2 intensity in HH can often be lower than that of heat pumps, and a comparison must be made for each individual technology. In case of electric resistance heating, switching to heat pumps would always lower total emissions, since it is much more energy-efficient (by a factor of 3-4). In case of biomass, the choice involves other factors, such as the source of biomass, and its potential impact on local air pollution (e.g., due to black carbon). For district heating, the relative advantage of electrification depends on the emission intensity of centralised heat plants, the decarbonisation of which can often be a viable alternative to decentralised low-carbon options.

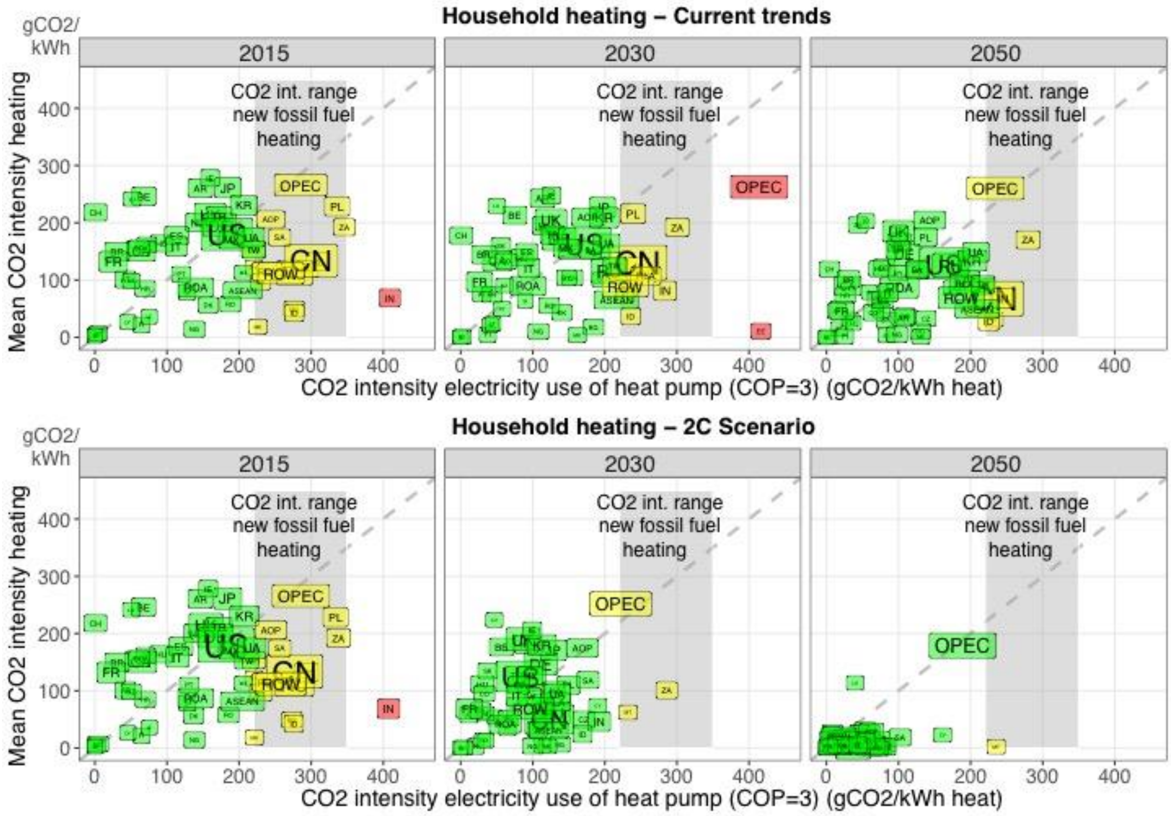

Figure 6 Current (2015) and projected (2030 and 2050) use-phase CO_2 intensities in HH (in gCO_2/kWh), under current trends of technology uptake (upper panels) and in the 2°C policy scenario (bottom panels). The x-axis shows the indirect CO_2 intensity from electricity use when operating a heat pump (with an average coefficient of performance of 3), which depends on the power sector's respective CO_2 intensity in different world regions. For comparison, the grey bar illustrates the range of CO_2 intensities of new fossil-fuel based HH systems (condensing gas up to non-condensing oil). When a region's label is left of the bar (indicated in green), indirect electricity emissions from heat pumps are lower than the direct emissions from HH with the most efficient fossil fuel system. The opposite holds for regions located right of the bar (indicated in red). The y-axis corresponds to a region's mean CO_2 intensity in HH (direct emissions only), averaged over the entire stock of HH systems. For regions above the dashed line, indirect emissions from heat pumps are below its mean CO_2 intensity. Label sizes indicate total CO_2 emissions HH in a region (direct plus indirect from electricity use).

5.6 *Changes in end-use CO_2 intensities by region*

Figures 5 and 6 show the projected changes in RT's and HH's direct, indirect and total CO_2 emission intensities between 2015-2050 – under current trends, the 2°C policy scenario, and in case of a transitions mismatch (in which the 2°C policies are only applied to end-use sectors, but not to PG).

