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The role of residential air circulation and cooling demand for electrification planning: Implications of climate change in sub-Saharan Africa

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A B S T R A C T

Nearly 1 billion people live without electricity at home. Energy poverty limits their ability to take autonomous actions to improve air circulation and the cooling of their homes. It is therefore important that electricity-access planners explicitly evaluate the current and future air circulation and cooling needs of energy-poor households, in addition to other basic energy needs. To address this issue, we combine climate, socio-economic, demographic and satellite data with scenario analysis to model spatially explicit estimates of potential cooling demand from households that currently lack access to electricity. We link these demand factors into a bottom-up electrification model for sub-Saharan Africa, the region with the world's highest concentration of energy poverty. Accounting for cooling needs on top of baseline household demand implies that the average electrification investment requirements grow robustly (a scenario mean of 65.5% more than when considering baseline household demand only), mostly due to the larger generation capacity needed. Future climate change could increase the investment requirements by an additional scenario mean of 4%. Moreover, the share of decentralised systems as the lowest-cost electrification option falls by a scenario mean 4.5 percentage points of all new connections. The crucial determinants for efficient investment pathways are the adoption and use of cooling appliances, the extent of climate change, and the baseline electricity demand. Our results call for a more explicit consideration of climate-adaptative energy needs by infrastructure planners in developing countries.

1. Introduction

About 800 million people (>10% of the global population) live without access to electricity at home (IEA et al., 2020). Energy poverty prevents households from meeting fundamental needs, such as taking actions to autonomously adapt to changing environmental conditions. A major adaptation action concerns indoor thermal discomfort mitigation. In fact, at different periods in the year, residential buildings are already major drivers of air circulation and cooling (ACC) service demand in large parts of the world. Moreover, anthropogenic climate change is projected to increase the absolute amount of heat in air, land, and water, and to skew its distribution over space and time. In turn, this will very likely boost the demand for ACC services (De Cian et al., 2019; van Ruijven et al., 2019), and therefore increase the thermal discomfort exposure of energy poor households (Mastrucci et al., 2019; Randazzo et al., 2020). It is estimated that more than 1.1 billion people globally face immediate risks from lack of access to cooling (SEforALL, 2018), including almost half a billion people in poor, rural areas. Moreover, 2.3 billion people may only be able to afford less expensive and less efficient cooling devices, irrespective of having access to electricity (SEforALL, 2018).

The use of ACC services has multiple socio-economic implications and human health ramifications. Indoor temperature affects health status (Deschenes, 2014; Tham et al., 2020; Vicedo-Cabrera et al., 2018; White-Newsome et al., 2012), night-time sleep quality (Lan et al., 2017, 2016; Obradovich et al., 2017; Pan et al., 2012), and work productivity (Akimoto et al., 2010; Cui et al., 2011; He et al., 2019; Lorsch and Abdou, 1994; Tanabe et al., 2007; Yu et al., 2019; Zivin and Kahn, 2016). This broad stream of literature agrees that ACC services can mitigate large part of the current (and future) indoor thermal discomfort, which disproportionately affects the poor and most vulnerable populations (Biardeau et al., 2020; Byers et al., 2018).

On the other hand, a steeply growing ACC demand has major implications for energy systems, both on the demand and supply sides

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(Ciscar and Dowling, 2014; Khosla et al., 2020), and for climate change itself. Currently, cooling energy already accounts for nearly 20% of the total electricity used globally in buildings (IEA, 2018). In turn, as highlighted by Sustainable Energy for All (2018), cooling is responsible for about 10% of anthropogenic global warming. According to that study, space cooling is also the fastest growing energy service in buildings; estimates from the report suggest that by 2050 the global cooling electricity demand will rise by 66–180%. Crucial factors determining the wide range of these estimates concern the future penetration of air conditioning units, the efficiency of such devices, their usage time, as well as materials used in buildings.

Global-warming-induced amplification of energy demand has been quantified in both seminal (Barker et al., 1995; Hekkenberg et al., 2009; Scott et al., 1994; Taseska et al., 2012) and recent (De Cian and Wing, 2019; van Ruijven et al., 2019) applications. Relatedly, this literature has also evaluated the residential-sector energy demand for heating and air conditioning under different climate change scenarios globally (Isaac and Van Vuuren, 2009) and for developing countries (Mastrucci et al., 2019; Wolfram et al., 2012). These assessments have shown that the future climate will be a strong driver of energy demand growth. Finally, some estimates of the consequent costs for households in different regions have been produced, e.g. for Africa (Parkes et al., 2019).

Despite this rich research backdrop, there remains a lack of a planning-oriented analysis explicitly linking potential household cooling demand to the large electricity access gap. The issue of access to electricity is at the core of Sustainable Development Goal 7 (SDG 7) to "ensure access to affordable, reliable, sustainable and modern energy for all", as part of the 2030 Agenda (United Nations, 2015). Efficient and effective electricity access infrastructure planning strongly depends on local energy demand targets and projections (Lucas et al., 2017). Energy demand density across space and time has a major impact on the optimal energy system set-up, including technology, generation capacity, and investment requirements. Therefore, it is crucial to understand how to meet the demand for cooling services which are likely to vary at different levels of adoption of cooling devices, and under different climate futures. These matters will certainly affect steps planners take to create inclusive electricity access plans. That is, planning approaches must incorporate ways to ensure thermal comfort – in addition to ensuring baseline household electricity needs. Without accounting for these requirements, electrification programs might leave many households in deprivation. This is because, even after electrification programs are rolled out, there may be insufficient power for meeting cooling needs (e.g., Poblete-Cazenave and Pachauri, 2019; IEA, 2017).

Assessing the interplay between cooling needs and electrification planning requires quantifying the degree of thermal discomfort that cannot be met because of the lack of electricity access, and examining how the situation may be exacerbated over time due to the extent of anthropogenic climate change that occurs. In turn, this necessitates an integrated understanding of the spatial distribution of populations living in energy poverty, of the variability of cooling needs across space and time, and of a modelling approach to estimate local electricity requirements. To address these questions, we build on the methods introduced in studies examining the linkages between temperature, climate change, income, air conditioning ownership and use – and, therefore, the future potential electricity consumption. We calculate spatially explicit model of monthly cooling degree days (CDDs) – a reference metric for space cooling needs (CIBSE, 2006; Heating et al., 2009). We use this to examine both the present and the post-SDGs horizon (2041–2060). We base our calculations on climate simulations from the Coupled Model Intercomparison Project – Phase 6 (CMIP6), a consortium of Global Climate Models (GCMs) underlying the reports of the Intergovernmental Panel on Climate Change (IPCC) (Eyring et al., 2016). We develop and implement a spatially explicit framework to estimate the electricity requirements (on top of archetypical baseline demand targets) for a variety of scenarios of cooling appliance adoption, efficiency, and use to guarantee thermal comfort in settlements currently without access to electricity. The assessment encapsulates assumptions on building and appliance characteristics and geo-referenced climate, solar irradiance, human settlement, and survey-based wealth distribution data. These steps culminate in the calibration of a geospatial electrification model for sub-Saharan Africa – the global "hotspot" of energy poverty. We evaluate the role of cooling needs in an electrification strategy that incorporates adaptation needs that will be likely to unfold by 2030, the SDG 7 target year. That is, we identify universal electricity access scenarios suitable for accommodating future household cooling needs. The analysis seeks to improve the understanding of the role of climate change adaptation actions in policies targeting the elimination of energy poverty. We pay particular attention to the potential for enabling the use of cooling devices through decentralised energy-access systems. Such systems have been identified by several sources (Dagnachew et al., 2017; IEA, 2019a) as a fundamental lever for closing the energy access gap.

2. Literature review

2.1. Energy poverty: definition, measurement, and implications

Energy poverty does not have a clear-cut definition. A universally accepted understanding of what it means to live below the energy poverty line has yet to be devised (Culver, 2017; Pachauri, 2011). In fact, the definition of energy poverty depends on socio-economic, cultural, and environmental factors in a given context. Energy poverty is not confined to low-income countries. For instance, the *EU Energy Poverty Observatory* measures energy poverty in EU countries by examining the share of income spent by households on energy bills, and by evaluating the inability to maintain thermal comfort at home; it finds that energy poverty is a major issue in different countries where income inequality is also prevalent (Thomson and Bouzarovski, 2018). At the same time, seminal inquiries into the definition of fuel poverty in high-income regions (e.g., the UK Government *Fuel Poverty Review* (Hills, 2011; the evaluation of fuel poverty in the EU by Thomson et al., 2016) cannot be transferred to low-income, developing regions. Despite some similarities, such as the fundamental economic nature of the problem, stark differences exist. In the developing world, nearly 800 billion people live without access to electricity, and 2.8 billion lack access to clean cooking (IEA et al., 2020). In these areas the lack of infrastructure is the primary cause of energy poverty, along with the high prices of modern energy services relative to income.

The lack of a concrete, unambiguous definition of energy poverty directly affects the capacity to measure it. Energy poverty can be evaluated in terms of energy access, energy inputs (e.g. energy consumed or income spent on energy), outcomes (e.g. adverse socio-economic impacts), or the quality of energy delivered (Culver, 2017). In our paper we focus on the concept of energy poverty in the context of developing countries. We target electricity access, latent demand for energy services (Poblete-Cazenave and Pachauri, 2019), and infrastructure planning to expand energy access.

Recent contributions have examined energy poverty measurement in the context of developing countries to overcome mono-dimensional evaluations, and to allow for a more comprehensive understanding of the challenges involved (Pelz et al., 2018). For instance, the IEA developed the Energy Development Index (EDI) by calculating an evenly weighted average of three normalized components: (i) per capita commercial energy consumption; (ii) the share of commercial energy in total, final energy use; and (iii) the electrification rate (IEA, 2011). Nussbaumer et al. (2012), who criticised the index for neglecting household energy deprivation, introduced the Multidimensional Energy Poverty Index (MEPI), which focusses exclusively on household-level energy poverty. Another measure, the Energy Poverty Index (EPI) created by Mirza and Szirmai (2010), pays strong attention to the issue of opportunity costs as a consequence of energy poverty. In a seminal xcontribution, Bhatia and Angelou (2015) introduced the World Bank Multi-Tier Framework, a matrix for measuring and planning energy access across different dimensions such as availability, affordability, reliability and consumption. Samarakoon (2019) built on this literature to create another framework with focus on the justice and well-being aspects that are crucial to eliminating energy poverty. A recent update of the debate on advancing energy poverty measurements as a way to assess progress on SDG 7 was offered by Pachauri and Rao (2020). The authors, who have criticised the complex nature of most multi-dimensional energy poverty measures, propose an alternative framework based on energy supply conditions and the status of household energy poverty.

