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

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6   **Abstract**

7   For over thirty years researchers have tried to estimate how much energy societies require to

8   provide for everyone's basic needs. This question gains importance with climate change, because

9   global scenarios of climate stabilization assume strong reductions in energy demand growth in

10   developing countries. Here, we estimate bottom-up the energy embodied in the material

11   underpinnings of decent living standards for India, Brazil and South Africa. We find that our

12   estimates fall within these countries' energy demand projections in global scenarios of climate

13   stabilization at 2°C, but to different extents. Further, national policies that encourage public

14   transportation and sustainable housing construction will be critical to reduce these energy needs.

15   These results offer one benchmark to compare countries' mitigation efforts and technology

16   transfer arrangements to assess the extent to which they address development priorities in an

17   equitable manner.

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21   **Main**

22   How much energy do societies require in order to meet everyone's basic needs? This question

23   first emerged after the oil crises of the seventies[1], and still continues to beg a satisfactory answer.

24   With the threat of climate change, the question assumes greater urgency. Global scenarios of

25   climate mitigation indicate that meeting the Paris Agreement goals will likely require rapid,

26   transformative changes in global energy supply, land use and potentially negative emissions,

27   among many other changes[2]. Notably, these scenarios also assume that energy demand will grow

28   more slowly than economic growth.[3] The implications of drastic reductions in energy demand

29   growth for developing countries has received limited attention[4]. If meeting even basic living

30   standards requires higher energy demand than projected in these scenarios, then the scale of the

31   energy supply transition required in developing countries would be even more daunting than is

32   currently expected. The promulgation of the Sustainable Development Goals (SDG) has

33   accelerated efforts to eradicate poverty and improve basic living standards. Their impact on

34   energy demand is a critical, but poorly understood, link to the climate challenge. This study starts

35   to fill this gap by calculating bottom-up the energy demand required to meet decent living

36   standards (DLS) in three exemplary countries, India, Brazil and South Africa.

37   Global scenarios from Integrated assessment models (IAM) estimate that average energy demand

38   growth in developing regions, typically modeled as Asia, Latin America and Middle East/Africa,

39   will rise to less than double present levels by 2050 in a 2°C world (*Supplementary Note 2*), while

40   GDP can more than quadruple. This is also the case for India, Brazil and South Africa in the few

41   scenarios where these countries are modeled individually. At the most aggregate level, average

42   energy demand in non-OECD countries would, starting from an average of 38 GJ/cap today,

43   grow up to at most 60 GJ per capita[5]. These scenarios encapsulate a wide range of

44   socioeconomic futures and mitigation measures. At the upper end, significant negative emissions

45   would be required to decarbonize high demand growth in a fossil-dominant world, while with

46   stronger demand-side measures, lower energy demand growth would reduce the reliance on

47   negative emissions. However, these scenarios provide very limited basis, if any, to assess the

48   adequacy of their energy demand estimates to sustain basic human needs. Energy is an

49   unavoidable input into the built environment that supports human life. Given that over three

50   billion people lack adequate access to clean cooking or electricity, and over a billion lack clean

51   water and sanitation,[6] among other essential services, it is important to know whether these

52   scenarios are compatible with support for a decent life for all and under what technological

53   conditions.

54   Numerous studies have attempted to quantify an energy threshold for human wellbeing, whose

55   results span an order of magnitude– from 10 GJ per capita to over 100 GJ per capita[7-14]. This

56   range is not informative, however, not only because of the high implied uncertainty, but also

57   because of its weak footing. Past studies aren't rigorous about establishing energy needs in the

58   first place. Most studies derive their estimates from an association between countries' energy use

59   and various aggregate 'outcome' indicators of human progress, such as the human development

60   index (HDI) or life expectancy. With few exceptions, these studies use cross-national or panel

61   data to estimate a relationship between countries' energy use and their chosen indicator, thereby

62   implicitly assuming the dominance of such a global order over other drivers of energy use.

63   However, these studies often do not control for income or country-specific drivers, such as

64   climate, neither do they explain the large variance observed around these estimated

65   relationships[15]. As such, these studies may be picking up energy use associated with affluence,

66 and ignoring legitimate differences in energy needs across countries. The evidence, therefore, is

67 indicative of a dependence on energy, but insufficient to establish its primacy.