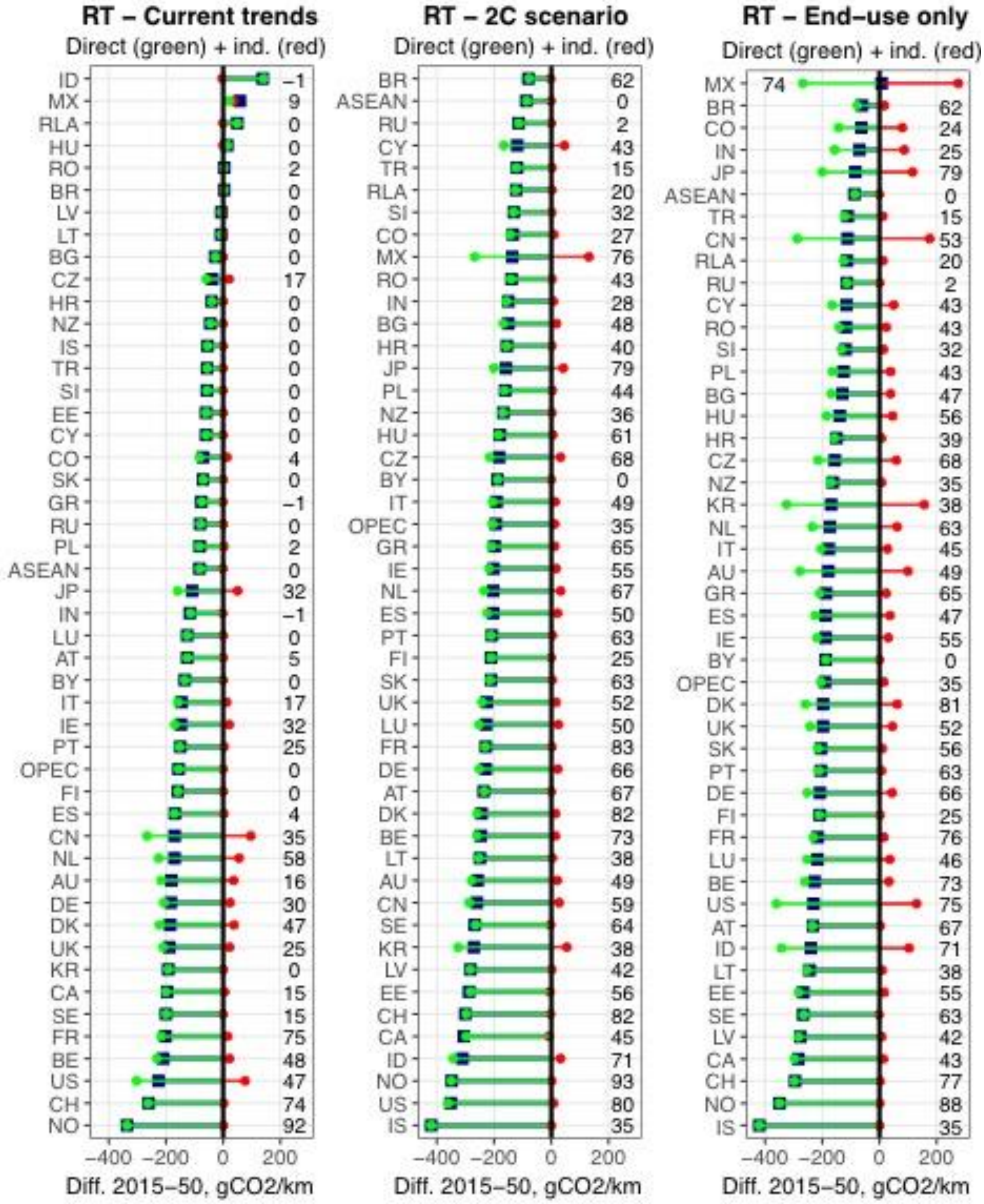

Figure 7 Projected changes in RT's direct CO_2 intensity (green), indirect CO_2 intensity from electricity use (red) and combined CO_2 intensity (blue), 2015-2050 (in gCO_2/v-km), for world regions which are explicitly modelled by FTT:Transport. Numbers on the right refer to the changes in market shares of EVs over the same period, in percentage points.

Under current trends of technology diffusion, total emission intensities are projected to either decrease or stay constant in most world regions,, both for RT and HH. Increases are only projected for four regions in case of RT, and six regions in case of HH (mostly due to a gradual replacement of biomass heating). In RT, increases in indirect emissions from electricity use are largely restricted to European countries, the US, China and Japan, as they form the main regions in which electrification takes place. In HH, electric heating in form of direct resistance heating is already a significant part of the technology mix in many regions, and resulting indirect emission intensities can be substantial. Therefore, under current trends, most regions would even see a reduction of the sector's indirect emission intensity, due the parallel decarbonisation of electricity generation and a slow replacement of electric heaters by more efficient heat pumps in some regions. In China, heat pumps (along with solar thermal) gradually replace coal, while the power sector remains coal-dominated – largely cancelling out the reductions in direct emissions.

In the 2°C policy scenario, indirect emission increases in RT are more wide-spread around the globe. However, both here and in HH, the increase in indirect emissions is limited, due to decarbonisation of PG. In HH, this often leads to reductions in indirect emission intensities which can be as large (or even larger) as direct emission intensity reductions.

In case of a transitions mismatch, indirect emission increases are much larger, compared the 2°C scenario. However, indirect emission increases would not exceed direct emission reductions in any region for RT, and in not more than three regions in case of HH (OPEC, Ukraine and Indonesia).

