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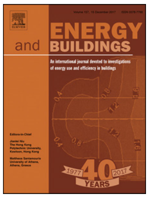

Improving the SDG energy poverty targets: Residential cooling needs in the Global South

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ABSTRACT

With growing health risks from rising temperatures in the Global South, the lack of essential indoor cooling is increasingly seen as a dimension of energy poverty and human well-being. Air conditioning (AC) is expected to increase significantly with rising incomes, but it is likely that many who need AC will not have it. We estimate the current location and extent of populations potentially exposed to heat stress in the Global South. We apply a variable degree days (VDD) method on a global grid to estimate the energy demand required to meet these cooling needs, accounting for spatially explicit climate, housing types, access to electricity and AC ownership.

Our results show large gaps in access to essential space cooling, especially in India, South-East Asia and sub-Saharan Africa. Between 1.8 to 4.1 billion, depending on the required indoor temperatures and days of exposure, may need AC to avoid heat related stresses under current climate and socio-economic conditions. This number far exceeds the energy poverty gap indicated by the Sustainable Development Goal for electricity access (SDG7). Covering this cooling gap would entail a median energy demand growth of 14% of current global residential electricity consumption, primarily for AC. Solutions beyond improved AC efficiency, such as passive building and city design, innovative cooling technologies, and parsimonious use of AC will be needed to ensure essential cooling for all with minimized environmental damage. Meeting the essential cooling gap, as estimated by this study, can have important interactions with achieving several of the SDGs.

1. Introduction

Space cooling is the fastest growing energy service in buildings worldwide. Cooling-related energy demand tripled since 1990 [1]. The demand for air conditioning (AC) is expected to dramatically increase in developing countries under severe climatic conditions induced by climatic change, population and income growth, and demand for comfort [2–4]. However, many households cannot afford cooling systems or live in buildings with poor design, resulting in poor service levels and health risks [5]. Significant heat wave related deaths have been reported in recent years, in particular in densely populated cities [6,7]. Access to adequate heating and cooling is increasingly seen as a deprivation that demands attention from policymakers, as reflected in recent efforts to improve measurement and tracking of energy poverty [8].

More than one billion people lack access to electricity [4]. The goal of universal electricity access by 2030 set by the Sustainable Development Goal (SDG) 7 remains an ambitious challenge. In this paper, we show that the energy poverty gap is even broader than indicated by the SDG7 electricity access indicator when the need for space cooling is also considered. However, AC is considered a luxury, due to its high cost, as reflected in its assignment to the top tier of electricity access in the World Bank's multitier framework [8]. With only 8% of the 2.8 billion people living in the hottest regions of the world possessing air-conditioning (AC) [1], access to cooling is a major equity issue [9]. Typically the most affluent in society can afford AC, but it is often the aged and poor who are most vulnerable to heat stress, particularly in climates with hot summers and in urban areas [10]. In tropics and sub-tropics, AC is also necessary to maintain a comfortable sleep environment [11], important for allowing the body to recover between hot days. More broadly, gaps in access to modern energy and technologies, poor housing design quality, and climate change-related heatwaves

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exacerbate this issue [10,12] by increasing the risk of heat-related mortality in many developing countries [13].

Ensuring electrification and affordable access to AC systems is part of the solution to meeting the space cooling energy poverty gap. This challenge also entails a massive increase in energy demand, grid issues in handling peak demand, and related environmental stresses, such as on climate change [1]. Policy strategies may include increasing the efficiency of AC systems, embracing passive design for buildings and cities, and district cooling and renewable energy [9].

Previous studies have estimated the demand for cooling at a global scale [3,14,15]. However, there is a lack of research in developing countries beyond large scale models [16,17]. Whilst many authors estimate a general increase in energy demand due to the future spread of AC units [18,19], nobody has examined where the combination of adverse climatic conditions and poverty coincide. The characterization of heat stress in homes as a dimension of energy poverty has thus, scarcely been explored. The energy requirements to meet this gap are also unexplored. Additionally, the quality of existing housing stocks, and potential of energy savings measures are often not considered even in conventional estimates of cooling energy demand. Identifying regions where populations lack access to suitable indoor comfort and estimating energy requirements to cover this gap are therefore essential to direct and prioritize climate adaptation efforts and policies to implement the SDGs [20].

In this paper we estimate spatially explicit residential cooling needs in the Global South in combination with access to space conditioning to highlight the location and size of populations potentially exposed to heat stress and the gap in cooling energy demand under current climate and socio-economic conditions. We apply a variable degree days (VDD) method to estimate space cooling needs at a high spatial resolution, accounting for climate, housing types and space conditioning technologies. Energy gaps are estimated by combining data on population distribution and access to cooling technologies with the estimated spatially explicit cooling needs, subject to a range of indoor temperature set points, users' behaviour and building design conditions.

The key outcomes of our study include an estimate of the number of people currently affected by the space cooling energy poverty gap, their distribution in the Global South, and the energy required to fill this gap.

In the following, we first discuss the state of the art on thermal comfort and well-being, and global energy demand modelling (Section 2). In Section 3 we describe the methods we apply in our estimations. Our key results on cooling gaps and energy requirements are presented in Section 4, with a deeper discussion of these included in Section 5. Finally, in Section 6 we conclude.

2. State of the art

2.1. Thermal comfort and well-being

Much is known about the adverse impacts of extreme heat on human health and functioning [21,22]. In particular, heat stress has been linked with increased risk of morbidity and mortality, cognitive impairment, restricted productivity and economic losses [23–27]. Differences in vulnerabilities based on age, gender, infrastructure and general health status are also well recognized. However, little consensus exists on temperature thresholds at which these adverse impacts are experienced. This is because heat stress depends on an interplay of environmental, contextual and behavioural factors such as local climate, building construction and, occupant clothing. Furthermore, acclimatization varies by geography and local climate. For these reasons, there are differences in estimated temperature thresholds for heat-related negative health outcomes across regions and climates [28,29]. A review of some of the literature suggests that heat-related health risks rise largely between a band of 21 °C to 36 °C [30,31]. Most of these studies are for Northern and Western nations, but there is some evidence that heat thresholds may be slightly higher in tropical and subtropical regions. Typical thermal comfort standards, which have largely been developed for commercial settings in the UK and USA, use lower temperatures (typically a base temperature of 18–22 °C has been used in cooling degree days (CDD) calculations), which result in likely exaggerated estimates of energy demand [32]. In order to more conservatively estimate energy demand to provide basic thermal comfort and reflect local climates in the Global South, we assume a relatively conservative indoor set point temperature of 26 °C and explore the sensitivity of our results to this value by varying it between 20–32 °C [11].

