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PAPER

Flexible emulation of the climate warming cooling feedback to globally assess the maladaptation implications of future air conditioning use

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Abstract

Rising affluence and a warming climate mean that the demand for air conditioning (AC) is rising rapidly, as society adapts to climate extremes. Here we present findings from a new methodological framework to flexibly couple and emulate these growing demands into a global integrated assessment model (IAM), subsequently representing the positive feedbacks between rising temperatures, growth in cooling demand, and carbon emissions. In assessing global and regional climate change impacts on cooling energy demand, the emulator incorporates climate model uncertainties and can explore behavioural and adaptation-related assumptions on setpoint temperature and access to cooling. It is also agnostic to the emissions and climate warming trajectory, enabling the IAM to run new policy-relevant scenarios (Current Policies, 2 °C and 1.5 °C) with climate impacts that do not follow Representative Concentration Pathways. We find that climate model uncertainty has a significant effect, more than doubling the increase in electricity demand, when comparing the 95th percentile cases to the median of the climate model ensemble. Residential AC cooling energy demands are expected to increase by 150% by 2050 whilst providing universal access to AC would result in the order of a 400% increase. Depending on the region, under current policies and limited mitigation, climate change could bring in the order of 10%–20% higher cooling-related electricity demands by 2050, and approximately 50% by 2100. Set point temperature has an important moderating role—increasing internal set-point from 23 °C to 26 °C, approximately halves the growth in electricity demand, for the majority of scenarios and regions. This effect is so strong that the change in set point temperature to both residential and commercial sectors outweighs the growth in demand that would occur by providing universal access to AC by 2050 to the 40% of the global population who would otherwise not afford it.

1. Introduction

Rising affluence and a warming climate mean that the demand for air conditioning (AC) is rising rapidly, making it one of the fastest growing energy demand sectors in recent years [1–3]. It has been estimated that more than 35% of electricity demand growth to 2050 could come from space cooling, with massive growth in the order of 4–10x [4], projected in warm, rapidly developing countries such as India, South Africa and Indonesia where population access to AC is currently below 10% [1]. Adequate space cooling, typically provided by AC, also reduces vulnerability to heatwaves and heat stress, but a vast proportion of the global south live in poorly constructed housing that fails to provide adequate thermal comfort and increasing risk of heat stress [5]. Similarly, many of those typically living in low quality accommodation may be unable to afford AC, which is primarily determined by income and air temperatures [4], but also affected by other factors [6, 7]. Furthermore, AC has come to be known as a maladaptation, or a mitigation-adaptation tradeoff [8], given that it is a climate adaptation option that operates in an undesirable positive feedback, increasing energy use and subsequently emissions, which further warm the climate and drives more need for cooling. At the same time, adequate cooling is considered as essential to basic human needs and has linkages across the Sustainable Development Goals [5, 9]. So how can representation of this feedback be flexibly integrated into global integrated assessment modelling to better understand the scale of this projected demand growth? Here we use an updated integrated assessment framework, to better explore some key climatic and socioeconomic uncertainties surrounding global projections of space cooling energy demands under updated, policy-relevant scenarios.

A number of previous assessments have explored this important topic area from the global to the city scale, integrating aspects of a range of disciplines spanning climate impacts and adaptation modelling, energy and building systems modelling, microeconomics, and epidemiology. One critical area is that of understanding the uptake of residential AC to project energy demand growth, typically using econometric methods [4, 10, 11], with subsequent country-level [6] and gridded [12] scenario-based projections based on socioeconomic and climatic projections. Of particular concern to some are the expected inequalities of AC access in developing countries with subsequent negative impacts on social circumstances such as health and labour productivity [5, 13]. The growth in demand, particularly during peak hours of the day, is expected to bring additional strain on electricity supply systems, requiring more peak capacity and subsequently higher consumer prices, in both developed and developing countries [14–16]. How these interactions play out at the macro level including the impacts of climate change has been assessed in a variety of ways, including the dynamics of demand growth in global south megacities [17], implications for CO_2 [18] and greenhouse gas [19] emissions, adaptation impacts on final energy demand electricity system costs [19], and the impacts on energy sector investments [20].

In recent years, process-based Integrated Assessment Models (IAMs) which primarily focus on developing global energy and land-use system emissions pathways such as those used in reports of the Intergovernmental Panel on Climate Change [21], have pursued efforts to include more comprehensively the impacts of climate change. Impacts can be included, for example, as biophysical impacts on processes like the changes in water resources [22], crop productivity and energy demands for heating and cooling [11, 18–20], or as economic damage impacts that affect productivity, economic growth and cost-optimal mitigation [23] and social cost of carbon frameworks [24]. However, typically, climate impacts models (CIMs) are very computationally and data expensive when compared to integrated assessment and energy systems models, meaning direct couplings are difficult to achieve. Whilst IAMs typically run scenarios in the order of minutes to hours, global climate, hydrological and dynamic vegetation models, for example, take from days to a few weeks to complete single full century simulations. Thus, despite efforts to include climate impacts, IAMs, like almost all modelling frameworks and climate impacts assessments, have been constrained to very limited sets of output simulations based on pre-determined emissions scenarios, such as the original RCP and SSP-RCP climate forcing scenarios. For policymakers, these SSP-RCP scenarios are not well aligned with the current understanding of what constitutes 'Current Policies' and mitigation consistent with the 2 °C and 1.5 °C targets mentioned in the Paris Agreement. Many of these studies also include RCP8.5 (or SSP5-8.5) which is interpreted as a baseline or business as usual trajectory, yet increasingly considered an implausible concentration pathway [25] (even if the climate outcomes remain plausible). Whilst using common scenarios facilitates model and study inter-comparison, such as those done in the ISIMIP project (Inter-Sectoral Impact Model Intercomparison Project) [26][1], it also limits the potential for updated assessments based on new warming trajectories, such as the recent trend of developing 'Current Policies' scenarios. So how can models explore climate impacts, for example on cooling, for scenarios that are different to the RCP-SSPs?

Here, we provide projections of cooling energy demand that incorporate the warming impacts of climate change, for three updated and policy-relevant scenarios—for Current Policies, and mitigation to 2 °C and 1.5 °C. In the assessment for these scenarios we also explore the importance of climate model uncertainty, set-point temperatures and AC access levels, on long term cooling energy demand. To assess these new scenarios, we demonstrate how an IAM can run new scenarios exploring temperature-based impacts on cooling demand, that are not limited to the pre-determined climate impacts pathways of the RCP-SSP framework. This means that new Current Policies or Paris Agreement compliant scenarios can be explored, and takes a much needed step towards closing the loop between general circulation models (GCMs), CIMs and IAMs. To do this, we emulate the climate impacts on energy demand for space cooling (i.e. AC) from a

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[1] The Representative Concentration Pathways and Shared Socioeconomic Pathways framework (SSP-RCP) was introduced by ScenarioMIP [59] to establish alternative scenarios of future emissions and land use changes produced by integrated assessment models. These scenarios were subsequently run by global climate models as part of the 6th phase of the Coupled Model Intercomparison Project (CMIP), which coordinates a range of earth system and climate modelling exercises used across the world in climate and global change research, including contributions to the Intergovernmental Panel on Climate Change (IPCC). In its latest phase, ISIMIP has used three of these scenarios, SSP1-26, SSP3-70 and SSP5-85 [31].

computational CIM, the buildings energy demand model CHILLED (Cooling and Heating gLobaL Energy Demand model) [5], that incorporates climate and socioeconomic scenarios and forms part of the MESSAGEix-Buildings module of the IAM, MESSAGEix-GLOBIOM. By linking cumulative carbon dioxide emissions to the climate impacts on space cooling energy demand for buildings, the method is agnostic to the emissions and temperature scenario of the IAM pathway and thus brings new flexibility to IAM modelling. Doing this for space cooling demands is particularly suitable for this test case due to the highly linear relationships between cumulative carbon emissions and global surface air temperatures [27], and as seen in this analysis, space cooling energy demands.

Thus, this study is one of the first global climate impact assessments of projected AC demand use through time, for full-century emissions and global warming scenarios that, specifically, do not follow either RCP or SSP-RCP trajectories. The approach extends a method used in another IAM study [19] which linked country-level mean temperatures to global mean temperatures, but in this case we forgo the use of a simple climate model and link cumulative emissions directly to our CIM. Subsequently, employing this framework enables us to answer important questions through an efficient exploration of climatic uncertainties, and technological and socioeconomic input assumptions that would otherwise be computationally impractical. For example, for a given level of societal CO_2 emissions under an updated Current Policies scenario, by how much will cooling energy demands increase if global warming is at the high end of the spectrum of climate model uncertainties? How much energy can be saved, globally, if indoor set point temperatures are assumed to be a slightly less comfortable 26 °C, compared to 23 °C? What if policymakers endeavoured to ensure that everyone who needs AC, regardless of socioeconomic status, had access by 2050? Using the new methods, we shed light on these three questions, seeking to understand the balance of these biophysical and socioeconomic drivers in projections of cooling energy demand in Current Policies, 2 °C and 1.5 °C pathways.

