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Efficiency improvement and technology choice for energy and emission reductions of the residential sector

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ABSTRACT

The residential sector currently accounts for one fifth of global energy use and corresponding greenhouse gas emissions, largely driven by increasing demand for space heating and cooling. Climate change mitigation action requires these to reduce, but the exact decarbonization strategies, the contribution of demand and supply side measures, and their heterogeneity is unclear. Using a regional energy system model with an explicit representation of residential energy use and building stocks, the contribution of this sector in long-term decarbonization pathways is explored. The projections show that in a 2°C scenario, global heating demand is expected to decrease from current levels by 27% and 66% by 2050 and 2100, respectively. However, due to increasing affluence in warmer regions, cooling demand is expected to increase by 176% and 286% respectively. Yet, direct residential emissions are almost eliminated by 2100 by combining increased envelope efficiency and advanced heating technologies in a synergistic manner, where the adoption of high efficiency heating and cooling reduces the need for increased insulation, and vice versa. By combining these measures with rooftop PV, the net energy demand of many household types approaches zero. The exact residential sector strategies vary across local climate, socio-economic, and building stock characteristics.

1. Introduction

The residential sector accounts for approximately 20% of 2017 global final energy use and is directly responsible for about 6% of energy related greenhouse gas (GHG) emissions. If upstream emissions from electricity are included, then residential buildings are responsible for almost 18% of global GHG emissions [1]. Globally, residential energy demand has been increasing steadily since 2000 at around 1% per year, driven by a growing population and increased demand of energy services, particularly for space and water heating, space cooling, and appliance use. These trends are expected to continue, given trends in population and household consumption and the expected impact on residential energy use and emissions [2–4]. Yet, to limit global warming within the targets of the Paris Agreement, net anthropogenic GHG emissions must fall to net-zero across all sectors within the next few decades [5,6].

The residential sector can contribute to the mitigation of global GHG emissions through a reduction of final energy demand and through a switch towards low or zero emission energy carriers. Existing studies have investigated how changes in technology choice can reduce emissions [7–9]. These studies typically show that technology changes could reduce total energy demand by up to 60% by the end of the century. Studies focusing on improving building envelope efficiency highlight the important role this can play, also limiting residential space heating and cooling demand by up to 60% [9,10]. Furthermore, these studies highlight the importance of the make-up and turnover of building stocks, which are an important determinant of the rate of improvement of aggregate building efficiency as potential lock-in into low efficiency infrastructure. Recent studies have also investigated the effect of demand side management options and lifestyle changes [11–14]. Finally, the residential sector can also contribute to decarbonization through rooftop solar photovoltaics (PV). It has been estimated that rooftop (PV) could provide 30% of global, or 70% of urban household electricity demand. This would fundamentally shift the role of buildings from energy consumers to so-called *prosumers* [15], allowing for a broader energy-system decarbonization.

While the above studies highlight the potential of individual

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measures, it is unclear how a full strategy to reduce emissions looks like. For instance, in the above studies which highlight the importance of behavioural change and technology adoption, the improvements in building efficiency through increased insulation is not explicitly dealt with, with exogenous assumptions on how this may develop [7]. In fact, the decision to invest in efficient technology depends on decisions on building envelope efficiency (in new buildings or renovation of existing buildings), and vice-versa. This raises the possibility for synergies and trade-offs between different measures, such as the reduced motivation to invest in extremely high building envelope efficiency if heating demand is produced from ultra-high efficiency technologies such as heat pumps.

These limitations have been highlighted as critical knowledge gaps in assessing climate change mitigation pathways for the residential sector. Integrated Assessment Models (IAMs) used to project global mitigation pathways used by the Intergovernmental Panel on Climate Change have so far focused on presenting supply-side emission reduction measures for the residential sector as they typically have a simplified representation of demand-side aspects and efficiency improvement [3,5,16]. The adoption and effectiveness of demand-side and efficiency improvement measures depends a lot on socio-economic, technological, building stock, and climatic heterogeneity households face [17,18]. The lack of these details in IAM projections make it difficult to assess the drivers and constraints which can allow for actionable and context-relevant climate mitigation strategies.

In the present study a techno-economic analysis of the global residential sector and its long-term pathways consistent with the Paris Agreement for different world regions was conducted. Using the recursive dynamic energy system model TIMER (part of the IMAGE 3.2 IAM) the interplay between - and adoption of - three key mitigation measures: building envelope efficiency improvement, heating/cooling technology choice, and investment in rooftop PV was investigated. The residential energy demand module (TIMER-REMG) explicitly accounts for development of residential building stocks, socio-economic heterogeneity of households, and climatic conditions across 26 world regions. Thus, the model is able to appropriately represent the drivers and constraints of efficiency improvements in the residential sector, the implications of building stock legacy, socioeconomic and climate conditions, and the interaction with the remaining energy system. To this end, the model projects the adoption of different mitigation measures and how they influence the energy demand and emissions of the residential sector in the 21st century, as well as their contribution to meeting the Paris Agreement.

2. Methods

2.1. Model

This analysis uses an updated version of the TIMER energy system model, which forms the energy system component of the IMAGE Integrated Assessment Model (IAM) [19]. TIMER is a recursive dynamic energy system model representing the global energy system, projecting developments in energy supply, conversion, and demand [20,21]. The model is driven by exogenous projections of population, GDP, value added, household expenditures (and inequality), and urbanization rates. For the residential sector, a stylized bottom-up sub-model (REMG) uses the above drivers to project changes in household size, floorspace, and the final energy demand for five end-use functions: cooking, lighting, space heating, space cooling, water heating, and appliances. The model has an explicit representation of 26 world regions with different climatic and socio-economic conditions, as well as five income quantiles for urban and rural households. Thus, TIMER-REMG captures the different energy use characteristics and investment motivations of 260 representative households. As such, the model represents the heterogeneities of households (technical, socio-economic, climatic, energy structure) which drive emission mitigation strategies, as well as the interactions of this sector with the rest of the energy system. Thus, it is appropriate to assess the dynamics, synergies, and tradeoffs of different mitigation strategies, consistently within the broader decarbonization of the energy system. Details are available in the Supplementary Material, while the motivation, formulation, and background data of the TIMER-REMG model are available in Ref. [22].

