Energy requirements for decent living in India, Brazil and South Africa

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Abstract

For over thirty years researchers have tried to estimate how much energy societies require to provide for everyone's basic needs. This question gains importance with climate change, because global scenarios of climate stabilization assume strong reductions in energy demand growth in developing countries. Here, we estimate bottom-up the energy embodied in the material underpinnings of decent living standards for India, Brazil and South Africa. We find that our estimates fall within these countries' energy demand projections in global scenarios of climate stabilization at 2°C, but to different extents. Further, national policies that encourage public transportation and sustainable housing construction will be critical to reduce these energy needs. These results offer one benchmark to compare countries' mitigation efforts and technology transfer arrangements to assess the extent to which they address development priorities in an equitable manner.

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Main

How much energy do societies require in order to meet everyone's basic needs? This question first emerged after the oil crises of the seventies[1], and still continues to beg a satisfactory answer. With the threat of climate change, the question assumes greater urgency. Global scenarios of climate mitigation indicate that meeting the Paris Agreement goals will likely require rapid, transformative changes in global energy supply, land use and potentially negative emissions, among many other changes[2]. Notably, these scenarios also assume that energy demand will grow more slowly than economic growth.[3] The implications of drastic reductions in energy demand growth for developing countries has received limited attention[4]. If meeting even basic living standards requires higher energy demand than projected in these scenarios, then the scale of the energy supply transition required in developing countries would be even more daunting than is currently expected. The promulgation of the Sustainable Development Goals (SDG) has accelerated efforts to eradicate poverty and improve basic living standards. Their impact on energy demand is a critical, but poorly understood, link to the climate challenge. This study starts to fill this gap by calculating bottom-up the energy demand required to meet decent living standards (DLS) in three exemplary countries, India, Brazil and South Africa.

Global scenarios from Integrated assessment models (IAM) estimate that average energy demand growth in developing regions, typically modeled as Asia, Latin America and Middle East/Africa, will rise to less than double present levels by 2050 in a 2°C world (*Supplementary Note 2*), while GDP can more than quadruple. This is also the case for India, Brazil and South Africa in the few scenarios where these countries are modeled individually. At the most aggregate level, average energy demand in non-OECD countries would, starting from an average of 38 GJ/cap today, grow up to at most 60 GJ per capita[5]. These scenarios encapsulate a wide range of socioeconomic futures and mitigation measures. At the upper end, significant negative emissions would be required to decarbonize high demand growth in a fossil-dominant world, while with stronger demand-side measures, lower energy demand growth would reduce the reliance on negative emissions. However, these scenarios provide very limited basis, if any, to assess the adequacy of their energy demand estimates to sustain basic human needs. Energy is an unavoidable input into the built environment that supports human life. Given that over three billion people lack adequate access to clean cooking or electricity, and over a billion lack clean water and sanitation,[6] among other essential services, it is important to know whether these scenarios are compatible with support for a decent life for all and under what technological conditions.

Numerous studies have attempted to quantify an energy threshold for human wellbeing, whose results span an order of magnitude– from 10 GJ per capita to over 100 GJ per capita[7-14]. This range is not informative, however, not only because of the high implied uncertainty, but also because of its weak footing. Past studies aren't rigorous about establishing energy needs in the first place. Most studies derive their estimates from an association between countries' energy use and various aggregate 'outcome' indicators of human progress, such as the human development index (HDI) or life expectancy. With few exceptions, these studies use cross-national or panel data to estimate a relationship between countries' energy use and their chosen indicator, thereby implicitly assuming the dominance of such a global order over other drivers of energy use. However, these studies often do not control for income or country-specific drivers, such as climate, neither do they explain the large variance observed around these estimated relationships[15]. As such, these studies may be picking up energy use associated with affluence, and ignoring legitimate differences in energy needs across countries. The evidence, therefore, is indicative of a dependence on energy, but insufficient to establish its primacy.

A few bottom-up studies do build up energy demand from specific energy uses[1,13,14]. Among the first of these, back in 1985, suggested the possibility of a ‘one kilowatt per capita’ (32 GJ) society that could meet human needs and more[1]. However, indirect energy used to manufacture products was assumed, rather than calculated. Furthermore, none of these studies are based on comprehensive formulations of human needs. In summary, after thirty years, the question of how much energy is necessary to meet human needs still remains unanswered.

We derive the energy needs for basic human wellbeing from its material prerequisites, or decent living standards (“DLS”), whose derivation and justification can be found in previous work[16]. In contrast to ‘outcome’ indicators of well-being, the DLS define the physical ‘means’ that enable, but do not define, wellbeing. The DLS approach is in line with the broadening trend in development indicators of representing the multiple non-income dimensions of poverty, starting with the HDI, and culminating in the Multidimensional Poverty Index (MPI) [17]. DLS includes not just requirements for physical wellbeing but also the means for social affiliation and political participation in society[18]. We chose conservative threshold quantities that correspond to a basic minimum for a decent life (*Supplementary Table 10*). For instance, cooling homes to a comfortable temperature and humidity to avoid heat stress may require air conditioning (AC). We calculate energy needs for building a minimally sized home ($10m^2$ per capita) and cooling just the bedrooms at night, to a conservative temperature threshold for comfort (26˚C) rather than to the level used in most studies (18˚C) [19]. We estimate, bottom-up, the energy embodied in the relevant materials and in the infrastructure to manufacture, deliver and provide these goods and services using standard tools of industrial ecology (See *Supplementary Figure* 1 for the conceptual framework and *Supplementary Methods* for details). The three chosen economies - India, Brazil and South Africa - represent a broad range of economic, climatic and cultural conditions in non-OECD countries. Due to this heterogeneity, a universal living standard gives rise to different energy requirements for decent living in each country – an important departure from previous approaches.