68 A few bottom-up studies do build up energy demand from specific energy uses[1,13,14]. Among the

69 first of these, back in 1985, suggested the possibility of a 'one kilowatt per capita' (32 GJ)

70 society that could meet human needs and more[1]. However, indirect energy used to manufacture

71 products was assumed, rather than calculated. Furthermore, none of these studies are based on

72 comprehensive formulations of human needs. In summary, after thirty years, the question of how

73 much energy is necessary to meet human needs still remains unanswered.

74 We derive the energy needs for basic human wellbeing from its material prerequisites, or decent

75 living standards ("DLS"), whose derivation and justification can be found in previous work[16]. In

76 contrast to 'outcome' indicators of well-being, the DLS define the physical 'means' that enable,

77 but do not define, wellbeing. The DLS approach is in line with the broadening trend in

78 development indicators of representing the multiple non-income dimensions of poverty, starting

79 with the HDI, and culminating in the Multidimensional Poverty Index (MPI) [17]. DLS includes

80 not just requirements for physical wellbeing but also the means for social affiliation and political

81 participation in society[18]. We chose conservative threshold quantities that correspond to a basic

82 minimum for a decent life (*Supplementary Table 10*). For instance, cooling homes to a

83 comfortable temperature and humidity to avoid heat stress may require air conditioning (AC).

84 We calculate energy needs for building a minimally sized home ($10m^2$ per capita) and cooling

85 just the bedrooms at night, to a conservative temperature threshold for comfort (26°C) rather than

86 to the level used in most studies (18°C) [19]. We estimate, bottom-up, the energy embodied in the

87 relevant materials and in the infrastructure to manufacture, deliver and provide these goods and

88 services using standard tools of industrial ecology (See *Supplementary Figure* 1 for the

89 conceptual framework and *Supplementary Methods* for details). The three chosen economies -

90 India, Brazil and South Africa - represent a broad range of economic, climatic and cultural

91 conditions in non-OECD countries. Due to this heterogeneity, a universal living standard gives

92 rise to different energy requirements for decent living in each country – an important departure

93 from previous approaches.

94 **Decent living standards**

95 We choose the DLS to represent a comprehensive, but minimum set of material requirements, so

96 as to estimate a lower bound on the energy needs. The DLS consumption basket includes

97 adequate nutrition, safe shelter with minimum space and thermal comfort, sufficient and in-house

98 water for drinking and basic ablutions, improved sanitation, lighting, clean cooking fuels, cold

99 storage, access to the Internet and broadcast media, and the use of motorized transport, including

100 public transit. In addition, it includes at the national level the provision of health care services

101 and education facilities to support both physical and social wellbeing. We refer to these aspects

102 as DLS dimensions. Threshold quantities for these dimensions are derived from international and

103 national standards and literature on basic needs (*Supplementary Table 10*)[16]. For different DLS

104 dimensions, universal requirements translate to country-specific materials and energy needs,

105 when operationalized in different contexts. For instance, a universal standard for adequate floor

106 space, durable housing and thermal comfort translates to different construction materials and

107 space heating and cooling requirements. Providing and maintaining these living standards to all

108 would in turn give rise to investments in and construction of infrastructure, such as public

109 transportation, water and sanitation, roads, housing, health and education facilities. Our analysis

110 aims to gain insights on the relative energy demand for hypothetically providing the same DLS

111 in different countries. We do not consider implementation challenges (See *Supplementary Note*

112   *3).* We also provide sufficient information to assess the energy needs using different threshold

113   quantities (See *Supplementary Tables 14-18*).