The updated model used in this analysis includes four key additions which have been identified in the literature as important in determining the energy demand reduction and emission mitigation potential of the residential sector [5,7,15,23,24]. These additions are the accounting of building stocks throughout the projection period (including the construction and decommissioning of stocks); calculation of investments in thermal insulation of these stocks at construction or renovation; inclusion of heat pumps as a space heating technology; and the possibility for households to invest in rooftop solar PV. The addition of these measures to the existing TIMER-REMG allows to model the interactions of the residential sector with the rest of the energy system (through solar PV electricity generation). Furthermore, they allow to model and identify the dynamics governing very high efficiency buildings, as well as so-called *prosumers* and *zero* or even *positive* energy households. The implementation of each of these is described in the following sections, with further details available in the Supplementary Material.

2.1.1. Residential stocks and insulation

The REMG model projects regional residential floorspace based on economic development and population density, calibrated to historic data of floorspace development [22]. Resultant changes in floorspace demand, together with regional building lifetime drive the stock accounting. The TIMER-REMG model starts its calculations in 1971 with an annual timestep, thus providing a 50-year “spin-up” period for building stocks.

The model determines the thermal efficiency of the building envelope (i.e. the U-values which denote the building envelope thermal conductivity, measured in $W/m^2/K$) by applying different levels of insulation. These can be applied either for new buildings or at a later stage via renovation. Furthermore, the model estimates the exposed surfaces and areas of residential buildings by assuming a “reference building” shape, described in the Supplementary Material. This exposed area was linked to increases in household floorspace, in line with previous assessments [25]. The model includes six insulation levels representing different use of thermally resistant materials on walls, windows, floors, and roofs. Each of these levels have their own capital costs and their thermal conductivity has been scaled for regional climate characteristics [26]. The decision to invest in insulation depends on (i) the annualized capital cost of insulation levels, and (ii) the possibility for lower fuel costs due to reduced heating and cooling demand. Concerning renovations, it was assumed that only stocks which have been in place for at least 15 years can be renovated, and the technical lifetime of renovation investments are limited by the remaining lifetime of the building stock. Thus, the discount rate of investments in renovations increases as buildings approach the end of their lifetime.

Following, the motivation to invest in insulation depends on regional and income class dependent discount rates, household floorspace, and heating and cooling energy demand. The market shares of the insulation levels (both for new constructions and renovations) are allocated based on their relative competitiveness using a multinomial logit function. Regional climate characteristics affect both the techno-economic parameters of insulation levels, as well as heating/cooling costs which were assumed to be a prime motivator for investing in insulation. As discount rates and heating and cooling demand vary across income groups, investments in insulation are skewed towards richer households. Finally, in climate policy scenarios where a price was attached to the emitted CO_2 (see Section 2.2), the fuel costs for heating and cooling increases. The extent of this increase depends on the CO_2 intensity of heating technology use and the makeup of electricity generation. Accordingly, these additional costs increase the competitiveness of higher insulation levels due to their lower heating/cooling demands.

2.1.2. Heating and cooling technologies

Projections of useful energy demand for space heating and cooling was based on the methodology developed and presented in Daioglou et al. [22] and van Ruijven et al. [27]. Space heating demand is modeled as a function of floorspace (m^2/capita), population (capita), and heating degree days (HDD), based on Isaac and van Vuuren [28]. The useful heating demand intensity (kJ/m^2/HDD) was calibrated to historic U-values and energy use for space heating. Its future development was linked to the improvements in building envelope efficiency (i.e. the U-values of different building stocks described above). Residential final heating demand is supplied through eight possible energy carriers (coal, fossil liquids, natural gas, hydrogen, traditional biomass, modern bioenergy, district heat, and electricity) each with a representative technology with associated costs (fuel and capital) and conversion efficiency. Specifically, for electricity, two technologies were included: Resistance heaters, and heat pumps. Thus, in total nine heating technologies compete for market shares of heating energy demand based on their relative costs using a multinomial logit function. The model is designed to explicitly represent the energy-ladder as households opt for cleaner (but more expensive) heating fuels as they become richer, with the poorest households heating with traditional biomass - assumed to have a zero cost.

Similarly, cooling demand is also a function of population, cooling degree days (CDDs), and cooling intensity which is linked to improvements in building envelope efficiency. Unlike heating, cooling demand can only be met via electricity with three possible cooling appliances: fans, evaporative air-coolers, and air-conditioners. Households which lack electrification do not satiate any of their cooling demand. The ability of households to invest in cooling appliances depends on their household expenditures (calibrated to historic cooling appliance ownership data), with the poorest households only fulfilling part of their cooling demand using fans. With increasing household expenditures, it becomes possible to invest in air-coolers and air-conditioners, fulfilling previously unmet cooling demand. The ownership as well as the energy use of air conditioners were related household expenditures, local CDDs and an assumed efficiency improvement.

2.1.3. Rooftop photovoltaic

The model includes a dynamic representation of residential rooftop PV including their potential, investments, and dispatch [29]. The regional potential of rooftop PV surface area was determined by relating projections of floorspace area to roof area, corrected for factors affecting suitability such as shading, architectural features and orientation. This was then combined with the regional solar energy flux, to get the technical potential of rooftop PV energy supply. Using data on module costs, operation and maintenance costs, and marginal load factors the supply curves of levelized costs of rooftop-PV electricity were determined. By including endogenous learning-by-doing and changes in floorspace, the economic potential through regionally explicit PV cost-supply curves were projected. Consequently, the geographic variation of the marginal costs was represented across 26 regions with varying solar irradiation (technical potential), while social variation was represented across 10 income groups with differing floorspace area (technical potential) and discount rates (economic potential).

These supply curves allow for a household investment decision to either buy electricity from the grid or invest in a PV system. A multinomial logit equation was used to determine the share of residential electricity demand, which was met by rooftop PV, by comparing the marginal PV levelized cost with the cost of grid-based electricity. Thus, investing in rooftop PV benefits from larger households, locations with higher irradiation, higher electricity demand, relatively higher costs of grid-based electricity, and lower discount rates enjoyed by wealthier households.

2.2. Scenarios

The scenarios used in this study are outlined in Table 1. The updated implementation of the SSP2 baseline from the IMAGE 3.2 model was used as the reference scenario [20,30,31]. The SSP scenarios provide some of the key exogenous drivers of the model (population growth, households expenditure growth, GINI coefficients, and urbanization rates) [32–35]. Also presented are the results for the residential sector according to an RCP2.6 climate target, representing a 2°C global mean temperature increase by 2100. Throughout the manuscript, these scenarios are referred to *Baseline* and *2°C* respectively. The 2°C scenario follows an emission price projection (determined in IMAGE) across all GHG emission sources (fossil fuels, industry, and AFOLU) applied globally which results in a cost-effective pathway meeting an emission budget consistent with a 2°C global mean temperature increase. It is important to note that all scenarios assume the same climate, thus climate feedbacks on energy demand and supply do not differ across scenarios. This is done to isolate economic effects of climate policy on investment decisions and to allow for comparability between the Baseline and 2°C scenarios.