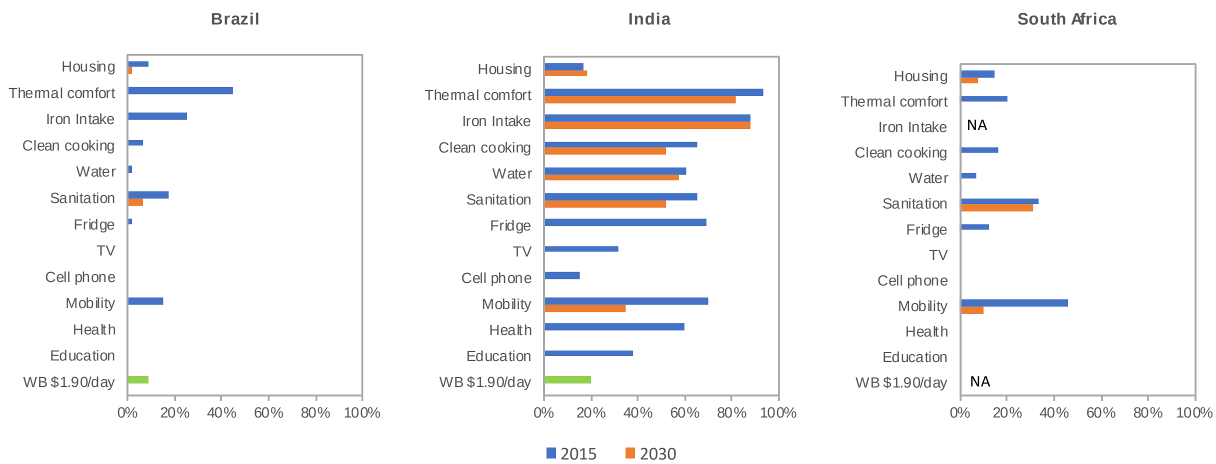
Decent living standards

We choose the DLS to represent a comprehensive, but minimum set of material requirements, so as to estimate a lower bound on the energy needs. The DLS consumption basket includes adequate nutrition, safe shelter with minimum space and thermal comfort, sufficient and in-house water for drinking and basic ablutions, improved sanitation, lighting, clean cooking fuels, cold storage, access to the Internet and broadcast media, and the use of motorized transport, including public transit. In addition, it includes at the national level the provision of health care services and education facilities to support both physical and social wellbeing. We refer to these aspects as DLS dimensions. Threshold quantities for these dimensions are derived from international and national standards and literature on basic needs (*Supplementary Table 10*)[16]. For different DLS dimensions, universal requirements translate to country-specific materials and energy needs, when operationalized in different contexts. For instance, a universal standard for adequate floor space, durable housing and thermal comfort translates to different construction materials and space heating and cooling requirements. Providing and maintaining these living standards to all would in turn give rise to investments in and construction of infrastructure, such as public transportation, water and sanitation, roads, housing, health and education facilities. Our analysis aims to gain insights on the relative energy demand for hypothetically providing the same DLS in different countries. We do not consider implementation challenges (See *Supplementary Note*

3). We also provide sufficient information to assess the energy needs using different threshold quantities (See *Supplementary Tables 14-18*).

Figure 1: Gaps in decent living.

Gaps in decent living (percent of population lacking in each dimension) in India, Brazil and South Africa, in 2015 (blue) and in 2030 (red, extrapolation of recent trends), compared to World Bank's International Poverty Line (green, WB $1.90/day). NA: Not available.



The DLS reveals the multidimensionality of poverty and its extent. More people lack DLS than the number of income poor, as defined by the World Bank's International Poverty Line (IPL) of $1.90/day (Figure 1)[20]. In India, 15-93 percent of the population lack various elements of DLS, which far exceed the IPL headcount of 20 percent. One dimension of particular importance to public health and climate change is the need for space cooling to avoid heat stress-induced health effects, which affects up to 3.4 billion worldwide[21], including over 93 percent (over a billion) of Indians[19]. We estimate that about 45 percent of Brazilians and 20 percent of South Africans also lack access to air conditioning (AC) to provide adequate thermal comfort. Otherwise, the DLS deficits in Brazil and South Africa are largely in access to mobility and sanitation.

