Decent living gaps and energy needs around the world

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Decent living gaps and energy needs around the world

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Abstract

In recent years, there has been growing interest in defining what exactly constitutes "decent living standards" (DLS)—the material underpinnings of human well-being. We assess the gaps in providing decent health, shelter, nutrition, socialization, and mobility within countries, across the world. Our results show that more people are deprived of DLS than are income-poor, even when numbers are measured against medium income poverty thresholds. We estimate the cumulative energy needs for building out new infrastructure to support DLS provision for all by 2040 to be about 290 EJ, which amounts to less than three-quarters of current annual global energy demand, at the final energy level. The annual energy requirements to support decent living for the global population after 2040 is estimated to be 156 EJ yr^{-1}. Present average energy demand levels in most countries exceed hypothetical DLS energy needs. Nevertheless, the required rate of increase in energy to provide decent living for all in the coming two decades would be unprecedented for many countries. Greater attention to equity would significantly reduce the need for growth. The per capita energy requirement of different countries to meet the same DLS levels varies by up to a factor of four due to differences in climate, urbanization, diets, and transport infrastructure. Transport energy dominates energy for decent living worldwide, while housing requirements dominate upfront energy investment needs. This study supports the claim that the increase in energy provision poverty eradication does not, in itself, pose a threat to mitigating climate change at a global scale. Distinguishing energy for affluence from energy for decent living could provide a basis for defining equitable access to sustainable development in energy terms.

1. Introduction

Eradicating poverty and avoiding ecological breakdown are both linked to energy use [1–7]. Each of these goals seems frustratingly out of reach despite much progress being made on international commitments, for example, the Sustainable Development Goals (SDGs) and the Paris climate agreement. The good news from recent research is that essential energy needs to meet everyone's basic needs, framed as "decent living standards" (DLS) [8], could constitute a small share of projected energy growth [9, 10], namely, around an order of magnitude lower than current US energy demand. For many poor countries, however, growth is inevitable and urgent. While in emerging and industrialized countries average energy needs may hypothetically be sufficient to meet DLS for all, widespread poverty still exists [11] alongside growing affluence [12]. It is unclear where countries stand today with respect to multidimensional poverty eradication, and how fast their energy sectors must grow to achieve DLS in the next few decades. Here, we estimate the energy investments needed to provide and sustain DLS under different commitments in order to accelerate poverty eradication efforts.

Decent living standards constitute a set of material satisfiers that are necessary for human well-being (DLS) [8]. They have served as the foundation for estimating the amount of energy hypothetically required for decent living [9, 10] but they also provide a set of universal material satisfiers with respect to human deprivations at an individual, household, communal, and national level [8]. These satisfiers include adequate shelter with thermal comfort, nutrition, water and sanitation for hygiene, clean cookstoves and cold storage, health and education, communication technologies, and adequate physical mobility through motorized transport.

Here, we advance the decent living framework by assessing energy needs based on currently observed multidimensional poverty around the world. As a result, this analysis directly addresses the implementation challenges of the poverty-related SDGs. Previous research estimates energy needs for providing DLS—defined similarly by this study—as being 13–40 GJ per capita globally [9, 10]. Values found in early bottom-up work based on different measures of basic needs also fall in this range [13]. However, as none of these studies assess the gaps in DLS, they cannot estimate the amount of energy needed to fill the gaps and therefore lack some power to place these energy needs in the context of historical energy demand growth. We assess region-specific energy needs that account for differences in climate, existing infrastructure, urban and rural requirements, population growth, and different diets. This allows for identifying the most energy-intensive dimensions of DLS globally. As previous work in three countries shows [9], energy intensities of sectors can differ significantly by region. Notably, we assume only modest efficiency improvements, rather than relying on an ideal, high-tech future.

Our estimates potentially inform both energy and climate policy. In this light, decent living energy (DLE) can help operationalize the principle of equitable access to development that undergirds equity in climate agreements. This gains importance with stronger climate ambition [14, 15].

2. Data and methods

We adopt previous definitions and threshold quantities of DLS dimensions [8, 9]. Here, we describe some of the elemental steps of this bottom-up approach and focus on describing the departures from past research necessary for a global study. In essence, this work makes two methodological advances: first, we account for country-specific variation in the material satisfiers based on climate, urbanization, culture, and prevailing technological and economic structure; second, we estimate DLS gaps more accurately by accounting for within-country distributions where relevant. We undertake the following steps. (a) Customize DLS threshold values to national circumstances, for instance by accounting for urban and rural differences. (b) Calculate the DLS gaps by dimension for all countries, using a set of heuristics to fill data gaps, as described below. (c) Calculate the current energy used for decent living standards per country, as well as the energy needs to fill the gaps in decent living. We do this by estimating final energy intensities of materials for both operation and construction. (d) Construct stylized scenarios of how quickly households obtain access to DLS, accounting for future demographic changes.

For convenience in presenting, we group all material satisfiers into five needs categories: *Nutrition, Shelter, Health, Socialization, and Mobility*. The components are further described below.

2.1. Nutrition

Food needs to be produced, prepared, and stored. Thus, we include in this category sufficient calories, access to clean cook stoves, and refrigerators. To determine the calorie gap, we follow the Food and Agriculture Organization of the United Nations (FAO) indicator of minimum dietary energy requirement at a national level [16]. Undernourishment is estimated assuming a lognormal distribution of calorie consumption, following FAO methodology [17]. This, combined with the daily energy supply and the coefficient of variation provided by the FAO, yields the depth of deficit by country, which serves as the decent living nutrition gap. For fridge and cook stove ownership, we use data from the Demographic and Health Surveys (DHS) Program [18], aided by national statistics where needed [19].

2.2. Shelter

Shelter includes sufficient space, durable construction, heating and cooling equipment, and clothing. We include clothing here because of its insulating function, which primarily determines the necessary quantity in different climates. To fill data gaps for the decent housing indicators, we devise a heuristic to determine the housing gap based on UN Habitat data on urban slum population [20] and survey data on rural housing with permanent walls [21] (see supplementary information (SI), available online at stacks.iop.org/ERL/16/095006/mmedia, for more detail and a sensitivity analysis). We combine household size distributions in countries with the per capita and per household space thresholds from [9] to derive the housing construction needs separately for urban and rural populations. We estimate gaps in heating and cooling equipment for the existing housing stock. Thermal comfort needs are calculated using the methodology from [22], taking into account regional building characteristics and weather, under the assumption of current climatic conditions. Traditional biomass for heating is not considered "decent" energy because of its adverse health effects and its inefficiency.