2.2. Global energy demand models for buildings

In the last decade, a few global models have been developed to estimate the energy demand of buildings and develop future energy scenarios. Some of these models rely on a considerable amount of statistical data to generate energy demand intensities for different world regions, building types and vintages [3]. While statistical models provide sound estimations for the current building stocks, they are of limited use in predicting the impact of new technologies [33]. In contrast, physical simulation models have the ability to overcome this issue, but they rely on a number of assumptions and require a considerable amount of input data [34]. The Degree Day (DD) method is a steady-state method broadly used for energy analyses for heating and cooling services (see e.g. [2,14,35]). DDs are defined as the sum of degrees each day the outdoor temperature exceeds a reference temperature (balance temperature). Whilst traditionally used at the building and local scale, increasingly studies have used cooling degree days (CDD) for the estimation of cooling loads for Europe [36–38], USA [35] and worldwide [2,14,15,34] using geographically extensive gridded climate data. Studies on developing countries are still limited [5,39,40]. Most of the CDD studies covering large scales use arbitrarily fixed balance temperatures, limiting the ability of analysing the effect of building configuration and fabric on the results. The variable degree day (VDD) method advances the DD method, by analytically calculating the balance temperature as the outdoor temperature at which neither heating, nor cooling is required [41,42]. This definition better represents actual balance temperatures of buildings, which depend on many factors, such as quality of construction, thermal insulation, internal and solar heat gains, thermostat settings, and behaviour of occupants. However, VDDs are rarely used for the estimation of building energy needs [43,44], and until now, have never been applied to a global grid. More detailed approaches, i.e. dynamic models, would more accurately account for dynamic effects on cooling loads, but they require an excessive amount of input data and computational load for global scale applications, thus being typically used for case studies and country-level analyses (see e.g. [45–47]).

3. Methodology

The energy demand for space cooling can be described as a function of three drivers [3,14]: the technological intensity driver, the structural intensity driver and the activity driver. Technological parameters include the efficiency for each of the n space cooling devices considered (η_i). In this study we consider two technologies to provide thermal comfort: AC units and fans ($i = \mathrm{AC, fans}$). Structural parameters include the conditioned floor surface per capita (A_f/P) and building-related features used to calculate the useful energy intensity per floor area for each cooling device ($E_{c,u,i}/A_f$) under contextual climatic conditions. Activity drivers include the population (P), appliance availability (a_i), and all other drivers related to service level, behaviour and life style. The final energy demand for space cooling (E_C) can therefore be expressed as:

$$E_C = P \cdot \frac{A_f}{P} \cdot \sum_{i}^{n} \left(\frac{E_{c,u,i}}{A_f} \cdot \frac{1}{\eta_i} \cdot a_i \right) \tag{1}$$

We calculate the space cooling needs using the VDD method and the penetration of AC ownership, applied to a spatial grid and using methods available in literature [14]. The space cooling gaps are then estimated in terms of both population in need of space cooling but without access to it, and the associated energy demand gap. A parametric analysis is run to estimate the effect of several technological and behavioural parameters on the results. Details of the calculations and input parameters are described in the following sections.

3.1. Space cooling demand model

The space cooling demand calculation is based on the VDD method [41]. This method advances the simple DD method by analytically calculating (as described already in Section 2.1), instead of assuming a fixed value for the balance temperature. Our calculations account for the use of both AC and fans, by assuming two distinct threshold temperatures: fans switch on after the balance temperature (T_{bal}) is exceeded and the AC after a maximum temperature ($T_{max} > T_{bal}$) is exceeded. The balance temperature $T_{bal,m}$ (°C) is calculated for each month using the following equation:

$$T_{bal,m} = T_{sp} - \frac{g_{sol,m} + g_{int}}{H_{tr} + H_{ve}} \tag{2}$$

where T_{sp} (°C) is the desired indoor set point temperature, $g_{sol,m}$ (W) is the heat flow from solar heat sources for the month m, g_{int} (W) is the heat flow from internal heat sources, H_{tr} (W/K) is the heat transfer coefficient by transmission and H_{ve} (W/K) is the heat transfer coefficient by ventilation. This equation assumes that ventilation is not introduced and all windows are closed. While H_{tr}, H_{ve}, and g_{int} depend solely on building characteristics and occupants' behaviour, $g_{sol,m}$ also depends on the climate (solar irradiation) and therefore is variable in space and time. Details of the calculations for heat transfer coefficients and heat flow from heat sources are reported in the Supplementary Material, sections SM1.1–1.2. The maximum temperature $T_{max,m}$ (°C) is calculated for each month assuming fan-powered ventilation and open windows:

$$T_{max,m} = T_{sp,max} - \frac{g_{sol,m} + g_{int}}{H_{tr} + H_{ve,\ max}} \tag{3}$$

Where $T_{sp,max}$ is the maximum indoor set point temperature when fans are operating and $H_{ve,max}$ (W/K) is the heat transfer coefficient by ventilation when windows are open. The monthly variable cooling degree days ($VDD_{c,m}$), based on T_{max}, are calculated as follows:

$$VDD_{c,m\ (Tmax)} = \sum_{d=1}^{Dm} \left(\bar{T}_{out,d} - T_{max,m} \right)^{+} \tag{4}$$

Where $\bar{T}_{out,d}$ is the average daily outdoor temperature, and D_m is the number of days in the month. The + sign indicates that only positive values are accounted. The annual final energy $E_{c,AC}$ for AC is then calculated as follows:

$$E_{c,AC} = \sum_{m=1}^{12} \frac{(H_{tr} + H_{ve}) \cdot f_c \cdot \left[VDD_{c,\ m\ (Tmax)} + \left(T_{max,m} - T_{bal,m} \right) \cdot N_{c,m} \right]}{\eta_{AC}} \tag{5}$$

Where f_c is the daily operation time fraction and $N_{c,m}$ the number of days per month when cooling is required ($T_{out,m} > T_{max,m}$) for the *m*-th month, and η_{AC} the efficiency of the AC system. The second term in square brackets accounts for AC operation at a set point T_{sp} (and not $T_{sp,max}$), even though AC is activated after T_{max} is exceeded. The electricity requirements E_f for fans are calculated using the following equation:

$$E_{c,fans} = f_f \cdot P_f \cdot \sum_{m=1}^{12} N_{f,m} \tag{6}$$

Where f_f is the operation time fraction for fans, P_f (W) is the power and $N_{f,m}$ the number of days for the *m*-th month when fans are used ($T_{out,m} > T_{bal,m}$).