The implications of energy poverty for livelihoods and well-being are huge, both in developing countries and in high-income regions. In the Global South, pervasive energy poverty and lack of energy access contribute to degradation of the natural environment, and to detrimental outcomes for development, public health, gender empowerment, and education (Sovacool, 2012). A discussion paper by Casillas and Kammen (2010) highlighted the crucial nexus linking energy poverty and climate change. The thermal comfort and indoor cooling issues that are at the core of our analysis fall under this umbrella issue of the implications of energy poverty and the lack of electricity access infrastructure in developing countries and elsewhere. Empirical evidence suggests that well-being is strongly affected among those living in fuel poverty in regions worldwide. Analysing data from Australia, Churchill et al. (2020) found that fuel poverty lowers subjective well-being substantially, with large social costs. A similar result was observed in Germany by Biermann (2016), who highlighted that the impact of *fuel* poverty extends beyond the impact of *income* poverty. Finally, analysing 32 European countries, Thomson et al. (2017) found a higher incidence of poor mental and physical health among the energy-poor populations of most countries, compared to non-energy-poor households.

2.2. Energy needs for climate change adaptation, ACC demand, and related greenhouse gas emissions

The expanded energy demand (including from the growing need for ACC) as a mean to adapt to climate change has been analysed by a literature dating back at least two decades. Early studies came from governmental reports in Germany and in the United States that quantified (in aggregated building-stock terms) moderate decreases in heating energy, and moderate increases in cooling energy. An important advancement was introduced by Scott et al. (1994), who evaluated the effects of climate change on commercial-building energy demand, and discussed the importance of considering disaggregated data in impact assessments. Their findings highlight that increased humidity could be a significant factor in building energy use.

More recent studies include the work by Hekkenberg et al. (2009), who underscore the importance of socio-economic dynamics in mediating the energy-demand response to changes in the outdoor temperature. Ciscar and Dowling (2014) carried out a systematic review of how integrated assessment models (IAMs) have estimated the impacts of climate in the energy sector and in the modelling of adaptation. They argue that further attention is needed on the modelling of possible adaptation measures and the assessing of the effects of climate extremes on the energy infrastructure. Another relevant contribution is the work of van Ruijven et al. (2019), who build on empirically estimated responses of energy use to income, and to hot and cold days globally. They forecast very substantial increases in global climate-exposed energy demand before adaptation for an array of scenarios, and on top of baseline energy demand growth. De Cian and Wing (2019) show similar results.

The literature has begun to focus on the impact of future air conditioning adoption and use in certain contexts. Davis and Gertler (2015) use high-quality micro-data from Mexico to describe the relationship between temperature, income, and air conditioning. They project future energy demand growth based on the estimated empirical model in which income is the main driver of ACC systems adoption; the findings highlight the important roles that energy efficiency and cooling technologies are likely to play in future scenarios. Isaac and van Vuuren (2009) carry out a global integrated assessment modelling study of residential-sector energy demand for heating and air conditioning in the context of climate change. They project that income growth will be the key driver of energy demand for air conditioning throughout the 21st century. The authors assume that the availability of air conditioners is a function of income; they do this by following a logistic function, with a threshold point beyond which ownership increases rapidly. They estimate the function using data on economic development and appliance adoption from different countries, and utilizing the approach outlined by McNeil and Letschert (2008). Isaac and van Vuuren (2009) examine the issue at a global scale by defining yearly household electricity consumption from air conditioning as a function of CDDs and the natural logarithm of income; they estimate the equation parameters based on consumption data from the literature. Another contribution comes from Gupta (2012), who estimates the climate sensitivity of electricity demand in Delhi using daily data on electricity demand and apparent temperature through a semi-parametric variable coefficient model. The author finds that electricity demand is a U-shaped function of temperature, with a steeper slope in the rise growing over the years analysed, implying an increase in cooling demand per unit increase in hot months.

Mastrucci et al. (2019) estimate the current location and extent of populations that are potentially exposed to heat stress in the Global South. The authors apply a variable degree-days method to estimate the energy demand required to meet these cooling needs. They account for spatially explicit climate, housing types, and access to electricity and air conditioning ownership; they find that covering the estimated cooling gap entails a median energy demand growth of 14% of current global residential electricity consumption. Similarly, Parkes et al. (2019) utilize the *apparent temperature* and *humidex* metrics to calculate current and future heat stress in Africa. They project that climate change is likely to increase the intensity of heat stress events in Sahelian Africa, and also likely to introduce new heat stress events in Northern and Central Africa, with consequent increase in energy-intensive cooling. Their projections show that energy-intensive cooling will increase with the increase in intensity of heat stress, with Nigeria likely to be the country most affected. They estimate that the total increase in energy costs to prevent heat stress in Africa will reach $51 billion by 2035 and $487 billion by 2076. Finally, the authors highlight the issue of supplying this cooling-energy demand in poor countries with low electrification rates, a topic at the core of our paper.

De Cian et al. (2019) analyse household survey data across eight temperate industrialized countries to explore how households of various socio-economic and demographic characteristics have been adopting air conditioning and thermal insulation to cope with different climatic conditions. Their findings stress the crucial role of income and urbanisation in ACC uptake and adoption. Examining the same primary data and countries, Randazzo et al. (2020) evaluate household air conditioning adoption and use patterns. The authors find that households on average spend 35%–42% more on electricity when they adopt air conditioning. They predict that adverse impacts of climate change on energy poverty will ensue – with larger population shares spending significant proportions of their income on electricity for cooling. Finally, Colelli and De Cian (2020) carry out a systematic review of the methodologies adopted in integrated assessment models to estimate cooling demand for thermal adaptation in commercial and residential buildings. They highlight that models lacking extensive margin adjustments (i.e., long-term demand responses driven by an increase in the penetration of ACC appliances) systematically underestimate the additional cooling needs of the building sector, suggesting future research to examine ACC appliance adoption modelling in greater detail.

Global modelling exercises carried out by the IEA (2018, 2019b) have estimated that by 2050 the global cooling electricity demand will rise by anywhere from 66% to 180%, with the global air-conditioner stock reaching about 5.5 billion units, up from the current ~2 billion. The IEA argues that a use scenario incorporating efficient cooling technology and building materials would imply an ACC electricity demand rise of about half the level forecast under a reference scenario; with such efficiency gains the growth in demand could be accommodated by roughly one-third less power-generation investment than would otherwise be expected, with costs falling from about $3 trillion to $2 trillion globally). Laine et al. (2019) evaluate the potential of the increased electricity demand for air conditioning to boost the expansion of solar PV capacity; this line of inquiry is based on the understanding that areas likely to face high cooling requirements are also likely to be areas with high potential to generate solar power. The authors argue that a majority of the rapidly increasing cooling demand could be met with PV power and small-scale distributed storage.

Building on this rich literature and background, our study is unique in that it explicitly draws the line between poverty, climate change, future demand for energy to meet cooling demand, and planning for access to electricity.

3. Materials and methods

3.1. General framework

Fig. 1 summarises the analysis carried out in this paper. The methodology is divided into four main parts, also highlighted in dedicated sections below:

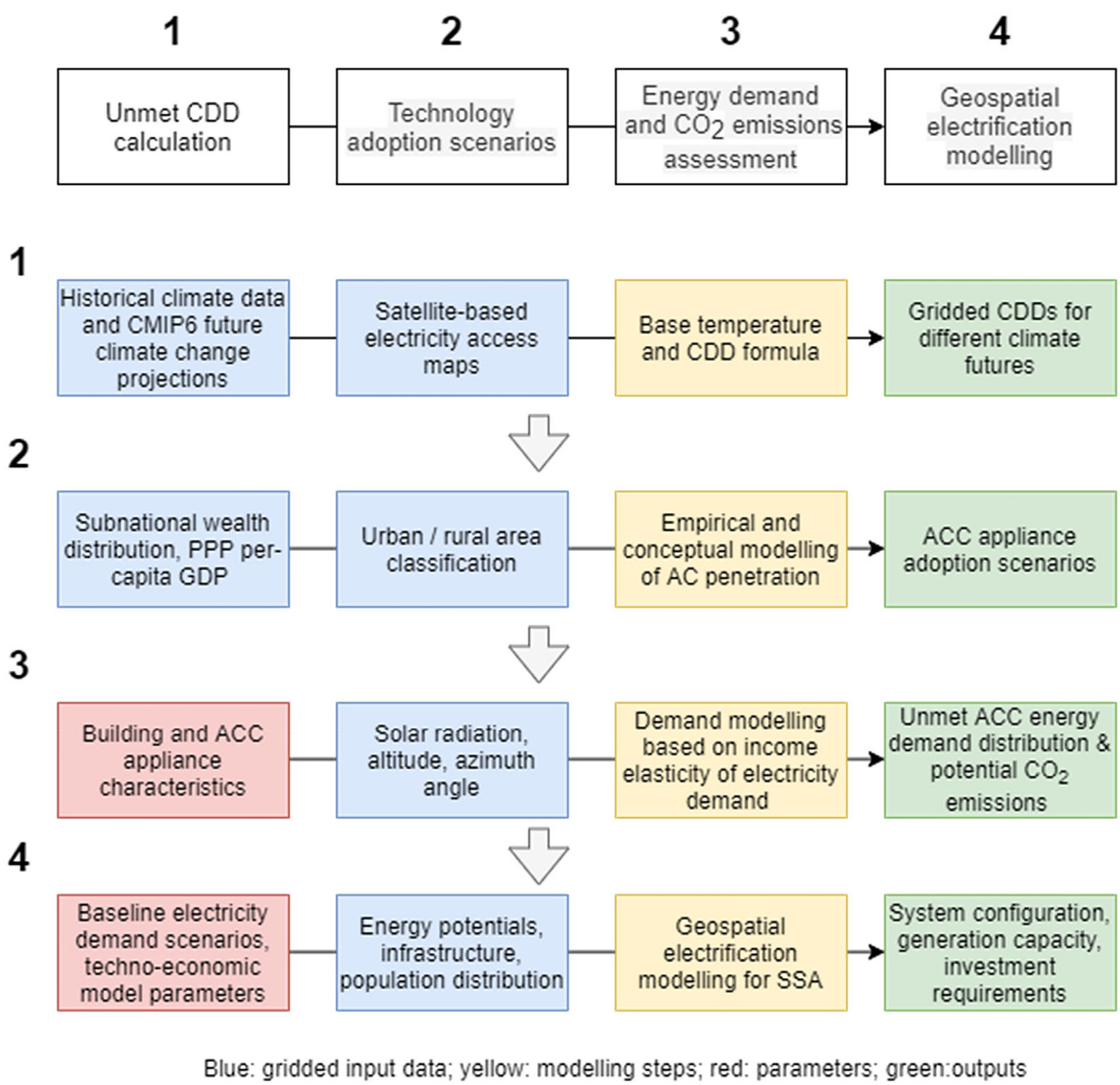

Fig. 1. Methodological framework of the analysis. **(1)** General workflow; **(2)** CDD calculation; **(3)** Electricity demand estimation; **(4)** Electrification modelling.