We derive the threshold quantity for clothing for the Global South regions (see SI for region definitions) based on the median kilogram consumption per capita in India (from [9]), and for the Global

North based on the analysis in [10], considering climatic differences. We assume no clothing gap in the Global North.

2.3. Health

We include access to safely managed clean water and sanitation with sufficient supply, hot water for showering, and general health care. Here, we use the World Bank's new, higher standards for water and sanitation access, which require on-premise potable water supply, and sanitation systems that separate sewage management from daily life. Where data are not available, we estimate these gaps using infant mortality data, which were found to correlate strongly with water and sanitation access (see SI).

2.4. Mobility

Motorized transport requires the construction and maintenance of public infrastructure like roads and rail, vehicles, and energy for operating such vehicles. We follow previous approaches [9, 10] in using motorized passenger kilometer (p-km) for our threshold indicator. We derive a national average threshold value (23.4 p-km d^{-1} cap^{-1}) from the average motorized transport within the daily living area in Japan [23]. The rationale for using Japan as a template is that it represents a society with relatively low travel demand with no significant mobility gaps. Thresholds are adjusted for projected urbanisation, based on the observed difference between rural and urban travel demand in the USA (see SI). To ascertain the mobility gap, we observe that motorized travel follows a lognormal distribution, much like income ([24, 25], SI). Accordingly, we estimate both the share of population below the threshold and the depth of deficit based on average p-km per region by modal share [9, 26, 27], and a regional Gini index of inequality [20]. This approach yields mobility gaps even in industrialized countries. In reality, such transport deprivation results more from high costs than from insufficient access. Affordability considerations are, however, beyond the scope of this study.

2.5. Socialization

A decent life includes education, communication services, and access to information to be able to participate in society. For the latter two, based on DHS data [18], we use the availability of a mobile telephone and a television per household as a proxy for access to information and communication. This estimate does not include back-end internet infrastructure, which would likely have been of the order of 1%, or less, of total DLE. Government expenditure per capita is used as an indicator of education access. We use the median of the most efficient half of government expenditure for countries with at least 95% completion rate for primary education and at least 90% for lower secondary education, based on data from the UNESCO Institute of Statistics [28].

2.6. Methods for a global decent living assessment

Calculating decent living gaps for 193 countries requires reasonable assumptions to be made to fill data gaps on the start year (2015) conditions. We used several heuristics, depending on the nature of the data—linear regression, cross-sectional correlation, or averaging—which are described in the SI.

To compare the extent of DLS deprivation with conventional income poverty, we aggregate DLS dimensions into the highest-level groupings of physical and social well-being, taking the mean of the mean headcounts of these two groupings. As there is no correct aggregation method, we discuss robustness alongside other aggregation methods in the SI. This headcount calculation does not affect the energy gap calculations, which are conducted individually for each dimension and depend only on the average gap in services.

To calculate the direct and indirect energy needs per DLS dimension for both operational and embodied energy, we used the energy demand model in [29]. We use a combination of a simulation model (housing), a multi-regional input-output database EXIOBASE [30] (clothing, education, health care, and nutrition), and lifecycle estimates from literature for the other dimensions.

Our energy estimates deliberately retain current conditions of technology and material intensity. We do not know of any data on realistic rates of autonomous energy efficiency improvements in the particular product categories that fall within DLS by region across the world; nor do we know of any reasonable method of estimating them.

2.7. DLS rollout scenarios

We construct two sets of scenarios of the rate at which DLS are achieved. This provides a range and timing of energy investment needs. The first set of scenarios takes three different target years (2030, 2040, 2050) for achieving DLS for all between 2030 and 2050, representing the ideal of SDG achievement and more realistic alternatives. New construction proceeds at a constant pace from the start year (2015) until the target year. The scenario with target year 2040 (from here on DLE-2040) serves as the default for analysis throughout.

In addition, we provide a rudimentary, stylized scenario in which DLS improvements track economic growth (DLE-GDP). The relationship implemented between DLS and economic growth is based on a cross-sectional analysis of decent living gaps against *log*(GDP per capita) in 2015 (see SI) and serves as a *what-if* scenario, while leaving more sophisticated projections of DLS as an area for further research.

We focus on population and GDP projections from Shared Socioeconomic Pathway (SSP) 2 (middle of the road) [31], with 2030 and 2050 targets and other SSPs reported in the SI.

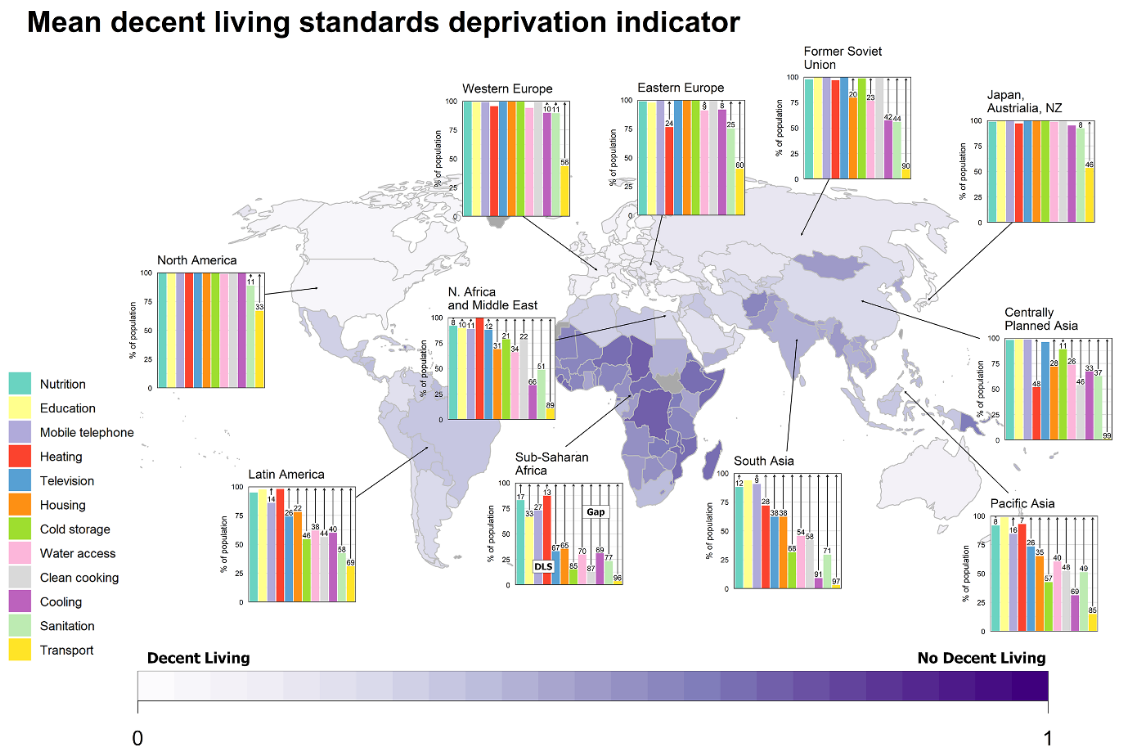

Figure 1. Mean decent living standards (DLS) deprivation indicator. The map shows the mean DLS deprivation for each country as a share of population from zero to one. Bars show the regional average percentage of population with decent living standards, with numbers indicating the decent living gap in percentages for each DLS dimension.