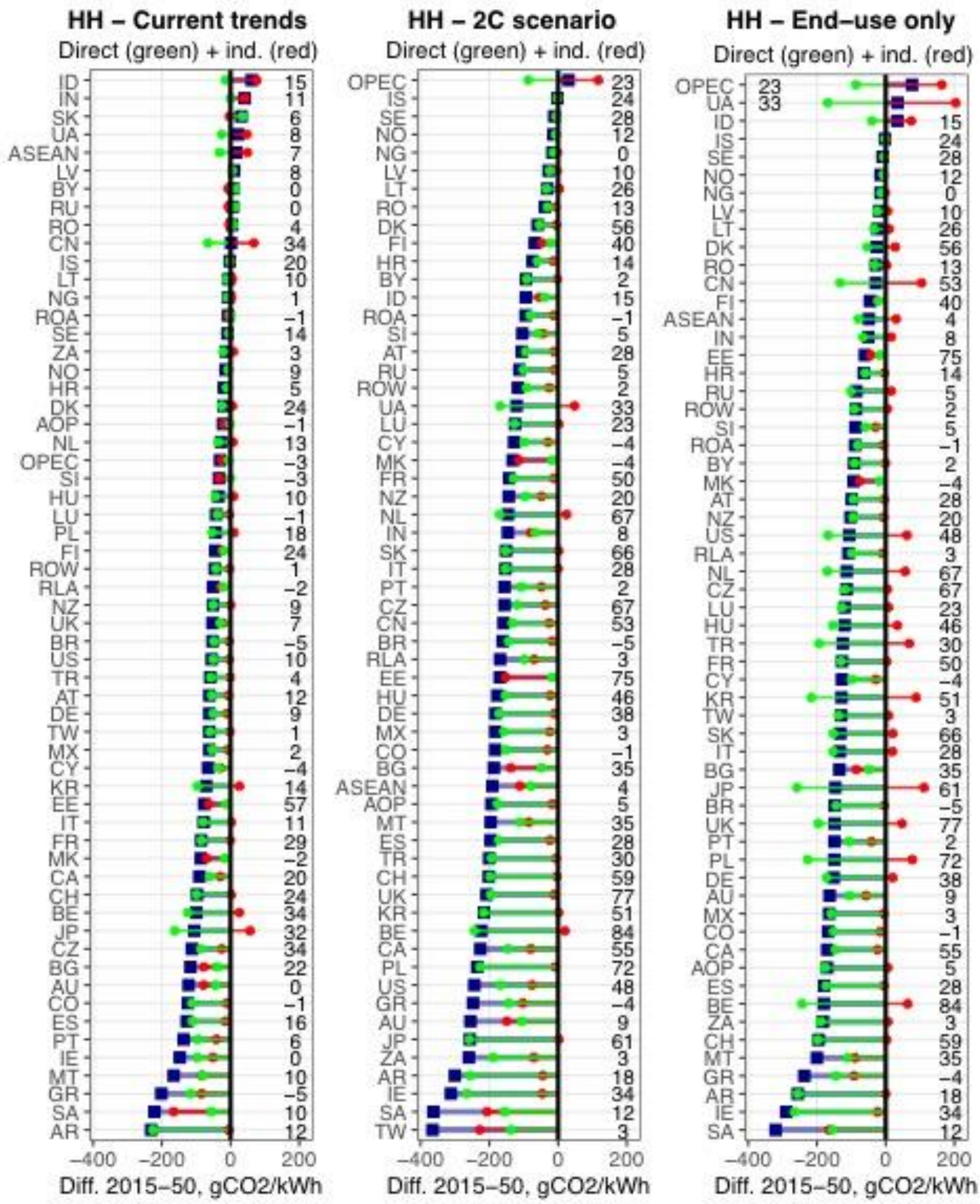

Figure 8 Projected changes in HH's direct CO_2 intensity (green), indirect CO_2 intensity from electricity use (red) and combined CO_2 intensity (blue) , 2015-2050 (in gCO_2/kWh of heat), for world regions which are explicitly modelled by FTT:Heat. Numbers on the right refer to the changes in market shares of electric heating (heat pumps and electric resistance) over the same period, in percentage points.