Two sensitivity cases to isolate and decompose the role of insulation and technology choices (heating, cooling, rooftop PV) were also projected. These scenarios act as references to determine the effect of specific mitigation actions. In these reference cases the heating and cooling technology choice of the Baseline projection was forced but the model determined if insulation was applied, influenced by the carbon tax trajectory of the 2°C case. In the first sensitivity case insulation was limited only to new buildings (*InsulNew*) and in the second it was allowed on the entire building stock (*InsulAll*). The results of these scenarios can be used to isolate the energy and emission mitigation effect of insulation, renovations, and technology improvement. The following were investigated:

- The effect of *renovations in the baseline* by comparing *Baseline* with *Baseline-InsulNew*
- The effect of *insulation in new buildings* in the mitigation scenario by comparing *Baseline* with *2°C-InsulNew*
- The effect of *renovations* in the mitigation scenario by comparing *2°C-InsulNew* with *2°C-InsulAll*
- The effect of *heating and cooling technology choice* in the mitigation scenario by comparing *2°C-InsulAll* with *2°C*

2.3. Scope and indicators

In TIMER-REMG all calculations are done across 26 regions, five urban quintiles and five rural quintiles. Unless otherwise stated, in

Table 1
Scenario protocol used in this study. InsulNew and InsulAll are counterfactuals used in the decomposition.

Scenario	Carbon Price	Heating/Cooling/PV Technology choice	Insulation
Baseline	None	Endogenous	Endogenous - new & renovations
Baseline-InsulNew	None	Baseline	Endogenous - only new buildings
2°C	Endogenous consistent with RCP 2.6	Endogenous	Endogenous - new & renovations
2°C-InsulNew	Same as 2°C	Baseline	Endogenous - only new buildings
2°C-InsulAll	Same as 2°C	Baseline	Endogenous - new & renovations

this manuscript all results are presented for six aggregated regions (Global, OECD, Reforming Economies, Asia, Middle East and Africa, Latin America) across all households. Regional definitions are provided in the Supplementary Material. Numerical results across 26 regions are available in the Supplementary Data. This paper focuses on results concerning final energy use per year (EJ) and emissions ($GtCO_2$/yr). In the Supplementary Data further information is provided including demand of "useful energy" (i.e. joules of heat demanded), final energy per energy carrier, and emissions including indirect energy system emissions (or indirect sequestration in the case of bioelectricity production combined with carbon capture and storage). Final energy carriers available to the residential sector are coal, fossil liquids, natural gas, hydrogen, traditional biomass, modern bioenergy, district heat, and electricity. Unless otherwise stated, all final energy results are "gross" residential energy demand, thus possible generation from rooftop PV is not deducted from heating or cooling electricity demand, and electricity generated from rooftop PV is presented separately. This was done to provide a clearer picture on energy demand structure. The difference between electricity demand (from all residential energy services) and rooftop PV generation is the net electricity demand of the residential sector.

Emissions only account for carbon dioxide from energy use and were determined by attaching emission factors based on the carbon content of primary energy carriers. Specifically, for modern bioenergy the emission factor includes land-use change emissions and requirement of non-renewable energy in the conversion of biomass into secondary energy carriers based on [36]. Indirect energy system emissions depend on the makeup of electricity, district heat, and hydrogen production, all of which are influenced by carbon prices and assumptions on technology availability including carbon capture and storage [37–39].

3. Results

3.1. Development of building stocks

Fig. 1 shows the projected trajectory in residential floorspace across six aggregated regions as well as the development of residential U-values in the Baseline and 2°C scenarios. Floorspace development disaggregated across age cohorts and insulation levels are presented in Figs. S1 and S2 in the Supplementary Material. Global residential floorspace is expected to approximately triple over the 21st century with most of the marginal growth coming from Asia and the Middle East & Africa regions. These regions also show the greatest relative improvement in their U-values in the Baseline, relative to the current situation. This is largely because they start from very inefficient building envelopes and they witness the greatest marginal growth in floorspace leading to significant opportunities to invest in efficiency in new buildings.

The projections also show the importance of local climate conditions. While there is some long-term convergence of regional U-values, colder regions (OECD, Reforming Economies) are projected to have lower values than warmer regions, as heating demand forms a significant financial burden. Reforming Economies are projected to have the lowest U-values, even though they have a lower GDP than the OECD region, because of their local climate which is considerably colder than the OECD. When focusing on specific regions represented in the IMAGE model Canada and Russia reach U-values below 0.5 $W/m^2/K$ by 2100, which is typically regarded as a very high efficiency building envelope.

Table 2 shows annual investments in building envelope efficiency (in new buildings and renovations) for 2030, 2050, and 2100, as well as the average renovation rate for the 2020–2050 and 2020–2100 periods. The figures in brackets are the investments in insulation during renovations only. As shown, already in the Baseline, there are significant investments in insulation via both renovations and new constructions. The OECD sees the highest renovation rate, as this region has an older standing stock, as well as a colder climate. However, investments increase significantly in other regions over time as they get richer. This is also reflected in the higher renovation rates for the 2020–2100 rather than 2020–2050 period as the proportion of older building stocks increases in the latter part of the projection period (see Fig. S1 in the Supplementary Material). To put these numbers into context on current investments in envelope efficiency, in 2016 total investment in building envelopes (residential + services) was 69.3 B$, most of it in the form of renovations[1], growing 12% compared to 2005 [23]. These compare with our global renovation investments in 2030 of 106.9 B$ in the Baseline and 127.7 B$ in the 2°C scenario, indicating increasing renovation investments, particularly in the OECD and Asia.

In the 2°C scenario, cumulative investments in insulation in renovations and new constructions increases across all regions. This is also reflected in the increased renovation rates. Global investments in renovation are projected to be 127.7 B$ in 2030 (i.e. a 19% increase compared to the Baseline), increasing to 195.2 B$ in 2050 and 320.3 B$ in 2100. However, as also reflected in the U-value projections of Fig. 1, the greatest difference between the Baseline and 2°C scenarios are in the OECD and Reforming Economies regions. This is because of their colder climates and higher household expenditures. As shown by the renovation rates in Table 1, for these regions most of the spending on efficiency is projected to happen in the shorter term, to renovate existing structures, with annual investments falling over time. On the other hand, for most other regions, annual investments are expected to increase over time as (i) their building stocks increase, and (ii) households become wealthier and investment in renovation becomes more financially attractive. Overall, the Middle East & Africa show the lowest renovation rates as they have milder climates and, on aggregate, lower household expenditures.