2. Methods

This study applies these emulation techniques to represent changes in the CHILLED and MESSAGEix-Buildings energy demands [18] in a feedback loop within the MESSAGEix-GLOBIOM IAM [28, 29] (figure 1). MESSAGEix-Buildings is a bottom-up building sector modelling framework including an energy demand model, CHILLED; and a stock turnover model, STURM (Stock TURnover Model of global buildings). CHILLED is a spatially explicit gridded building systems heating & cooling demand model that takes gridded GCM data as input. CHILLED energy demands vary according to the air surface air temperature changes, and it is well established that global mean temperature change is strongly linearly correlated with cumulative CO_2 emissions—this is known as the Transient Climate Response to Emissions [27]. Thus—for any level of cumulative CO_2 emissions along an emissions pathway, the approximate global mean temperature is known. Subsequently, with the global mean temperature, the resultant, spatially explicit local energy demands from CHILLED can be determined.

To do this, CHILLED was run using a range of parameterizations and climate model scenarios to statistically derive response functions that represent the linear relationships between cumulative CO_2 emissions and the energy intensity demand for cooling. These response functions will inform the final energy projections used as inputs in a MESSAGEix run—which when iterated produce an emissions scenario with final energy demand for cooling that is consistent with the cumulative emissions, and subsequently a changing climate, through the century. In this particular case and in contrast to two recent IAM studies [19, 20], it is important to note that changes in cooling demands as used here, do not include elasticity of demand in response to changes in prices, which would occur if the emulation was fully endogenously represented within the MESSAGEix optimization.

2.1. Scenario data generation

The cooling demand emulator calculates the energy intensity required for space cooling at the regional level due to climate change—compared to the case when no climate change is considered—for a given scenario and timeline. To generate the input data for the emulator, residential energy demand intensity for cooling was calculated using a set of four climate scenarios based on the CMIP6 SSP-RCP pathways[2]. The Baseline scenario is based on the emissions and warming profile of SSP1-26 during 2015–2020, which is used for the full century to represent static climate assuming no climate impacts. It projects the energy intensity through time with changes only as a result of socioeconomic input assumptions, such as population and income growth fixed on SSP2. To generate the sample space for CO_2 emissions-induced warming, three climate

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[2] In this updated emulation, an ensemble of 5 CMIP6 global climate models was used (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL), which have been bias-corrected and downscaled to 0.5° grid resolution (approximately 50 km at the equator) [30] as part of the ISIMIP3b simulation round [31].

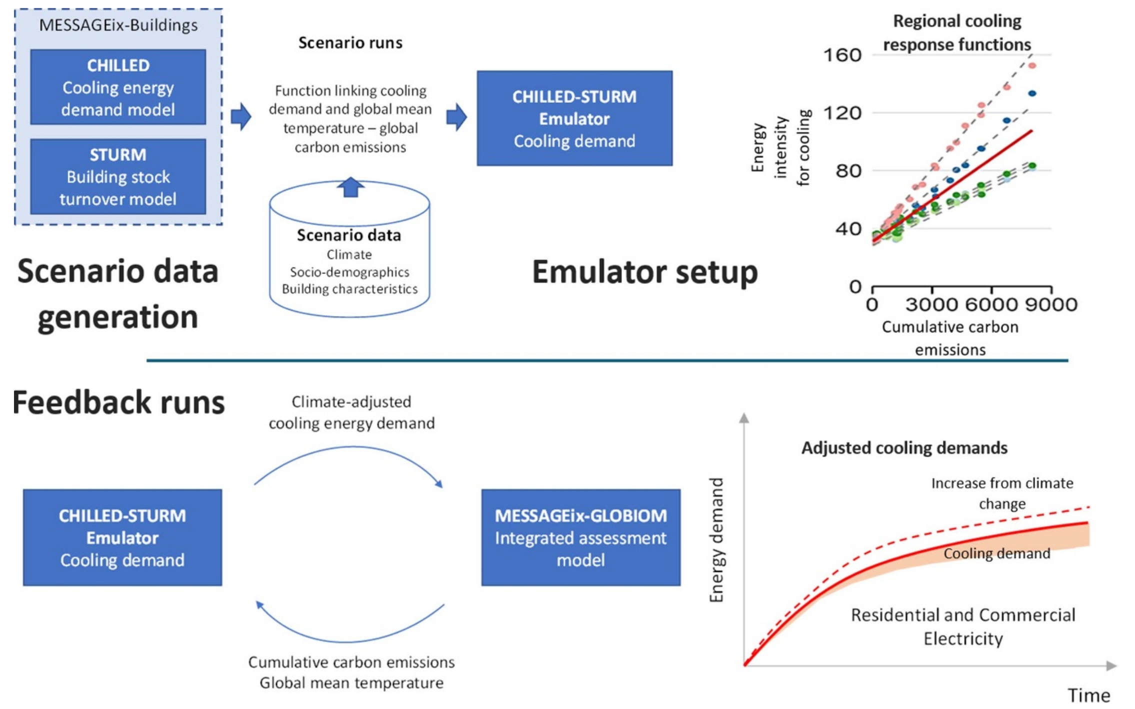

Figure 1. Framework diagram illustrating the setup of the emulator and subsequently the feedback runs between MESSAGEix and the emulator.

scenarios based on the CMIP6 ScenarioMIP emissions and warming profiles of SSP1-26, SSP3-70 and SSP5-85 are used from an ensemble of five GCMs. These scenarios project the energy intensity through time with changes resulting from both the SSP socioeconomic input assumptions, and the transient warming temperatures from the three Representative Concentration Pathways (RCPs)[3].

A significant innovation compared to previous assessments using CHILLED [5, 17, 18], is the inclusion of climate model uncertainty in the cooling demand projections and subsequently emulation of this large ensemble. An ensemble of 5 bias-corrected and downscaled GCMs [30] from the ISIMIP protocol [31] (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL) that span a large part of the climate model uncertainty in warming response, are used. The combination with three emissions scenarios and 5 models gives a 15-member ensemble of CHILLED runs that span a wide range of global warming trajectories (between +1 °C and +3.3 °C) and the subsequent responses in cooling energy intensity.

Cooling energy intensities per floorspace unit for residential and commercial are calculated separately for: (1) existing buildings (built before a base year of 2015) representing current average stock characteristics, such as building shell insulation (U-values); and (2) new buildings (built after 2015) compliant to current construction standards and improved energy efficiency. We consider progressive improvement of the conversion efficiency of cooling systems on a regional level based on previous studies [18].

For context, running one member through CHILLED on a server with 2.6 GHz 8 cores, 16 threads and 128GB RAM takes about three hours, thus running the 15 members for the two setpoint temperatures presented here takes in the order of four days of continuous computational time and generates approximately 220 GB of compressed netCDF output data. This only needs to be done once, in order to generate the data required for emulator setup.

2.2. Cooling demand emulator setup

Output energy intensity results from CHILLED, expressed as $\mathrm{MJ \cdot m^{-2} \cdot y^{-1}}$, are aggregated from grid- to country-level, weighted according to the spatial population distribution of SSP2 through time [32, 33]. These are subsequently aggregated to an 11-region definition (figure SI 2, table SI 1) used by MESSAGEix. For each SSP scenario, global cumulative CO_2 emissions from 2015 are calculated through time, for each timestep (10 years) of CHILLED output, such that every year and regional value of EI can be matched to a corresponding level of cumulative CO_2 emissions. Linear regressions are applied to derive relationships

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[3] Although the temperature profiles come from new CMIP6 SSPx-RCPy scenarios that theoretically have different SSPs ascribed to them, the SSP related to the warming profile is irrelevant in this case. We use only the temperature data and fix the socioeconomic assumptions within CHILLED to SSP2.