The equations are modelled on a flexible and scalable spatial grid, conforming to the resolution of the input data, allowing for analyses from global to local scales depending on data availability and application. In this study, VDD and cooling energy needs calculations are run across the entire Global South. Results were compared to dynamic building simulation for a series of selected locations to check for consistency (see Supplementary Material, section SM2.5).

We use the observed historical weather datasets, EWEMBI (EarthH2Observe, WFDEI and ERA-Interim data Merged and Bias-corrected for ISIMIP), with global coverage at 0.5° grid resolution (approximately 50 km at the equator) and at daily time step between 1979 and 2013. EWEMBI combines observed global climate data variables from a number of sources, consistently downscaled and bias-corrected for use in climate impacts assessments [48].

We use daily data of 30 years (1980–2009) to capture the full variability of the recent climate. In this implementation data is aggregated to monthly means, whilst making use of the daily temperature data to calculate number of days per month requiring cooling, D_m (Eq 4). The framework is predominantly implemented in Python using xarray [49] and Dask [50], to enable parallelized processing of multidimensional datasets. Monthly horizontal solar irradiation (from EWEMBI) was processed using the R package "solaR" [51] to calculate vertical solar irradiation for different expositions on the 0.5° grid.

3.2. Housing characterization

The energy demand of housing is influenced by building characteristics, such as geometry and construction materials. A thorough characterization of the housing across different world regions is beyond the scope of this study. Instead, we rely on a limited set of housing archetypes transversal to different world regions and representing prevailing construction practices ("reference case", see Table 1), similar to other global studies [3]. We then run sensitivities to account for ranges of variability for key technological and behavioural parameters. Rural housing is represented by a single-family house with brick masonry and a mix of tile and concrete roofing. For urban housing, we consider an average height of four storeys, concrete structure and roofing, and brick masonry. Main construction features and U-values are set based on a review of relevant literature for developing countries (see Supplementary Material, section SM1.3–1.4). A window surface of 1/8th of the floor surface area and single-glazing are assumed for all archetypes. While considering only a restricted number of archetypes is a limitation of this study, our methodological framework allows including additional regional building typologies, once they become available, and estimating the sensitivity to building stock heterogeneity.

In the reference case (Table 2, values in bold), we assume that homes are equipped with ceiling fans of 55 W rating [52], and AC systems with energy efficiency ratio (EER) of 2.9, close to the current average value for developing countries [1]. Fans penetration is

Table 1
Housing archetypes (Reference case).

Description	Envelope area (m^2/m^2 floor area)	Roof area (m^2/m^2 floor area)	Wall material	Roof material	U-value Envelope (W/m^2K)
Rural	3.70	1.00	Brick masonry	Clay tiles - Concrete	2.11
Urban	1.61	0.25	Brick masonry	Reinforced concrete slab	2.18

Table 2
Overview of the parametric analysis. Values for the reference case in bold.

Parameters	Unit	Values	Description
Technological parameters			
Average U-value of the building envelope	$W/(m^2K)$	Rural: 1.08, **2.11**, 4.08 Urban: 1.32, **2.18**, 4.23	Estimate the effect of different building envelope materials. Values from literature review (see Supplementary Material, section SM1.4)
EER	–	**2.9**; 3.5; 4.0	Efficiency of AC units (adapted from [1] and own elaboration): average for developing countries; high end of typically available in most countries; best available in most countries.
Behavioural parameters			
S et point temperature (T_{sp})	°C	20; 22; 24; **26**; 28; 30; 32	Evaluate the effect of different indoor set point temperatures in the range 20–32 °C [11].
Hours of AC operation (f_c)	Hours per day	4; **8**; 12	Assess the effect of different user schedules for AC.
Hours of fans operation (f_f)	Hours per day	4; **8**; 12	Assess the effect of different user schedules for fans.
Use of AC only (no fans)	–	**AC and fans**; AC only.	Evaluate the effect of AC in combination with fans. If only AC is used (no fans), AC operates when $T_{out,d} > T_{bal,m}$.

defined on a country basis depending on the existing national level of electrification (data source: World Bank. See Supplementary Material, section SM1.6). A dedicated model is used to estimate the penetration of AC (see Section 3.3). We consider a wide range of indoor set point temperatures T_{sp} (20 °C to 32 °C) and warm days of exposure before AC adoption to investigate the effect of different thresholds for avoiding potential heat stress, on the basis of the literature review (Section 2.1). For the reference case, we illustrate results for an indoor set point of 26 °C, being the central value of the investigated temperature range. The allowed number of warm days of exposure over the maximum temperature T_{max} before adopting AC is also a key parameter for cooling gaps. In the reference case, we exclude from the cooling gaps those locations with less than five days of exposure over T_{max}. We allow, according to the ASHRAE 55–2013 standard [53], the operation of ceiling fans (air velocity up to 0.8 m/s), which enables an extension of the comfort zone and an increase in set point temperature by 2 °C ($T_{sp,max} = T_{sp} + 2$ °C) for achieving the same comfort levels [54]. AC is turned on when the outdoor temperature exceeds T_{max} and operates at T_{sp}. In the reference case, AC and fan operation schedules are set to 8 h per day based on typical schedules in tropic and sub-tropic areas [11]. We refer the readers to the Supplementary Material (section SM1) for a detailed description of the input data.

An overview of the parametric analysis to investigate the influence of key technological and behavioural parameters on per-capita energy needs is reported in Table 2. We vary building characteristics and system efficiency starting from the reference case to consider the variability in housing construction, cooling systems and potential future improvements. We also vary the set point temperature, hours of operation of AC and fans and combined use of AC and fans to account for different service levels and preferences connected to thermal comfort standards and health risks. The option of using AC only, without fans, though more energy intensive, may be suitable for areas where open windows are not recommended, e.g. due to outdoor air pollution or mosquitos.