There is no easy way to predict how these gaps will evolve. If current trends continue, deficits in India would persist in some measures beyond 2030. The slowest progress is in gaining access to improved sanitation, clean cooking, minimum mobility services, and AC for thermal comfort. In Brazil, gaps in access to improved sanitation would persist beyond 2030, while in South Africa mobility and housings gaps would also exist past 2030. If population growth were to exceed, and income growth were to fall below, current trends, gaps in most of these dimensions would increase, but the demand for basic mobility could reduce if this shift were accompanied by less urbanization.

As an illustrative exercise, we create three principal scenarios for how DLS gaps may evolve over time. The first is an extrapolation of historical trends (DLS_BAU). We create two other scenarios of full achievement of DLS by 2030, consistent with the SDGs: the first, DLS_ACCEL; and a variation (DLS_ACCEL_LCT) that incorporates development strategies that improve DLS while also reducing energy demand growth. These include public transit to support future mobility in cities[22], energy efficiency measures in industry and buildings[23] and diet diversification[24] (*Supplementary Table 11-13*). These measures illustrate, rather than encompass, the potential for lowering the energy intensity of providing DLS from ‘no regrets’ measures. We do not include drastic technological advances such as deep electrification of transport, which in any case are modeled in traditional IAM scenarios. Together, these scenarios provide a range of energy demand estimates under different rates of progress in DLS in different contexts and under different types of development policies. We also capture the combined effect of uncertainty in the DLS gaps and key material requirements in DLS_HIGH and DLS_LOW sensitivity scenarios, which capture the high and low bounds of this uncertainty, respectively (See *Supplementary Note 1*, *Supplementary Figure 7*).

Below, we present the results and their implications for energy demand, energy policy and climate change mitigation. The last section presents the methods behind these estimates.

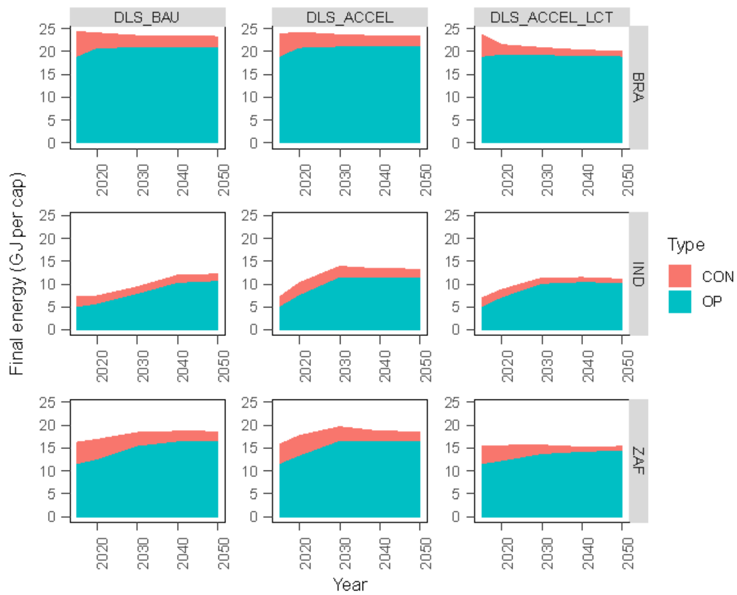
The energy demands of basic human needs

Below we first describe the aggregate energy needs, and the contribution of DLS dimensions. We compare their composition across countries with respect to new construction requirements and operating energy. We then discuss the implications of these findings for national policy, climate equity, and future energy research. Note that construction energy includes the energy to build out and turnover of new capital, including vehicles, appliances, housing and infrastructure. As capital outlays are front-loaded, and reduce to capital turnover in later years, we present the construction energy investment as an average per capita energy requirement per year over the time period 2015-2050. Operating energy includes the economy-side energy required to deliver DLS to all, expressed in GJ per capita per year. We focus on the operating energy post 2030, when DLS is hypothetically achieved.

We find, somewhat surprisingly, that operating energy dominates total energy needs, despite the large infrastructure gaps, particularly in India (Figure 2). Between the DLS_ACCEL_LCT and DLS_ACCEL scenarios, total annual operating energy is 10-11 GJ per cap in India, 14-16 GJ per cap in South Africa, and 19-21 GJ per cap in Brazil, in final energy terms, once the infrastructure to provide DLS has been built out (that is, post 2030). In addition, the construction energy over the 2015-2050 period lies between 1.4-2.3 GJ per cap in India, 2.1-3.2 GJ per cap in South Africa, and 1.9-2.9 GJ per cap in Brazil. In the case of India, which has the largest gaps, meeting DLS for all by 2030 (the target for achieving SDGs) would require 23 percent greater capital (and related energy) infusion compared to BAU trends. Notably, these energy requirements are a likely lower bound, as they are based on conservative thresholds.

Figure 2: Energy requirements for providing decent living standards.

Energy (final) requirements per capita for providing decent living standards (DLS) in Brazil (BRA), India (IND) and South Africa (ZAF) in three scenarios of progress: left, business as usual, where full access is not achieved by 2030 (DLS_BAU); middle, full achievement by 2030 (DLS_ACCEL); right, full achievement by 2030 with climate-friendly strategies (DLS_ACCEL_LCT). Values include construction energy (CON, red) to build out and maintain infrastructure; and economy-wide energy demand to support DLS (OP, blue).