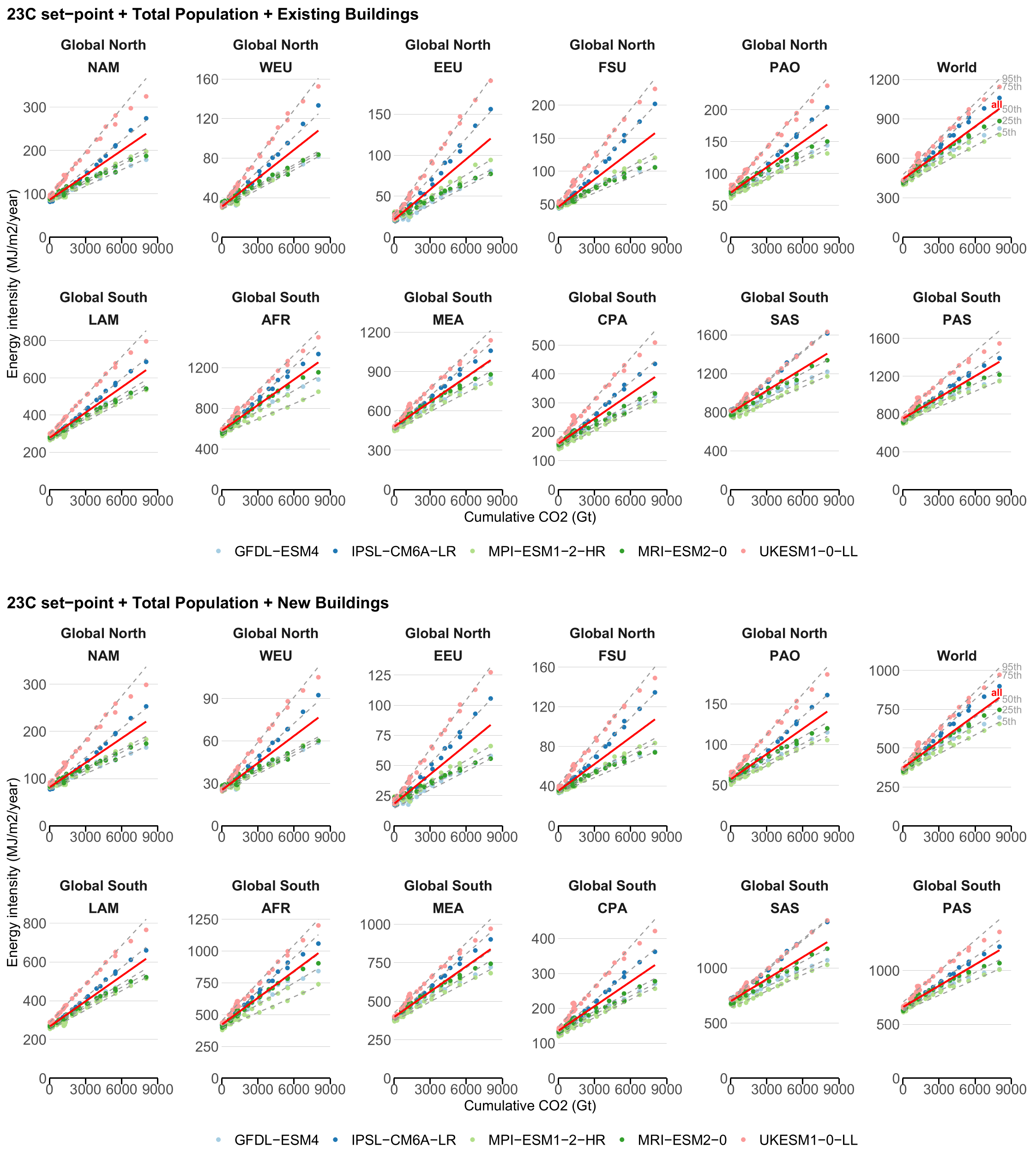

Figure 2. Regional linear response functions (and input point data) for energy intensity by cumulative CO_2 emissions. The top figure showcases the response function for existing building stock, while the bottom figure is for new building stock. Both figures are at a set temperature of 23 °C and for total (urban and rural) population. Each dashed line represents a quantile regression (5th, 25th, 50th, 75th, and 95th percentiles, not models), while the solid red line is the result of a simple ordinary least squares regression also applied on all data points.

between cumulative CO_2 emissions and regional energy intensity across regions, set point temperatures and building stock types. To capture the uncertainty introduced by the different GCMs, linear quantile regressions are used to calculate the emissions-energy intensity response across the distribution, in this case the 5th, 25th, 50th, 75th, and 95th percentiles (figure 2).

The response function takes the regionalized parameters and returns regional projections of energy intensity, for both existing and new building stock (figure 2). Already just from setting up the regional response functions, the propagation of climate model uncertainty by the end of century is substantial, with potentially 50%–125% difference in energy intensity between the coolest and warmest climate models in the ensemble (figure 2), depending on the region.

2.3. Final energy demand calculation

For each climate scenario, s, the total final energy demand $E_{c,s,r,t}$ for residential and commercial space cooling is calculated for each of the 11 regions, r, in MESSAGEix at a given timestep, t, and summed up across building cohorts, i, using the following equation:

$$E_{c,s,r,t} = \sum_{i} \frac{A_{i,r,t} \cdot F_{i,r,t} \cdot e_{c,s,i,r} \cdot f_{op,c,i,r}}{\eta_{i,r,t}}$$

where:

$A_{i,r}$ is the access to air-conditioning (share on total stock)

$F_{i,r}$ is the total floorspace

$e_{c,s,i,r}$ is the useful energy demand intensity per unit of floorspace

$f_{op,c,,i,r}$ is the share of daily hours of air-conditioning operation

$\eta_{i,r,t}$ is the efficiency conversion coefficient of the cooling system

Inputs from STURM are used to inform about scenario-specific building stock characteristics, AC access, and behaviour of building occupants, in line with a baseline SSP2 scenario [18] The increase in total cooling energy demand, $\Delta E_{c,s,r,t}$, is finally calculated for each climate scenario, s, at the level of the 11 regions, r, and over time t, using the following equation:

$$\Delta E_{c,s,r,t} = E_{c,s,r,t} - E_{c,ref,r,t}$$

where:

$E_{c,s,r,t}$ is the total final energy demand for the given climate scenario(s)

$E_{c,ref,r,t}$ is the total final energy demand for the baseline scenario

2.4. Application to MESSAGEix-GLOBIOM

The IIASA IAM framework [29, 34, 35] consists of a combination of five different models or modules—the energy model MESSAGEix [28], the land use model GLOBIOM, the air pollution and GHG model GAINS, the aggregated macro-economic model MACRO and the simple climate model MAGICC—which complement each other and are specialized in different areas.

For this study, we only use the MESSAGEix module of the IAM framework together with a parametric emulator of GLOBIOM[4]. For the integration of the climate impacts on cooling energy demand, we use the 11-regional version of MESSAGEix-GLOBIOM with simplified energy end-use sector representation[5]. The increase of cooling energy demand $E_{c,r}$ from CHILLED/STURM (figure 1, SI 1, figure SI 1) is then added to the electric residential and commercial sector demand $D^{\text{spec}}_{r,t}$ after scaling with relevant final-to-useful efficiencies $e^{\text{final}-\text{useful}}_{r,t}$ from MESSAGEix-GLOBIOM.

$$D^{\text{spec}}_{c,r,t} = D^{\text{spec}}_{r,t} + E_{c,r,t} \cdot e^{\text{final}-\text{useful}}_{r,t}$$

Based on this approach final energy electricity demand of the residential and commercial sector in MESSAGEix-GLOBIOM will increase as calculated by the CHILLED/STURM model. With the additional cooling energy demand added, the energy system implications including electricity generation and GHG emissions can be estimated and compared with scenarios that assume the continuation of current climate.

2.5. Scenario setup

Primary results are explored for three IAM climate policy scenarios, one so-called *Current Policie*s and two mitigation cases, from an existing study [36, 37]. For these three climate policy scenarios, a *Default* scenario *set* defines the standard settings used for the CHILLED/STURM setup, with additional variants used to explore changes in climate impacts and uncertainty, behaviour and adaptation.

The *Current Policies (CurPol) scenario* incorporates climate and energy policies that have been enacted until 2020 and which are extrapolated via a modest GHG emissions price beyond 2030 that approaches about 110 USD2010/tCO_2eq by the end of the century. The other two scenarios follow the Current Policies scenario until 2020 and then focus on limiting long-term warming to below 2 °C and 1.5 °C as articulated by the Paris Agreement, and implemented in MESSAGEix via CO_2 emissions budgets of 1400 and 300 GtCO_2, respectively, between 2018 and 2100. The *Current Policies* scenario results in a global median peak temperature of 3.31 °C in 2100. The *2* °C scenario, results in a global median peak temperature of 1.95 °C, returning to 1.83 °C in 2100, while the 1.5 °C scenario results in a global median peak temperature of 1.64 °C, returning to 1.25 °C in 2100.

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[4] https://docs.messageix.org/projects/global/en/latest/land_use/emulator.html.

[5] https://docs.messageix.org/projects/global/en/latest/energy/enduse/index.html.