3.3. Air-conditioning penetration model

Data on the stock of AC are available for only a limited number of countries. However, it is likely that AC use is prevalent among high-income households across the globe, particularly in subtropical and tropical climates. Previous research has shown that AC ownership is driven by income, but that the climatic conditions determine the maximum penetration of ACs, even among high-income households [14,18]. These studies rely on an empirical estimation of the maximum AC ownership as a function of cooling DD in the United States, which spans many climatic conditions and where arguably for most income is not a constraint to owning AC. We adopt this model to estimate existing levels of AC ownership in countries across the world, using the population-weighted average cooling DDs and GDP per capita as inputs for each country. The results match reasonably well with the actual ownership shares for countries where data are available, with few exceptions, such as Brazil (10 percent vs the predicted 65 percent in 2009, due to the high concentration of population along the coast where the climate is milder). See the Supplementary Material for details of the model (section SM1.8) and a comparison between predicted and actual penetration rates for select countries (section SM2.1).

3.4. Gap estimation and aggregation

The energy demand for AC is calculated for every housing archetype and then aggregated to the country scale and global scale using Eq. (1) separately for rural and urban areas. A reference floor surface of 10 m^2 per capita is assumed for this analysis, based on a space standard identified by previous studies [54]. While floor surface value per-capita may vary greatly across different world regions, previous studies show the linearity of dwelling size with operational energy consumption, therefore allowing for an easy extension of our results to different floor space values. We use rural and urban population data (see Supplementary Material, section SM1.5) to upscale per-capita energy demand of the two housing archetypes to the country and global scale.

Gaps are expressed both in terms of space cooling energy demand gap and population needing but lacking space cooling. Energy gaps are calculated as the difference between the potential energy demand with universal access to AC and fans, where needed (i.e. where VDD>0 and the allowed number of warm days of exposure is exceeded), and the current access to cooling technologies, under the assumption that AC and fans are operated only to achieve the selected indoor set point temperature. Access to cooling devices is estimated at a national level by applying the AC

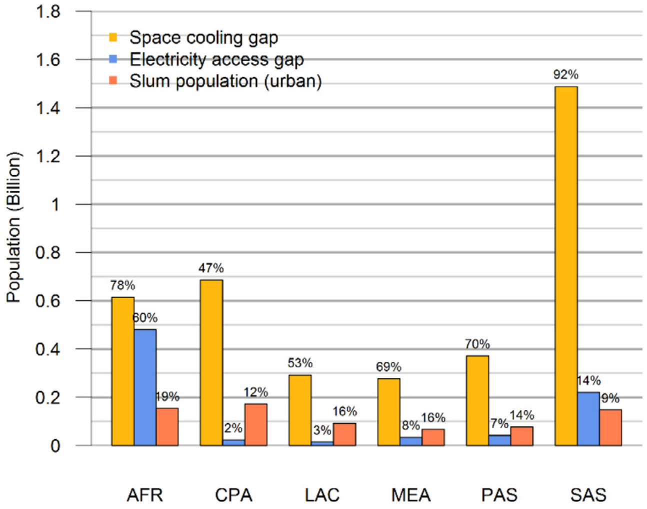

Fig. 1. Comparison of global population lacking different services related to housing: space cooling, electricity access and slum conditions. Share on total population (%) reported on top of the bars (share of slum is on urban population). Electricity access and slum population data from World Bank [57].

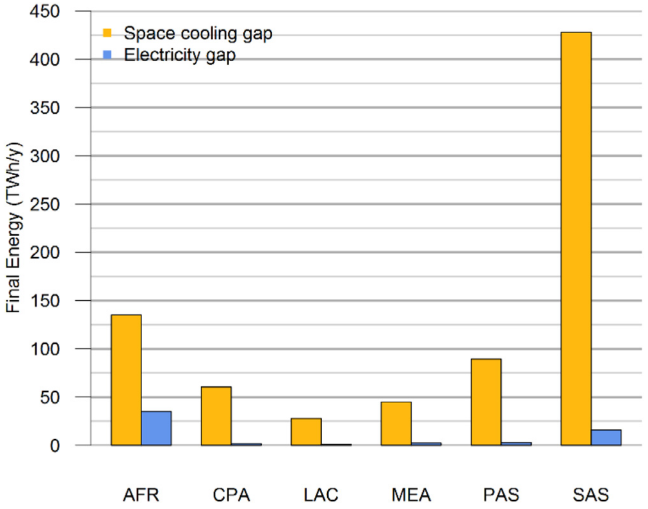

Fig. 2. Comparison of the space cooling energy gaps and basic electricity access gaps, assuming for the latter a Tier 2 threshold of household electricity supply (200 Wh/day) [8].

penetration model and considering fans penetration equivalent to electricity access. Results are presented at the country level, and for six of the eleven world regions used in the global energy-economy integrated assessment model MESSAGE [55] that cover the Global South: sub-Saharan Africa (AFR), Centrally planned Asia and China (CPA), Latin America and the Caribbean (LAC), Middle East and North Africa (MEA), Other Pacific Asia (PAS), and South Asia (SAS). Sensitivity analysis is conducted on two key parameters influencing the magnitude of the energy gap and population affected: the temperature threshold and set point for AC, and the allowed number of days over the temperature threshold before adopting AC.

4. Results

Our results suggest that up to four billion people are potentially at risk of exposure to heat stress in the Global South, mostly in India, South-East Asia and sub-Saharan Africa. The following sections report our results of the space cooling gap estimation, and per-capita energy needs to fill the gap under variation of key technological and behavioural parameters.