Taking construction and operation together, total DLS energy needs (averaged over the period 2015-2050) lie at the lower end of the 10-100 GJ per capita range in literature, but significantly dependent on context. This is not surprising, considering that most studies estimate global relationships between energy and outcome-based indicators, which may not isolate energy that supports only basic living standards. In comparison to previous bottom-up studies, this range falls between them (10 and 32 GJ final energy per cap per year). The limitations of these have already been mentioned.

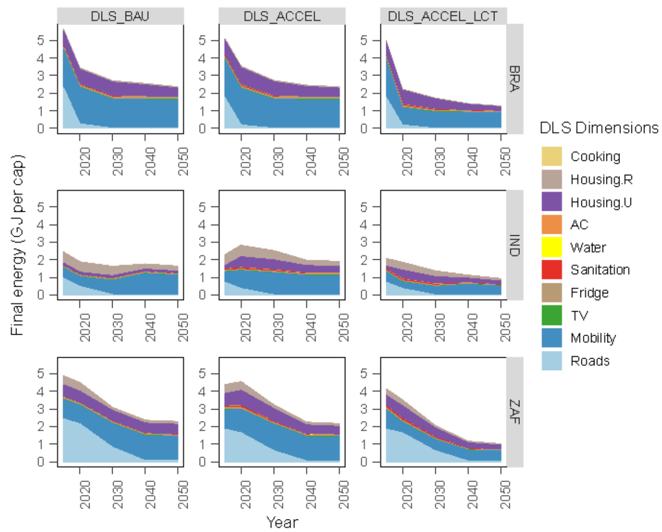
The DLS dimensions that dominate total energy needs are mobility (51%-60%), food for production and cooking (21%-27%), and housing (5%-12%), including thermal comfort. Health care provision, clothing, water and sanitation (together), and the remaining social wellbeing requirements (basic education and ICT) are of comparable magnitude, at 2-3 percent of the total each.

The construction energy requirements per capita are similar across the three countries, even though the gaps in decent living differ so widely between them. This is due to different circumstances related to mobility in each country, which dominates construction energy (45-66 percent, across scenarios and countries) (Figure 3). In Brazil, which is reliant on road transport, just the replacement of retiring stock of private vehicles dominates this investment. In India, the overall stock of transport infrastructure has to grow more than in Brazil, but with a higher share of public transit, which is less energy intensive to build. In South Africa, paving unpaved roads in rural areas dominates its construction energy.

It is also noteworthy that with sustainable development policies, the construction energy to provide DLS for all can be reduced by over 34 percent for all countries (DLS_ACCEL_LCT scenario vs DLS_ACCEL). In the case of India, such a sustainable path would entail less energy demand than that associated with DLS_BAU — a slower expansion of DLS access and less efficient technology choices. Most of this potential is in transport, and to a lesser extent in housing. In particular, the construction energy for mobility for all countries can be reduced by 36-48 percent (the latter in India, where growth is highest) if incremental demand in cities is met by public transportation alone. This would reflect an increase in the share of public transport, rail or bus, in 2050 from 20 to 80 percent in South Africa, from 2 to 26 percent in Brazil, and from 63 percent to 78 percent in India. Replacing slums and overcrowded homes with multi-storey housing, and over 30 million sub-standard homes in rural India, and a million in rural South Africa with durable alternatives would require (~0.6-0.9 GJ/cap, 2010-2050), depending on the construction practices deployed.

Figure 3: Construction energy requirements for providing decent living standards.

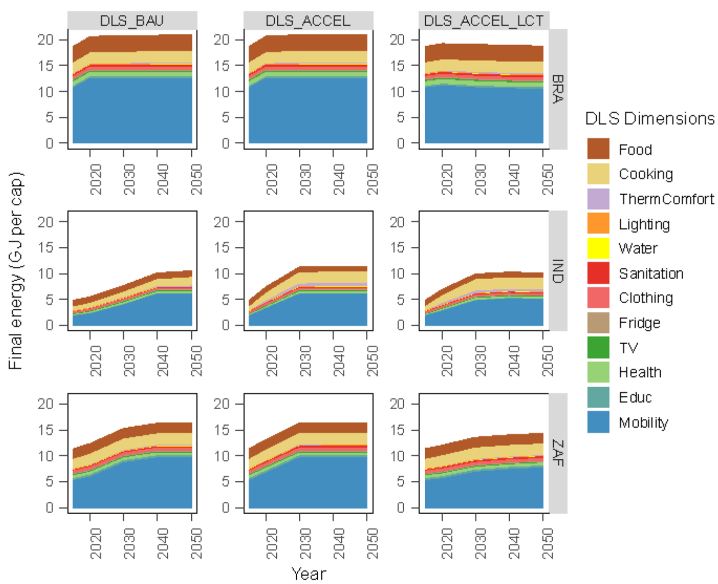
Construction energy per capita (including infrastructure and product manufacturing) breakdown by sector for providing decent living standards to all in Brazil (BRA), India (IND) and South Africa (ZAF) in three scenarios of progress: left, business as usual, where full access is not achieved by 2030 (DLS_BAU); middle, full achievement by 2030 (DLS_ACCEL); right, full achievement by 2030 with climate-friendly strategies (DLS_ACCEL_LCT).