1. Calculation of cooling degree days (CDDs) based on both historical data and future climate change projections; assessment of the distribution of CDDs among households without electricity access.
2. Empirical modelling to define ACC appliance adoption based on household wealth and its evolution, and urban/rural prevalence; design of additional appliance-adoption scenarios to appraise potential ACC policy objectives.
3. Energy demand modelling to estimate potential ACC-driven energy consumption among households without electricity access under different scenarios.
4. Geospatial electrification modelling to evaluate the role of potential ACC energy demand in electricity access infrastructure planning; results on system configuration, power generation capacity requirements, and investment needs.

3.2. Cooling degree days: data and calculation

We calculate the average monthly CDDs – defined as the number of degrees that the average day of each month's temperature is above an arbitrarily defined comfort temperature (T_{base}) – at each 0.5° grid cell. To derive CDDs from average monthly minimum, mean, and maximum temperature values, we implement the CDD methodology developed by the UK Met Office (Spinoni et al., 2018) (reported in Table 1). The methodology represents a step forward from the traditional CDD calculation because the difference between the daily or monthly mean temperature and T_{base} explicitly accounts for the temporal distribution of heat during the average day of a given month. The main limitation of the methodology is that it does not directly account for humidity, which can alter the amount and perception of heat in the air. Humidity is considered in the sensitivity analysis, in which we use wet-bulb temperature CDDs (Appendix D); however, these are not used as the reference variable because relevant data are still lacking for the latest CMIP6 climate projections.

In the analysis, a base temperature (T_{base}) of 26° C is considered. While most global assessments use a T_{base} of 18.3 °C, we calculate CDDs at a base of 26 °C because the electricity-access deficit is concentrated in areas with tropical and equatorial climates where the annual mean temperature is significantly higher than the annual global mean temperature. This base temperature is also adopted in the literature on cooling needs in the Global South (Mastrucci et al., 2019). T_{base} values of 22°, 24° and 28° are also utilized for examining the sensitivity of the results to the choice of comfort temperature (T_{base}) following Dongmei et al. (2013).

CDDs are calculated on both historical and projected future climate data for the 2041–2060 horizon. The calculation of historical CDDs is based on 1970–2000 monthly average data from WorldClim (Fick and Hijmans, 2017), while future (potential) CDDs are projected based on the median of CMIP6 downscaled, bias-corrected climate change simulations produced from eight GCMs (*BCC-CSM2-MR, CNRM-CM6–1, CNRM-ESM2–1, CanESM5, IPSL-CM6A-LR, MIROC-ES2L, MIROC6, MRI-ESM2–0*) for the period 2041–2060. For the future climate change, we refer to the CMIP6 scenarios SSP245 (the update of RCP2.6 based on SSP1) and SSP370 (the update of RCP4.5 based on SSP2) scenarios. These integrated scenarios describe interactions between two global socio-economic development pathways: the Shared Socio-Economic Pathways (SSPs) which take into account the drivers of greenhouse gas (GHG) emissions from anthropogenic activities; and the Representative Concentration Pathways (RCPs), which assess the resulting GHG concentrations in the atmosphere. The logic and construction of SSP-RCP-integrated scenarios are described in detail in O'Neill et al. (2016). Scenarios SSP245 and SSP370 represent intermediate emission variants that assume sustainability-focused and middle-of-the-road socio-economic trajectories, respectively. SSP245 is more likely than not to result in global mean temperature rise between 2 and 3 °C by 2100. By contrast, SSP370 represents the medium-to-high end of the range of future emissions and warming; it is a baseline outcome rather than a mitigation target (Pachauri et al., 2014).

3.3. Electricity access deficit and CDD allocation

First, the spatial distribution of populations currently living without access to electricity is approximated based on the methodology described in Falchetta et al. (2019, 2020). The approach combines the 2019 NOAA Suomi NPP-VIIRS (*National Oceanic and Atmospheric Administration, Suomi National Polar-orbiting Partnership satellite, Visible Infrared Imaging Radiometer Suite sensor*) night-time light imagery to proxy for proximity to electricity-access infrastructure. The proxy is calculated as the median raster of monthly nighttime light composites (with a 0.3 $\mu W \cdot cm^{-2} \cdot sr^{-1}$ noise threshold) overlaid to the WorldPop 100-m-resolution gridded population dataset (Tatem, 2017). The approach estimates populations living in areas that are dark at night, and thus are considered to lack reliable electricity access. The estimation methodology produces a global total of ~880 million people without access to electricity. The figure is quite consistent with recent assessments of global electricity access deficit (IEA et al., 2020). As discussed in Falchetta et al. (2019), this estimate is highly correlated with field-measured electricity-access levels at both national and subnational levels. Note that in the electrification-modelling exercise, the population is then projected to 2030 with heterogeneous urban-rural population growth based on UN-DESA (2018) projections.

Then, we estimate *potential ACC demand* (*PACC*), defined as the CDDs that cannot be mitigated at time *t* because of the lack of electricity access, but which would drive energy consumption if households had both an electricity connection and an ACC appliance available. We calculate PACC at each grid cell *i* as a weighted sum:

$$PACC_i = \sum_{t}^{T=12} \frac{POP_{it}^{noacc}}{HHsize_i} \times CDD_{it} \tag{1}$$

where:

- POP^{noacc} is the population without electricity access estimated with night-time light data;
- $HHsize_i$ is the local average household size (calculated at each grid cell using UN-DESA, Population Division (2019) data on country-level average household size and a urban-rural adjustment factor);
- *CDDs* are the local cooling degree days (*CDDs*) for each month of the year *t* for both the present and future climate change scenarios.

3.4. ACC technology adoption

3.4.1. Empirical modelling of air conditioning penetration

AC penetration occurs mostly at the extensive margin, i.e. in response to changing income and climate conditions (Colelli and De Cian, 2020; IEA, 2020). Urbanisation also plays a significant role (De Cian et al., 2019). Following the seminal, empirical two-stage model of AC adoption based on country-level analysis worldwide (Isaac and van Vuuren, 2009; McNeil and Letschert, 2008), we define AC penetration P_i^{AC} as:

$$P_i^{AC} = AV_i \times CMS_i \tag{2}$$

where AV_i is *availability* (a function linking income and the potential to purchase AC units), defined through the following empirical logistic function (from Isaac and van Vuuren, 2009):

$$AV_i = \frac{1}{1 + e^{4.152} \times e^{\left(-0.237 \times \frac{PPPGDP_i^{2030}}{1000}\right)}} \tag{3}$$

where:

- $PPPGDP_i^{2030}$ is the purchasing-power-parity, per capita GDP in year 2030 in 1995 US dollars at grid cell *i*
- *e* is the exponential function
- CMS_i the climatic maximum saturation (a function linking local CDDs with the probability of purchasing AC units), as defined by McNeil and Letschert (2008).

Table 1
CDD calculation methodology.

Condition	CDDs
$T_{max} \le T_{base}$	$CDD = 0$
$T_{avg} \le T_{base} < T_{max}$	$CDD = \frac{(T_{max} - T_{base})}{4}$
$T_{min} \le T_{base} < T_{avg}$	$CDD = \left[\frac{(T_{max} - T_{base})}{2} - \frac{(T_{base} - T_{min})}{4}\right]$
$T_{min} \ge T_{base}$	$CDD = T_{avg} - T_{base}$

In turn, CMS_i (also from Isaac and van Vuuren, 2009) is defined as:

$$CMS_i = 1 - 0.949 \times e^{\left(-0.00187 \times CDD_i^{yearly}\right)} \quad (4)$$

where:

- CDD_i^{yearly} are the cumulative CDDs experienced each year at each grid cell *i*.

Because our analysis looks at future adoption and use of AC, we estimate future subnational-level income change with respect to the present. Here, future PPP per capita GDP in year 2050 ($PPPGDP_i^{2050}$) at each grid cell *i* is calculated as:

$$PPPGDP_i^{2050} = \sum_{k}^{K=5} WQ_k^{DHS} \times \left(1 + HGR_k^{DHS}\right)^{30} \times PPPGDP_k^{2020} \times \left(1 + HGR_c^{WB}\right)^{30} \quad (5)$$

where:

- WQ_k^{DHS} is the share of the population in each wealth quintile *k* according to the latest available DHS survey. Our proxy for household income is wealth distribution, expressing the share of households in each wealth quintile compared to the national distribution.
- $HGR_k^{DHS}$is the assumed yearly average rate of change in the share of people living in wealth quintile *k*. It is used to (linearly) project future wealth distribution. It is calculated based on the historical evolution of the distribution of wealth at the subnational scale from DHS surveys. Virtually all provinces have been surveyed more than one time in the last 20 years, so we can calculate the average historical shift in the distribution of wealth (based on the number of years between the different survey waves).
- $PPPGDP_k^{2020}$ is each country's PPP per capita GDP in year 2020.
- HGR_c^{WB} is the average PPP per capita GDP growth rate for the 2020–2050 period based on the SSP2 projections (Riahi et al., 2017).

In the calculation, we assume that the $PPPGDP_k^{2020}$ approximates the average income level of people in the third wealth quintile (50% richest share of the population). Thus, we derive PPP per capita GDP at other wealth quintiles for both the present and the future. We convert current GDP to 1995 PPP constant USD using the World Bank GDP deflator (indicator *NY.GDP.DEFL.ZS)*. Because DHS surveys incorporate stratification of urban and rural areas, the AC penetration assessment includes urban-rural heterogeneity.

Fig. 2 plots the estimated AC penetration rate around year 2050 at the pixel level for SSP2. The results show significant variability, with southern and western African countries achieving significant AC penetration. AC penetration remains below 5% even after 2050 in broad areas of central and eastern Africa, with the exception the main urban centres. These results are consistent with the modelling results of country-level AC ownership in 2050 carried out in IEA (2020), which also forecast that most SSA countries will continue to show generally low levels of AC adoption. Alternative estimates under other SSP scenarios can be found in Fig. B.3 in the Appendix.