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[1] As explained in the IEA report: "Only a small share of the spending on new buildings is considered energy efficiency investment, as the majority is considered an autonomous improvement. However, three-quarters of spending on existing building energy efficiency renovation was considered energy efficiency investment in 2016″

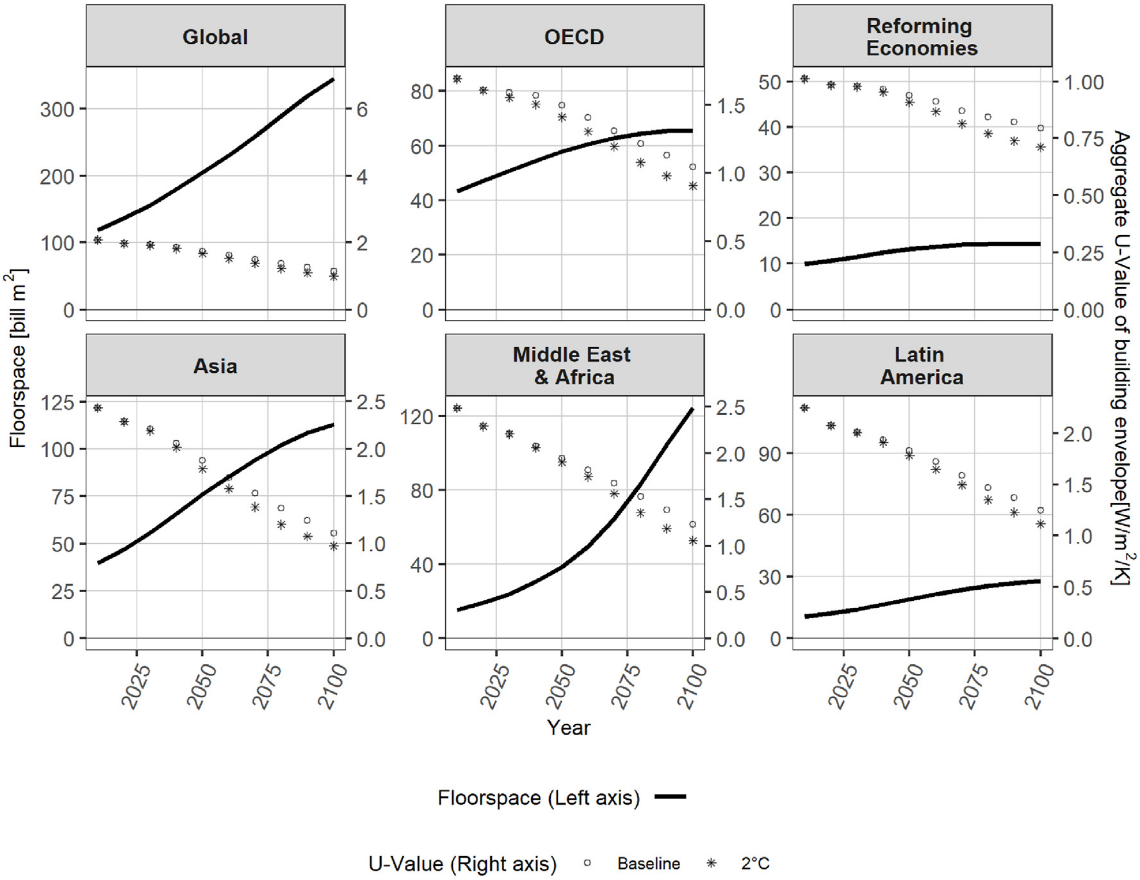

Fig. 1. Changes in residential floorspace over the projection period (left axis), and changes in building envelope efficiency (U-value, right axis) in Baseline and 2°C scenarios. Note different scales across panels.

Table 2
Annual investemtens in residential building envelope efficiency (renovations and new buildings) and average renovation rates. Investments for renovations only shown in brackets.

		Total annual investments in envelope efficiency improvements (bill. $/yr) (Investments in renovations only in brackets)			Renovation rate	
Baseline		*2030*	*2050*	*2100*	*2020–2050*	*2020–2100*
	OECD	80.4 (42.3)	78.3 (38.6)	72.9 (38.7)	1.4	1.4
	Reforming Economies	19.3 (9.4)	21.3 (11.3)	17.6 (9.8)	1.1	1.3
	Asia	121.2 (38.8)	183 (68.6)	202.2 (111)	0.8	1.2
	Middle East & Africa	45 (6.8)	74.5 (14.5)	225.3 (108.2)	0.4	0.8
	Latin America	29.7 (9.5)	35.4 (12.3)	38.8 (19.8)	0.9	1.2
2°C	OECD	96 (54.8)	86.1 (44.4)	76.5 (39.4)	1.6	1.5
	Reforming Economies	19.6 (9.6)	26.1 (14.2)	19.9 (10.3)	1.3	1.6
	Asia	127.6 (43.6)	216.4 (98)	214 (113.9)	1.1	1.6
	Middle East & Africa	45.5 (7.3)	84.1 (22.2)	263.5 (136.1)	0.6	1.2
	Latin America	32.8 (12.4)	40 (16.4)	41.3 (20.6)	1.1	1.6

3.2. *Energy and emissions for heating and cooling*

Final energy demand for heating and cooling for the Baseline and 2°C scenarios are shown in Fig. 2. Also shown are the electricity available for heating and cooling from residential rooftop PV (presented as a negative demand), as well as the emissions arising from residential and cooling (excluding indirect emissions from electricity or district heat production). Final energy demand per region and energy carrier are available in the Supplementary Data. As expected, total heating and cooling demand depends a lot on local climate characteristics. In the Baseline, while heating demand is expected to slightly increase in the Middle East and Africa, and Latin America – due to increasing incomes and overall floorspace – globally it is expected to plateau and decrease slightly. This is due to increases in building envelope efficiency in colder regions (see Fig. 1), as well as a shift towards more efficient heating fuels over time (particularly natural gas and/or electric heaters, see Supplementary Data). Contrastingly, cooling demand is projected to increase across all regions, with the increase being particularly pronounced in Asia, the Middle East and Africa, and Latin America. This is due to the expectation that the many households in these regions will reach household expenditures which will allow them to transition from the use of fans to larger air-conditioning units to meet their cooling demands. Combined with growing floorspace