Supporting mobility on an ongoing basis dominates DLS operating energy as well (Figure 4). The energy requirements for mobility depend significantly on existing mode shares, because different transport modes have very different energy intensities. Despite high growth in private vehicles in India, over two-thirds of the population that use motorized transport still rely on public bus and rail. Between meeting all future urban demand with public transport (in the DLS_ACCEL_LCT scenario) and keeping the mode shares the same as today (DLS_ACCEL scenario), the annual mobility energy requirements in India would vary between 4.7-6.0 GJ/cap/yr. after 2030. If future urbanites purchase an increasing share of cars over two-wheelers, from the current share of three-quarters to half by 2030, the operating energy for mobility would increase by about 9 percent. In Brazil, due to the present dominance of road transport and passenger vehicles, its mobility operation energy needs alone (~10-12 GJ/cap/yr.) would be comparable to India's entire DLS energy needs, even if public buses serve the bulk of future demand growth.

Figure 4: Operational energy requirements for providing decent living standards.

Operating energy per capita for delivering decent living standards to all in Brazil (BRA), India (IND) and South Africa (ZAF) in three scenarios of progress: left, business as usual, where full access is not achieved by 2030 (DLS_BAU); middle, full achievement by 2030 (DLS_ACCEL); right, full achievement by 2030 with climate-friendly strategies (DLS_ACCEL_LCT).



After mobility, the production and preparation of food comprises the largest share of annual energy needs, albeit to different extents in the three countries. Food production contributes 1.1 GJ/cap/yr., 2.1 GJ/cap/yr. and 3.2 GJ/cap/yr. in India, South Africa and Brazil respectively to energy demand. This is explained in large part by the extent of meat consumption,[25] which contributed 12, 35 and 51 grams of protein per day to an average person in the three countries respectively in 2012-13[26]. Actual food-related energy demand in India would likely grow, as meat consumption is on the rise, but previous work shows that nutritional requirements can be met with modest diet changes that reduce energy use.[24] In keeping with our approach to calculating minimum energy needs, we do not count this growth in the DLS energy needs.

Energy demand for cooking (including stove and fuel production) would decrease with DLS to ~2 GJ/cap/yr. for all three countries, due to the replacement of inefficient and toxic solid fuel combustion with cleaner and more efficient stoves and fuels such as liquid petroleum gas (LPG)[27]. The energy for conditioning a minimal amount of residential `space at night to a comfortable range of temperature and humidity amounts up to only 0.5 GJ in India per person per year.

Implications for sustainable development policy

The lifestyles people adopt as they rise out of poverty will influence their wellbeing and, through their material content, energy demand growth.[28] This study helps relate energy demand growth to aspects of lifestyles associated with basic needs and affluence. Compared to the modest energy needs required to avoid heat stress in homes, more luxurious use of AC can entail energy demand of five times this minimum level[29]. Means of social affiliation, including basic education, and access to broadcast and social media, require just a few gigajoules of energy per capita. In contrast, electronics are a growing and non-trivial share of household energy use in affluent countries[30].

For India in particular, the findings reveal the extent to which national energy demand mirrors inequities in living standards. Current final energy use was 17.5 GJ per cap in 2015, of which, given the large gaps in DLS, about 7 GJ/cap of current demand likely serves basic needs. Further, only 12-15 GJ per cap per year would be required to meet DLS for all, and only a small fraction of that to build out the necessary infrastructure. Although this is not a comprehensive estimate of the energy use needed to support an economy, it reveals that the scale of the energy gap to eradicate poverty is comparable to current energy use.

These insights also help define policy choices that can support climate mitigation and enhance wellbeing. Over a third of construction energy can be avoided if slums and poor quality rural homes were upgraded with energy-saving housing construction practices,[23] and if public transportation were scaled up to serve future urban mobility demand. Targeting future energy infrastructure expansion and improvement towards newly emerging urban areas, particularly in support of such improved housing and public transit, can be an effective way to dovetail energy-efficient and equitable growth. Expanding access to clean cooking and encouraging healthy diets are already well-known strategies to improve wellbeing and reduce energy demand[31].

The analytical framework can also provide stakeholders with insights into the sensitivity of the DLS energy needs to different threshold values of the DLS dimensions, since the final results are a linear combination of these inputs and their respective embodied energy intensities (*Supplementary Tables* 15-18). For instance, one can compare the impact on energy needs of changing the minimum standard of floor space in public housing to that of changing minimum mobility requirements.