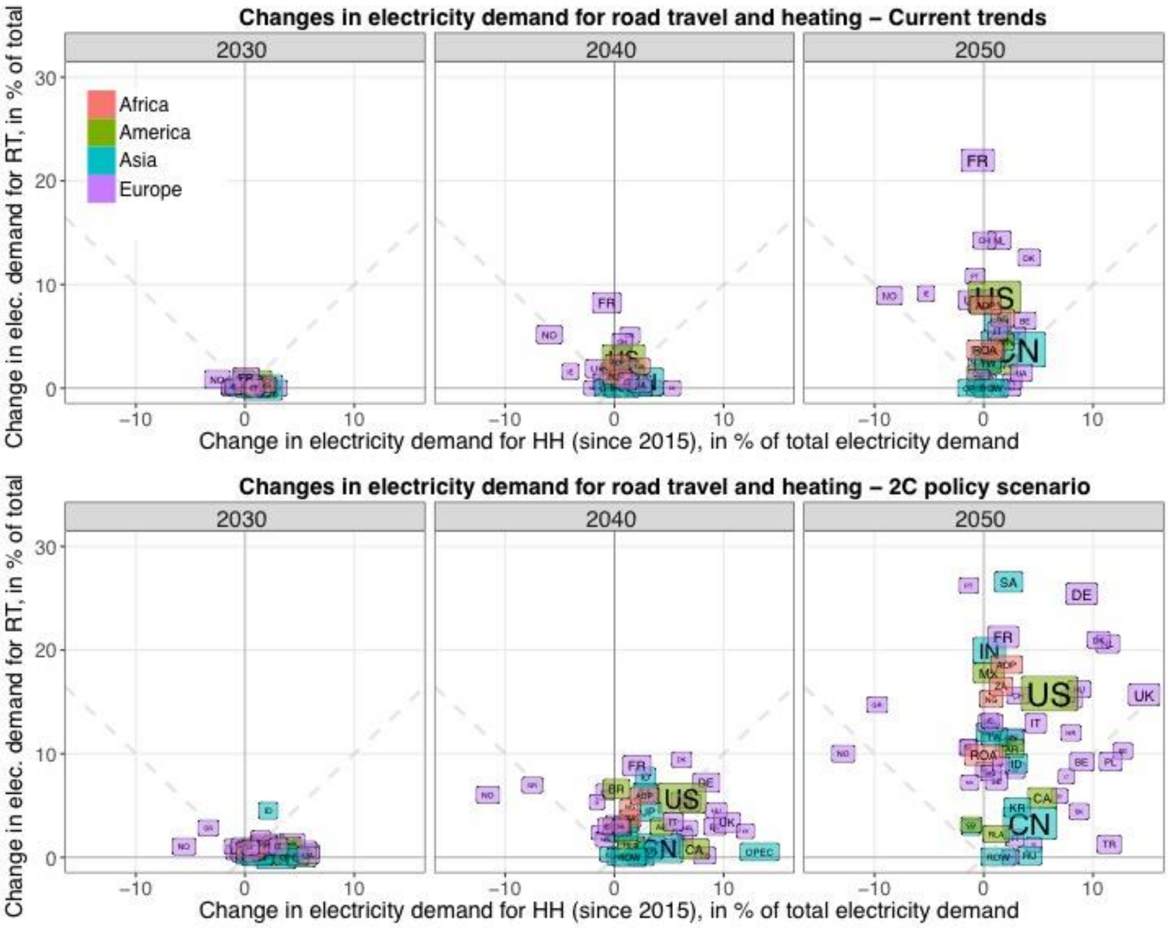

Figure 9 Projected changes in electricity demand (in 2030, 2040 and 2050) for HH (x-axes) and private RT (y-axes), as a percentage of a region's total projected electricity demand in that year. The upper panels show projections under current trends of technology uptake, the bottom panels in case of the 2°C policy scenario. Label sizes indicate the combined electricity demand of RT and HH, label colours correspond to continents.

5.7 Potential impacts on electricity demand

Apart from its implications for CO_2 emissions, an electrification of end-use sectors may lead to significant increases in a region's overall electricity demand, with potentially important implications for the power sector, which needs to adapt its production and storage capacities accordingly (depending on overall scale, flexibility, load patterns, grid architecture, etc.). Figure 5 illustrates the demand increases that are projected to result from an electrification of RT and HH, both under current trends and in our 2°C policy scenario. To make the analysis comparable across regions, demand changes are not given in absolute numbers (e.g., +100GWh/y), but in relative terms: as the percentage change in annual region-wide electricity demand, compared to a hypothetical scenario in which electricity demand in both sectors would stay constant at 2015 levels. Total changes correspond to the sum of changes in both sectors (x-axis plus y-axis).

Under current trends of technology diffusion, electricity demand in 2030 is projected to change by not more than +/-3%. In 2040, projected increases due to the increasing electrification of RT and HH are up to +5% each (+10% in total). Notably, the uptake of heat pumps can take place demand-neutral or even lead to demand reductions in some regions, in case that it replaces (less energy-efficient) electric resistance heating (such as in Norway). Electricity demand for RT would further increase. By 2050, it could reach up to +20% in some countries (such as France), but would be limited to not more than +10% in most regions.