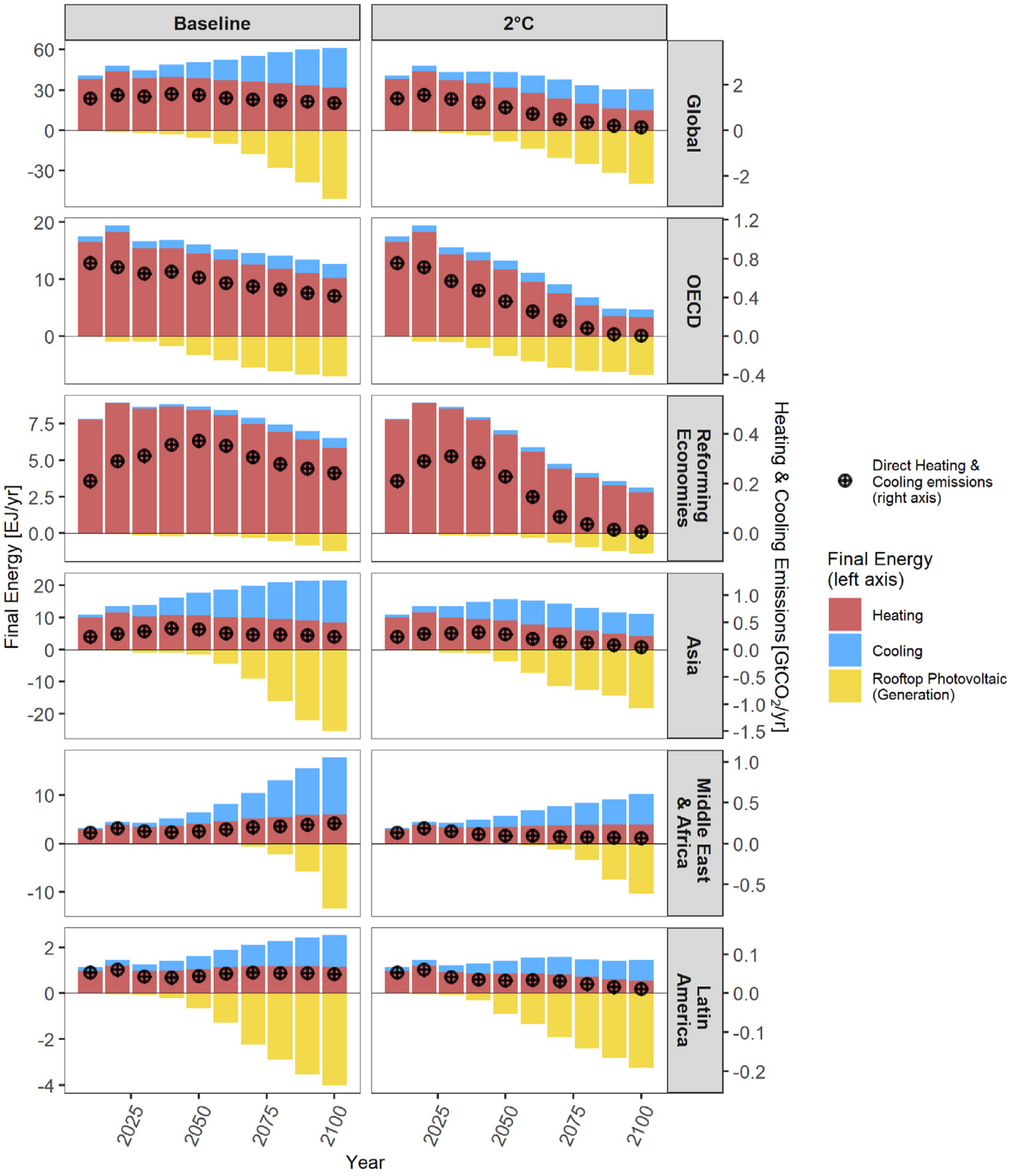

Fig. 2. Final energy for residential heating and cooling (coloured bars, left axis), and direct residential emissions (points, right axis). Rooftop PV electricity generation (gross) shown as negative demand (left axis). Baseline and 2°C scenarios.

and local climatic conditions, this leads to a large increase in cooling final energy demand.

In the 2°C scenario, final energy demand for both heating and cooling drops significantly compared to the Baseline. The use of emission prices in this scenario promotes increased building efficiency as shown in Fig. 1, which reduces the overall heating and cooling demand. Emission prices also drive fuel switching towards cleaner and more efficient heating fuels, particularly electric resistance heaters and heat pumps, further driving down final energy demand. As expected, the use of fossil-based heating fuels is completely phased out in the 2°C scenario. Even though heat pumps are extremely efficient, due to their higher costs they are projected to be used primarily in regions with significant heating demand (OECD, Reforming Economies, and to a lesser extent Asia and Latin America). In warmer regions, the 2°C scenario shows a significant drop in cooling demand, again due to a combination of investments in appliance and building envelope efficiency. Globally, compared to the Baseline, in the 2°C scenario total heating demand is projected to fall by 18% and 53% in 2050 and 2100 respectively. For the cooling demand the drop is 5% and 46% respectively. Compared to final energy demand today, in the 2°C scenario global heating demand is expected to decrease by 27% and 66% by 2050 and 2100 respectively. On the other hand, cooling demand is expected to increase by 176% and 286% respectively, but lower than the projected increase in the absence of climate policy.

The (direct) emissions follow final energy demand for heating, as all emissions from cooling are indirect (i.e. emissions take place at electricity generation). Since in the 2°C scenario long-term heating is almost completely electrified (with some use of district heat or hydrogen), direct emissions drop to near zero. In the absence of an emission price, global heating emissions are projected to remain at the same levels as today by 2050, subsequently falling to 77% of current levels. The use of electricity, district heating or hydrogen as heating fuels puts pressure on indirect emissions, with these being more than double the direct emission by 2100 in the Baseline. However, in the 2°C scenario, due to extensive use of renewables and bioenergy with carbon capture and storage, indirect emissions fall to very low levels, even going negative after 2050 [20,21].