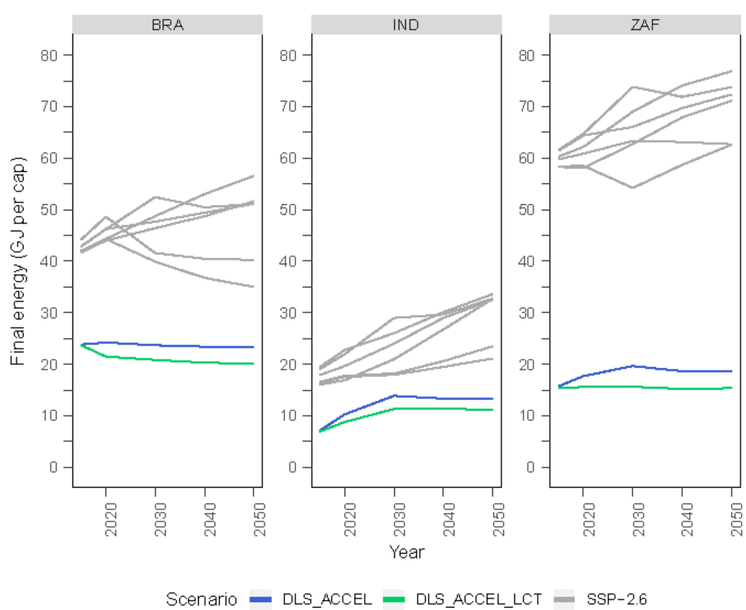
Implications for climate equity

Climate agreements have for long expressed in their call to action an intent to protect development rights[32,33]. However, without a concrete articulation, the compatibility of such an entitlement with meeting ambitious climate mitigation has eluded policy debates. The DLS can be a basis to characterize such an entitlement. Its related energy demand is one critical link to the many societal transformations required for climate mitigation. This study shows that the energy demand in global scenarios of 2°C can support DLS in the three chosen countries. However, the extent of this compatibility differs across the countries.

The gap between countries' DLS energy requirements and IAMs' projected energy demand pathways in a 2˚C world (Figure 5) reflects the energy demand associated with affluence, above a DLS. India, as the poorest country with the largest DLS gap (Figure 1), has the least 'headroom' under the IAM trajectories, despite already having lower average demand of DLS. This implies that India's future affluence from income growth would have to be achieved with relatively less growth in energy demand or have to bear a higher carbon price tag than elsewhere. International cooperation on technology transfer and diffusion in future negotiations have to address such inequities if countries like India are expected to pursue ambitious mitigation. These questions require exploration in the broader context of greenhouse gas emissions and not just energy, but the DLS framework offers a common foundation for such a discussion.

Figure 5: Comparison of energy demand scenarios for decent living standards and national projections.

Comparison of energy demand scenarios for decent living standards (DLS_ACCEL, DLS_ACCEL_LCT) to national projections from two IAMs (IMAGE, GCAM) under available socioeconomic futures (Shared Socioeconomic Pathways SSPs 1, 2, 4) that all achieve climate stabilization at 2.6W/m^2 (2˚C) (SSP-2.6). Variability of DLS pathways to socioeconomic futures is relatively small. See *Supplementary Note 1*. Note: DLS for all achieved only in 2030.



Questions about fair efforts and technology transfer have immediate practical significance for countries' Nationally Determined Contributions (NDCs) under the Paris Agreement. Current pledges fall well short of what is required to meet the targets. Many stakeholders believe that equitable efforts-sharing is central to ratcheting up ambition[34-36]. The global stock stake, starting in 2023, obligates parties to develop more ambitious plans for mitigation, adaptation and means of implementation, which include technology transfer and climate finance. The energy needs and climate impacts of providing DLS can be one lens through which subsequent NDC pledges are viewed. Its underlying components provide a concrete basis to debate comparability of countries' demand-side climate mitigation efforts. For instance, India's significantly lower energy demand for the same DLS compared to Brazil raises questions about convergence. What factors justify these differences? How should path dependence and the maturity of Brazil's transport infrastructure be considered against its higher income and transport energy intensity? Similar questions can be asked of food and culture, or housing characteristics and climate, among others.

Implications for future research

The analytical approach pursued here builds on a new direction of research that bridges between IAM and industrial ecology research. This link has been recognized as a way to formally assess climate policy alongside other sustainability impacts of a changing industrial system[37,38]. This study extends this link to consumption and its contribution to wellbeing. Future sustainability research can assess trade-offs and impacts between policies that influence consumption, materials and energy system changes against environmental and social objectives. We create a common point of comparison through energy demand, which we relate to consumption through

IE and to climate impacts through IAM. Future work can derive other sustainability impacts of DLS from IE and relate these to climate mitigation goals.