3.4.2. Representative ACC technology-adoption scenarios

In the empirical AC penetration modelling, large shares of rural populations remain without AC. Yet, there is the possibility that the historical relationship between income, climate and AC adoption considered in the assessment will not hold in the future or in the context of SSA. Thus, we simulate two other representative scenarios of ACC appliance adoption. These scenarios can be thought of as archetypical policy objectives that seek to offer more people the ability to mitigate the CDDs they experience. In these representative scenarios, we consider separate adoption rates for rural and urban households (HHs). We build these representative scenarios exploiting the most recent information on provincial wealth distribution across households from DHS surveys. Urban and rural areas are identified based on the GHS-SMOD 2015 settlement classification to classify populations grid cells either as urban (GHS-SMOD≥30), rural (11 ≤ GHS-SMOD≤23), or uninhabited (GHS-POP = 0) (see Pesaresi et al., 2015 for classification details). We then define the number of households in each rural and urban cell of each country by referring to the United Nations' statistics on the average household size in urban and rural areas of each country (United Nations, Department of Economic and Social Affairs, Population Division, 2019).

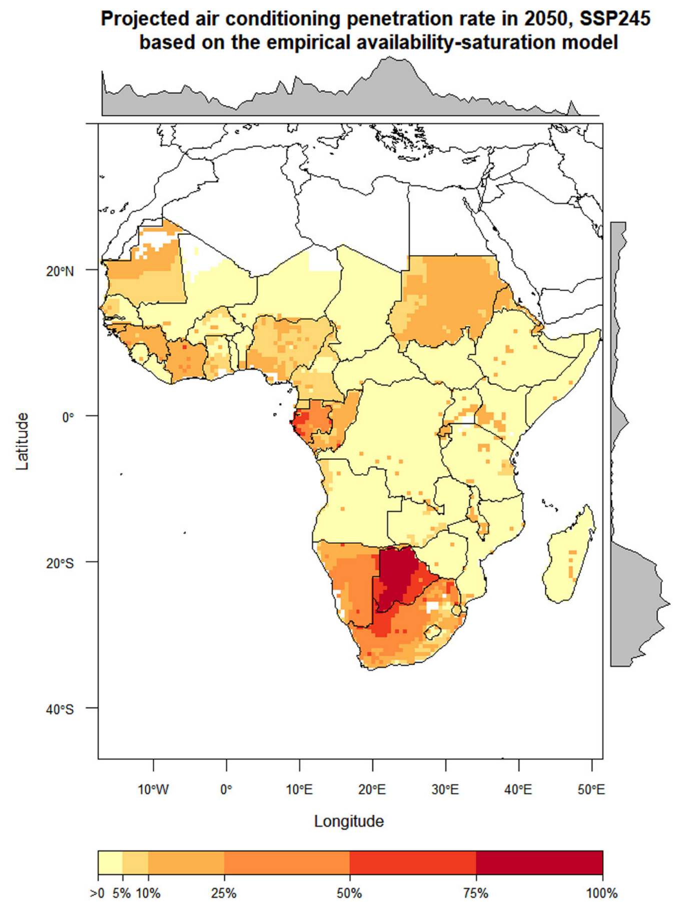

Fig. 2. Map of the modelled air conditioning penetration rates in 2050 in the empirical appliance-adoption scenario for SSP2–45.

Based on this information, we design two representative technology-adoption scenarios, in addition to the empirical scenario (referred to as S0):

- S1 (*lower AC penetration*): In this scenario, urban households above the 20th income percentile use AC; rural households above the 80th income percentile use AC; the remaining households use fans.
- S2 (*higher AC penetration*): In this scenario, 100% of urban households use AC; in rural areas, households above the 50th income percentile use AC; the remaining households use fans.

How can one frame these targets, which are significantly more ambitious those estimated from the empirical AC penetration modelling based on historical global trends? Currently, total AC-penetration rates in some rapidly developing countries with a warm climate, such as Mexico, Brazil, and Indonesia, stands between 10% and 20%. But in China they reach 60%, irrespective of similar PPP per capita GDP levels to those countries. This disparity highlights the crucial role of policy. According to Goldstein Market Intelligence (2020), air conditioner stocks will reach 1.5 billion units in Africa by 2030, more than double the stock in 2015. As but one example, in Nigeria, more than half a million air-conditioning units are bought each year, and the number is increasing by 4%–5% annually (SEforALL, 2018). Recent reports (Anderson et al., 2020) discuss how up-and-coming, cost-effective and efficient units might boost the policy support for AC.

In our analysis, we focus on appliance adoption among households that current lack electricity access, and are thus exposed to unmet cooling demand. Consistent with previous findings in the literature, adoption is conditional on the geographical distribution of wealth and on the urban or rural status of households (Davis and Gertler, 2015; Isaac and van Vuuren, 2009), and with electricity consumption in recently electrified areas (Lenz et al., 2017; Taneja, 2018).

3.5. ACC electricity-demand assessment

3.5.1. Air cooling (air conditioning)

Once AC adoption is modelled, we estimate electricity consumption at each location. We first model technical ACC electricity requirements as the physical energy that would be required to mitigate all the CDDs at each location. We then model economic demand as function of the expected income growth at each location, and of the electricity demand response based on literature-derived empirical estimates of the income elasticity of electricity demand. (Appendix A provides details of the technical modelling of AC demand.) This section focuses on the energy-economic modelling.

Since we are analysing households that currently do not have access to electricity, and, thus, have no electricity consumption, we modulate the effect of income on future AC use. To estimate future electricity consumption ($ELCONS_{2030}^{projected}$) We assume baseline consumption at the representative values of WB-MTF Tiers 2–3 and 3–4 in urban and rural areas (depending on the scenario considered, and to match the baseline electricity consumption values considered in the geospatial electrification analysis; see Section 3.7). The projection is based on empirical estimates of the income elasticity of electricity demand ϵ_d in developing countries from the literature (Table 2) coupled with average and (future) estimated income-level change:

$$ELCONS_{2030}^{projected} = f(\epsilon_d) \tag{6}$$

Consistent with the approaches taken by Poblete-Cazenave and Pachauri (2019) and Fouquet (2014), a non-constant income elasticity of electricity demand schedule is considered, with declining elasticities as income (based on income quintiles) grows.

Based on these elasticities, we then define the effective AC consumption that could be achieved at a given income level (AC_i^{cons}) as

$$AC_i^{cons} = \begin{cases} AC_i^{techD} \ if \ AC_i^{techD} < ELCONS_{i2030}^{projected} \\ AC_i^{techD} \times ratio_i \ if \ AC_i^{techD} \geq ELCONS_{i2030}^{projected} \end{cases} \tag{7}$$

where:

- AC_i^{techD} is the estimated technical electricity demand (without the income constraints; based solely on the physical cooling needs), as detailed in the Appendix.
- $ELCONS_{2030}^{projected}$ is the total electricity consumption i (inclusive of ACC use) that household i can achieve by 2030 based on its projected income and the associated income elasticity of electricity demand ϵ_d.

Thus, if $ELCONS_{2030}^{projected}$ is sufficient to accommodate AC_i^{techD}, then we assume that the technical energy demand will be met. If it insufficient, it is modulated by $ratio_i$, defined as

$$ratio_i = \frac{ELCONS_{2030}^{projected}}{AC_i^{cons}} \tag{8}$$

Namely,
$ratio_i$ applies to those cases in which AC_i^{techD} cannot be met because it is greater than $ELCONS_{2030}^{projected}$. $ratio_i$ expresses the share of potentially achievable demand $ELCONS_{2030}^{projected}$ over the locally estimated technical ACC energy consumption (AC_i^{cons}).

Note that this income constraint is only applied to AC_i^{techD} in S0 (the empirical AC-adoption scenario). For this scenario, Fig. B.6 in the Appendix shows the residual unmet cooling energy demand gap as a result of income constraints. For the representative scenarios S1 and S2, the whole estimated technical energy requirement to ensure thermal comfort is considered. For the purpose of our analysis, this decision enables quantifying the economic barrier to the achievement of indoor thermal comfort.

3.5.2. Air circulation (fans)

In both the empirical and the representative technology-adoption scenarios, fans are assumed to be adopted by all households who do not own AC. The monthly hours of fan use are set to range between a minimum of zero and a maximum of 16 h × 30 days = 480 h per month. The variation in use is proportional to the CDDs experienced at location i in month m relative to the mean monthly CDDs in the entire year. The fan is modelled as a 70 W appliance absorbing continuous peak power, and thus consuming 0.07 kWh/h of use. Note that a fan is not a perfect substitute to an AC system. Fans do not cool the surrounding space, and thus do not truly mitigate CDDs. However, they move air and disperse humidity – both of which still help people facing high temperatures.

3.6. Sensitivity analysis

Sensitivity of the electricity requirements and potential CO_2 emissions is carried out over two crucial parameters: the base temperature T_{base} and the energy efficiency ratios (EERs) of the representative urban and rural houses. The parametric space of the sensitivity analysis is summarised in Table 3. The baseline value is listed in bold.

3.7. Geospatial electrification modelling

We implement the Open-source Spatial Electrification Tool (OnSSET) geospatial electrification model introduced in Mentis et al. (2017) and updated in Korkovelos et al. (2019). We use the tool to evaluate the ceteris paribus relevance of considering different demand scenarios, both with and without ACC, and based on different baseline values, for: (i) the optimal electricity access planning technological set-up; (ii) the power generation capacity requirements; and (iii) the investment needs.

Table 2
Literature estimates of the income elasticity of electricity consumption in developing countries considered in the current analysis.

Study	Country	ϵ_d	Linked to
Maria de Fátima et al. (2012)	Mozambique	0.69	Wealth Q1
Filippini and Pachauri (2004)	India	0.637	Wealth Q2
Tiwari and Menegaki (2019)	India	0.41	Wealth Q3
Anderson (2004)	South Africa	0.32	Wealth Q4

Table 3
Parameters considered in the sensitivity analysis.

Parameter	Values
Tbase (°C)	22, 24, ***26***, 28
EER (urban)	2.2, ***2.9***, 3.2
EER (rural)	2, ***2.2***, 2.9

OnSSET is a bottom-up electrification planning tool that estimates the locally least-cost energy access system locally (that is, the technology with the lowest cost of electricity at that location) at every geographically defined location of a region for the achievement of electricity access goals. The tool takes as inputs spatially explicit datasets (reported in detail in Table C.2 with the corresponding sources for the data used in this analysis). These datasets include the local renewable energy potential; the price of diesel in every settlement; additional information, such as distance from the currently existing transmission grid; and – crucially for the aims of the current analysis – the electricity demand at each grid cell. The technology choice space includes central grid expansion and densification; mini-grids powered by solar PV, wind, hydro or diesel; or standalone PV systems and diesel generators. Details about the functioning of the model are reported in the official documentation of the model at *https://onsset.readthedocs.io*. In this paper, the analysis is carried out at a 1 km resolution, meaning that optimisation is carried out recursively for each real unit.