Fig. 2 also shows the generated electricity from residential rooftop PV, as a negative demand. This is gross generation and thus it can also be used for other residential energy services (appliances, cooking, lighting), or for export to the grid. Investment in rooftop PV is promoted in the 2°C scenario as aggregate increases in the price of electricity make this investment worthwhile, leading to more rapid buildup in rooftop PV capacity compared to the Baseline. However, investments in efficiency lead to an overall lower electricity demand in the 2°C scenario, and so the total rooftop PV generation in 2100 is slightly lower than the Baseline. Investments in increased building and heating/cooling efficiency, as well as rooftop PV makes households into so-called *prosumers*. By combining investments in appliance and building envelope efficiency, as well as rooftop PV, households may become *zero-energy*, or even *positive energy* by becoming net exporters of final energy. Fig. S5 of the Supplementary Material shows how urban and rural households of different income quintiles approach this status in the 2°C. As shown, richest households get closest to meeting their energy needs (including heating, cooling, cooking, appliances, and lighting) as they can invest in high efficiency (appliance and building envelope) and have larger floorspace allowing for increased rooftop PV generation. By 2100 it is projected that the richest urban households in Latin America become *positive energy households* as they also benefit from a climate which limits their final energy demand.

3.3. Technology factors contributing the energy demand and emission reductions

As shown in Section 3.2, decisions concerning investments in heating/cooling technologies as well as building envelope efficiency dictate the projected energy demand and emissions. In the 2°C scenario the extra price on emissions leads to further investments on all fronts. Fig. 3 outlines the contribution of (i) insulation in new buildings, (ii) improved insulation in existing buildings via renovation, and (iii) investment in more efficient heating/cooling technologies, to reducing final energy demand and emissions between the Baseline and 2°C scenario. The figure also shows the effect of renovation in the Baseline, giving a better understanding of the total impact of renovations.

On a global scale, it is shown that the application of more insulation in new buildings accounts for most of the reduction in secondary energy demand. On a regional scale it can be seen that regions where older buildings make up most of the building stock (see Fig. S1 in Supplementary Material) or most of the final energy demand is for heating, renovations also contribute to reduced energy demand. For the OECD region, while renovation rates are amongst the highest (see Table 1), the improvement on final energy is limited. This is because OECD households on aggregate start with higher quality buildings than in other regions, leading to lower marginal gains from renovation. This conclusion has also been observed with detailed national studies [40]. The Reforming Economies and Asia benefit the most from renovations (in both the Baseline and 2°C scenarios) as they have a large existing stock with low efficiency levels in the Baseline (Asia) or experience increasing household expenditures combined with very cold climates (Reforming economies). Conversely, in the Middle East and Africa as well as Latin America renovations have a more limited role since most of their energy demand is for cooling, which benefits less from high levels of insulation. Furthermore, as the Middle East and Africa, and Asia, are projected to have a large increase in residential floorspace in the future (see Fig. 1), they benefit more from applying improved insulation in new buildings. The effect of increased efficiency in heating and cooling technologies reduces final energy demand mostly in colder regions as the efficiency gain from electrifying heating (through resistance heaters and heat pumps) can lead to large final energy demand reduction.

Concerning emission mitigation, while increased insulation does contribute, most of the projected mitigation is expected to come from changes in cooling and heating technologies. The electrification of heating in the OECD, Reforming Economies, and Asia, leads to steep declines in direct emissions. Similarly, the use of more efficient air-conditioning units in warmer regions plays a very important role.

These results show an emergent result from our recursive system-dynamic model formulation. The model highlights that neither insulation nor technology change dominates energy and emission mitigation efforts, that is, neither option is applied to its maximum. Rather, an equilibrium is reached where improved levels of both heating/cooling efficiency and building envelope efficiency are applied. The modeled households benefit from a self-limiting feedback between these two, where improved heating/cooling efficiency reduces the need (or the economic incentive) for increased insulation, and vice versa. In this system, the applied emission price (which is calculated on total energy and land use greenhouse gas emissions) acts as a pressure on how far this equilibrium is pushed.

4. Discussion

This paper presents an updated version of the TIMER-REMG model, part of the IMAGE (IAM). The improvements presented here are an important step forward for how IAMs represent the residential sector, which do not typically track changes in building stocks, dynamics driving changes in building energy efficiency, and the interaction between supply-side and demand-side energy and emission mitigation options. Thus, existing residential mitigation strategies projected by IAMs are at very aggregate levels, limiting their explanatory power and projecting mitigation strategies focused primarily on fuel switching [3,16]. The explicit representation of different residential energy services, income levels, local climate conditions, insulation levels, renovation and construction of building stocks, selection of heating and cooling technologies, and rooftop PV, allow for an improved understanding of the effect of both efficiency and technological choices, as well as the dynamics which determine emission mitigation strategies of this sector.

The use of this model however does introduce certain methodological issues which have to be considered. The additional detail of the improved TIMER-REMG imposes significant data requirements and associated uncertainty. A sensitivity analysis conducted on several parameters (building lifetimes, insulation cost, learning rates and technological improvement) identified that investments in building envelope efficiency are most sensitive to assumptions on the shape of the representative household (see Table S1 in Supplementary Material) [41]. This implies that advanced architectural techniques could considerably contribute to reducing the heating and cooling demand of buildings, something which was not investigated in this analysis and poses an important future addition to the model. Limited information exists about the variation of multiple parameters across countries and time, with the model based on limited datasets with a strong geographical focus [26,42]. Regional data availability also limits the level at