4.1. *Residential cooling gaps*

4.1.1. *Population exposed to potential heat stress*

We estimate cooling gaps across the Global South using different set point temperatures and report here results for 26 °C indoor set point with a five-day allowance above the set point threshold before AC adoption is required (full results of the sensitivity are in Section 4.1.4). Fig. 1 shows the population potentially affected by cooling gaps in different world regions in comparison with gaps in electricity access and extent of slum population as a proxy for lack of access to proper housing (see Supplementary Material, sections SM1.6–1.7 for electricity access and slum population data) . The cooling gap is particularly severe in the SAS region with almost 1.5 billon people (92% of the total population) potentially affected, due to a combination of severe climatic conditions and low access to AC (see Supplementary Material, section SM2.1 for detailed AC access results). Other regions, such as AFR, MEA and PAS, also exhibit a high share of population exposed (70% or more), even though the absolute numbers of people are lower. The cooling gap is further exacerbated by large gaps in electrification, especially for the AFR region (see Supplementary Material, section SM1.6). In this case, the provision of fans or ACs would require the precondition of electrification of regions currently lacking access. The space cooling gap is also related to the lack of proper housing, which can be expected to result in much poorer comfort conditions and higher energy demands since fans and ACs would be less effective with poor construction quality. The average share of population living in urban slums ranges between 10% and 20%, depending on the region. However, the housing gap is expected to be much larger in many countries due to poor quality housing in the countryside, overcrowding and homeless populations [56]. Closing the cooling gap in this setting would require a significant improvement to housing conditions as a first step to providing proper cooling devices.

4.1.2. *Cooling energy gap*

Fig. 2 shows the space cooling energy gap, assuming an indoor set point temperature of 26 °C for different world regions. The energy cooling gap is dominated by the SAS region with a total energy gap of 428 TWh/y which, to put into context, is 70 percent higher than India's current total residential electricity consumption [58]. The total energy gap is also high in AFR (135 TWh/y) and PAS (89 TWh/y) regions. Other regions, in particular CPA, have a relatively lower energy gap in comparison with the population exposed (Fig. 1) due to the combination of high population density but wider electricity access and milder climatic conditions.

The comparison of gaps shows that the energy needed to bridge the space cooling gap would be much higher than the energy required for providing all with the basic services such as lighting, television and radio, assuming a Tier 2 threshold of 200 Wh/day per capita [8], and current unelectrified population. This highlights the importance of considering the space cooling gap alongside other basic energy needs.

4.1.3. *Spatial distribution of the cooling gap*

Sources of spatial variation in the cooling gap include population distribution, climatic conditions and access to cooling technologies. While the diffusion of regional housing typologies and construction materials are expected to influence the spatial distribution of cooling gaps to some degree, in this study we consider homogeneous building characteristics across the Global South and distinguish rural and urban housing, therefore only partially capturing the effect of building characteristics.

The map of population exposed to potential heat stress (Fig. 3) shows that the largest gaps are in areas characterized by

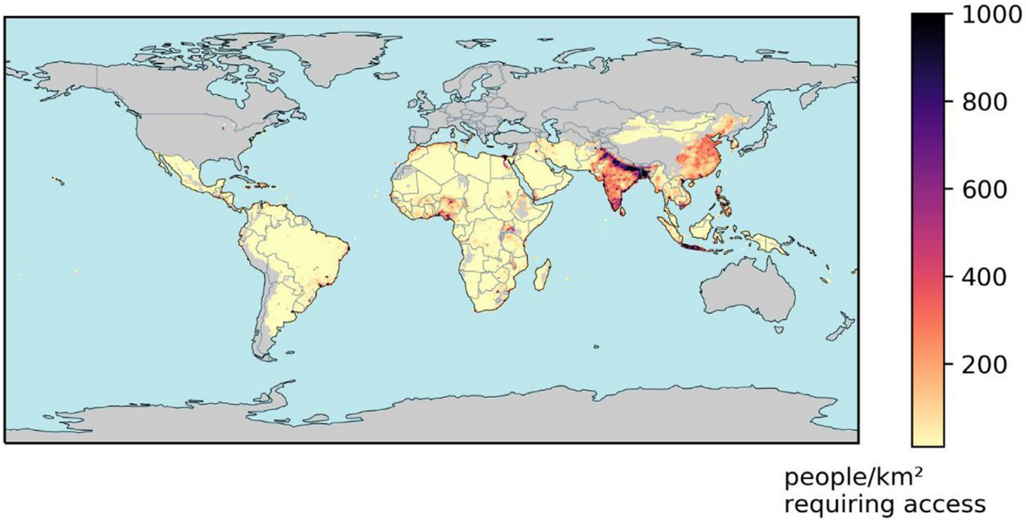

Fig. 3. Space cooling gaps: population without access to AC where needed.

concurrent high population density, severe climatic conditions and low AC ownership (see Supplementary Material, Fig. SM1 for spatial distribution of population density, Fig. SM9-10 for VDD, and Fig. SM4 for AC access). Large gaps cover most parts of India and parts of Pakistan and Bangladesh. Other significant gaps exist in South-East Asia, notably in Indonesia, China, sub-Saharan Africa and the Nile valley. Latin America and Southern African regions exhibit lower gaps due to both milder climatic conditions in the populated areas and lower population density overall. Other areas such as the Middle East, are affected by the gap to a lower extent, despite their severe climate, as a consequence of higher GDP and AC ownership. While in most regions the cooling gap is due to lack of access to AC, for specific areas of AFR and SAS, including Nigeria, Uganda, Burkina Faso and Bangladesh, the gap is even bigger due to lack of access to electricity, and consequently to fans (see Supplementary Material, section SM2.4).

Only three countries – India, China and Indonesia – cover more than 50% of the population potentially exposed to heat stress in the Global South (see Supplementary Material, Table SM6). India dominates by far the list of top countries affected by the cooling gap with 1.1 billion people potentially exposed to heat stress and an energy cooling gap of almost 335 TWh/y for an indoor set point of 26 °C (see Supplementary Material, Table SM7). China comes second with around half as many people affected. However, due to the milder climate, the energy requirements are an order of magnitude lower than that of India. Indonesia, Pakistan, Bangladesh and Nigeria rank among the top countries for both energy gap and potential population affected.

4.1.4. Sensitivity to set point temperatures and warm days of exposure

The set point temperature and the number of days of exposure to temperatures above this threshold strongly influence the affected population and energy demand. For an indoor set point temperature between 20 °C and 32 °C (Fig. 4), the total population potentially exposed to heat stress ranges between 1.8 and 4.1 billion people (3.7 billion people for 26 °C), and the energy gap from 100 to 2014 TWh/y (786 TWh/y for 26 °C). In comparison, the current electricity gap (for basic services like lighting, television and radio) affects one billion people and requires an additional 73 TWh/y, assuming a threshold of 200 Wh/day per capita [8]. The population affected by the gap rapidly increases when moving from 32 to 26 °C, due to a progressive expansion of the regions requiring cooling. Further reducing the set point from 26 °C to 20 °C entails less of an increase in the affected population, but energy gap increasing proportionately with the required thermal comfort level. For India alone, the cooling energy gap could range between 59–748 TWh/y with a potentially exposed population of 1.00–1.15 billion.