While we intend the DLS to be universal, material satisfiers can differ in terms of quality and other characteristics. As we aim for a comparative assessment of energy needs, we would ideally want to normalize DLS, adjusting for such differences. For most dimensions, this is beyond the scope here and remains a point of improvement for future work (including for instance, material requirements for good water quality or health care). However, the mobility dimension merits special attention. Energy intensities and user characteristics vary strongly by mode of transport. Private vehicles provide a unique degree of freedom and require a unique extent of infrastructure (road network). Countries vary widely in their car dependence, which largely correlates with income. Keeping countries' mode shares constant implicitly grandfathers inequities in mobility-related energy and service provision. We therefore assume that all regions with high private modal shares converge to levels of public mode share observed in Japan in 2015 (40%) [23].

For further information, including a sensitivity analysis on our estimates, see the SI.

3. Results

We present below, first, the current average DLS deprivations and their comparison to income poverty. This is followed by the energy estimates for filling the gap and supporting DLS, and the distribution of energy for basic needs. Finally, we turn to the implications for climate mitigation and the scale of the development challenge from an energy perspective. We present our analysis in aggregated form for 11 world regions (see SI).

3.1. Current decent living gaps

We find considerable gaps in decent living across the world (figure 1). The highest shares of population living below DLS are found in sub-Saharan African countries, where, on average, over 60% of the population does not meet DLS thresholds for more than half of the decent living indicators (household appliances, cooling, housing, sanitation, transport, and water access). South and Pacific Asia also have large gaps in the same dimensions, including clean cooking and heating (mostly traditional biomass with negative health impacts). Western Europe, Japan, Australia and New Zealand, and North America do not have large gaps, although there are significant population shares without safely managed sanitation services. In Eastern Europe, additionally, about a quarter of the population has coal-based heating. Countries in North Africa and the Middle East, Latin America, Centrally Planned Asia, and countries from the former Soviet Union are in-between, with considerable sanitation, water access, thermal comfort, and clean cooking gaps. Education and nutrition gap estimates are respectively, 33% and 17% for sub-Saharan Africa, 6% and 12% for South Asia, and 10% and 8% for North Africa and the Middle East.

The *mean DLS deprivation indicator* may be a helpful indicator for identifying multidimensional

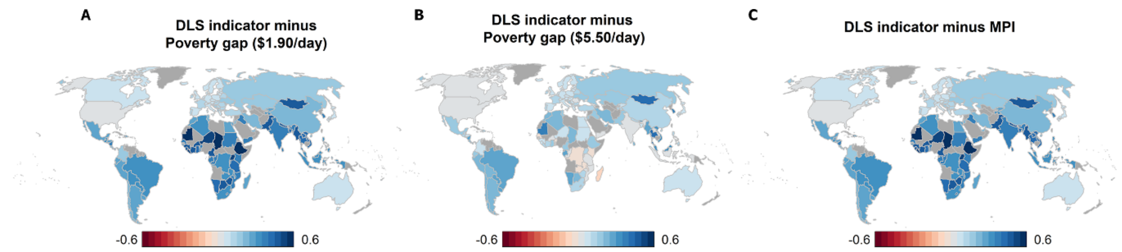

Figure 2. The difference between the mean DLS deprivation indicator and other poverty indicators. Visualized as mean DLS indicator minus the share of population below \$1.90 d^{-1} (A) and the share of population below \$5.50 d^{-1} (B) comparing against World Bank data [20], and multidimensional poverty indicator data (MPI, (C) [32]). Grey indicates that data is not available for this country.

poverty from a material perspective. As shown in figure 2, regional variations in DLS match those in income poverty, with some anomalies. For instance, while China has a relatively high level of household amenities, including electric appliances, a high population share burns coal for heating.

However, DLS gaps generally far exceed income poverty, even at a threshold of \$5.50 d^{-1} (figure 2(B), SI). Notably, *all* countries in the Global South show higher headcounts for DLS gaps than for extreme income poverty; the same holds true for DLS gaps and the Multidimensional Poverty Index (MPI) [32].

For further information on regional variations and the underlying distributions, see the SI.

3.2. DLE requirements

3.2.1. Energy for new capital infrastructure

Building the new infrastructure to fill the DLS gaps that exist today and for future populations would require in total about 290 EJ of cumulative energy by 2040, which is around three-quarters of global annual energy use today. Roughly half of this amount is required to replace substandard housing, and a quarter to build transport infrastructure, mainly public transit, to enable everyone to enjoy a minimum level of mobility to meet their basic needs (figure 3(A)). The energy for building the infrastructure to support good health, hygiene, and nutrition is less than the energy required to enable foster socialization including education.

The largest shares of this construction energy would be required in sub-Saharan Africa (89 EJ) and South Asia (63 EJ), followed by China (38 EJ) (figure 3(A)). On a per capita basis until 2040, the DLS construction gaps in sub-Saharan Africa (71 GJ cap^{-1} of the current population, or 2.8 GJ cap^{-1} yr^{-1}) are the most energy intensive by a significant margin, with Latin America second at 1.7 GJ cap^{-1} yr^{-1}.

3.2.2. Total final energy for decent living

If full decent living is achieved in 2040, then final energy for decent living in 2050 in our reference case is 156 EJ yr^{-1} (up from 88 EJ in 2015), or ∼17 GJ yr^{-1} per capita, of which 108 EJ yr^{-1} is for Global South regions. This total is close to the total calculated in a previous study ([10], 149 EJ yr^{-1}), but higher on a per capita basis (with a lower assumed population of 9.2 billion vs 10 billion) due to the use of current technology as a baseline. One additional difference is the average p-km threshold for transport, which is lower in our study with a threshold derived from recent empirical data [23].