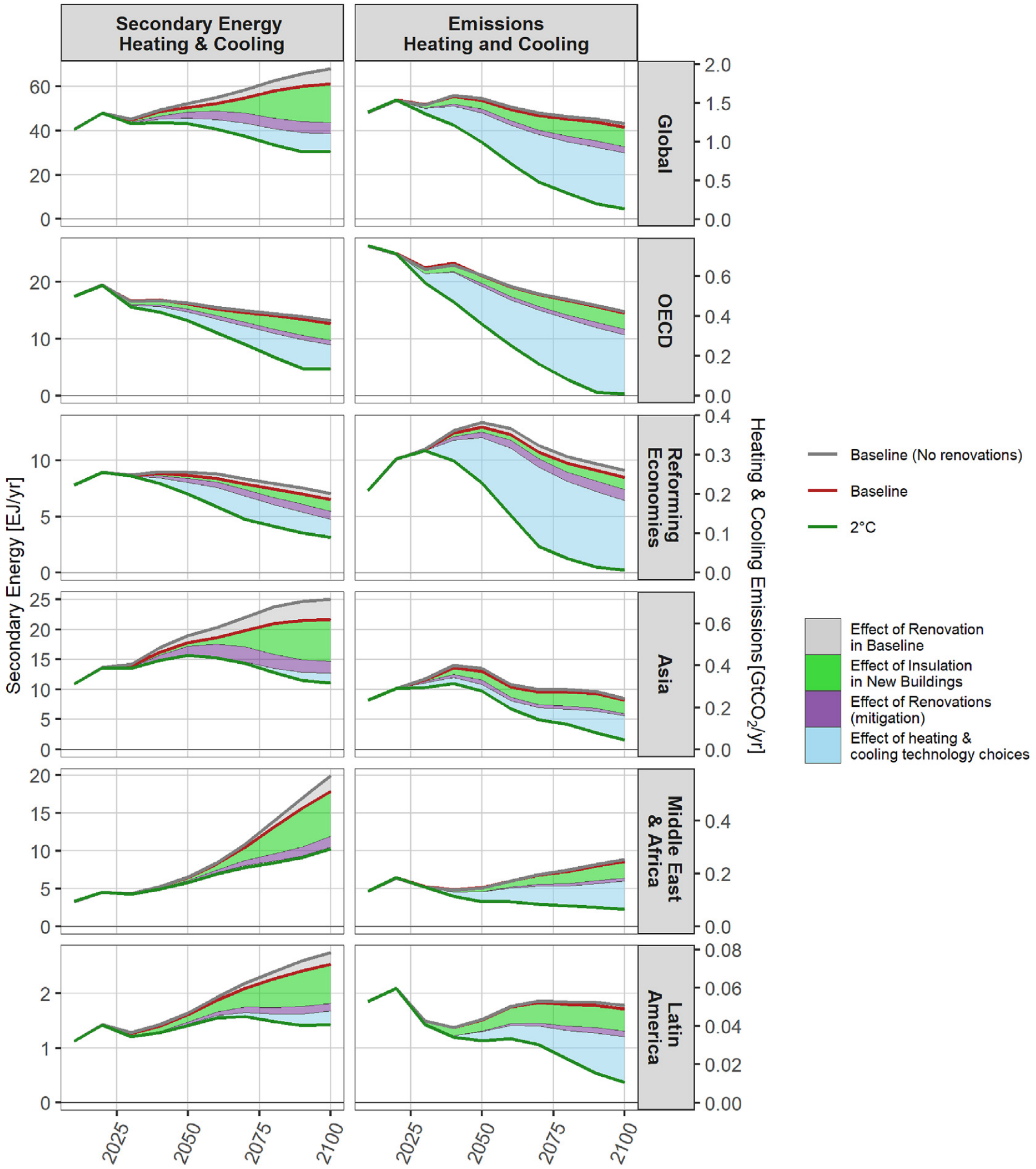

Fig. 3. Final energy (left) and direct emissions (right) for heating and cooling, decomposed for the mitigation effect of (i) insulation in new buildings, (ii) Insulation via renovations of existing buildings, and (iii) Improvements in heating and cooling technologies. Baseline and 2°C scenarios.

which the model can be calibrated. In the above scenarios, TIMER-REMG was ultimately calibrated to reflect historic (1971–2018) data on final regional residential final energy demand [43]. Additionally, floorspace, household size, appliance and air-conditioning ownership, and heating fuel demand are calibrated for each region and income level, subject to data availability [22]. Residential building stock and building envelope efficiency are calibrated to limited country level data, particularly for the European context [42]. Parameterization, calibration, and data availability issues can benefit in the future from ongoing “big-data” activities concerning the built environment (i.e. https://insights.sustainability.google/).

Our reported results for current building stock age profile and thermal efficiency are in line with other similar studies [9,10]. Concerning the projections of heating and cooling demand, and the potential to reduce them, our results are broadly in line with other global modelling studies which show that this energy demand can be reduced from current levels through the use of advanced technologies, but not completely eliminated [2,7,9,44]. These studies highlight that complete decarbonization of the residential sector is possible through increased electrification - combined with decarbonization of electricity supply to avoid indirect emissions. The conclusion that decarbonization of the residential sectors depends on a synergistic use of both improvements in thermal insulation and technological improvements in heating and cooling, corroborates the results from more detailed national modelling exercises [40,45]. These studies also concur with our observation that the extent of required insulation improvements depends a lot on local climate characteristics, with warmer regions not benefiting significantly from marginal improvements. Concerning our result that renovations lead to a modest improvement on total energy demand, particularly in the OECD, this result concurs with a recent detailed study for the Dutch building sector, which concluded that increasing the insulation levels of the entire Dutch building stock would lead to a reduction in heating demand between 7 and 27%.

These low levels of savings result from the fact that a large portion of the Dutch building stock already have high insulation levels, leading to low marginal gains [40]. The potential importance of rooftop PV is in line with conclusions from the IEA which has stated that there is technical potential to meet up to 70% of urban electricity demand, with strong regional variation [15]. This is in line with our results where rooftop PV contributes significantly to meeting households' electricity demand, even leading to certain households becoming *energy positive* (see Fig. S5). However, PV generation is very sensitive to price developments (both PV and grid-electricity), and as shown in Ref. [29]; a 50% decrease in PV costs could lead to a 3-fold increase in generation.

The TIMER-REMG model does not include certain important dynamics which would affect the results. Of particular importance is the so-called *tenant-landlord* effect in rented households, where landlords and tenants are not willing to invest in efficiency measures, due to their limited personal benefits and lack of long-term returns, respectively. Furthermore, the model assumes that the investment in efficient appliances and building envelopes automatically leads to reduced energy demand and/or emissions. However appropriate usage is of central importance to ensure that these benefits are reaped. Finally, while the model includes financial motivations which affect technology adoption dissagregated across income quintiles (heating/cooling demand, fuel costs, capital costs, discount rates), it does not include social dynamics of technology adoption. Studies of consumer behaviour have shown that besides economic incentives, consumer awareness, personal and social norms, and household composition are just as important [18,46]. Previous studies that included an explicit representation of consumer archetypes (early adopters, laggards) and social influence effects showed these to influence technology diffusion [47,48].

The updated TIMER-REMG can act as a basis for improved understanding of mitigation strategies and costs, as well as a starting point for the analysis of the energy and material demand of the residential sector. By explicitly modelling the construction and decommissioning of building stocks the model can be used to project material demand futures [49,50]. By making an explicit connection to material use, the model can be used to explore the potential negative emissions arising from the substitution of steel and cement with wooden or bio-based structures which in principle lock-up atmospheric carbon if produced appropriately [51–53]. Additionally, the model can be expanded to disaggregate between different residential building strategies (detached, hi-rise, terraced). This could then be supplemented with Multi Regional Input Output (MRIO) databases and Life Cycle Assessment (LCA) inventories to better understand environmental impacts (beyond energy and GHG emissions) of different urban settlement types and material use strategies.