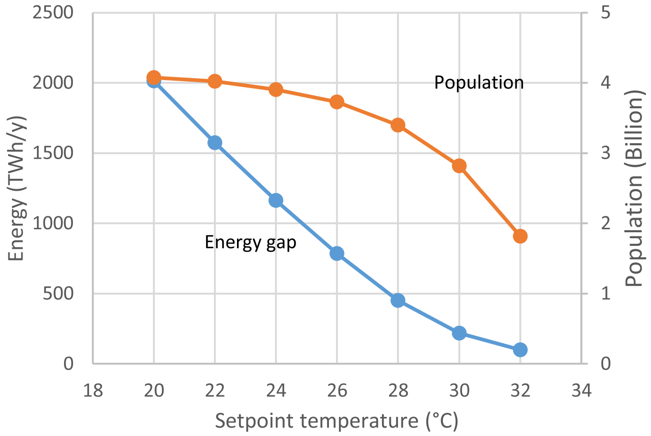

Fig. 4. The sensitivity of exposed population and energy requirements to indoor temperature set point (T_{sp}).

There are a very limited sets of conditions under which the number of warm days of exposure over a given temperature threshold has a sharp effect on the estimated at risk population (Fig. 5). For less than five days of exposure over a threshold, the exposed population increases steeply with increasing levels of the temperature threshold and fewer days of exposure. Otherwise, beyond five days, the at risk population is considerably less sensitive to the number of days of exposure for any given temperature threshold. Naturally, with higher threshold temperatures, fewer people in need of cooling are estimated to be at risk.

4.2. Cooling energy needs to fill the gap

4.2.1. Residential cooling demand in different world regions

Fig. 6 illustrates the average, population-weighted final cooling demand intensity estimated for different world regions and different housing types. Cooling energy demand intensity is higher in South Asia (SAS), Other Pacific Asia (PAS), and sub-Saharan Africa (AFR), where temperatures are on average warmer. Urban homes have lower demand intensity than rural homes, due to their more

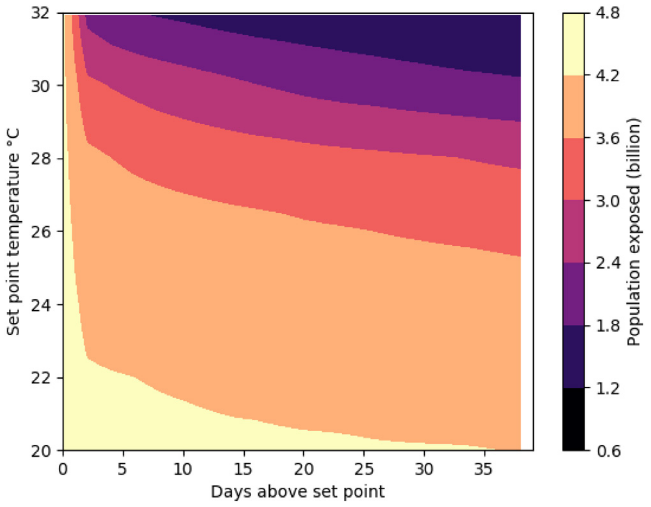

Fig. 5. The sensitivity of exposed population to warm days of exposure and indoor set point temperature (T_{sp}).

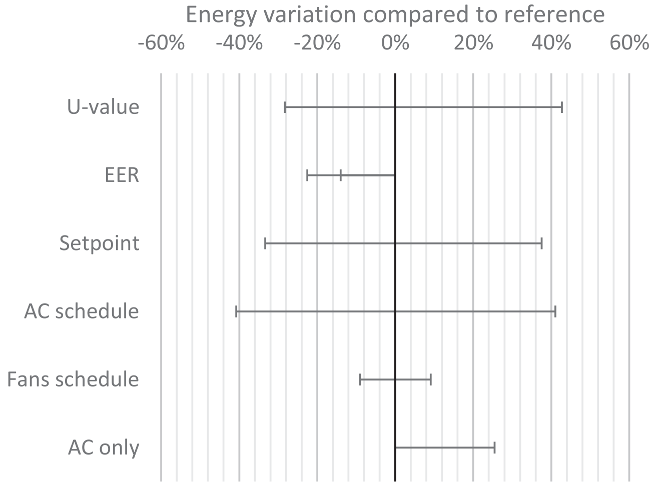

Fig. 7. Sensitivity of technological and behavioural parameters to per capita energy needs for space cooling. Indoor set point temperature (T_{sp}) was varied by ±2 °C, assuming 26 °C as a reference.

compact shape and lower average roof U-values limiting the heat load. Energy demand for AC dominates that for fans in all regions, comprising 63–79% (80–88%) of the total demand for rural (urban), despite the much lower hours of use. The share of AC demand is higher for regions with more severe climates (SAS and MEA). The spatial distribution of energy intensities (see Supplementary Material, Fig. SM12-13) is mainly driven by climatic conditions, and to a minor extent by the share of urban and rural buildings (due to population weighting). While we assumed homogeneous characteristics of the housing stock across different world regions, different building types might result in additional energy intensity variations on a regional level (see Section 4.2.2).

4.2.2. Sensitivity to technological and behavioural parameters

Fig. 7 illustrates the influence of various technological and behavioural parameters on the per capita energy needs for space cooling. Varying the thermal properties of the building envelope (U-value) entails major variations of the energy needs. Building envelopes with poor thermal quality (high U-values) entail an increase in energy needs over 40%, due to additional heat gains. Conversely, insulating the building envelope (low U-values) has a beneficial effect on the energy needs (−28%). Increasing the efficiency of AC (reference EER 3.9) contributes to reduce the energy needs from 13% (EER 4.5) to 22% (EER 5.0).