In case of the 2°C policy scenario, projected changes in overall electricity demand are of a similar pattern, but much more pronounced. Demand increases due to RT and HH would each reach up to +10% by 2040. Sectoral demand increases are not strongly correlated with each other (i.e., when electricity demand for RT is projected to grow by 10%, demand for HH may change by more or less than that), so that the cumulative increase is not larger than +15% in most regions. By 2050, projected increases in overall electricity demand are up to +12% due to HH, and up to +25% due to RT. Cumulative increases can be as large as +35% in some regions (such as in Germany), but largely stay below +20%.

6. Conclusion

Our results illustrate how technology diffusion in the PG, RT and HH sectors is mutually interdependent, and how these interdependencies may dynamically develop until 2050. In particular, we have shown to which extent emission reductions in end-use sectors by means of electrification depend on the current and future characteristics of electricity generation in individual world regions. Technology diffusion in transport and heating will change electricity demand, leading to indirect emission changes in the power sector, depending on its parallel decarbonisation. All three sectors' transitions towards a low-carbon state are thus characterised by multi-sectoral interactions, the implications of which are important considerations for the effectiveness of policy strategies to reduce economy-wide emissions.

We have demonstrated that mismatches in multi-sectoral transitions can occur when end-use electrification outpaces the decarbonisation of the power sector, in regions where power generation is still relatively carbon-intensive. While such mismatches can potentially lead to lower than anticipated emission reductions, they would only rarely result in emission increases. We have shown that the risk for and potential extent of transition mismatches is region-specific, with a large variation between countries. The risk in terms of indirect emission increases is largest in regions where

(i) PG is still carbon-intensive, at the point in time when
(ii) end-use sectors would see significant electrification.

The extent of resulting indirect emission increases is mitigated by the high conversion efficiencies of the considered end-use technologies (EVs and heat pumps, respectively). In most regions, this implies that an electrification of end-use could reduce overall emissions, even under the current carbon intensity of electricity generation. Only in very few regions would switching to electric alternatives increase the overall emission intensity.

Perhaps most importantly, we have analysed how the risks of multi-sectoral mismatches are mitigated by the characteristic inertia and path dependence of technology diffusion: new technologies typically diffuse gradually, and it can take considerable time to steer the technology composition into a new direction. For potential mismatches, this implies that:

(i) In most world regions, PG is decarbonising already. This trend is projected to continue, even without further policies, making PG less and less carbon-intensive over time.
(ii) The parallel electrification of end-use sectors occurs only very gradually, with a still slow (or inexistent) uptake of EVs and heat pumps in most markets. We find that end-use electrification would only gain momentum in 10-20 years, when PG is very likely less carbon-intensive than today.
(iii) When new policies are introduced, they need time until they show significant absolute impacts on the technology composition, leaving room for correcting course in case of unexpected mismatches.

The type of analysis presented here crucially relies on a modelling methodology which is simulation-based, taking into account the real-world dynamics and imperfections of transitions and technology diffusion. We have shown that E3ME-FTT is capable of doing so. While its representation of transition dynamics necessarily remains simplified and abstract, the model incorporates them in a stylised form, without assuming society-wide optimisation by a social planner, as most other IAMs do. Therefore, E3ME-FTT is perhaps the IAM which is currently closest to transitions theory, as it allows a quantitative analysis of transitions on a multi-sectoral level, covering the globe.

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Appendix

Table 2 List of world regions in E3ME-FTT (alphabetically sorted by their abbreviations), with their respective 2015-demand for private road travel (in billion vehicle km and percentage share of global demand) and household heating (in TWh thermal and percentage share of global demand). Regions with a transport demand of 0 are not explicitly modelled by FTT:Transport. Part I/II.