Table 4 summarises the parametric space for the scenarios considered in the electrification analysis. The scenarios are derived from the interplay of (i) the baseline demand, differentiated in urban and rural settlements, and imposed from the top down, referring to the electricity consumption levels from the World Bank Multi-Tier Framework (Bhatia and Angelou, 2015); (ii) the ACC appliance-adoption scenario, which determines the share of households at each grid cell adopting either air conditioning systems or fans for air circulation purposes; and (iii) the underlying climate change scenarios, based on the monthly local CDDs, and expressing the location-specific energy need to mitigate excess heat. NoAC scenarios consider only the baseline demand; the other variants add the estimated ACC demand on top of baseline demand based on the interplay of technology adoption (determining ACC and fan adoption) and climate change scenarios (determining the CDDs experienced).

The intertemporal dimension of the analysis merits mention; the electrification modelling aims at achieving 100% access by 2030 for the simulated scenarios. Yet, apart from the baseline climate scenario, the SSP245 and SSP370 scenarios are relative to warming levels for the 2040–2060 period. This is a deliberate choice. The objective of the analysis is to assess the planning of energy access solutions that can prove effective in mitigating future heat stress, at least over the medium run and for the systems' lifetimes. It is also worth mentioning that AC use is considered only in Tier 5 of the Bank Multi-Tier Framework (see Bhatia and Angelou, 2015, *Conceptualisation Report*) – alleviating any potential concern about double accounting of consumption. Conversely, fan use is already accounted for in Tier 2 (minimum 29.2 kWh/hh/yr), Tier 3 (minimum 87.6 kWh/hh/yr) and Tier 4 (minimum 175.2 kWh/hh/yr). These values are therefore subtracted to avoid overcounting fan use.

Finally, Table C.1 details the assumed average techno-economic specific parameters, which refer both the specific electrification technologies represented in the model, and to the general analysis (such as the discount rate, which is set in line with the yield of long-run governmental bonds of SSA governments as reported at *https://www.investing.com/rates-bonds/african-government-bonds*).

4. Results

4.1. Potential ACC service demand and energy poverty

Fig. 3 summarises the results of the calculation for both the present and future climate change scenarios. Globally, CDDs in areas currently without electricity access exhibit considerable spatiotemporal variation across regions and seasons (Fig. 3A). On average, at $T_{base} = 26$ °C households without access to electricity are currently experiencing 450 CDDs/year of unmet cooling. Notably, three-quarters of the populations without access experience only about one-sixth of the global unmet CDDs due to electricity access deficit. Conversely, nearly half of the CDDs are faced by just about 10% of the population that lacks access. This implies that *in those areas it is particularly crucial to plan for technological solutions to provide electricity access that are compatible with the provision of ACC services*.

In the first months of the year, unmet CDD hotspots are observed in the regions near the equator and in southern Africa. In the following months, a strong intensification is observed in the Sahel and Southeast Asia (e.g., India, Bangladesh) until the onset of the rainy season. The last months of the year display a less extreme but also more widespread diffusion of unmet cooling across global hotspots of electricity access deficit. In absolute terms, the Sahel stands out as the region with the absolute highest number of unmet cooling needs during CDDs. On the other hand, east Africa is the region with an electricity access deficit that displays the least ACC requirements throughout the year. Additional details on the country-level yearly distribution of unmet cooling needs during CDDs is found in Fig. B.1 in the Appendix, both in terms of the absolute number of CDDs (Panel A) and relative to the number of people living without access to electricity (Panel B).

We address the future evolution driven by anthropogenic climate change (using data from the CMIP6 simulations for 2041–2060 under the SSPs 245 and 370 scenarios). Our work shows that CDDs will grow robustly worldwide. If assuming ceteris paribus climate change, households currently without electricity access might become exposed to an average additional 265 CDDs/year by 2050; the strongest intensification will likely be observed in large parts of southern and eastern Africa in June–August. The maps in Fig. 3B and C also provide evidence of the difference between the two warming scenarios, considered in terms of the relative change in unmet needs for CDDs in current electricity-access deficit hotspots from today's baseline. Finally, Fig. B.1C in the Appendix plots the absolute change in the CDDs in the current situation with the potential growth over the 2041–2060 period under SSP370. The results reveal that the harshest consequences of anthropogenic global warming on cooling needs (thus also depending on the exposed population without electricity access) are expected in Nigeria (+25,000 million CDDs),[1] the Democratic Republic of Congo (+15,000 million CDDs), and India and Sudan (both at about +10,000 million CDDs). Greater detail on the distribution of CDDs across months of the year and across the three scenarios considered can be drawn from Fig. B.2 in the Appendix. Sensitivity analysis results based on daily historical data and wet bulb CDDs, both at a higher resolution of 0.25°), are reported in the Appendix D. In a supplementary file we provide a csv file containing the monthly estimated country-level CDDs in areas without electricity access for the three primary data sources of historical temperature considered.

4.2. Potential electricity requirements for ACC services

The summary of the results of the energy-demand assessment for the scenarios of different levels of technology adoption and global warming forcing are displayed in Fig. 4 for a set of T_{base} comfort temperature targets (the baseline value being 26C°) and AC-unit EERs (energy efficiency ratios). The numbers refer exclusively to households currently without access to electricity in sub-Saharan Africa. Grid-cell scale maps of the results are visualised in the Appendix B.

The assessment reveals that the scenarios where the empirically modelled appliance adoption and electricity demand is assumed imply significantly lower demand than what would be needed to meet the representative targets of S1 and S2; under the latter scenarios, higher

Table 4
Parameters considered in the sensitivity analysis.

Baseline demand (kWh/hh/yr)	Tech. adoption scenario	Climate change scenario
U: 1250; R: 365; U: 365; R: 73	noAC, Empirical (S0), S1, S2	Baseline, SSP245, SSP370

[1] These figures refer to the CDDs multiplied by the population experiencing them.

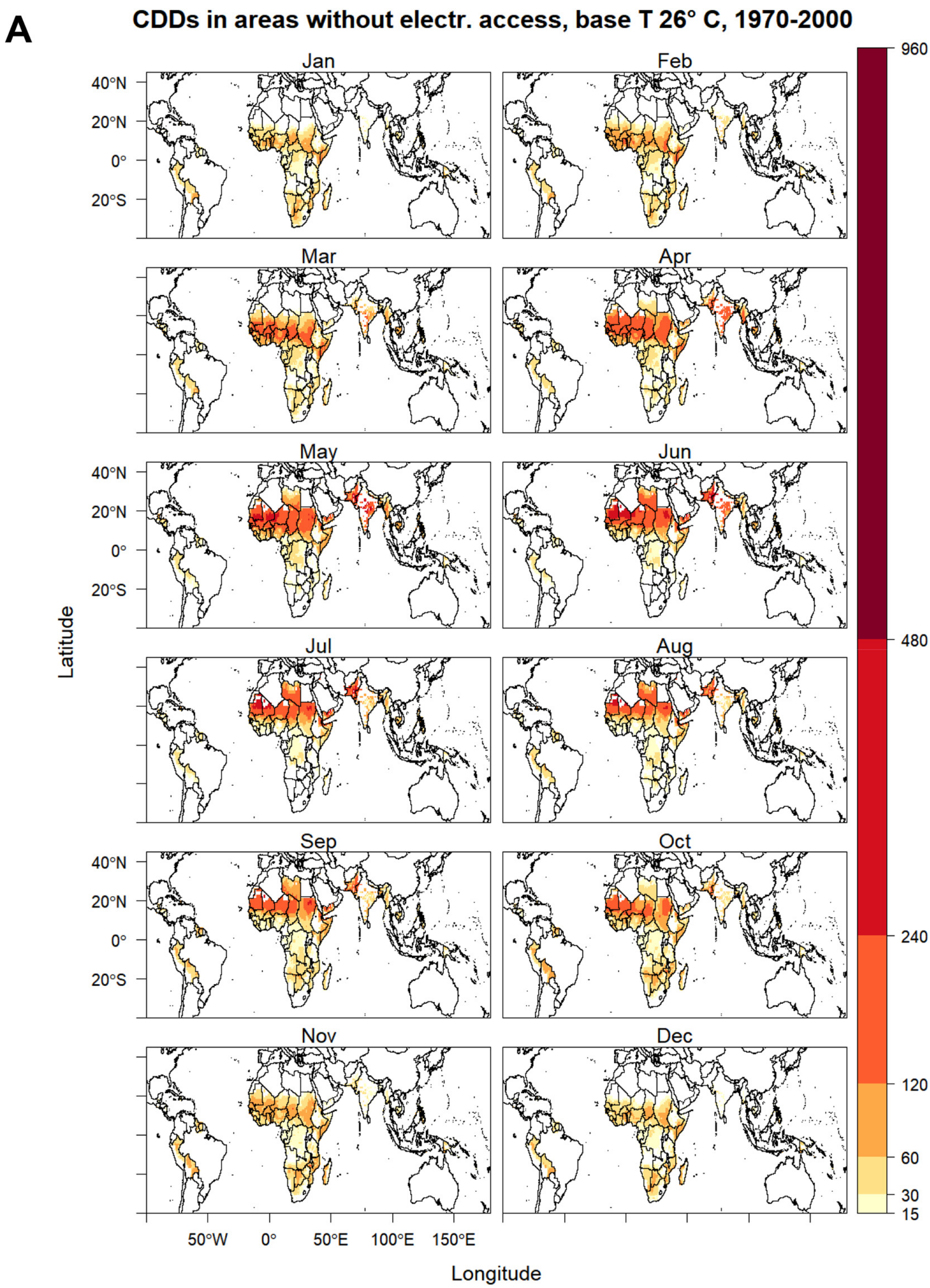

Fig. 3. Average monthly CDDs for 2020 and the 2040–2060 period in areas with deficits in access to electricity. (A) Historical CDDs based on WorldClimate 1970–2010; (B) Projected % change in CDDs for CMIP6 output from the eight CMIP6 GCMs considered forced on SSP245; (C) Projected % change in CDDs from the eight CMIP6 GCMs considered forced on SSP370.