The annual construction energy for the replacement of current stocks and population growth (of ∼21 EJ yr^{-1}) is thus a relatively small share of the total energy requirements for DLS, which are dominated by the energy for DLS delivery. The operating energy in turn is dominated by transport (∼65 EJ yr^{-1}), health and hygiene (∼27 EJ yr^{-1}), shelter (∼19 EJ yr^{-1}), and nutrition (∼20 EJ yr^{-1}). Socialization accounts for ∼4 EJ yr^{-1} (figure 3(B)). In the SI we provide more information on the sensitivity of these energy requirements for different threshold values, including greater floorspace and water consumption.

3.2.3. Differential regional energy needs for decent living

While the entire global population in these scenarios is provided with the same universal standard of DLS, the energy requirements to meet them differ by region by up to a factor of four. Thus, like current total final energy and current DLE, average energy per capita per year determined by the DLS thresholds differs per region, ranging from ∼9 GJ cap^{-1} yr^{-1} for SAS to ∼36 GJ cap^{-1} yr^{-1} for NAM (figure 4). These differences stem from different material intensities of DLS arising from different geographies (e.g. heating/cooling needs), cultures (e.g. diets), urbanization (e.g. travel needs), existing infrastructure (e.g. transport modes) and from different energy intensity of use (e.g. occupancy rates and household size). While at a regional level current final energy demand exceeds the required energy for DLS for each region, there are several countries in sub-Saharan Africa whose national demand is lower than the DLE threshold.

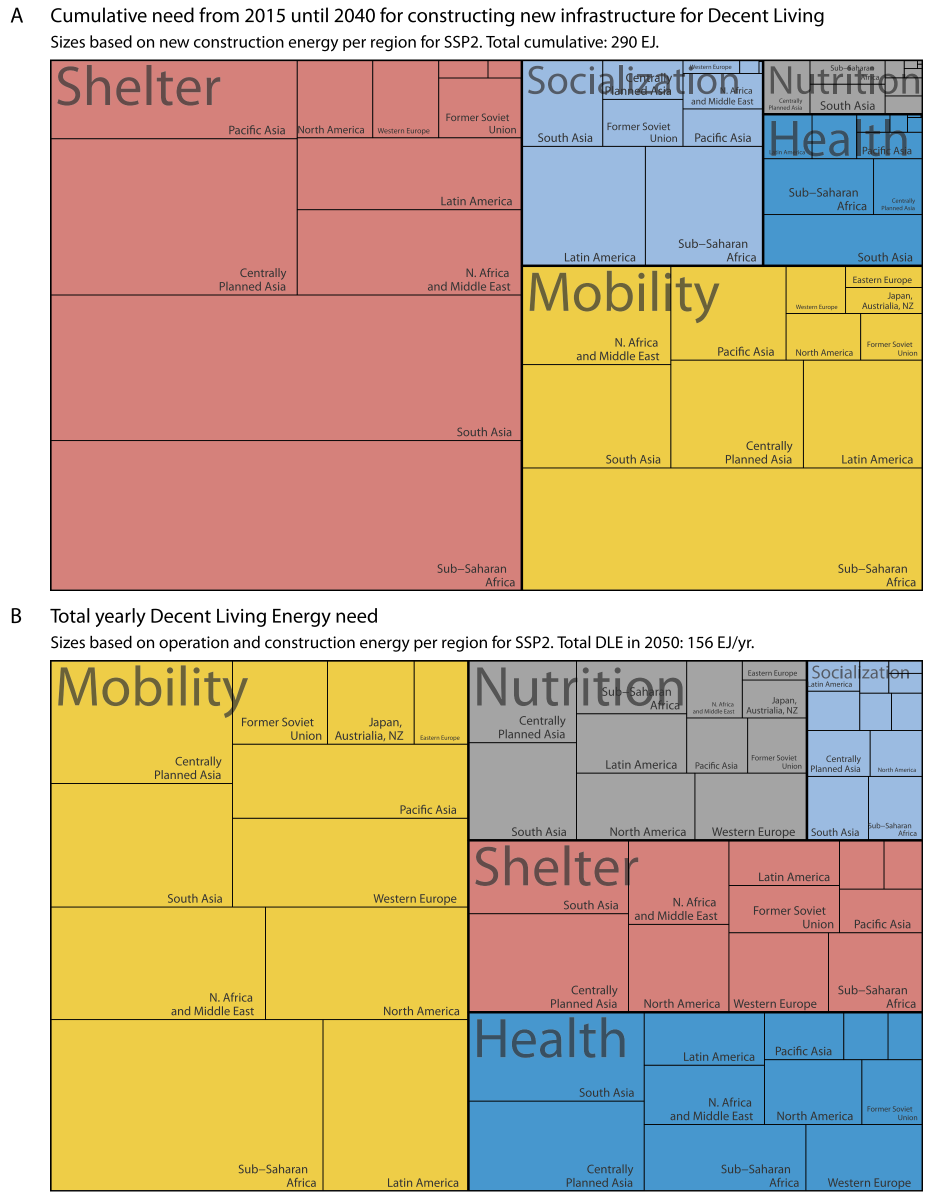

Figure 3. Energy requirements for decent living by need group and regions. (A) The cumulative global energy need for constructing new infrastructure to support decent living standards, accounting for population growth under SSP2 over the period of 2015–2040. (B) Total annual energy requirements for supporting decent living energy to the total global population under SSP2 in 2050.

Even when constraining rich countries to approach mode shares of Japan (40% public transit, leading to a DLE reduction in several regions, see SI), poorer countries have higher public transit shares, and therefore lower average transport energy intensities. If present car-dominant transport were to continue (most starkly in North America and Europe), energy demand would be an additional 5.9 EJ yr^{-1} higher in 2050. This is the equivalent of nearly 4% of the global energy demand for DLS. Notably, this is slightly more than the combined final energy need for health, shelter, and nutrition related provisioning in sub-Saharan Africa (1.7 billion people).

Thermal comfort also affects regional energy requirements differently, with heating needs in cold climates being generally higher than cooling needs in warmer countries. The third important factor is diets. Energy consumption tracks meat consumption, which is also a function of affluence.