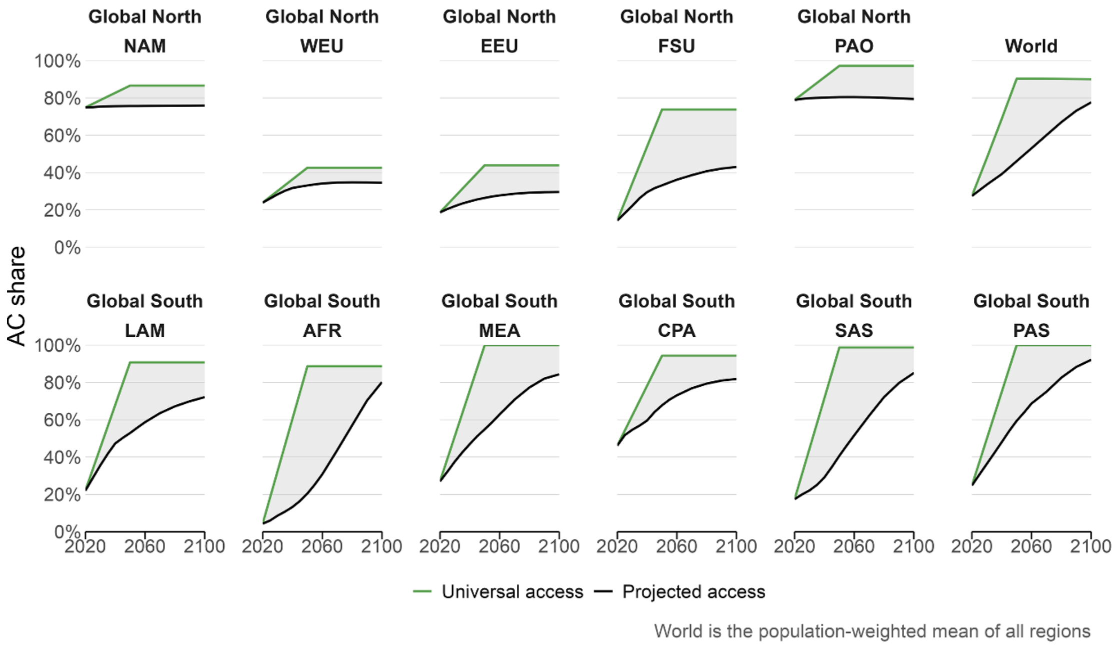
Table 1. Summary table of the scenario sets explored to understand variation in key input assumptions.

Dimension	Scenario set	Climate policy scenarios	Climate percentile[1]	Set-point temp.[1] (°C)	Level of AC access[2]
Impacts of climate change	Default	CurPol, 2 °C, 1.5 °C	50th	23	Projected
	No climate impacts	CurPol, 2 °C, 1.5 °C	N/A	23	Projected
	Climate model uncertainty	CurPol, 2 °C, 1.5 °C	5th, 95th	23	Projected
Behaviour and Adaptation	High set-point	CurPol, 2 °C, 1.5 °C	50th	26	Projected
	Decent living	CurPol, 2 °C, 1.5 °C	50th	23	Universal by 2050
	Decent living + High set-point	CurPol, 2 °C, 1.5 °C	50th	26	Universal by 2050

Notes:

[1] Parameter in the CHILLED model.

[2] Parameter in the STURM model.



World is the population-weighted mean of all regions

Figure 3. Differences in AC share between projected access (Default) and universal access by 2050 (Decent Living). Note that this is applied only to the residential sector (and not the commercial sector) and that Universal access is taken to mean all those who need it, have access, hence why in temperate regions this does not reach 100%.

2.5.1. Default scenario set and variants

Regarding the settings for CHILLED/STURM and applied to the these three climate policy scenarios (CurPol, 2 °C & 1.5 °C), the *Default* scenario *set* consists of the 50th percentile of the CHILLED results based on the 5-member GCM ensemble that covers the range of climate model uncertainty, a 23 °C internal set-point temperature, and national AC ownership projections based annual cooling degree days and constrained by income (figure 3) [11].

Other *sets* of scenarios were developed, each comprising the three climate policy scenarios, to test the emulator capabilities and explore variations in input assumptions and uncertainties along socioeconomic and climatic dimensions. Variant scenario sets are thus assessed through two lenses (table 1):

- ***the impacts of climate change*** and how space cooling energy demands will change in a warming world. A *no climate impacts* set, whilst not realistic, enables the counter-factual quantification of the impact of climate warming. Comparison to the 5th and 95th percentile CHILLED results is also done, to understand

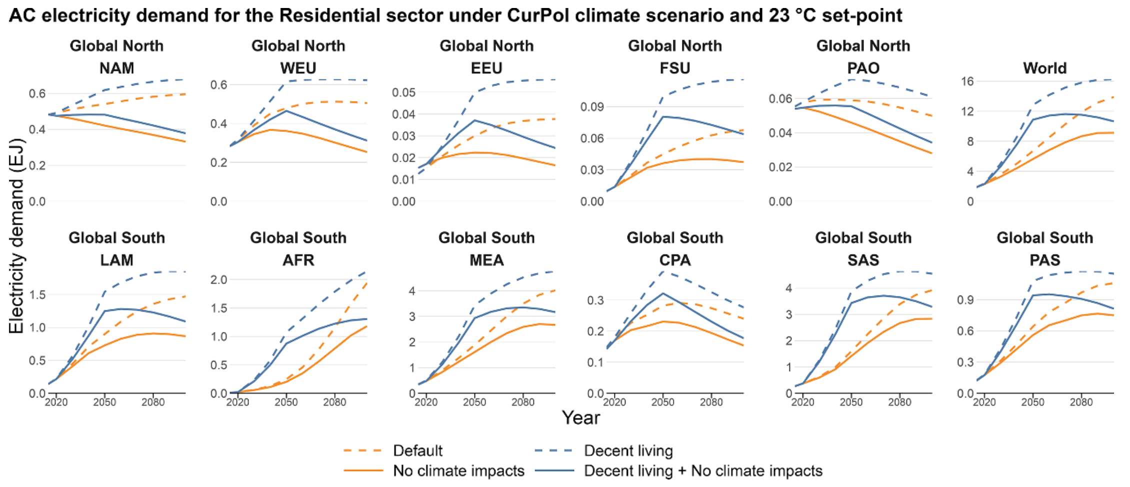


Figure 4. Projections of residential AC electricity demand in the CurPol scenario.

the upper and lower scenarios of *climate model uncertainty*. Different climate models have different warming sensitivity to emissions, so this explores the potential variation in energy demand depending on the earth systems' response to GHG emissions.

- ***behavioural & adaptation*** lens examines the effects of different socioeconomic factors. Firstly, the *High set-point* set uses a higher internal set-point of 26 °C to explore a lower bound of energy intensity and behaviour change with people accustomed to higher and less comfortable internal temperatures. The *Decent Living* set integrates projections that achieve universal AC access, whereby all those that need AC [5], have access by 2050, resulting in higher projections of energy intensity (figure 3).

3. Results

First, the results for the default scenario set are presented, investigating changes final energy for residential AC, final energy for the residential and commercial sector, electricity production and CO_2 emissions. Subsequently, the sensitivity of final energy to key parameters and variables is explored using the new emulation capabilities.

3.1. Main results

Overall, the changes to the AC final electricity demand and the residential and commercial final electricity demand are most responsive because these are specifically where changes to cooling demand are represented in the model framework. In the Default set, residential AC energy demand is expected to grow by a factor of approximately 2.5–2.8 by 2050 depending on the climate policy scenario. In the Current Policies scenario (CurPol) with minimal climate mitigation and ultimately passing 3 °C by end of century, rising air temperatures substantially drive energy demand for space cooling. Growth in this demand segment is less pronounced in the mitigation scenarios, as would be expected given the lower temperatures.

The Default scenario setup with and without climate change (figure 4) reveals underlying socioeconomic dynamics. Global North regions and Centrally Planned Asia (CPA) see peak and decline of residential AC energy demand, driven by efficiency improvements in the building stock and AC units, and overall low growth or shrinking populations. In Global South regions, growing population and incomes drive rapid demand growth in the near term that stagnates after mid-century. AC access growth in wealthier Global North regions (e.g. MEA, Middle East & North Africa) is far less constrained by affordability, unlike South Asia (SAS) and sub-Saharan Africa (AFR) where less than 40% of the population is still not wealthy enough to afford AC access by the 2050s.

Global residential AC energy demand growth is projected to increase, compared to 2020, by 145% by 2050 without climate change impacts, and between 155%–180% with climate impacts, between the 1.5 °C and CurPol scenarios (table 2). Adding the warming impacts of climate change on residential AC energy demand results in 8%–19% additional energy demand by mid-century between the 1.5 °C and CurPol scenarios (table 3), and 1%–52% additional in 2100. The largest relative increases by region are an approximate doubling in North America (NAM), Western and Eastern Europe by 2100, with 80%, 100% and 129%, respectively (table SI 2).

Table 2. Projections of global residential AC electricity demand for the main scenarios in 2020, 2050 and 2100.% differences have been rounded to nearest 5%.