Behavioural parameters appear to have a large effect on the energy gap variation. Varying the reference indoor set point temperature (26 °C) by 2 °C higher or lower entails a difference of respectively −33% and +38%. Similarly, doubling or halving the daily number of hours of AC usage, has an impact of almost ±40% on the results. Varying the number of daily hours of fans usage has a much lower influence on the estimated total gap (±10%). Using AC without fans to ensure the same set point of 26 °C entails an increase of 25% in the energy needs, relative to the condition of windows permanently closed, e.g. against external air pollution or mosquitos.

Combining all input variations simultaneously results in a range of energy needs variation from −78% to +200% compared to the reference case. While this is a very broad range of variation, it

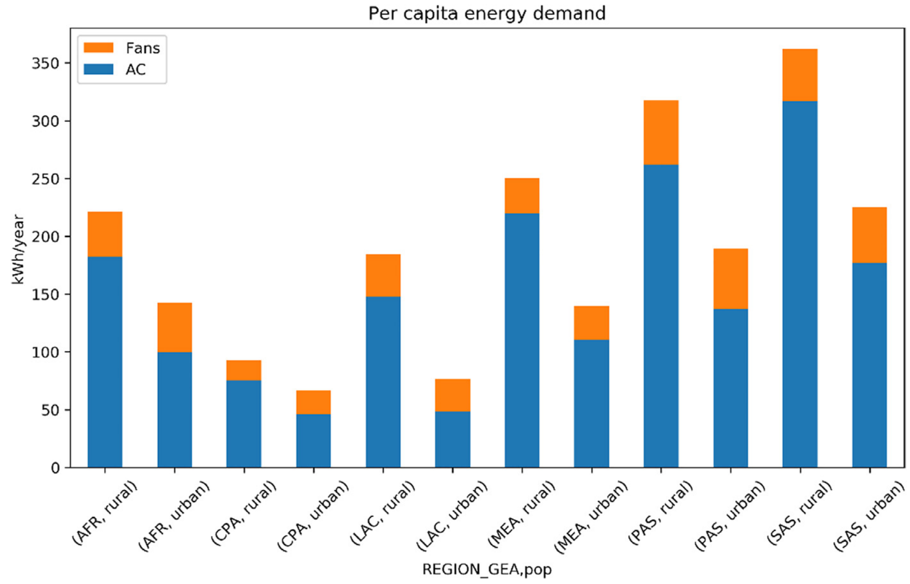

Fig. 6. Per capita energy demand for space cooling of urban and rural housing in different world regions (indoor set point 26 °C).

is in line with previous studies on developing countries [54,59]. The large sensitivity of energy demand to user-related parameters highlights the importance of carefully considering the lifestyle and behavioural dimension in space cooling assessments. The heterogeneity of building envelope characteristics across the Global South is also an important driver of energy needs variation. Future research should focus on identifying regional building typologies and recurrent materials to improve the accuracy of the model on a regional level, as discussed further in Section 5.4.

5. Discussion

5.1. Vulnerability due to lack of access to cooling

This study confirms the importance of inadequate space cooling, including the lack of AC, as a dimension of energy poverty beyond that currently within the ambit of SDG7. We estimate that between 1.8 and 4.1 billion people in the Global South, with a median of 3.7 billion for 26 °C set point threshold and at least 5 days of annual exposure, are potentially exposed to heat stress in their homes. This population includes almost 1 billion without access to electricity, thereby highlighting that accounting for the lack of cooling significantly increases the energy poverty gap defined by SDG7. Additionally, the gap includes the population with electricity access but lacking ACs, most likely due to their being too expensive or unsuited to people's housing conditions. These results are consistent with a recent report by the UN Sustainable Energy for All (SE4All), which estimates that 3.4 billion people face issues with adequate cooling access [9]. The UN report is based on a cruder assessment of potential heat stress but examines a wider set of channels that could lead to such stress, such as the need for cold storage for food and vaccines. In contrast, this study has two primary novelties: first, the space cooling access gaps are estimated based on a detailed, spatially explicit assessment of climate, housing conditions and AC ownership, for a wide range of target temperatures and days of exposures that could result in heat stress; second, it provides a first estimation of the energy demand associated with meeting this household space cooling gap. Previous energy demand studies have estimated AC use based on standard CDD calculations using much lower (typically 18.3 °C) set point temperatures. These estimates therefore, go beyond the energy needed to avoid heat stress and extend to that for providing comfort.

Notably, our estimate of 1.8–4.1 billion represents people *potentially* at risk based on their avoiding heat stress relative to a range of assumed set point thresholds for indoor comfort and exposure days per year. In reality, the specific exposure conditions, acclimatization and acceptable comfort thresholds, might vary across different subpopulations, so that different set point thresholds and standards may be applicable to each. Furthermore, far fewer than those estimated to be potentially at risk are likely to be exposed to conditions that pose serious health risks (very high temperatures over consecutive, even if for only a few, days). Added to this fact, since we do not filter the population by income level, age or physiological conditions, the vulnerable among the potentially exposed are also likely to be fewer. Our results, thus include a large population who might face only functioning impairments.

An important area for future work is to understand how many of the 1.8–4.1 billion at risk would adopt ACs and mitigate these risks from income growth alone. The International Energy Agency (IEA) estimates that by 2050, 2 billion residential ACs will be installed in India and China alone [1]. But it is not clear how many of these 2 billion units will be installed in homes that aid in avoiding heat stress, and consequently how many of the estimated potentially exposed, and in what locations, would still remain at risk.

5.2. Energy requirements

We estimate the median energy demand required to fill the cooling access gap to be 786 TWh per year, around 14% of current global residential electricity consumption [60], for the 26 °C set point and at least 5 days of annual exposure. Seventy-five percent of this demand is from India, Africa and East Asia. This can be compared to the IEA estimates of 2800 TWh growth between now and 2050 of residential cooling demand from income growth. Our energy estimate is conservative, since we assume that AC functions only to achieve our moderate risk alleviation thresholds. As with the population at risk, it is not possible to know how much of this projected energy growth would serve to fill the 'cooling energy poverty gap'. This is particularly a challenge in emerging economies with hot climate and high levels of both income growth and poverty, such as India, China, Indonesia, and Nigeria. The utility of this study is to provide a lower bound of cooling energy demand for basic well-being, and a starting point to identify its geographic distribution. In addition to the spatial variation of at-risk population, the per capita energy demand to meet the cooling energy poverty gap varies significantly, due to climate conditions and income, for the same set point. The per capita energy requirement is highest in rural parts of South and East Asia, and lowest in China and Latin America.