Name	**Country**	**Demand RT**	**Share RT**	**Demand HH**	**Share HH**
		Billion v-km	*%*	*TWh thermal*	*%*
AOP	59 Africa OPEC	0	0%	53	0.5%
AR	45 Argentina	0	0%	64	0.6%
ASEAN	51 Rest of ASEAN	79	0.6%	51	0.5%
AT	11 Austria	78	0.6%	52	0.5%
AU	37 Australia	174	1.4%	45	0.5%
BE	1 Belgium	105	0.9%	64	0.6%
BG	26 Bulgaria	20	0.2%	16	0.2%
BR	44 Brazil	1096	8.9%	85	0.9%
BY	40 Rest of Annex I	71	0.6%	46	0.5%
CA	36 Canada	243	2%	260	2.6%
CH	29 Switzerland	60	0.5%	40	0.4%
CN	41 China	1494	12.2%	2224	22.2%
CO	46 Colombia	12	0.1%	18	0.2%
CY	18 Cyprus	6	0%	2	0%
CZ	16 Czech Republic	66	0.5%	49	0.5%
DE	3 Germany	636	5.2%	452	4.5%
DK	2 Denmark	36	0.3%	37	0.4%
EE	17 Estonia	11	0.1%	8	0.1%
ES	5 Spain	220	1.8%	81	0.8%
FI	13 Finland	49	0.4%	48	0.5%
FR	6 France	444	3.6%	308	3.1%
GR	4 Greece	67	0.5%	31	0.3%
HR	31 Croatia	20	0.2%	17	0.2%
HU	21 Hungary	29	0.2%	39	0.4%
ID	50 Indonesia	162	1.3%	57	0.6%
IE	7 Ireland	35	0.3%	21	0.2%
IN	42 India	607	5%	157	1.6%
IS	30 Iceland	3	0%	3	0%
IT	8 Italy	421	3.4%	213	2.1%

Table 3 List of world regions in E3ME-FTT (alphabetically sorted by their abbreviations), with their respective 2015-demand for private road travel (in billion vehicle km and percentage share of global demand) and household heating (in TWh thermal and percentage share of global demand). Regions with a transport demand of 0 are not explicitly modelled by FTT:Transport. Part II/II.

Name	**Country**	**Demand RT**	**Share RT**	**Demand HH**	**Share HH**
		Billion v-km	*%*	*TWh thermal*	*%*
JP	35 Japan	538	4.4%	192	1.9%
KR	48 Korea	110	0.9%	140	1.4%
LT	20 Lithuania	9	0.1%	11	0.1%
LU	9 Luxembourg	5	0%	2	0%
LV	19 Latvia	9	0.1%	10	0.1%
MK	33 Macedonia	0	0%	2	0%
MT	22 Malta	0	0%	0	0%
MX	43 Mexico	127	1%	74	0.7%
NG	56 Nigeria	0	0%	80	0.8%
NL	10 Netherlands	106	0.9%	87	0.9%
NO	28 Norway	35	0.3%	42	0.4%
NZ	38 New Zealand	39	0.3%	4	0%
OPEC	52 OPEC excl Venezuela	243	2%	272	2.7%
PL	23 Poland	179	1.5%	132	1.3%
PT	12 Portugal	72	0.6%	11	0.1%
RLA	47 Rest of Latin America	156	1.3%	77	0.8%
RO	27 Romania	45	0.4%	43	0.4%
ROA	58 Rest of Africa	0	0%	306	3%
ROW	53 Rest of world	342	2.8%	537	5.4%
RU	39 Russian Federation	747	6.1%	1005	10%
SA	55 Saudi Arabia	0	0%	14	0.1%
SE	14 Sweden	74	0.6%	65	0.7%
SI	24 Slovenia	19	0.2%	9	0.1%
SK	25 Slovakia	18	0.1%	17	0.2%
TR	32 Turkey	68	0.6%	121	1.2%
TW	49 Taiwan	0	0%	16	0.2%
UA	54 Ukraine	0	0%	183	1.8%
UK	15 UK	401	3.3%	309	3.1%
US	34 USA	2684	21.9%	1692	16.9%
ZA	57 South Africa	0	0%	42	0.4%

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