3.2.4. The implementation challenge

In comparison to historical growth rates in countries' energy demand, meeting DLS for all by 2040 would require unprecedented growth in much of the Global South, or significantly more equitable distribution of future growth (figure 5(A)). The challenge for sub-Saharan Africa is particularly worrisome, as energy demand has been largely flat for the last two decades (figure 5(B)). Even if countries in Africa departed from the past and grew energy use at rates that matched our reference GDP growth projections, SSP2, (the DLE-GDP scenario), they would not have

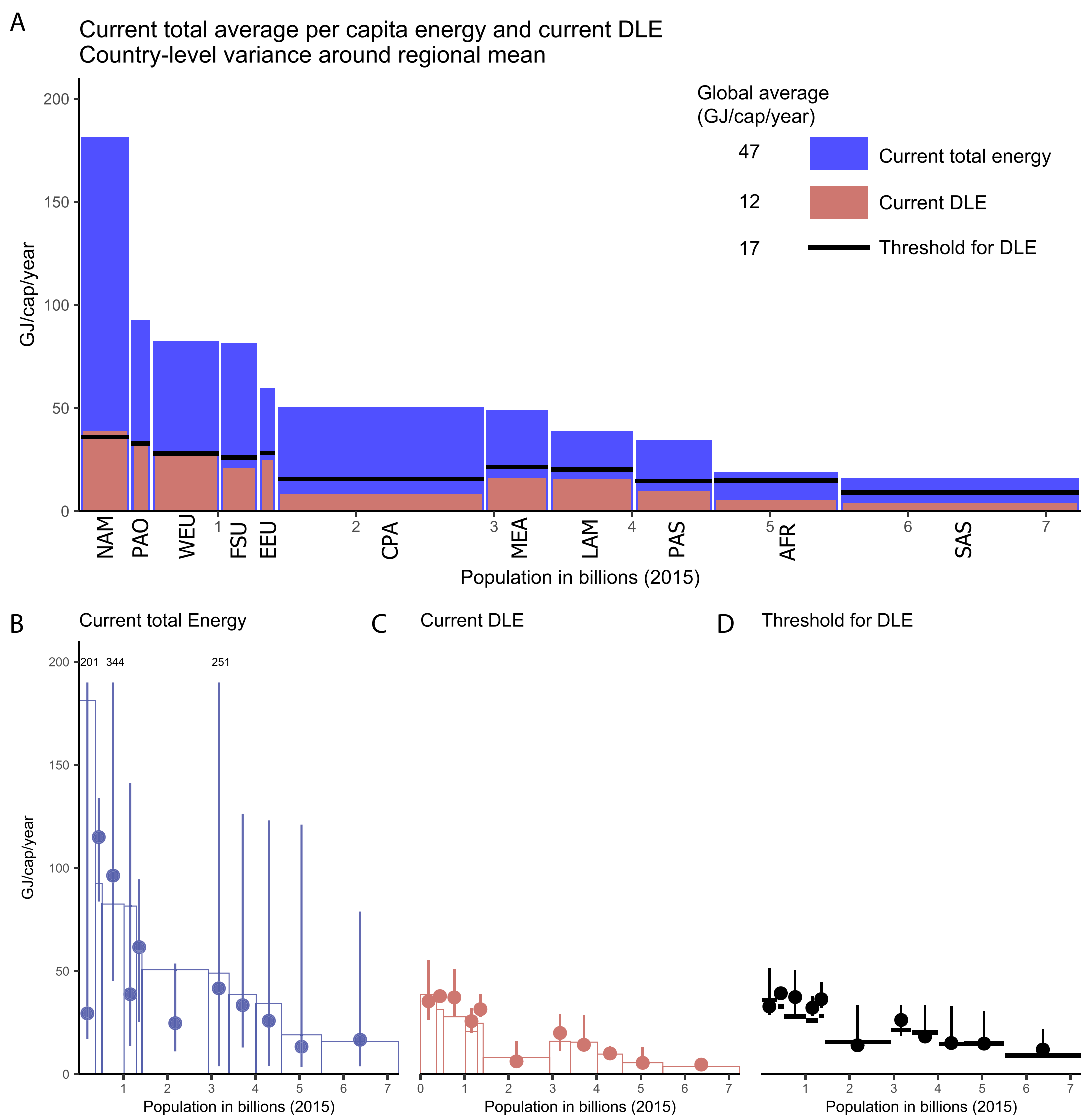

Figure 4. (A) Regional current total energy (current total energy) and the part of this total energy going towards a supporting a decent life (current DLE), compared to the regional threshold value of decent living energy (threshold for DLE). Current estimates are for 2015, while the DLE threshold is derived from the year 2050 in the DLE-2040 simulation. (B)–(D) Regional average energy per capita (bars) compared to the ranges (minimum and maximum national energy per capita) and median national energy per capita within each region, for (B) average per capita final energy use (data from [20]), (C) current regional DLE, and (D) the threshold for DLE. AFR: sub-Saharan Africa, CPA: Centrally Planned Asia, EEU: Eastern Europe, FSU: Former Soviet Union, LAM: Latin America, MEA: North Africa and Middle East, NAM: North America, PAO: Japan, Australia, New Zealand, PAS: Pacific Asia, SAS: South Asia, WEU: Western Europe.

enough energy to fill DLS gaps even by 2050. This is also the case outside Africa (e.g. Pakistan and Bangladesh). Whereas under SSP2 the global energy need is 156 EJ yr^{-1}, our income-tracking projections estimate 117 EJ yr^{-1} used to support decent living. There are exceptions. In China, and to a lesser extent in Brazil and India, historical final energy per capita has grown faster over the past 15 years than annual DLE would need to increase in the future to meet energy requirements by 2040.

3.2.5. Compatibility with climate ambition

Global total DLE in 2050 (under DLE-2040) is only 23%–28% (model median 24%) of the size of total future energy demand projected in 2050 for the SSP2 baseline simulated by multiple models (figure 6(A)). Compared to climate mitigation scenarios, which forecast aggressive decoupling of energy from economic growth, these ratios increase to 27%–42% for SSP2-26 (2 °C compatible) scenarios and to 28%–39% for SSP2-19 (1.5 °C compatible) scenarios. The highest share is unsurprisingly for Africa and the Middle East, with a median value of 53% for SSP2-19 (figure 6(B)). In contrast, despite higher DLE requirements per capita, the ratio is lowest for the OECD region, at 26% for SSP2-19.