	2020	2050		2100	
	Electricity demand (EJ)	Electricity demand (EJ)	% difference from 2020	Electricity demand (EJ)	% difference from 2020
Default					
CurPol	2.4	6.7	180	13.9	485
2 °C	2.4	6.4	170	10.5	340
1.5 °C	2.4	6.1	155	9.3	290
No climate impacts	2.3	5.6	145	9.1	295
High set-point					
CurPol	2.4	3.9	65	8.9	270
2 °C	2.4	3.6	50	6.1	155
1.5 °C	2.4	3.4	40	5.2	115
No climate impacts	2.3	3.1	35	5.1	120
Decent living					
CurPol	2.4	12.9	440	16.3	585
2 °C	2.4	12.3	415	12.2	415
1.5 °C	2.4	11.7	390	10.8	355
No climate impacts	2.3	10.9	375	10.7	365
Decent living + high set-point					
CurPol	2.4	7.6	215	10.5	440
2 °C	2.4	7.1	195	7.2	200
1.5 °C	2.4	6.6	175	6.0	150
No climate impacts	2.3	6.0	160	5.9	155

Providing universal access to AC by 2050 for all those who need it (Decent Living scenario, table 3), increases global demand by 92% in 2050 (compared to the Default in 2050), ranging from approximately 14%–21% in wealthier NAM and Pacific OECD (PAO) regions and 143% and 333% in the poorer SAS and sub-Saharan AFR and
regions.

Regional populations also play an important role—whilst in the global north, Eastern Europe does experience a significant increase in the Current Policies scenario, the population is comparatively a fraction compared to regions such as Latin America and Caribbean (LAM), sub-Saharan Africa, and South Asia.

For Final Energy Electricity for both Residential and Commercial sectors, the ordering of the scenarios can also appear counter-intuitive. Mitigation scenarios have overall higher rates of electrification in the residential sector, for example with a shift from fossil-fuel boilers to heat pumps, alongside higher energy efficiency. Thus, in mitigation scenarios, residential final energy demands for *electricity* are higher due to this carrier-switching (figure 5), but overall are lower across all carriers (figures 6, SI 5 and SI 6).

In the warmest Current Policies scenario, differences in electricity production are only noticeable towards end of century, but for some regions can be substantial. In the mitigation scenarios differences are not visible here. The wider changes observed are more structural—decarbonization in the mitigation scenarios with greater electrification of end use services results in higher electricity production, compared to the Current policies scenario.

In terms of emissions (figure 6), the low mitigation Current Policies scenario has the highest changes in CO_2 emissions, because in these cases the electricity sector is not decarbonized. Differences in the mitigation scenarios approach negligible by end of century, because despite increased electricity demands for cooling,

Table 3. Projections of regional residential AC electricity demand in 2050 and % additional demand, denotes same values as 2 °C.

	No climate impacts	Default in 2050, EJ/yr increase to no climate impacts, %			Decent living in 2050, in EJ/y increase to default in 2050, %		
2050	EJ/yr	1.5 °C	2 °C	CurPol	1.5 °C	2 °C	CurPol
World	5.63	6.06	6.39	6.7	11.66	12.26	12.85
		8%	13%	19%	»	92%	»
AFR	0.2	0.22	0.23	0.25	0.95	1.01	1.07
		9%	16%	23%	»	333%	»
CPA	0.23	0.25	0.27	0.28	0.35	0.37	0.39
		10%	16%	22%	»	39%	»
EEU	0.02	0.02	0.03	0.03	0.04	0.04	0.05
		6%	21%	34%	»	66%	»
FSU	0.04	0.04	0.04	0.04	0.09	0.09	0.10
		6%	15%	24%	»	122%	»
LAM	0.73	0.81	0.85	0.90	1.38	1.46	1.54
		11%	17%	24%	»	72%	»
MEA	1.61	1.7	1.79	1.88	3.09	3.26	3.43
		5%	11%	17%	»	82%	»
NAM	0.42	0.48	0.51	0.54	0.55	0.58	0.62
		13%	21%	28%	»	14%	»
PAO	0.05	0.05	0.06	0.06	0.06	0.07	0.07
		14%	21%	29%	»	21%	»
PAS	0.56	0.59	0.62	0.64	0.99	1.04	1.08
		6%	10%	15%	»	68%	»
SAS	1.41	1.49	1.55	1.6	3.62	3.75	3.87
		6%	9%	13%	»	143%	»
WEU	0.36	0.41	0.45	0.48	0.53	0.57	0.62
		15%	24%	33%	»	29%	»

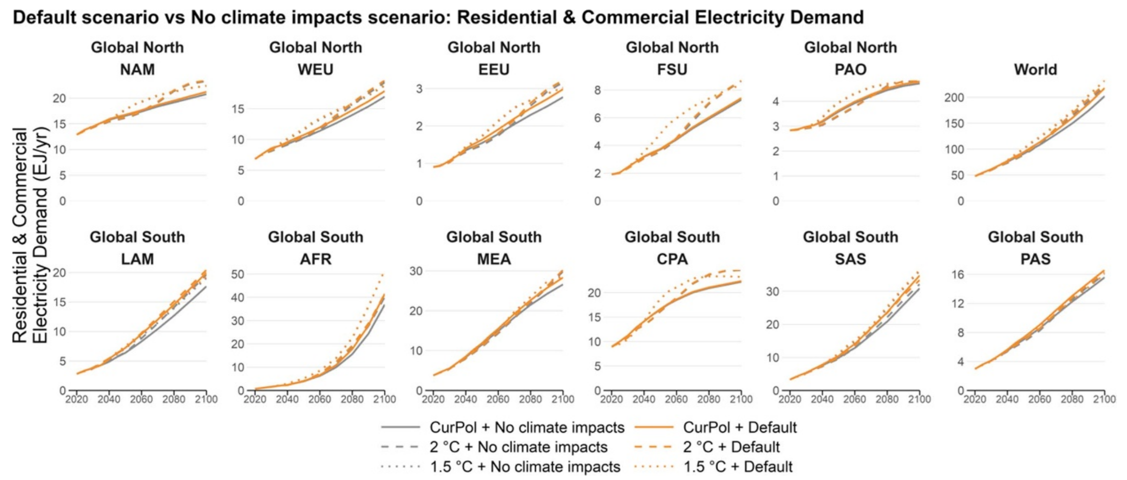


Figure 5. Final energy demand for electricity in residential & commercial sector, with (default) and without climate change impacts.

electricity sector emissions are close to zero. For carbon prices, changes were also found to be negligible (figure SI 1).

3.2. Sensitivity analysis

The results exploring the scenario input assumptions demonstrate both the new flexibility of the framework and important insights on key determinants of space cooling energy demand. Here the results presented are focused on residential and commercial final energy electricity demand, to provide wider, systemic context to the changes that have been modelled. Relative to the no climate change and default scenarios, the percentage differences relative to the default of each scenario set are shown together in figure 7.

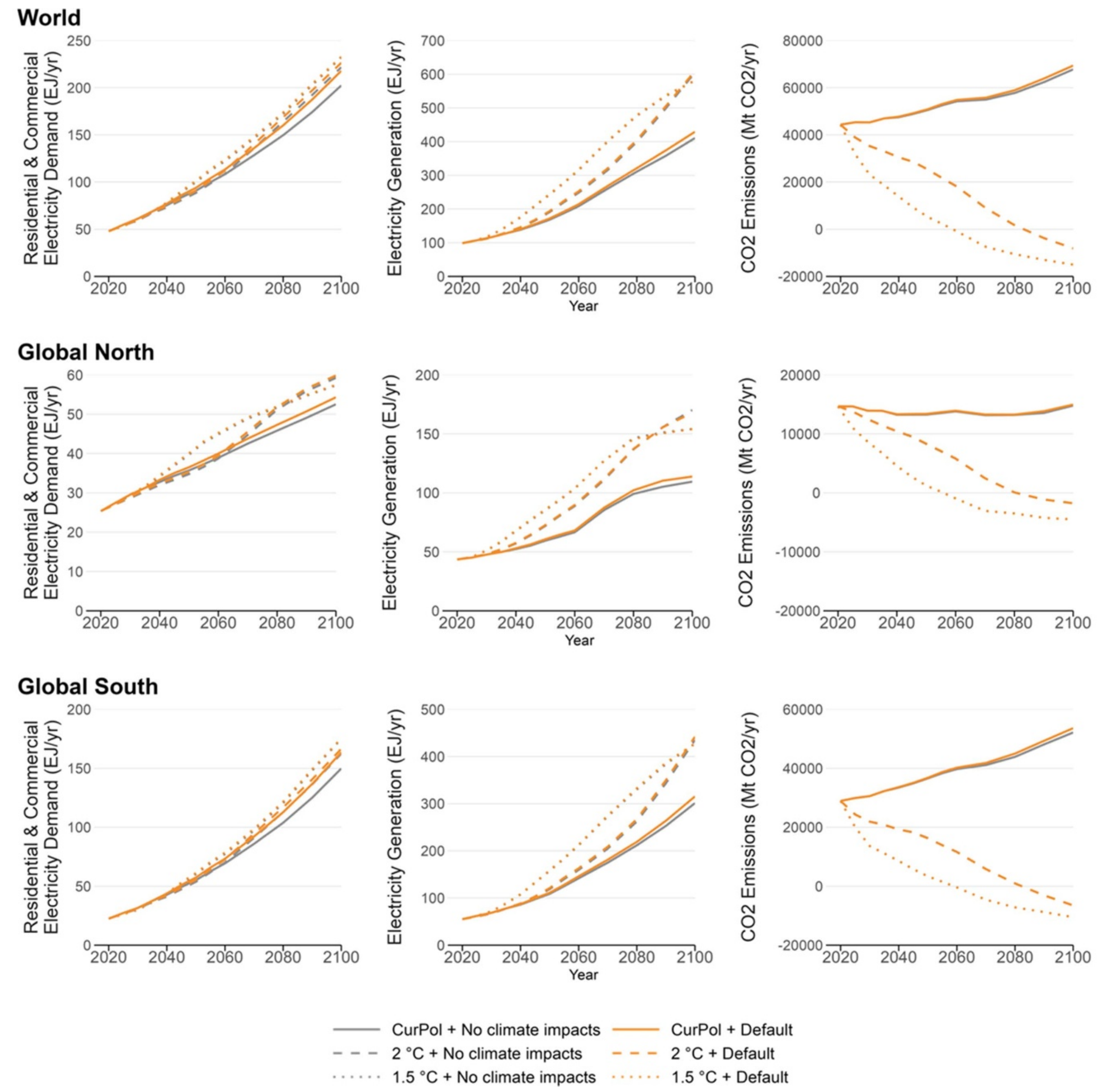


Figure 6. Global, Global North and Global South projections of residential & commercial sector final electricity demand, electricity generation and total CO_2 emissions.