Methods

This study utilizes a service-driven energy accounting model (SEAM) to map countries' progress in living standards to their energy use (*Supplementary Figure 1*). SEAM builds on a foundation of previous studies, particularly for the definition and justification of DLS[16] and the simulation of building construction and operation[29]. SEAM calculates embodied energy intensities of DLS dimensions using standard methods in industrial ecology[39], including multi-regional input-output (using the EXIOBASE MRIO[40]) and life cycle assessment (LCA)[41,42]. The MRIO is linked to household consumption and expenditure surveys for the three countries so that embodied energy intensities can be calculated for all household consumption categories[43]. We use this household footprinting approach for calculating, by country, the embodied energy for food, clothing, health and education. The LCA tools are used primarily to calculate the embodied energy of construction and manufacturing, for appliances, buildings and infrastructure. In both methods, we track final energy use (instead of primary energy) through the supply chain, in order to capture actual energy demand, so as to remove the dependence of the results on the fuel mix of the respective countries and thereby enable legitimate comparisons of energy needs across countries. The quantification process involves several similar steps for each DLS dimension. First, based on normative thresholds quantities for DLS dimensions, supported by academic literature[16] and prevailing regulations and standards, estimate shortfalls in DLS from household survey and other national data (*Supplementary Methods*, *Supplementary Note 4*). Second, using statistical or simulation techniques, where needed, to determine the material satisfiers that best relate to the chosen DLS dimension. For instance, for cold storage and adequate shelter the material satisfiers are straightforward – refrigerators and buildings. The chosen material basis for health and education standards – national expenditure – is less obvious but was found to best correlate to outcomes compared to other physical indicators, such as hospitals or schools. Third, we use MRIO and LCA, as appropriate, to estimate the embodied energy intensity of the chosen material satisfiers. MRIO was used for food, health, education and clothing, while LCA was used for buildings, appliances, vehicles and infrastructure. The choice was based on the specificity of material requirements and their alignment with sector or product definitions in each method. Fourth, we estimate pathways of progress for the DLS dimensions under the chosen scenarios of development and climate policies. In the DLS_BAU scenarios we extrapolate historical rates of progress/growth in each DLS dimension; in DLS_ACCEL we accelerate growth to fill all gaps in DLS by 2030, in line with the SDGs. In the DLS_ACCEL_LCT scenario, different measures are adopted in each dimension, which are described later. We operationalize these choices in a simple capital stock and flow model to represent the material stock that deliver DLS and their operational characteristics. Capital is replaced in accordance with the assumed lifetimes of durables.

The rest of this section first briefly summarizes the principles underlying the estimation approach, and then presents how the above steps were operationalized for each dimension. The full details of the material stocks, operating assumptions and the resulting energy demands can be found in the *Supplementary Tables 14-18.*

With foundations in theories of basic capabilities and basic needs, the DLS identifies a common universal set of material prerequisites, or ‘satisfiers’, for attaining physical and social wellbeing in modern society[16]. Everyone ought to have adequate nutrition, shelter, health care and education, decent living conditions, and the opportunity to participate in society. The DLS operationalizes these universal satisfiers into context-dependent material and energy requirements. The use of industrial ecology tools allows us to comprehensively capture the hierarchy of material dependence, and therefore, the full extent of the built environment, needed to provide DLS. The threshold quantities of individual satisfiers, where relevant (e.g. daily allowance for micronutrients, or floor space), are based on prevailing international and national standards or global trends and translated to actual material consumption based on local conditions. For instance, in all countries a universal floor space threshold (10m^2 per person) and range of thermal comfort is used, but country-specific building types (e.g. urban multi-storey vs rural single-storey), local construction materials and prevailing efficiency standards, determine the housing and space conditioning energy requirements. Adequate nutrition translates to different daily calorie and micronutrient requirements based on the bioavailability of available foods, which in turn translate to different foods based on prevailing diet choices.

The results obviously depend on the chosen thresholds, whose determination involves some level of subjectivity, and ought to, in principle, be driven by policy. We have selected values with the intent of capturing a basic minimum, and provide results that scale proportionately with alternative threshold values. We describe each dimension and its related content next.

Food requirements and nourishment are conventionally characterized as average calories per day, which masks and understates the extent of malnourishment in the form of deficiencies in micro-nutrients, such as iron, zinc and vitamins[44]. We estimate these deficiencies with reference to national standards for nutritional adequacy. The diet composition for the countries are based on weighted averages from national (representative) household surveys for Brazil and South Africa in all scenarios. In previous work, we use optimization methods to find regional diets in India that meet these nutritional constraints and energy use while minimizing deviations from existing diets[24]. The DLS_ACCEL and DLS_ACCEL_LCT scenarios for India adopt this nutritionally optimal (low-rice) diet. In the cases of Brazil and South Africa, the same granularity on household diets and their nutritional content was not available. We instead assess DLS in terms of total calorie requirements. We calculate the embodied energy of DLS diets using the MRIO-based household footprinting tool described above (*Supplementary Methods* for further details).

Food preparation inside homes has a significant effect on well-being due to emission of harmful pollutants from solid and liquid fuel based cook stoves. Thus, DLS require that households have gas or electric stoves, which do not emit these pollutants. We calculate the embodied energy in manufacturing and using stoves based on typical usage in middle-income households in India.

We find support for a minimum space requirement of 10 m^2 per person, above a minimum home size of 30 m^2 (for up to three persons), in several national standards for public housing. For instance, populated regions such as Hong Kong and Taiwan, have regulations for minimum living space between 8-13 m^2 per capita[16]. To avoid heat stress, maximum indoor temperature is restricted to 26°C and 60 percent humidity[19,29]. The material requirements, the embodied energy intensities of construction and the cooling energy are calculated using a building simulation model developed elsewhere that uses multi-storey and single-storey building archetypes for urban and rural areas respectively[29]. This model uses the *EnergyPlus* software to simulate space conditioning and an LCA engine to calculate the embodied energy in materials. For the DLS_ACCEL_LCT scenario, we deploy aerated earth blocks for construction and energy efficient materials and cooling equipment, which previous work shows reduces both construction energy and cooling energy requirements relative to conventional masonry[23].