This ratio at a minimum reveals the diversity in the amount of energy required to provide DLS around the world, in the context of current and projected energy use. However, it also supports earlier

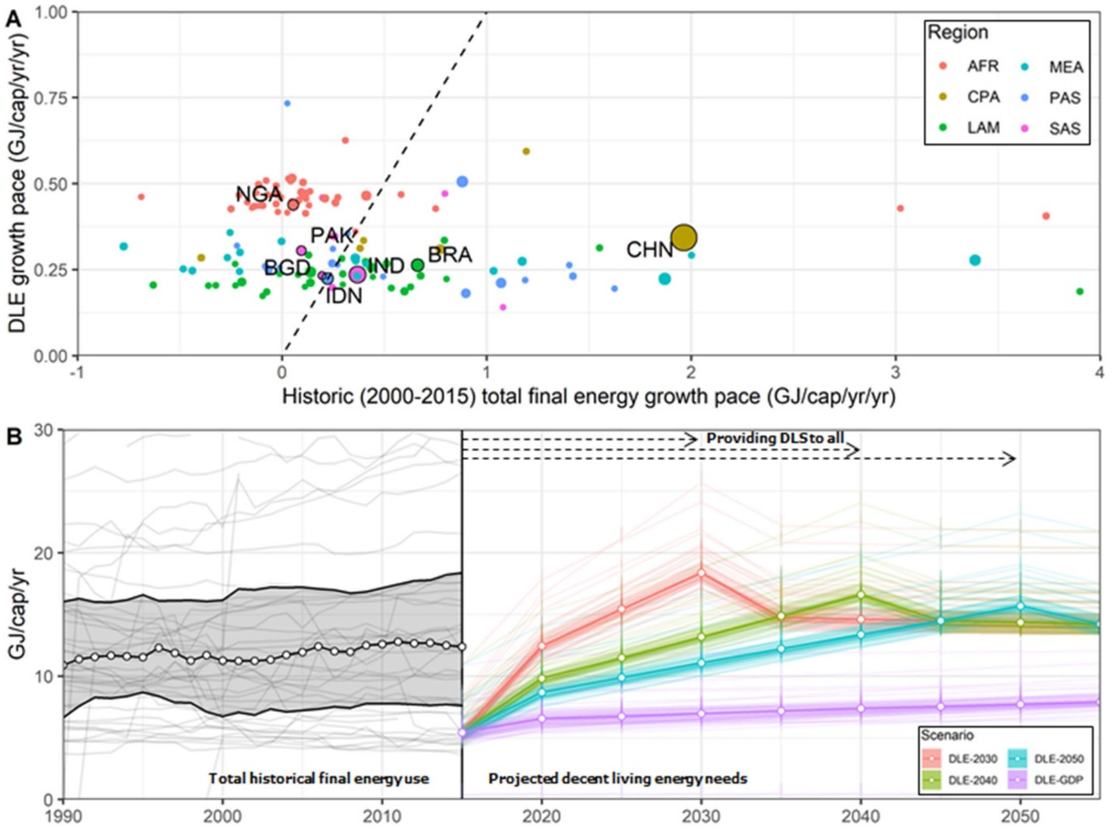

Figure 5. The implementation challenge of energy for decent living for all in the Global South and sub-Saharan Africa. (A) Historically observed (2000–2015) average national annual final energy growth for countries in the Global South, compared to the annual final energy growth in energy for decent living for the DLE-2040 scenario, until 2040 when full decent living is provided. Dot sizes indicate the 2015 total final energy per country. Several outliers are not visualized. The dotted line illustrates equality between both rates. (B) Timeseries of total historical final energy use for countries in sub-Saharan Africa, and the decent living energy increase under alternative decent living standards rollout scenarios. Ranges indicate the 25th and 75th percentile, the marked line indicates the median. Several outliers are not visualized. AFR: sub-Saharan Africa, CPA: Centrally Planned Asia, LAM: Latin America, MEA: North Africa and Middle East, PAS: Pacific Asia, SAS: South Asia, BRA: Brazil, BGD: Bangladesh, CHN: China, IDN: Indonesia, IND: India, NGA: Nigeria, PAK: Pakistan.

ie reducing consumption doesn't mean forfeiting DLE

findings that climate mitigation is not fundamentally incompatible with eradicating poverty [6, 33–35]. Our finding is significant because it adopts a more expansive view of poverty, but is not conclusive, because we do not consider decarbonization explicitly. Rather, we only show that countries with DLS deprivations might still have the scope to undertake *some* mitigation while exempting energy that serves those in or at the margin of poverty. Further work ought to extend this analysis to examine minimum emissions pathways.

4. Discussion and conclusions

The number of people lacking DLS exceeds the number of income-poor, even at a threshold of \$5.50 d^{-1} defined for upper-middle income countries. This is consistent with previous work on MPI, only starker, as DLS consider more services.

We also show that to achieve DLS for all by the SDG target date of 2030, or even 2050, would require transformative changes in energy growth and development. This challenge is the largest for countries in the Global South. Our results suggest that if future DLS achievement would track 'middle-of-the-road' economic growth projections, DLS provisioning would fall well short of universal multidimensional poverty eradication. For most countries, achieving the requirement for universal DLS access implies either unprecedented rates of total energy demand growth or more equitably distributed growth. For many poor countries in Africa a combination of both is likely essential.

This study provides a new perspective on the trade-offs between growth and redistribution. There has been a long-standing debate on how economic growth and redistribution interact to lift people out of poverty, and how the interaction between these may be dependent on the local context [36–38]. Because we know that income and energy consumption are linked [24], our insights can be linked to this debate. As the absence of monetary poverty does not, however, automatically mean that multidimensional poverty is eradicated (figure 2), bottom-up distributional work is informative. Future work can use the insights presented here to study the roles of energy