Exploring the uncertainty across the five climate models and subsequently the ensemble statistic percentiles (5th, 25th, 50th, 75th & 95th percentiles), a considerable effect on the overall change in demand is possible. The 50th percentile projected change in residential final electricity demand approaches 5% in the 2050s and 7.5% by end of century under the Current Policies scenario. Under mitigation scenarios, increases are approximately 3% and 1.5% by the 2050s, for the 2 and 1.5 °C scenarios, respectively. The ranges of uncertainty are considerably high, with the 95th percentile scenario range more than doubling the projected changes in electricity demand compared to the median case (figures SI 12, SI 13 and SI 16). In Global North regions, because of both the temperate climate and that space cooling demands are overall lower, relative changes tend to be higher than the Global South regions.

Set point temperature also has a substantial effect on the projected demands. In the default scenarios 23 °C is used, whilst the tests with 26 °C, a seemingly small change, indicate that projected growth in demand would be approximately half compared to 23 °C. In the 1.5 °C mitigation scenario, where changes in demand are relatively smaller, a high set point temperature means that there is scarcely any change from the baseline, thus these graphs are not shown because the lines oscillate around zero (figures SI 12, SI 14 and SI 17).

The Decent Living scenario tested here projects steady growth in AC access, with universal access by 2050 for all those who need it (figures SI 12, SI 15 and SI 18). Comparison is also made with a Decent Living high set point scenario (26 °C) which would have lower energy demands. Subsequently, compared to the default scenario the Decent Living scenarios have higher demands in all regions. The differences are generally greater

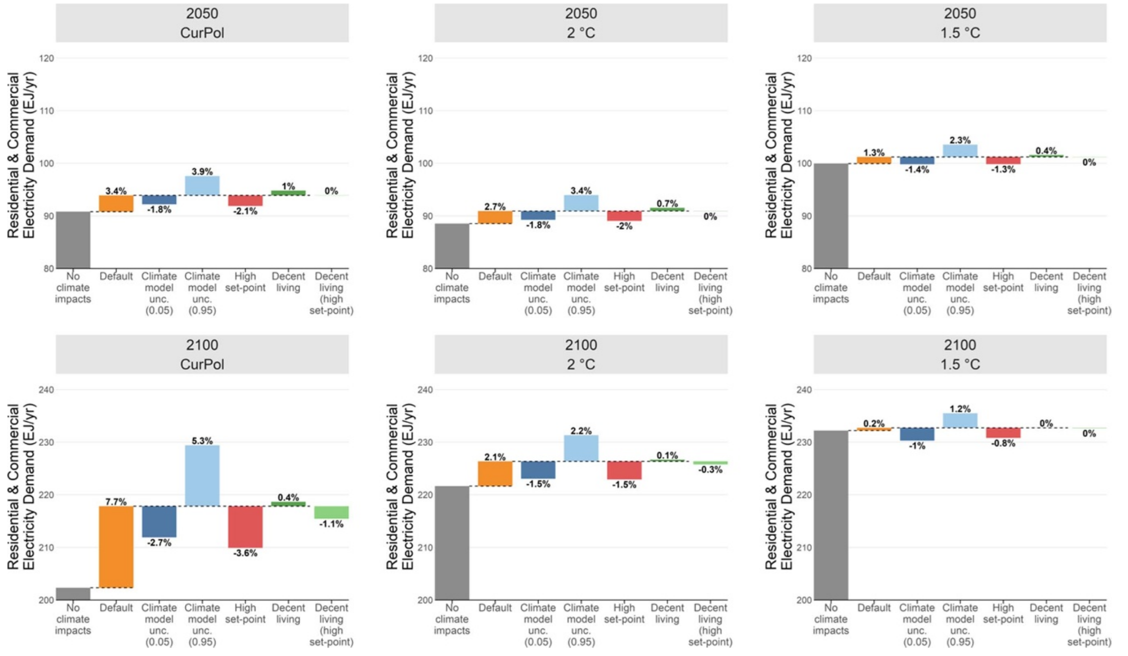


Figure 7. Changes to global results in 2050 and 2100. The warmer current policies scenario is overall most sensitive to changes in climate model uncertainty, set point temperature and decent living access requirements. The default scenario is plotted relative to the no climate impacts scenario, and the percent difference value on top of the default scenario is relative to the no climate impacts scenario as well. All other scenario sets are plotted relative to the corresponding default scenario, and their respective percent difference values are relative to the value of the default scenario.

in the global south regions, given that these regions have the lowest incomes, for example sub-Saharan AFR, LAM, and CPA. So whilst the demand growth for residential AC electricity demand almost doubles (92%, table 3) for universal AC access, when combined with commercial sector cooling (figure SI 8) which is typically 2–3 times larger, the effect on residential and commercial final energy electricity demand is low, at only 0.4%–1% (figure 7). Again the differences to the Decent Living high set-point scenario are substantial, in most cases considerably lower than the Default scenario. This illustrates that energy savings from operating higher set point temperatures approximately compensates for the additional demand that is incurred by providing the poorest with AC access.

4. Discussion

4.1. Comparison with the literature

A rapidly growing body of literature [38, 39] seeks to understand the effects of climatic and socio-economic change on heating and cooling demands and is in general agreement with the findings presented here, nuance on the different effects is important and often difficult to disentangle. With exception of a few studies [8, 17, 19, 40], there is typically little distinction of the socioeconomic-driven and climate change driven energy demand growth, also referred to as the extensive margin and the intensive margin, respectively. Nonetheless, this study finds agreement (tables 2 and 3) with two general expectations. Firstly, that socioeconomic change, primarily income growth, will drive the majority of global growth in cooling-related energy demand, in the order of 2–5 times by 2100 [18, 41, 42]. Secondly, that the warming effects of climate change will increase these demands further, globally in the order of 10%–20% [19, 40], depending on the warming scenario.

With a warming climate and fixed socioeconomic and technologic factors, average potential demands over the year will reduce for heating and will increase for cooling, but as has also been shown here, the extent of these changes is substantially uncertain due to climate model sensitivity [3, 43]. The balance of these effects, compensatory in nature, also depends on the local climate under consideration and service technologies used, such that typically higher latitude locations will save more in heating, whilst warmer low-latitudes will save little, if anything, on heating and only use more for cooling [18, 44, 45]. Combined with the fact that, higher latitude and 'northern' populations tend to be wealthier, and low-income countries in the global south have faster growing populations, higher vulnerability, and higher within country inequalities in AC access [13], we can see that the burden of climate risk here is highly unequal.

Our results on set-point temperature, although difficult to directly compare, complement those of the few macro studies investigating energy-saving benefits of set-point temperature moderation (consumer behaviour) [5, 18, 46]. In a similar example but for heating, a reduction in 1 °C set-point for heating across Europe would save 240 TWh yr^{-1} of gas, equivalent to a sixth of historical imports from Russia [47]. Such assumptions about set-point temperatures however are contingent on consumer behaviour and their sensitivity to energy prices. For many, heating set-point temperatures and subsequent energy expenditure are partly constrained by income, thus potential heating-related savings from warmer winters can result in a partial rebound, typically in the order of 0%–30% when considering both direct and indirect effects [44, 48–53]. Along the same lines, adoption and levels of cooling use in developing countries are also income-constrained, highlighting the need for more studies that investigate how people may change their behaviour and adapt with ever-rising temperatures and cooling-related expenditure [6–8], particularly in hot countries and for low-income households.