It is important to note that the results presented are based solely on a “no policy” baseline, and a scenario which meets a 2°C target by applying a globally uniform price on GHG emissions from all sources. Neither of these scenarios are realistic and thus our projections should not be interpreted as forecasts. Rather they aim to highlight the key dynamics of the sector and the potential emissions mitigation of different strategies. It is important to investigate the effect of specific policies (subsidies, building codes), how they may benefit or burden poorer households, and possible economic side-effects such as the free-rider and rebound effects.

The limitations of the study point the way for required future research. One of the key limits of the above study is that due to the global and long-term nature of IAM projections, generalizations and aggregations are required concerning critical aspects, including technologies, household characteristics, and investment drivers. Consequently, further work is needed to translate the aggregate aspects of these projections into finer detail (spatial, temporal, technological, social) to further understand how to effectively design climate change mitigation policies. This has already been done using the TIMER-REMG model for the diffusion of heating technologies [7], and the effects of lifestyle change [14,54]. By coupling to detailed socio-economic and agent-based models, a better understanding of the diffusion and appropriate use of technologies can be investigated. Furthermore, further stressors which may affect residential energy, such as extreme weather events, or the heat island effect should be investigated. These are important as they may provide significant risks of climate change on energy demand, and how their effect on fine temporal scales (hourly, daily) may interact with energy systems which largely depend on variable renewable sources [55]. The results presented above highlight the differentiation between poor and rich households concerning their energy demand and mitigation capacity. This raises important concerns of equity, as rich households may be better equipped to deal with rising energy costs (even becoming “energy positive”, see Fig. S5) of decarbonization strategies, while poorer households are locked into lower quality energy supply and demand structures. This raises important concerns surrounding the achievement of the sustainable development goals, reiterating that it is important to investigate the effectiveness of specific policy measures such as subsidies and standards, besides carbon pricing, at promoting the uptake of energy efficiency— especially how these can help poorer households benefit from the energy transition.

5. Conclusions

The results presented in this paper aim to show the potential role of technology and energy efficiency decisions in reducing energy demand and emissions from residential heating and cooling. The updated model used includes key dynamics including building-stock turnover, regional climate characteristics, and economic decision making. Several conclusions can be drawn from the results.

Investments in insulation play an important role in reducing energy demand from residential heating and cooling. These investments are expected even in scenarios with no additional climate policy; however, they are significantly increased in a scenario meeting a 2°C target. Renovation is most important in regions where existing building stocks are of relatively low-quality given local climate characteristics. Globally, investments in improved building envelope efficiency are shown to have to increase to more than $450 billion per year by 2050, almost half of which is in renovations, if efficiency levels are to be in line with the 2°C target. Most of these investments must be made in regions with higher heating demand (OECD, Reforming Economies, Asia). Regions which are projected to increase their residential floorspace in the coming decades (particularly Asia, the Middle East and Africa, and Latin America) are shown to in efficient new buildings in the 2°C scenario, indicating that they risk getting locked-in into poor infrastructure if these investments are not made early on.

For greenhouse gas emission mitigation, fuel switching accounts for more than half of the emission reduction. Investing in efficient building envelopes can reduce the energy demand for heating and cooling. Compared to today, in the 2°C scenario global heating demand is expected to decrease by 27% and 66% by 2050 and 2100 respectively. On the other hand, cooling demand is expected to increase by 176% and 286% respectively, but lower than the projected increase in the absence of climate policy. However, meeting the extremely strict emission targets require a near complete decarbonization of the buildings sector. In the 2°C scenario, global residential heating reduces its direct emissions by 90%, with the OECD and Reforming economies achieving almost 100% reduction. In this light, moving to electrified heating in combination with the complete decarbonization of the power system is required. Heat pumps offer a particularly attractive solution, despite their high upfront investment costs, due to their extremely high efficiency. As such they both reduce total final energy demand and direct emissions.

Neither efficiency improvements nor fuel switching are a silver bullet to reducing residential emissions, with households meeting emission requirements for a 2°C scenario by combining efficiency improvements and fuel switching – but neither to extreme levels. Investments in further insulation approximately double aggregate building envelope efficiency compared to today. The greatest improvements are projected to be in poorer regions, while colder regions have the highest absolute efficiency (see Fig. 1). However, even at very high emission prices, extremely high building envelope efficiency levels (leading to U-values below 0.5 $W/m^2/K$) are not extensively adopted. These investments take place in-tandem with fuel switching and increased efficiency in heating and cooling technologies. The results show that an equilibrium is reached where improved levels of both heating/cooling efficiency and building envelope efficiency are applied, but neither to their maximum level. Households benefit from a self-limiting feedback between these two, where improved heating/cooling efficiency reduces the need for increased insulation, and vice versa. In this system, the applied emission price (which is calculated on total energy and land use greenhouse gas emissions) acts as a pressure on how far this equilibrium is pushed.

Regions with greater space heating demand benefit more from insulation and electrification of heating. Accordingly, they have the greatest potential to limit their energy demand and emissions throughout the 21st century. Warmer regions are expected to have an increasing final energy demand as currently unfulfilled cooling demand is met, driven by expected increases in household expenditures. Thus, while their energy demand is expected to increase, they can still benefit from improvements in cooling efficiency and, to a lesser extent, building envelope efficiency.

The energy use of the residential sector can become net-zero - or the sector can even become a net producer – but the potential varies a lot across demographics. The model projects that households produce 8 EJ/yr of electricity in 2050, increasing to 40 EJ/yr in 2100 in the mitigation scenario. By combining the electrification of heating (and other energy services), energy efficiency, and the adoption of rooftop PV, the model projections show that households approach, and in some cases surpass, their own energy demand. It is shown that the richest households benefit from this since they are most able to invest in efficiency measures and rooftop PV. Furthermore, they benefit from their large floorspace, increasing their rooftop-PV potential. Warmer regions reach net-zero status first as they benefit from greater solar irradiation and lower heating demand. The increased emergence of *prosumer* households in the projected 2°C scenario highlights the importance of power grids and electricity storage technologies which would be able to manage the increased mismatch and variability of supply and demand. However, poorer households may face difficulties in investing in technologies and insulation with very high upfront costs, thus keeping them in a low-efficiency, high-demand, high-emission situation – while richer households can lower the energy demand and emissions and benefit from the potential *prosumer* status. This would further exacerbate economic inequalities as richer households can invest their way out of long-term energy and emission costs.

Author contribution

V.D: Conceived of the study, contributed to the model, conducted the analysis, analysed the model projections, wrote the manuscript. **E.M**: Contributed to the model, analysed the model projections, contributed to the manuscript. **D. G**: Contributed to the model, contributed to the manuscript. **D.P.v.V**: Contributed to the manuscript.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2021.122994.

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