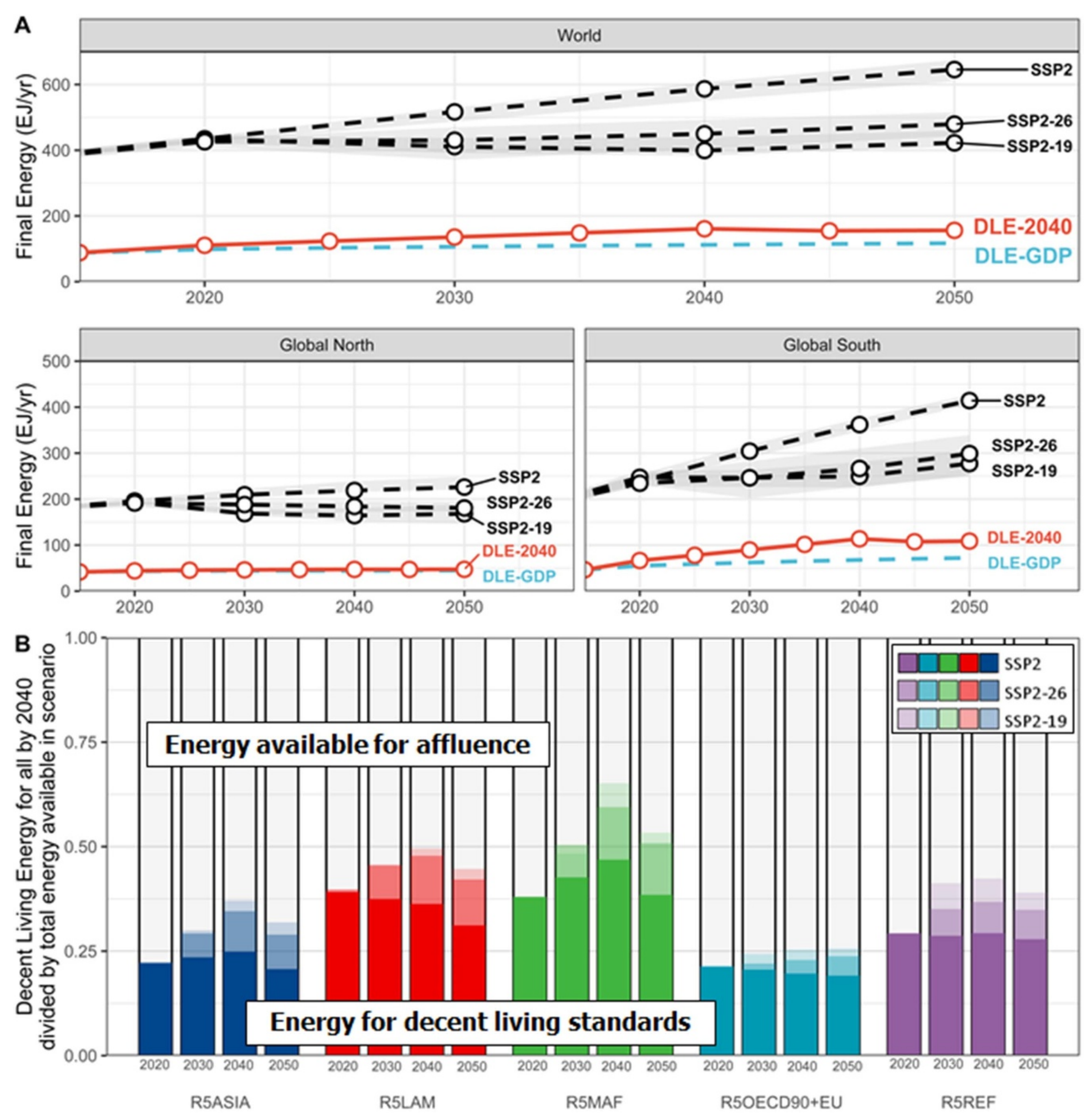

Figure 6. Decent living energy pathways in the context of annual final energy projections of baseline and climate mitigation shared socioeconomic pathway 2 (SSP2). (A) Timeseries of future pathways of decent living energy under a scenario in which decent living is provided to all by 2040 (DLE-2040), and a scenario in which decent living provision is related to economic growth (DLE-GDP), compared to SSP2 and its 2 °C (SSP2-26) and 1.5 °C (SSP2-19) compatible pathways. Lines show the median scenario values, with ranges showing the 25th and 75th percentile. (B) The ratio of DLE divided by the total final energy projected under SSPs with mitigation variants for a globally extensive set of five regions. Data is taken from [33]. ASIA: Asian countries, LAM: Latin America, MAF: Middle East and Africa, OECD90 + EU: OECD member countries in 1990, REF: Eastern Europe and Former Soviet Union.

consumption related to basic services and changes in energy distributions in the context of climate change. A crucial next step would be to distinguish basic energy needs within emissions pathways. This invites fresh thinking that builds on existing literature on equitable efforts-sharing both within and between countries, taking into account changing technology landscapes.

Our regional estimates of per capita DLE (9–36 GJ cap^{-1} yr^{-1}) are very close to those from a previous study (13–40 GJ cap^{-1} yr^{-1}), as the methodologies are similar [10]. This paper pays closer attention to estimating the incremental energy needs required today to fill DLS gaps. We show that the upfront energy investment required globally to extend infrastructures to provide these services (roughly 12 EJ yr^{-1} from 2015 to 2040) is small, compared to the annual energy of 68 EJ yr^{-1} required to support and maintain the services and infrastructure to meet the basic needs of those in poverty today and in the future. In total, this amounts to roughly 23%–28% of total final energy projected under SSP2.

The single-most important policy lesson for national governments is the impact of investing in public transit to slow the growth of passenger vehicles, which generally have much higher energy use per passenger-kilometre because of low occupancy. Public transit is the predominant mode of travel for low-income households everywhere, and transport is the most energy-intensive basic need.

Providing decent shelter accounts for the largest share of upfront energy investments in countries with high overall DLS deprivation to achieve DLS. In general, the use of shared infrastructure lowers per capita energy intensity. Hence, services such as water supply, sanitation, and education need relatively low energy per capita.

These estimates arguably represent one interpretation, or component, of "equitable access to sustainable development", a foundational principle of climate justice. They also show that an equitable distribution of energy for decent living is not an equal distribution. We find that regional requirements differ by up to a factor of four due to essential differences such as heating requirements, but also due to potentially malleable conditions of the built environment and lifestyles. Even allowing for these differences, equity in living standards demands significant convergence between rich and poor countries' energy use.

Due to limited data availability for many countries, our estimates depend on assumptions and generalizations which make the results more suitable for broad inferences rather than specific country-level estimates of energy needs. However, with improved data, the analytical approach used here can well be applied at a national or regional level.

The theoretical closeness of the DLS indicators to material footprints opens up further possibilities for investigating ecological pressures from material use that serves basic needs. Just as immediate energy investments to meet SDGs are estimated, so too capital requirements could be examined for cement, phosphorous and other materials.

Further research can additionally explore the interactions between improvements in decent living and demographics. For instance, policies that increase the levels of (female) education are likely to affect population projections, which comes with both aggregate (total population) and within-country (e.g. school-going population) effects. Additionally, multiple dimensions could be analyzed in more detail. For instance, we have estimated current transport services at a regional level, which leaves room for improvement of national-level DLE estimates. In the future the DLS threshold for mobility could also be improved by a more detailed exploration of geographical contexts of populations by including spatial analysis. Moreover, our energy need pathways could be improved by accounting for changing energy needs for different climate futures. For instance, the DLE need for thermal comfort would be affected by different climate projections.

Thresholds in our work are universal and time-independent in line with previous theoretical work [8]. We acknowledge that people's preferences may change over time and with different contexts beyond the aspects considered here. Participatory approaches and historical analyses could shed more light on this.