Studies investigating the impacts of climate change on the electricity system suggest different dynamics with important distinctions, albeit largely consistent with our findings. In Europe, while the net effect of climate change on annual electricity consumption, considering both heating and cooling, is expected to be near zero, peak electricity demands will increase in southern Europe and mildly decrease or remain stable in the north [8, 16]. However, this assumes the same electricity demand structure, which is currently shifting for heating given the uptake of heat pumps, for example. In wealthier regions such as the U.S. and Europe, where AC adoption is closer to saturation and thus not particularly income-constrained, changes in peak demands are largely temperature-driven, whereas in warmer developing regions, such as India, demand change is predominantly driven by socioeconomics [8]: population growth, housing stock turnover and AC adoption. In the U.S., the changes in average demands for both heating and cooling are occurring faster and more robustly than those for peak demands, and whilst growth in peak cooling demand is robust, reductions in peak heating demand are less robust, as extreme cold events can have outsized effects [54].

4.2. Limitations and avenues for further research

The sensitivity to climate model uncertainty have been shown to be considerable and can be expected to vary region to region, whilst there is little that can be done to limit the uncertainty around this dimension. Running different climate model data is by far the most computational aspect of the framework, thus the emulator capabilities bring a new flexibility to this type of scenario analysis. It even works in overshoot scenarios, whereby global temperatures start to cool again, although whether society subsequently reduces its cooling related energy demand in a linear fashion is thought to be unlikely due to lock-in and rebound effects [44, 48, 49, 52].

Some climate-related aspects remain unresolved and warrant further study. Urban heat island (UHI) effects are not captured by GCMs and can significantly increase urban temperatures, in the order of 2 °C–6 °C on the hottest days, thus the calculations likely underestimate energy demand in this regard. Correcting for this has been attempted by some at higher resolutions using regional climate models and city level studies [55], but there are many influencing factors, such as vegetation cover, urban form, wind speeds, hourly data, that make this currently infeasible in framework presented.

Technological factors that may be explored include, the coefficient of performance of air conditioners, which can vary widely around the world and by age, and also deteriorates in the hottest temperatures (including UHI), and, the impacts of refrigerant F-gases and their safe management in a world with many more air conditioners [56]. Energy sector impacts are also worth of further exploration, in particular accounting for intra-day fluctuations in electricity demand driven by temperature extremes [19] which can also substantially drive peak capacity requirements and investments [20].

Socioeconomically, the results presented here have also assumed fixed hours of cooling operation, which can be scaled easily, but for which data is particularly lacking across the world. The study has found substantial effects of the set point temperature, putting them into context with the impacts of climate change and in comparison to providing everyone with cooling access. Further understanding regional and income-level adjusted set point temperatures could be explored.

Here the results for SSP2 have been presented, but the framework and emulation are easily reproduced for other SSP trajectories, which are currently undergoing a major update at the time of writing. Not only does this impact on total population, but also urban-rural splits, spatial distributions and income levels which are used in the AC access models, and thus warrant further investigation for example through incorporating other factors relating to AC access [6], and more generally societal adaptive capacities to deal with the effects of climate change [57].

5. Conclusions

Global mean temperatures will continue to rise until net-zero CO_2 emissions, not realistically expected before the 2050s and expected to surpass 1.5 °C even with the most ambitious mitigation actions [58].

Primarily rising incomes, but also warmer summers but also more frequent heat extremes are already and will drive substantial adoption of AC, particularly in the low latitudes and Global South. The warming effects of climate change on energy use will be in addition to this.

Climate model uncertainty has a significant effect on the changes in electricity demand, with the 95th percentile cases being substantially higher than the differences between the 5th and 50th percentile scenarios. Thus, if global warming accelerates more than expected, or extremely hot years are experienced, electricity demands from AC may rise even more rapidly.

Set point temperature has been shown to have an important role in modulating the demand. Increasing internal set point from 23 °C to 26 °C, approximately halves the growth in electricity demand, for the majority of scenarios and regions. Such is the effect that the change in set point temperature almost outweighs the growth in demand that would occur by providing universal access to AC by 2050, to the 40% of the global population who would otherwise not afford it.

Overall, the study in the default settings, does not bring major changes to the majority of results in the overall IAM runs, particularly in the mitigation scenarios where the effect of climate impacts is fairly small. Depending on the region however, the effects of climate change could bring in the order of 10%–20% total higher electricity demands in the residential & commercial sector. Compared to the growing electricity demands and overall energy demands which are rising, the effects are fairly negligible at the system scale, but may be felt by individual consumers.

Methodologically, in order to run the new scenarios with consistent climate impacts, this study has made a significant advance in the flexible representation of climate impacts within IAM frameworks. The emulator is now able to flexibly provide residential cooling energy intensity trajectories taking into account climate impacts from for a wide range[6] of emissions trajectories, bringing three key benefits: (1) Previous cooling demand trajectories were constrained by available climate model data thus subsequently limited to a small set of global warming trajectories, namely the Representative Concentration Pathways. Now, a cooling demand trajectory can be developed for a wide range of emissions trajectories based on cumulative CO_2 emissions, up to 8000 Gt CO_2. (2) The emulator incorporates information from a 5-member ensemble of climate models, thus making available estimates of the model uncertainty around global warming response to cumulative CO_2 emissions. (3) Once set up with the background data and regression functions, the emulator can generate many cooling intensity trajectories at negligible computational cost on standard computers, in minutes instead of hours on computational servers, substantially saving computational time and data storage requirements. The methodology also demonstrates and paves the way for inclusion of other climate impacts in integrated assessment modelling, that is similarly not constrained to a small set of emissions scenarios.

Data availability statement

The data and code for running this assessment and that support the findings of this study are openly available at the following URL/DOI: GCM input temperature data: ISIMIP (3b) data repository: https://data.isimip.org/; MESSAGEix-Buildings with the CHILLED module and its emulation: https://github.com/iiasa/message-ix-buildings/releases/tag/eren-2024; MESSAGEix: https://github.com/iiasa/message_ix; scenario input data for running MESSAGEix: https://zenodo.org/records/10514052; figures and data in this paper: https://zenodo.org/records/12818644.

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[6] Based on the available data, the regression was run between 0 and ∼8000 Gt CO_2 cumulative emissions, although presumably this could be extended to higher levels, albeit an unlikely case.

References

[1] IEA 2018 The future of cooling: opportunities for energy-efficient air conditioning (International Energy Agency (IEA)) (available at: www.iea.org/reports/the-future-of-cooling)

[2] Scoccimarro E, Cattaneo O, Gualdi S, Mattion F, Bizeul A, Risquez A M and Quadrelli R 2023 Country-level energy demand for cooling has increased over the past two decades *Commun. Earth Environ.* **4** 1–17

[3] van Ruijven B J, De Cian E and Sue Wing I 2019 Amplification of future energy demand growth due to climate change *Nat. Commun.* **10** 2762

[4] McNeil M A and Letschert V E 2008 Future air conditioning energy consumption in developing countries and what can be done about it: the potential of efficiency in the residential sector (available at: https://escholarship.org/uc/item/64f9r6wr) (Accessed 29 April 2024)

[5] Mastrucci A, Byers E, Pachauri S and Rao N D 2019 Improving the SDG energy poverty targets: residential cooling needs in the Global South *Energy Build.* **186** 405–15

[6] Andrijevic M, Byers E, Mastrucci A, Smits J and Fuss S 2021 Future cooling gap in shared socioeconomic pathways *Environ. Res. Lett.* **16** 094053

[7] Pavanello F, De Cian E, Davide M, Mistry M, Cruz T, Bezerra P, Jagu D, Renner S, Schaeffer R and Lucena A F P 2021 Air-conditioning and the adaptation cooling deficit in emerging economies *Nat. Commun.* **12** 6460

[8] Colelli F P, Wing I S and Cian E D 2023 Air-conditioning adoption and electricity demand highlight climate change mitigation–adaptation tradeoffs *Sci. Rep.* **13** 4413

[9] Khosla R, Miranda N D, Trotter P A, Mazzone A, Renaldi R, McElroy C, Cohen F, Jani A, Perera-Salazar R and McCulloch M 2021 Cooling for sustainable development *Nat. Sustain.* **4** 201–8

[10] Sailor D J and Pavlova A A 2003 Air conditioning market saturation and long-term response of residential cooling energy demand to climate change *Energy* **28** 941–51

[11] Isaac M and van Vuuren D P 2009 Modeling global residential sector energy demand for heating and air conditioning in the context of climate change *Energy Policy* **37** 507–21

[12] Falchetta G Inequalities in global residential cooling energy use to 2050 *Nat. Portf.* accepted (https://doi.org/10.21203/rs.3.rs-3441530/v1)

[13] Davis L, Gertler P, Jarvis S and Wolfram C 2021 Air conditioning and global inequality *Glob. Environ. Change* **69** 102299

[14] Miller N L, Hayhoe K, Jin J and Auffhammer M 2008 Climate, extreme heat, and electricity demand in California *J. Appl. Meteorol. Climatol.* **47** 1834–44

[15] Auffhammer M, Baylis P and Hausman C H 2017 Climate change is projected to have severe impacts on the frequency and intensity of peak electricity demand across the United States *Proc. Natl Acad. Sci.* **114** 1886–91