AC penetration rates are simulated, and their use is bounded not by household income but only by the physical need to mitigate indoor thermal discomfort. The results for the current climate and an indoor temperature objective of 26C° vary – ranging from about 25 TWh/year to nearly 100 TWh/year, and highlighting this large cooling gap. T_{base} is found to exert a significant impact on energy demand across all scenarios, while climate change becomes a significant driver of energy demand only in S1 and S2; S0 displays AC penetration rates that are too low to create a large impact. The same pattern is observed for the sensitivity analysis over the efficiency of AC units adopted. For S1 and S2, at constant T_{base}, the key role of AC unit efficiency stands out as a pivotal factor in determining energy demand outcomes. Overall, the results suggest that the electricity requirements are very sensitive to appliance adoption and, thus, to income. If AC penetration is bounded by the global historical income-adoption relationship, and if AC use is restricted to the range of income elasticity of electricity demand in developing countries, then thermal discomfort is bound to persist, even if universal electrification is achieved. Conversely, if different pathways

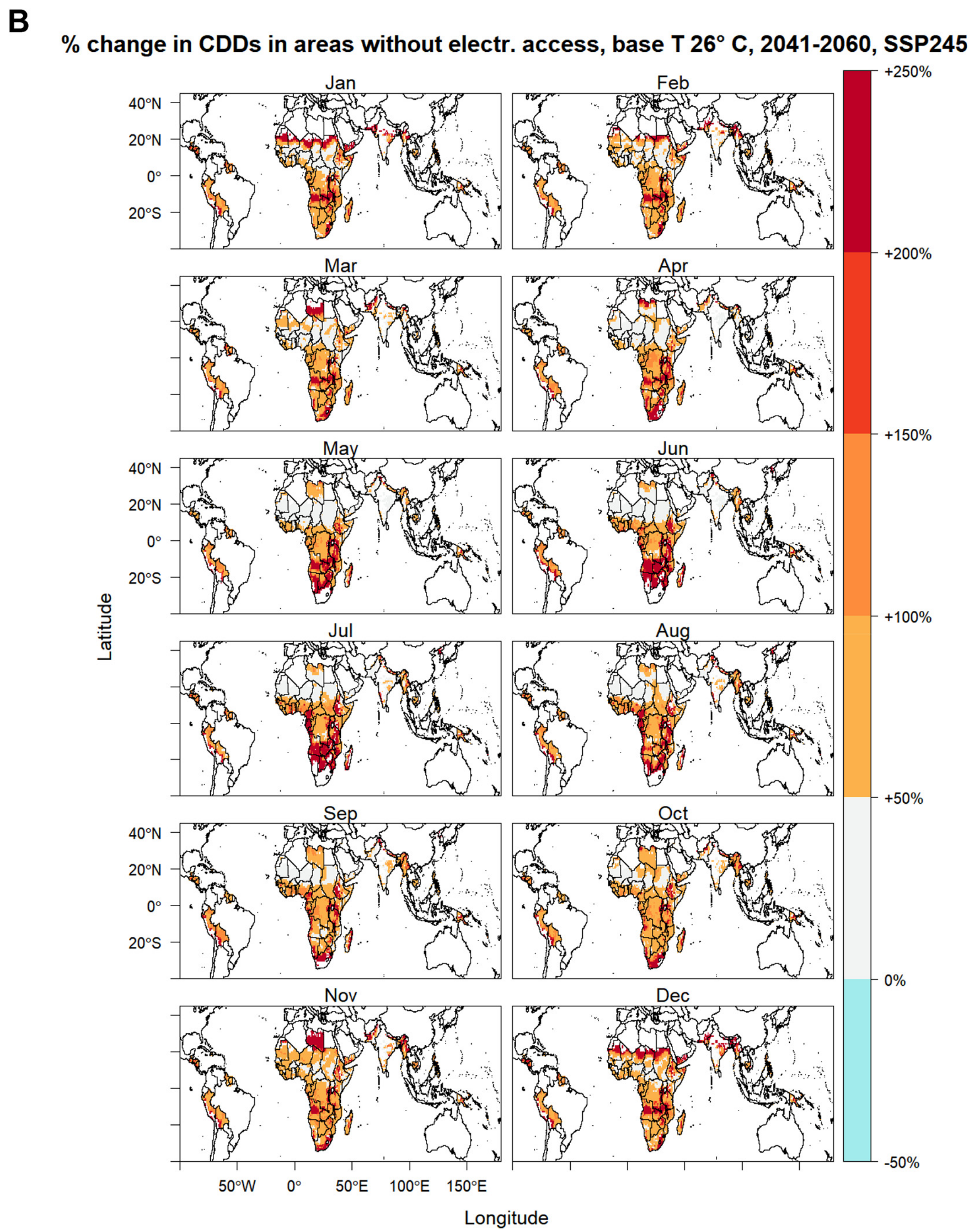

Fig. 3 (*continued*).

are followed (e.g., if AC use is pushed by policy support, technology cost reductions, or faster economic growth), outcomes similar to those described by S1 and S2 could be witnessed, with a significantly greater energy demand. To complement the analysis, in Appendix B we report the estimated CO_2 emissions from ACC use in each scenario considered.

The results of our bottom-up calculations are in line with recent regional estimates (IEA, 2018) projecting that Africa will witness an increase in air circulation and cooling electricity demand from the current 11 TWh to 112–223 TWh/year by 2040 depending on the efficiency of appliances and their use, and the efficiency of buildings. Yet, it must be remarked that the numbers reported in those studies also include air cooling energy needs from households that have electricity at home but lack ACC appliances at home; by contrast our estimates are a subset of those comprehensive figures because they are only relative to households currently without electricity access at home. Another comparison can be made with the regional estimates from Mastrucci et al. (2019), who estimate a consistent cooling energy gap of 135 TWh/year for sub-Saharan Africa.

4.3. Role of cooling services for electrification planning in sub-Saharan Africa

Energy demand is a crucial variable in electrification planning. It defines the outcome of the trade-off between central grid expansion and the uptake of decentralised solutions (mini-grids or stand-alone generation technologies). It also affects power generation capacity

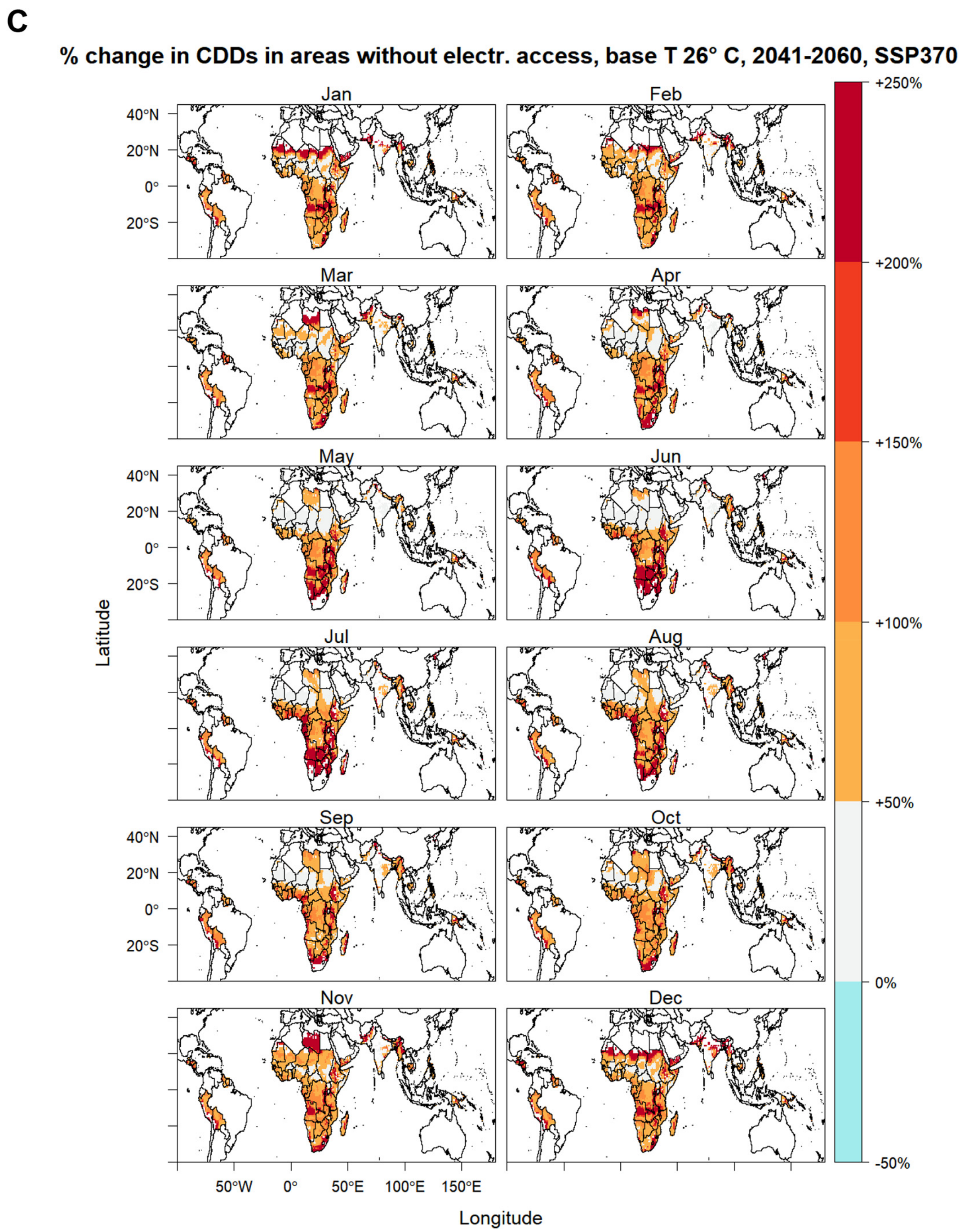

Fig. 3 (*continued*).

requirements, and, therefore, the overall investment requirements. Previous regional-scale assessments about the optimal electrification strategy in sub-Saharan Africa have highlighted a relevant share of stand-alone solutions: the IEA's *Africa Energy Outlook 2019* (IEA, 2019a) argues that mini-grids and stand-alone systems will serve 30% and 25% of those gaining access by 2030, respectively. For more than half of the households currently without electricity access, the problem could be solved by decentralised energy technologies. According to Dagnachew et al. (2017), stand-alone systems (dominated by solar home systems with battery storage) could generate power sufficient for more than 40% (at Tier-1 target) or less than 5% (at Tier-5 target) of needs, with mini-grids in all scenarios accounting for less than 10% of the new connections. Levin and Thomas (2016) find that that, given current technology costs, central grid expansion is extensively required to enable higher levels of consumption; however, they express confidence that technological cost-reduction trends will disrupt the paradigm, giving a comparative advantage to decentralised systems over the centralised electrification paradigm.