In conclusion, this study presents a comprehensive characterization of material deprivations of people at a global scale. Our results support the view that on a global scale, energy for eradicating poverty does not pose a threat to climate change mitigation. However, to provide decent living for all, energy redistribution across the world and unprecedented final energy growth in many poor countries are required.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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References

[1] Nilsson M, Lucas P and Yoshida T 2013 Towards an integrated framework for SDGs: ultimate and enabling goals for the case of energy *Sustainability* **5** 4124–51
[2] Vera I and Langlois L 2007 Energy indicators for sustainable development *Energy* **32** 875–82
[3] McCollum D L *et al* 2018 Connecting the sustainable development goals by their energy inter-linkages *Environ. Res. Lett.* **13** 033006
[4] Fuso Nerini F *et al* 2018 Mapping synergies and trade-offs between energy and the sustainable development goals *Nat. Energy* **3** 10–5
[5] Baltruszewicz M, Steinberger J K, Ivanova D, Brand-Correa L I, Paavola J and Owen A 2020 Household final energy footprints in Nepal, Vietnam and Zambia:

composition, inequality and links to well-being *Environ. Res. Lett.* **16** 025011

[6] Rao N D, Riahi K and Grubler A 2014 Climate impacts of poverty eradication *Nat. Clim. Change* **4** 749–51

[7] Rao N D and Min J 2018 Less global inequality can improve climate outcomes *Wiley Interdiscip. Rev. Clim. Change* **9** e513

[8] Rao N D and Min J 2018 Decent living standards: material prerequisites for human wellbeing *Soc. Indic. Res.* **138** 225–44

[9] Rao N D, Min J and Mastrucci A 2019 Energy requirements for decent living in India, Brazil and South Africa *Nat. Energy* **4** 1025–32

[10] Millward-Hopkins J, Steinberger J K, Rao N D and Oswald Y 2020 Providing decent living with minimum energy: a global scenario *Glob. Environ. Change* **65** 102168

[11] González-Eguino M 2015 Energy poverty: an overview *Renew. Sustain. Energy Rev.* **47** 377–85

[12] Wiedmann T, Lenzen M, Keyßer L T and Steinberger J K 2020 Scientists' warning on affluence *Nat. Commun.* **11** 1–10

[13] Goldemberg J, Johansson T B, Reddy A K N and Williams R H 1985 Basic needs and much more with one kilowatt per capita (energy) *Ambio* **14** 190–200

[14] Creutzig F *et al* 2018 Towards demand-side solutions for mitigating climate change *Nat. Clim. Change* **8** 268–71

[15] Klinsky S, Waskow D, Northrop E and Bevins W 2017 Operationalizing equity and supporting ambition: identifying a more robust approach to 'respective capabilities' *Clim. Dev.* **9** 287–97

[16] Food and Agriculture Organizaiton (FAO) ESS website ESS: food security indicators (available at: www.fao.org/economic/ess/ess-fs/ess-fadata/en/) (Accessed 8 December 2020)

[17] Food and Agriculture Organizaiton (FAO) 2020 *The State of Food Security and Nutrition in the World 2020* FAO, IFAD, UNICEF, WFP and WHO (https://doi.org/10.4060/ca9692en)

[18] ICF 2012 The DHS program STATcompiler. Funded by USAID (available at: www.statcompiler.com) (Accessed 24 April 2020)

[19] National Bureau of Statistics of China 2012 People's living conditions (available at: https://data.stats.gov.cn/english/)

[20] World Bank 2020 (available at: https://databank.worldbank.org) (Accessed 14 October 2020)

[21] Minnesota Population Center 2020 Integrated public use microdata series (IPUMS), international: version 7.3 Minneapolis

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

[23] Gi K, Sano F and Akimoto K 2020 Bottom-up development of passenger travel demand scenarios in Japan considering heterogeneous actors and reflecting a narrative of future socioeconomic change *Futures* **120** 102553

[24] Oswald Y, Owen A and Steinberger J K 2020 Large inequality in international and intranational energy footprints between income groups and across consumption categories *Nat. Energy* **5** 231–9

[25] GEA 2012 *Global Energy Assessment—Toward a Sustainable Future* (Cambridge and Laxenburg: Cambridge University Press, and the International Institute for Applied Systems Analysis (IIASA))

[26] The International Council on Clean Transportation (ICCT) Transportation Roadmap: roadmap model baseline results (August 2017) (available at: https://theicct.org/transportation-roadmap) (Accessed 21 February 2021)

[27] National Bureau of Statistics of China 2019 Transport, postal and telecommunication services (available at: https://data.stats.gov.cn/english) (Accessed 21 February 2021)

[28] UNESCO Institute for Statistics (UIS) 2020 Sustainable development goals 1 and 4

[29] Mastrucci A, Min J, Usubiaga-Liaño A and Rao N D 2020 A framework for modelling consumption-based energy demand and emission pathways *Environ. Sci. Technol.* **54** 1799–807

[30] Stadler K *et al* 2018 EXIOBASE 3: developing a time series of detailed environmentally extended multi-regional input-output tables *J. Ind. Ecol.* **22** 502–15

[31] Riahi K *et al* 2017 The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview *Glob. Environ. Change* **42** 153–68

[32] Alkire S, Roche J M, Ballon P, Foster J, Santos M E and Seth S 2015 *Multidimensional Poverty Measurement and Analysis* (Oxford: Oxford University Press)

[33] Hubacek K, Baiocchi G, Feng K and Patwardhan A 2017 Poverty eradication in a carbon constrained world *Nat. Commun.* **8** 1–9

[34] Chakravarty S and Tavoni M 2013 Energy poverty alleviation and climate change mitigation: is there a trade off? *Energy Econ.* **40** 67–73

[35] Soergel B, Kriegler E, Bodirsky B L, Bauer N, Leimbach M and Popp A 2021 Combining ambitious climate policies with efforts to eradicate poverty *Nat. Commun.* **12** 2342

[36] Lakner C, Mahler D G, Negre M and Prydz E B 2020 How much does reducing inequality matter for global poverty? pp 1–32

[37] Ferreira F H G and Ravallion M 2008 Global poverty and inequality: a review of the evidence The World Bank, 4623, May (available at: https://ideas.repec.org/p/wbk/wbrwps/4623.html) (Accessed 23 July 2021)

[38] Bourguignon F 2003 The growth elasticity of poverty reduction: explaining heterogeneity across countries and time periods *Inequality and Growth: Theory and Policy Implications* vol 1 pp 3–26