5.3. Policy options towards reducing the cooling gap

Filling the cooling energy poverty gap requires integrated strategies, beyond simply providing access to affordable and efficient AC. Populations in many regions still lack electricity access and decent housing, requiring a profound rethink in energy supply, building design, and urban planning as a whole to effectively address adaptation challenges to heat stress. Interconnections and potential synergies between filling the cooling gaps and reaching other SDGs are also of utmost importance. In addition to the obvious implications for SDG7, the interactions with SDG1 (poverty), SDG3 (health), SDG9 (infrastructure), SDG10 (inequalities), SDG11 (cities) and SDG13 (climate) are of particular significance, as discussed further below.

Access to electricity is still limited in many regions where space cooling is required, in particular sub-Saharan Africa and South Asia, as shown by our results. Achieving universal access to electricity (SDG7) is a prerequisite to access space cooling technologies. Off-grid solar solutions, such as solar home systems or solar mini-grids, may contribute to completing electrification in rural areas [4]. More renewable-based AC options might also need to be considered to meet cooling gaps.

With more than one billion people currently living in slum conditions [61], providing access to adequate, safe and affordable houses is a challenge (SDG11). Poor-quality informal houses not only raise issues of safety and decent living, but also provide inadequate protection against climate-related extreme events (SDG1), increasing the risk of temperature-related mortality (SDG3) [62]. Provision of new homes and slum-upgrading (SDG9) are therefore essential to fill the cooling gaps in many countries. Low-energy and sustainable housing design further contributes to reduced space cooling requirements and does not necessarily entail higher investment costs [46].

Promoting energy-efficient and low-emitting AC systems has been identified as a needed mitigation measure to reduce the energy requirements associated with closing the cooling gap [19,63]. Potential solutions include, using better coolants and refrigerants, more efficient cooling units, centralized systems for multi-family buildings and, where viable, district cooling networks (e.g. in dense urban areas). However, cooling demand is also subject to the rebound effect [64]. Our results showed that the behaviour of occupants have a large influence and should be addressed by policy, e.g. by limiting the set point temperatures for AC, as already implemented in Japan for commercial buildings [65].

The high demand for AC in the Global South poses both a challenge and opportunity for mitigating climate change. Efforts to switch out of using climate warming refrigerants as required under the Kigali amendment will be important to limiting the climate impacts of AC (SDG13). In addition, timely policies to make higher-efficiency ACs affordable, and to improve the design of cities and buildings to reduce heat-island effects could be a win-win for climate and development.

5.4. Limitations and further research

In establishing this global, scalable modelling framework, there are several caveats to our conclusions and a number of possible further refinements are possible. First, we characterize the housing stock with a limited set of building archetypes that describe common building configurations in the Global South, and run a sensitivity analysis to account for key variations in building parameters. Yet, these archetypes cannot comprehensively represent the full variety of materials and construction techniques available across world regions, rather they indicate different recurrent housing types. With continued collection of data from national studies, future efforts can extend this work to incorporate a wider variety of materials and housing characteristics within the same modelling framework. While the spatial distribution of cooling gaps and energy requirements is largely driven by climatic conditions, population and AC access, accounting for greater variability in building characteristics may contribute to more precise results on a regional level.

Whilst previous studies at this scale have used DDs to analyse trends and compare alternatives [41], our use of the VDD method explicitly considers building characteristics, user behaviour, and temperature set points. However, this method has limitations, for example: cooling loads estimation can be impacted by the limited capacity to account for the dynamics of the building, in particular due to thermal inertia; average daily temperatures are used, thus not fully accounting for diurnal fluctuations; latent loads, which become more significant at higher outdoor temperatures [66], are ignored. The characteristics of user behaviour we consider in this work are only those with respect to temperature set points and reductions in use of fans and AC from varying user schedules.

The AC adoption model is derived from data on AC ownership data in just one country, the United States. Future model development ought to integrate a broader base of data on ownership, income and climate. Humidity is also likely to influence AC adoption, but has not been assessed in previous models of AC penetration. Estimations of both fans and AC adoption in this work are done at the national level and neglect within nation differences in affordability and penetration across rural and urban areas.

Further research is expected to overcome part of these issues by using intra-day temperature data, allowing for more accurate scheduling, provide a better description of the building stock in the different regions by using micro-survey data, and including latent loads in the calculation. Future works could also focus further on behavioural and lifestyle aspects which, we show, have a major influence on energy requirements, and related policy options to avoid overuse of AC. The current study aimed at giving a snapshot of the gaps in the current situation. Rapid changes in the housing stock, socio-economics and access to cooling devices are undergoing in many developing countries, and require the inclusion of a temporal dimension to the cooling gaps analysis. The development of such future scenarios, including the dynamics of socio-economics and climate change, is envisaged for future research.

6. Conclusions

This study estimated spatially explicit residential cooling needs in the Global South in combination with access to space cooling technologies to highlight the location of populations potentially at risk of heat stress and to quantify the cooling energy gap. We applied a methodology based on VDD to estimate space cooling at a high spatial resolution, accounting for climate, housing types, and space conditioning technologies.

Our results show that a total of 1.8–4.1 billion people are potentially exposed to heat stress due to lack of access to cooling, mostly located in India, South-East Asia and sub-Saharan Africa. These results suggest much larger energy poverty gaps compared to the current definition in SDG7, when considering lack of access to essential space cooling. Covering this gap could lead to a substantial median increase in energy requirements of 786 TWh/y, 14% of current global residential electricity consumption [60], primarily for running ACs. Solutions beyond improved AC efficiency and fan use, such as passive building and city design and innovative cooling technologies will be needed to ensure essential cooling for all that minimize environmental damage. The large influence of behavioural aspects on energy requirements, suggests that parsimonious use of AC and moderate set point temperatures should be promoted.

This study has contributed to developing a more comprehensive measure of energy access, by introducing the dimension of space cooling, which has been largely overlooked so far, but has broad implication for human health and functioning. Meeting the essential cooling gap, as estimated by this study, can have important interactions with achieving several of the SDGs.

Acknowledgments

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Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.enbuild.2019.01.015.

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