Our ACC-related potential electricity demand estimates allow to explore the tight interconnections between SDG 7's electricity access target and ACC needs. We calibrate a geospatial electrification model for sub-Saharan Africa, which has the largest deficit in electricity access in the world (the region is home to more than 75% of the global population without electricity access, IEA and IRENA, 2019) To calibrate the model for this critical regions, we add the local ACC electricity requirements for the different warming and technology-adoption scenarios on top of a

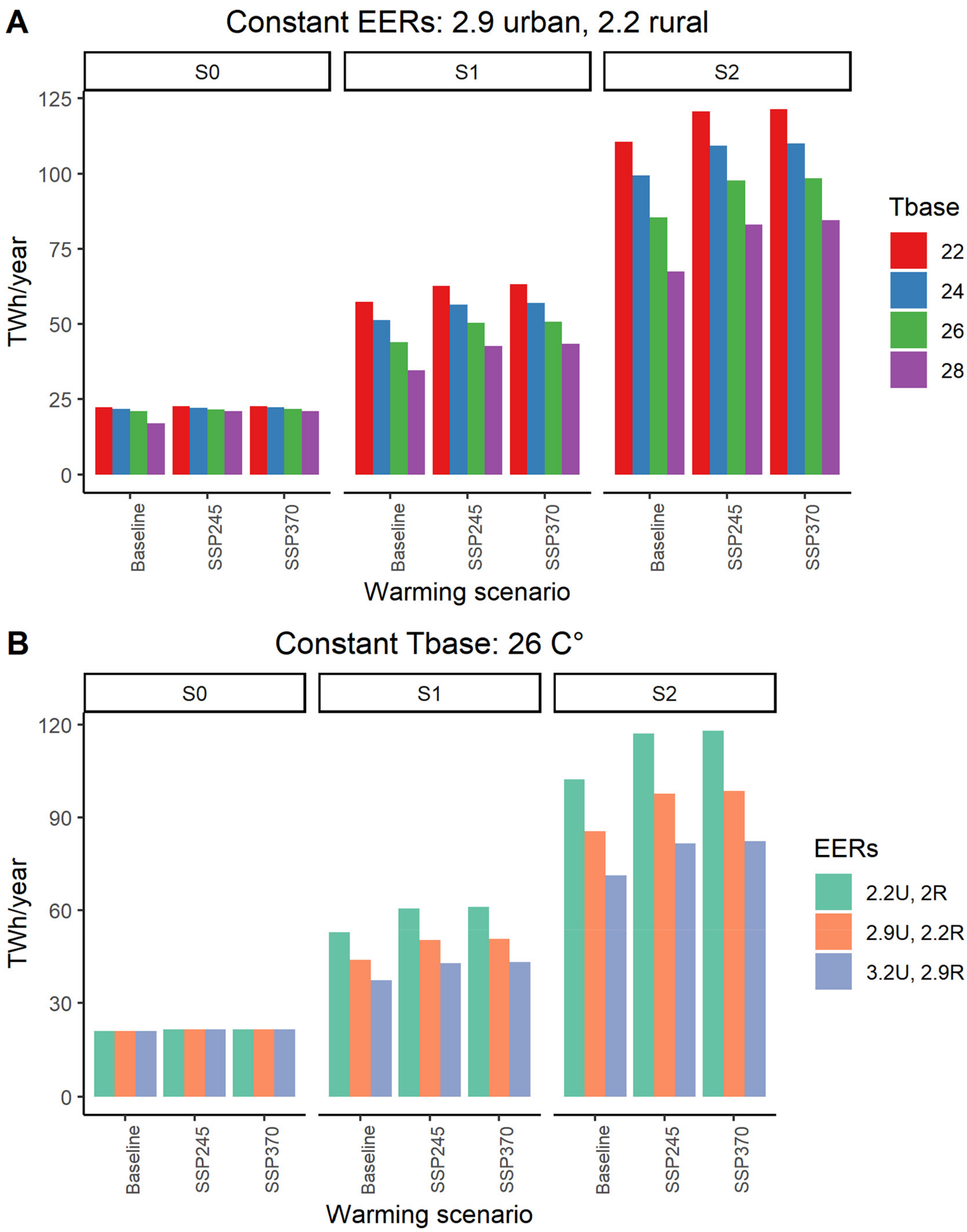

Fig. 4. Average yearly potential ACC electricity demand from households currently without electricity access in sub-Saharan Africa under the assumed parameters for three technology-adoption scenarios and three climate scenarios (baseline, SSP245, SSP370). (A) Results under different T_{base} (comfort temperature) targets; (B) Results under different AC-unit EER (energy efficiency ratio) variants, where U and R are the assumed EERs of AC units of urban and rural households, respectively.

set of baseline yearly household electricity consumption. The model is forced to provide universal household access to electricity by 2030 under the different demand scenarios considered. Note that the model projects heterogeneous urban-rural population growth to 2030 (Table C.1) and, thus, also total ACC energy demand.

Recent empirical evidence (Bensch et al., 2019; Chaplin et al., 2017; Hoka Osiolo et al., 2017; Lenz et al., 2017; Taneja, 2018; Tesfamichael et al., 2020) suggests that communities that gain access generally consume little electricity. Under the context of the World Bank Multi-Tier Framework for Measuring Energy Access (WB-MTF), most households consume electricity at levels that would be between Tiers 2 and 3 in rural areas, and between Tiers 3 and 4 in cities. Tiers 4, 3 and 2 imply consumption levels of 423, 160, and 44 kWh/HH/year, respectively. Our baseline consumption targets are therefore set around these values because as policymakers and companies will likely seek to invest their resources optimally when sizing electrification solutions. To these baseline consumption targets we add ACC energy needs according to our ACC appliances adoption and climate scenarios. The materials and methods sections provide detailed information about the electrification analysis approach, the techno-economic assumptions, and the data sources. The final aim of the assessment is to evaluate the role of the estimated ACC energy requirements on the optimal technology set-up and investment requirements to achieve universal electrification.

Our results (Fig. 5A) show that accounting for the estimated ACC needs on top of baseline residential consumption targets implies a scenario-mean reduction of 4.5% (varying between 0.4% and 9.3% across scenarios) in the share of decentralised systems as the least-cost electrification option by 2030. This result reflects the shift in the cost-optimality between central grid extension and stand-alone energy access systems. Fig. 6 maps a representative shift between scenarios of equally low baseline demand but differentiated ACC appliance adoption (noAC and S0). While the impact of considering cooling energy on the optimal electrification systems set-up is evident, the most remarkable impact is observed on the investment requirements to achieve universal electrification (Fig. 5B).

The scenario-mean investment ramps up considerably, up 65.5% (varying between 18% and 118% across scenarios) with growing AC adoption as a result of both the different optimal electrification technology set-up to supply the required energy demand itself, and, to a much larger extent, as a result of the growing load and power consumption under growing AC adoption. Cumulative investment requirement to 2030 vary from a low of about \$146 bn (\$14.6 bn./year) under *t32* baseline demand and no inclusion of AC needs, and nearly \$1058 bn (\$106 bn./year) for a scenario of high baseline demand (t43), substantial air conditioner system uptake (S2), and a warmer climate (SSP370). Finally, as shown in Fig. 5C, climate change alone increases the scenario-mean investment requirements by 4% (the mean of 1%–8.7%).

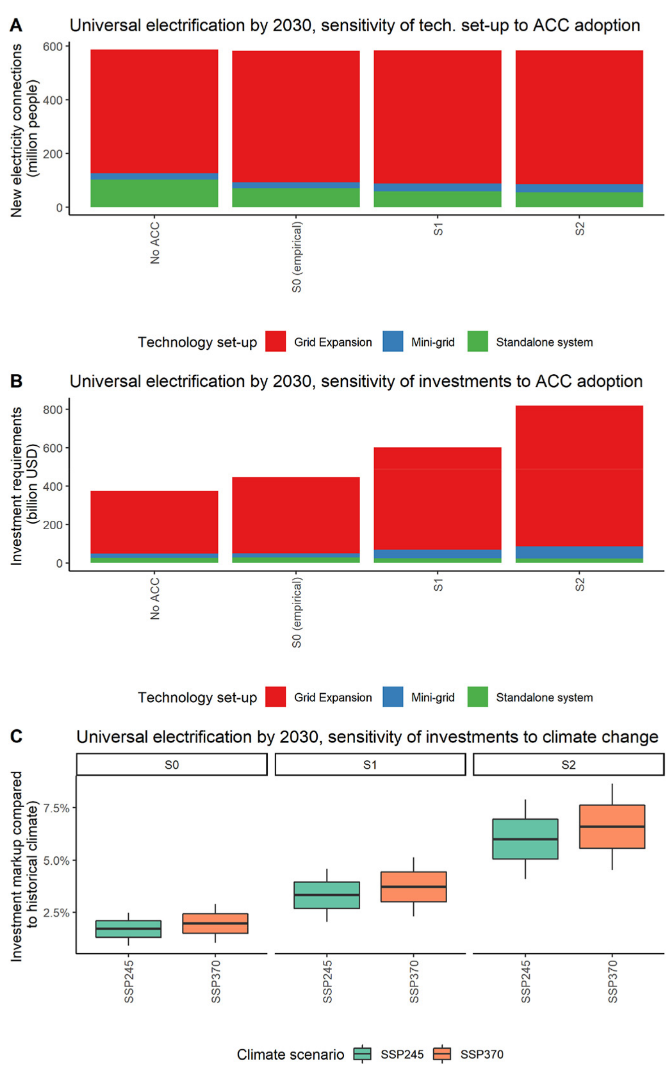

Fig. 5. Results of the geospatial electrification analysis under a universal electrification by 2030 target. (A) Optimal technology set-up (% of new connections) across a variety of demand scenarios and electrification systems under different ACC appliance- adoption scenarios. (B) Cumulative investment requirements for electrification (bn. USD) under different ACC appliance adoption scenarios. (C) Investment mark-up (% increase) as a result of climate change compared to historical climate conditions.

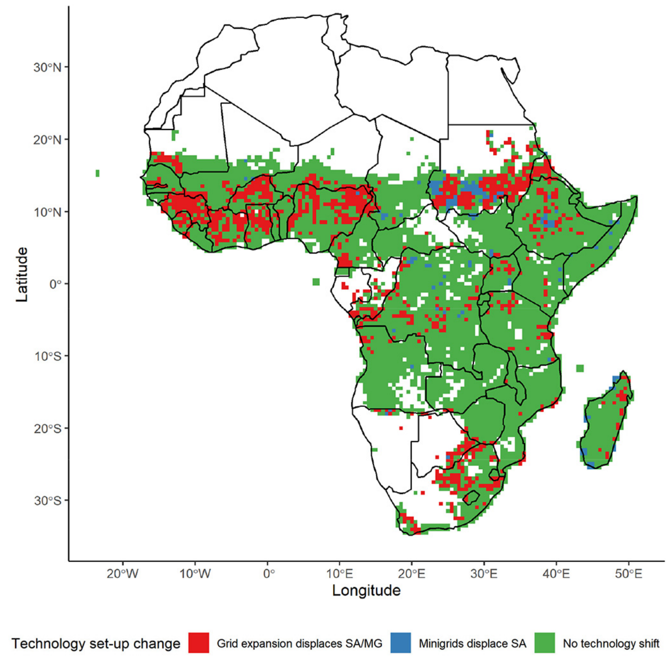

Fig. 6. Map of sub-Saharan Africa showing the ceteris paribus shift in the least-cost electrification set-up when considering baseline and ACC-inclusive demand scenarios.