For clothing, we find a robust relationship, using linear regression, between quantity of clothing (from household surveys) and climate. We accordingly determine minimum clothing requirements for the three countries using population-weighted climate index (a variation of Heating Degree-Days HDD, see *Supplementary Methods*), and combining with their respective embodied energy intensities from the MRIO. We keep the clothing requirements fixed over time and across scenarios.

Decent standards for water supply and sanitation entail in-house access to a minimum quantity of clean water per person per day to support drinking needs, basic ablutions and in-house toilets. Energy for water use in agriculture and industry is accounted for in the indirect energy accounting for other DLS dimensions. The embodied energy for constructing the infrastructure and supplying water are drawn from the LCA literature. Both quantities and intensities are invariant in all scenarios.

Households are equipped with basic appliances to meet the needs for cold storage and connectivity to society, including a television, based on the most widely prevalent technology and size options in each respective country[45]. In the DLS_ACCEL_LCT scenario, we assume full penetration of the best available technologies, as modeled in previous work.

The provision of health care and education is through shared facilities (e.g. hospitals and schools). The literature reveals that indicators of good health (life expectancy and infant mortality) and education completion correlate well with national per capita health and education expenditures respectively, and stronger than other physical indicators such as the number of hospitals or schools[16,46]. These minimum expenditures were combined with embodied energy intensities from MRIO to yield energy requirements for health and education.

Uncertainty analysis

We characterize uncertainty in our results following the types of uncertainty identified by the IPCC[47]: unpredictability in behavior related to society and institutions; value uncertainty, related to data inputs; and structural uncertainty in models related to the underlying energy intensity calculations. Note that we already illustrate policy uncertainty through the scenario design. We describe how we represent each type of uncertainty below.

We represent two types of societal uncertainty: socioeconomic futures, and institutional conditions. We select key influential variables in each, and combine them, for ease of presentation, to show the outer bounds of energy needs, using two scenarios, DLS_HIGH and DLS_LOW. The socioeconomic uncertainty influence primarily the DLS gap, and the latter the characteristics of new capital required to fill this gap. We use population, income and urbanization projections from available socioeconomic futures from the climate literature (Shared Socioeconomic Pathways, or SSPs)[48]. Population influences the overall gap; income influences the secular uptake of appliances (TV, cell phone and AC); and urbanization influences the share of urban and rural housing requirements, which have different archetypes, and therefore different energy use for the same comfort thresholds. in the DLS gaps. We use the DLS gap most closely related to current trends (SSP2) for the main results (DLS_ACCEL and DLS_ACCES_LCT scenarios), and use SSP1 and SSP3 for the DLS_LOW and DLS_HIGH variations respectively, because they yield the most contrasting values for the DLS gaps.

The lifetime of capital, particularly housing, vehicles and roads, and the share of two-wheelers and four-wheelers in India, constitute the most influential institutional uncertainties. In addition, we incorporate uncertainty in the health care sector expenditures that would be required to achieve DLS.

Regarding value uncertainty, several data inputs go into the embodied energy intensity calculations. As described below, the literature does not typically offer a logical basis to estimate ranges for these inputs. Instead, we present a sensitivity analysis of the main results to key input parameters. The input data fall into two categories: threshold material requirements in DLS; and the technical parameters in the energy intensity calculations. The threshold quantities of DLS dimensions are a normative input representing consumption levels, which, as mentioned earlier, have been chosen conservatively to develop a lower bound on energy needs for DLS. As the final result is a linear combination of these quantities and their respective embodied energy intensities, the individual components scale proportionately with different threshold values. Regarding energy intensities, aside from our simulations, we have drawn many estimates of embodied energy intensity of products from the LCA and IO literature, for which authors typically do not provide sensitivities. For convenience, we have tabulated the sensitivity of the overall result to a 10 percent change in every threshold value and input parameter that influence these embodied energy intensities (*Supplementary Figure 7*).

The primary structural uncertainties lie in the LCA and IO inventories and databases that we rely on in our calculations. However, these uncertainties are only known generally in the field, not for the specific studies and databases from which we draw. Nevertheless, we quantify the extent of this uncertainty (See *Supplementary Note 1*). A comparison of the main results to the uncertainty scenarios can be found in *Supplementary Table 25*.

Data Availability Statement

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request. Publicly available data used in the analysis include nationally representative household consumption expenditure surveys in India[49], Brazil[50] and South Africa[51], and the Ecoinvent 3[52] and EXIOBASE 3[40] databases. Further details available in *Supplementary Note 4*.

Code Availability Statement

The code used to manipulate the data and generate the results are available from the corresponding author upon reasonable request.

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Contributions

NDR designed the study; NDR, JM and AM conducted the analysis and wrote the manuscript.

Financial and non-financial competing interests

The authors declare no competing interests.

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