[16] Wenz L, Levermann A and Auffhammer M 2017 North–south polarization of European electricity consumption under future warming *Proc. Natl Acad. Sci.* **114** E7910–8

[17] Mastrucci A, Byers E, Pachauri S, Rao N and Van Ruijven B 2022 Cooling access and energy requirements for adaptation to heat stress in megacities *Mitig. Adapt. Strateg. Glob. Change* **27** 59

[18] Mastrucci A, van Ruijven B, Byers E, Poblete-Cazenave M and Pachauri S 2021 Global scenarios of residential heating and cooling energy demand and CO_2 emissions *Clim. Change* **168** 14

[19] Colelli F P, Emmerling J, Marangoni G, Mistry M N and De Cian E 2022 Increased energy use for adaptation significantly impacts mitigation pathways *Nat. Commun.* **13** 4964

[20] Khan Z, Iyer G, Patel P, Kim S, Hejazi M, Burleyson C and Wise M 2021 Impacts of long-term temperature change and variability on electricity investments *Nat. Commun.* **12** 1643

[21] Riahi K, Schaeffer R, Arango J, Calvin K, Guivarch C and Hasegawa T 2022 Mitigation pathways compatible with long-term goals *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed P R Shukla *et al* (Cambridge University Press) (available at: www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter03.pdf)

[22] Awais M *et al* 2024 MESSAGEix-GLOBIOM nexus module: integrating water sector and climate impacts *Geosci. Model Dev.* **17** 2447–69

[23] van der Wijst K I *et al* 2023 New damage curves and multimodel analysis suggest lower optimal temperature *Nat. Clim. Change* **13** 434–41

[24] Kikstra J S, Waidelich P, Rising J, Yumashev D, Hope C and Brierley C M 2021 The social cost of carbon dioxide under climate-economy feedbacks and temperature variability *Environ. Res. Lett.* **16** 094037

[25] Hausfather Z and Peters G P 2020 Emissions—the 'business as usual' story is misleading *Nature* **577** 618–20

[26] ISIMIP 2024 Inter-sectoral impact model intercomparison project (available at: www.isimip.org/) (Accessed 25 February 2024)

[27] Allen M R, Frame D J, Huntingford C, Jones C D, Lowe J A, Meinshausen M and Meinshausen N 2009 Warming caused by cumulative carbon emissions towards the trillionth tonne *Nature* **458** 1163–6

[28] Huppmann D *et al* 2019 The MESSAGE integrated assessment model and the ix modeling platform (ixmp): an open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development *Environ. Model. Softw.* **112** 143–56

[29] Krey V *et al* 2020 MESSAGEix-GLOBIOM documentation—2020 release (available at: http://pure.iiasa.ac.at/id/eprint/17115/) (Accessed 30 January 2023)

[30] Lange S 2019 Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1.0) *Geosci. Model Dev.* **12** 3055–70

[31] Frieler K *et al* 2024 Scenario Set-up and the new CMIP6-based climate-related forcings provided within the third round of the inter-sectoral intercomparison project (ISIMIP3b, group I and II) *Geosci. Model Dev.* **17** 1–51

[32] Kc S and Lutz W 2014 Demographic scenarios by age, sex and education corresponding to the SSP narratives *Popul. Environ.* **35** 243–60

[33] Jones B and O'Neill B C 2016 Spatially explicit global population scenarios consistent with the shared socioeconomic pathways *Environ. Res. Lett.* **11** 84003

[34] Fricko O *et al* 2017 The marker quantification of the shared socioeconomic pathway 2: a middle-of-the-road scenario for the 21st century *Glob. Environ. Change* **42** 251–67

[35] Fricko O, Frank S, Gidden M, Huppmann D, Johnson N A and Kishimoto P N 2024 MESSAGEix-GLOBIOM 1.1 R11 no-policy baseline *Zenodo* (available at: https://zenodo.org/records/10514052) (Accessed 24 March 2024)

[36] Riahi K *et al* 2021 Cost and attainability of meeting stringent climate targets without overshoot *Nat. Clim. Change* **11** 1063–9

[37] Byers E, Krey V, Kriegler E, Riahi K, Schaeffer R and Kikstra J 2022 AR6 scenarios database. (International Institute for Applied Systems Analysis) (available at: https://doi.org/10.5281/zenodo.7197970)

[38] Li Y, Wang W, Wang Y, Xin Y, He T and Zhao G 2021 A review of studies involving the effects of climate change on the energy consumption for building heating and cooling *Int. J. Environ. Res. Public Health* **18** 40

[39] Khourchid A M, Ajjur S B and Al-Ghamdi S G 2022 Building cooling requirements under climate change scenarios: impact, mitigation strategies, and future directions *Buildings* **12** 1519

[40] Davis L W and Gertler P J 2015 Contribution of air conditioning adoption to future energy use under global warming *Proc. Natl. Acad. Sci.* **112** 5962–7

[41] Levesque A, Pietzcker R C, Baumstark L, De Stercke S, Grübler A and Luderer G 2018 How much energy will buildings consume in 2100? A global perspective within a scenario framework *Energy* **148** 514–27

[42] Gi K, Sano F, Hayashi A, Tomoda T and Akimoto K 2018 A global analysis of residential heating and cooling service demand and cost-effective energy consumption under different climate change scenarios up to 2050 *Mitig. Adapt. Strateg. Glob. Change* **23** 51–79

[43] Deroubaix A, Labuhn I, Camredon M, Gaubert B, Monerie P A, Popp M, Ramarohetra J, Ruprich-Robert Y, Silvers L G and Siour G 2021 Large uncertainties in trends of energy demand for heating and cooling under climate change *Nat. Commun.* **12** 5197

[44] Labriet M, Joshi S R, Vielle M, Holden P B, Edwards N R, Kanudia A, Loulou R and Babonneau F 2015 Worldwide impacts of climate change on energy for heating and cooling *Mitig. Adapt. Strateg. Glob. Change* **20** 1111–36

[45] De Cian E and Sue Wing I 2019 Global energy consumption in a warming climate *Environ. Resour. Econ.* **72** 365–410

[46] Bienvenido-Huertas D, Rubio-Bellido C, Pérez-Fargallo A and Pulido-Arcas J A 2020 Energy saving potential in current and future world built environments based on the adaptive comfort approach *J. Clean. Prod.* **249** 119306

[47] Staffell I, Pfenninger S and Johnson N 2023 A global model of hourly space heating and cooling demand at multiple spatial scales *Nat. Energy* **8** 1328–44

[48] Dimitropoulos J 2007 Energy productivity improvements and the rebound effect: an overview of the state of knowledge *Energy Policy* **35** 6354–63

[49] Sorrell S, Dimitropoulos J and Sommerville M 2009 Empirical estimates of the direct rebound effect: a review *Energy Policy* **37** 1356–71

[50] Hens H, Parijs W and Deurinck M 2010 Energy consumption for heating and rebound effects *Energy Build.* **42** 105–10

[51] Volland B 2016 Efficiency in domestic space heating: an estimation of the direct rebound effect for domestic heating in the U.S *Report No.:* 16–01 (IRENE Working Paper) (available at: www.econstor.eu/handle/10419/191481) (Accessed 24 March 2024)

[52] Gonseth C, Thalmann P and Vielle M 2017 Impacts of global warming on energy use for heating and cooling with full rebound effects in Switzerland *Swiss J. Econ. Stat.* **153** 341–69

[53] Hediger C, Farsi M and Weber S 2018 Turn it up and open the window: on the rebound effects in residential heating *Ecol. Econ.* **149** 21–39

[54] Amonkar Y, Doss-Gollin J, Farnham D J, Modi V and Lall U 2023 Differential effects of climate change on average and peak demand for heating and cooling across the contiguous USA *Commun. Earth Environ.* **4** 1–9

[55] Le Roy B, Lemonsu A and Schoetter R 2021 A statistical–dynamical downscaling methodology for the urban heat island applied to the EURO-CORDEX ensemble *Clim. Dyn.* **56** 2487–508

[56] Purohit P, Borgford-Parnell N, Klimont Z and Höglund-Isaksson L 2022 Achieving Paris climate goals calls for increasing ambition of the Kigali amendment *Nat. Clim. Change* **12** 339–42

[57] Andrijevic M, Schleussner C F, Crespo Cuaresma J, Lissner T, Muttarak R, Riahi K, Theokritoff E, Thomas A, van Maanen N and Byers E 2023 Towards scenario representation of adaptive capacity for global climate change assessments *Nat. Clim. Change* **13** 778–87

[58] Shukla P R, Skea J, Slade R, Khourdajie A A, van Diemen R and McCollum D (eds) 2022 IPCC. Summary for policymakers *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press) (available at: www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_SummaryForPolicymakers.pdf)

[59] O'Neill B C *et al* 2016 The scenario model intercomparison project (scenariomip) for CMIP6 *Geosci. Model Dev.* **9** 3461–82