It is challenging to directly compare these investment requirements with figures reported in previous studies due to the variety of assumptions, scenarios, baseline years, and demand targets. Yet, these figures are in the same range of variability of seminal findings (Mentis et al., 2017; Pachauri et al., 2013; PBL Netherlands Environmental Assessment Agency, 2017), suggesting that plausible techno-economic assumptions are made.

The results of our analysis confirm that planning electricity supply effectively depends on energy demand. In turn, the results suggest that if thermal discomfort in SSA is to be mitigated, ACC services need to become much more pervasive than under a baseline scenario. In turn, in this scenario ACC use would drive a very strong increase in energy demand in the residential sector, particularly among households that should gain access to electricity over the next decade (provided SDG 7 will be achieved).

Yet, several modelling and policy inputs suggest that in many areas the only financially viable options in the medium run appear to be electricity-access plans based on large-scale uptake of stand-alone solutions, or those based on conservative demand targets. Policymakers should be aware, however, that such electrification strategies might leave many without indoor cooling adaptation options under a warming climate and, therefore, in persistent energy poverty, with potential repercussions on welfare and development prospects. On top of that, adjusting adaptation needs plays a major role in the required power generation capacity for ACC and therefore in the total investment needs to deal with a changing climate. We argue that these hidden costs and benefits should receive more relevant consideration in electrification policy.

4.4. Main limitations

The key limitations of these results include: *(i)* the uncertainty over the distribution of the population without access to electricity. This uncertainty comes both from the quality of the primary census data on which gridded population products are based, and the proxy nature of the global, spatially explicit electricity access assessment based on night-time lights (Falchetta et al., 2019). *(ii)* The consideration of the CDD metric. Standard CDDs are useful for their simplicity and standard use in the climate and energy engineering fields. Yet, they overlook important dimensions affecting the perceived heat such as relative humidity and wind chill. Given the large spatiotemporal scale of the analysis, CDDs were preferred as climatic indicators. Additional results considering wet-bulb CDDs that account for relative humidity are reported in Appendix D. *(iii)* The unavoidable degree of uncertainty or arbitrariness in the scenarios of ACC appliance adoption and use. While we modelled both empirically grounded and archetypical policy-descriptive scenarios, each comes with data and scenario uncertainty. The estimates cannot be validated on real data for SSA countries, as there are no extensive data on household ACC appliance ownership and use for the countries considered in the analysis. It must be remarked that while the seminal model of McNeil and Letschert (2008) is only fit on 64 data points between 1991 and 2007, an African-specific calibration based on more recent data (e.g. from the *Integrated Public Use Microdata Series*) would not be meaningful in the context of the current analysis. In fact, projected income levels for 2050 would mostly fall outside of the calibration range (the current distribution of income levels in SSA counties), and the estimate would thus rely on a highly uncertain extrapolation. To mitigate these concerns, supplementary material provides data and code to facilitate ready replication of the analysis, including modifications in the scenario assumptions and future ad-hoc calibration upon availability of survey data. *(iv)* The lack of consideration of alternative technologies such as evaporative cooler technologies, passive buildings, and urban planning options that can mitigate CDDs while requiring less energy. Note however that most of the electricity access deficit is concentrated in rural areas, where these architecture and urban planning options are less viable. Further research examining the linkages between energy poverty and ACC needs could consider these important aspects. An ad hoc decomposition analysis – beyond the scope of this paper – could help to shed light on the degree of significance of each determinant in the optimal system outcome.

A final remark concerns the necessary consideration of aspects related to utility capacity to plan the power system and regulatory quality of the energy sector. As benchmarked by the RISE (Regulatory Indicators for Sustainable Energy) such planning capacity and regulatory quality are still lagging behind in several SSA countries. Institutional and regulatory quality are fundamental conditions for the expansion of generation, transmission and distribution capacity – including enabling private investment in standalone and mini-grid solutions (Ahlborg et al., 2015; Emery, 2003; Sergi et al., 2018). Our geospatial electrification analysis is purely techno-economic, and therefore it does not specifically embed these dimensions. An application in this direction is found in Falchetta et al. (2021).

5. Discussion and conclusions

5.1. Future cooling demand from energy-poor households

In this paper we carried out a planning-oriented assessment of energy-poor households' exposure to thermal discomfort and heat-related health threats in coming years. The ultimate aim is to estimate the energy requirements to meet cooling needs among the world's energy-poor households, which are likely to experience higher temperatures on many more days of the year as a result of climate change. We considered an empirically grounded scenario and a set of archetypical, policy-descriptive scenarios to analyse the ramifications of expected income growth, climate change, and future adoption and use of cooling devices.

The results from climate-energy ACC modelling show that *the mix of air circulation and cooling technologies adopted by households is the single most impactful driver of energy demand.* The penetration of air conditioning will play a disproportionately larger role than a universal adoption of fans, even at very high intense use of fans (as recently discussed in IEA, 2020, 2018). Our empirical modelling suggests that income is a severe constraint to AC use. This will continue to be the case unless costs, priorities, or policies change on the demand side – and in ways that run counter to the historical relationship between income, electricity demand and the adoption of air conditioning globally. The representative scenarios model these archetypical pathways for estimated energy-consumption levels needed to guarantee universal indoor thermal comfort. The gap between the empirical and representative scenarios is wide. This gap highlights the risk of persistent thermal comfort discomfort and heat-related hazards to health for many people worldwide – even if an expected rise in the affluence of countries in sub-Saharan Africa takes place. This should be a reason for concern among relevant decision-makers worldwide.

Finally, irrespective of the base temperature considered, the efficiency of the installed AC units will have very substantial impacts on energy consumption, especially if the penetration of air conditioning grows significantly. Indeed, this issue is already at the centre of recent institutional reports aiming to minimise various impacts on the costs and energy required to use air conditioning in the future (Anderson et al., 2020; IEA, 2018). For example, some countries – Ghana, Nigeria, Kenya, and South Africa, among them –have established minimum performance standards for new air conditioners, and they have banned the import of second-hand, inefficient units.

5.2. Policy implications for electricity-access planning and investment needs in sub-Saharan Africa

Based on the wide range of cooling-related, energy-demand scenarios estimated, we carried out electricity-access planning analysis specifically targeted to sub-Saharan Africa. This region is home to the greatest concentration of populations who lack access to electricity, and it is also vulnerable to rising temperatures that are forecast to occur as the climate changes. Our results show that providing universal electricity supply compatible with scenarios in which different cooling technologies are adopted and used requires significantly larger investments than under baseline demand; indeed, to accommodate such use, investments would need to grow by a mean 65.5% (varying between 18% and 118% across different scenarios). This markup will grow further when one quantifies the impact of future climate change on energy demand for thermal cooling. When we compare the historical climate with two different scenarios forecast for the 2040–2060 period, we find that the electric energy to address the increased number of cooling degree days that energy-poor households are likely to experience grows by an additional 4% (between 1% and 8.7% under different scenarios).

Moreover, adding cooling-related energy needs to conservative demand targets has important technological implications. In some areas, the optimal technology set-up shifts away from decentralised energy access systems. This is because decentralised energy access systems – particularly stand-alone and home systems – might not be able to meet the high peak-power requirements of air conditioning, unless very efficient appliances are adopted (IEA, 2017). In addition, a high density of electricity demand can make decentralised solutions economically inefficient compared to the costs of extending the national grid because of economy-of-scale dynamics (Deichmann et al., 2011).

The key lesson from this study is that planning universal household electrification without explicitly accounting for thermal comfort needs may result in large energy-supply deficits and persistent energy poverty – even with the nominal universal electrification that might be achieved even with small-scale, low-power systems. Leaving millions of households with unmet and growing needs for cooling to deal with the increase in the number and intensity of cooling degree days could negatively affect the broader socio-economic development of low-income countries as a result of the negative repercussions on physical and mental health, and on productivity.

Our findings should not be interpreted as arguing against decentralised energy access systems; to the contrary, these systems have the major advantage of allowing for minimum levels of electricity access at relatively lower prices – and chiefly in areas where the grid extension would require very large investments. In fact, decentralised systems are only growing in relevance and potential thanks to emerging, innovative business models and technological advances (Mazzoni, 2019) that can abate upfront cost barriers. Energy-ladder (Chattopadhyay et al., 2015) and energy-development nexus theories (Riva et al., 2018) argue that basic energy access can provide the spark to initiate socio-economic development, and allow households to “climb the ladder” towards more robust energy supply systems. The empirical evidence testing the validity of these claims is still mixed (Grimm et al., 2017; Urpelainen, 2019). Yet, from a public-policy perspective, regions relying on stand-alone electricity access risk finding themselves on the periphery of policymakers' attention. Such areas may not be considered priority destinations for investment of funds to expand central infrastructure. Therefore, irrespective of whether they become nominally electrified with standalone solutions, these regions could remain in energy poverty for a long time. They could find themselves unable to operate cooling services, and unable to adopt other autonomous adaptation measures.

Overall, we encourage decision-makers to consider cooling needs and other energy-consumptive adaptation actions in policies targeted at expanding electricity access. These cooling needs should be integrated into power-generation capacity planning. Such needs will almost certainly be strong drivers of electricity demand growth from the residential sector in the coming years. These needs should also be reflected in national greenhouse gas mitigation policies, and planning needed to meet countries' Nationally Determined Contributions to the Paris Agreement. These issues merit the attention of many related players at the interface between institutions that deal with energy access,[2] cooling planning,[3] and overall government planning. These organizations face enormous tasks to address the complex issues of expanded electricity access, greater cooling demand, the implications for human health and safety, and the wider context of achieving global sustainable development and adapting to climate change.

Declarations of interest

None.

Data availability

Input data are accessible from the following Zenodo repository: https://zenodo.org/record/4010319. Computer code to replicate the analysis can be retrieved from https://github.com/giacfalk/cooling_electrification.

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[2] e.g., E4ALL, ISA, ESMAP, Power Africa, RES4Africa

[3] e.g., Cool Coalition, KCEP, United for Efficiency, Global ABC, PEEB, Solar Cooling Initiatives

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2021.105307.

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