114   **Figure 1: Gaps in decent living.**

115   Gaps in decent living (percent of population lacking in each dimension) in India, Brazil and
116   South Africa, in 2015 (blue) and in 2030 (red, extrapolation of recent trends), compared to World
117   Bank's International Poverty Line (green, WB $1.90/day). NA: Not available.
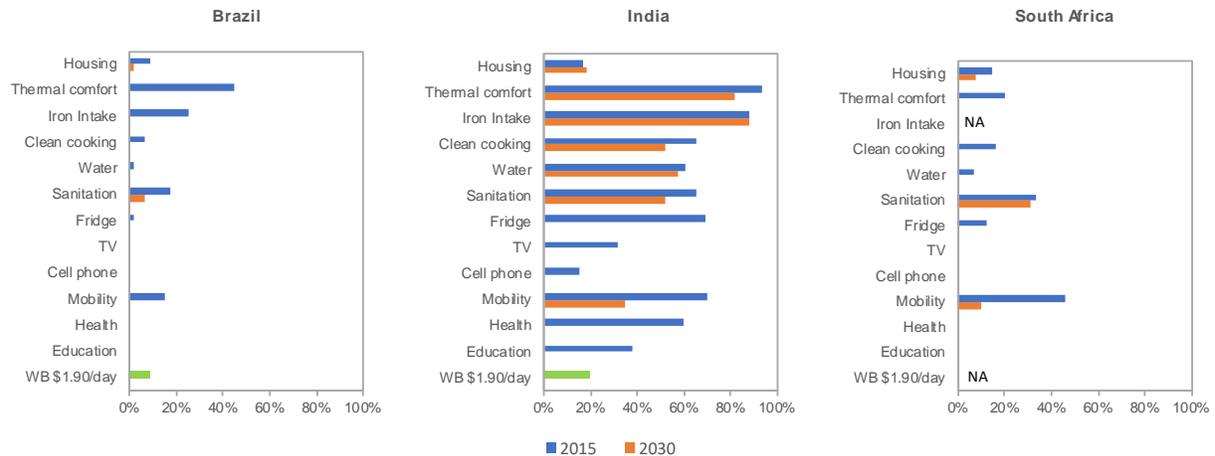
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119   The DLS reveals the multidimensionality of poverty and its extent. More people lack DLS than

120   the number of income poor, as defined by the World Bank's International Poverty Line (IPL) of

121     $1.90/day (Figure 1)[20]. In India, 15-93 percent of the population lack various elements of DLS,

122   which far exceed the IPL headcount of 20 percent. One dimension of particular importance to

123   public health and climate change is the need for space cooling to avoid heat stress-induced health

124   effects, which affects up to 3.4 billion worldwide[21], including over 93 percent (over a billion) of

125   Indians[19]. We estimate that about 45 percent of Brazilians and 20 percent of South Africans also

126   lack access to air conditioning (AC) to provide adequate thermal comfort. Otherwise, the DLS

127   deficits in Brazil and South Africa are largely in access to mobility and sanitation.

128   There is no easy way to predict how these gaps will evolve. If current trends continue, deficits in

129   India would persist in some measures beyond 2030. The slowest progress is in gaining access to

130   improved sanitation, clean cooking, minimum mobility services, and AC for thermal comfort. In

131   Brazil, gaps in access to improved sanitation would persist beyond 2030, while in South Africa

132   mobility and housings gaps would also exist past 2030. If population growth were to exceed, and

133   income growth were to fall below, current trends, gaps in most of these dimensions would

134   increase, but the demand for basic mobility could reduce if this shift were accompanied by less

135   urbanization.

136   As an illustrative exercise, we create three principal scenarios for how DLS gaps may evolve

137   over time. The first is an extrapolation of historical trends (DLS_BAU). We create two other

138   scenarios of full achievement of DLS by 2030, consistent with the SDGs: the first,

139   DLS_ACCEL; and a variation (DLS_ACCEL_LCT) that incorporates development strategies

140   that improve DLS while also reducing energy demand growth. These include public transit to

141   support future mobility in cities[22], energy efficiency measures in industry and buildings[23] and

142   diet diversification[24] (*Supplementary Table 11-13*). These measures illustrate, rather than

143   encompass, the potential for lowering the energy intensity of providing DLS from 'no regrets'

144   measures. We do not include drastic technological advances such as deep electrification of

145   transport, which in any case are modeled in traditional IAM scenarios. Together, these scenarios

146   provide a range of energy demand estimates under different rates of progress in DLS in different

147   contexts and under different types of development policies. We also capture the combined effect

148   of uncertainty in the DLS gaps and key material requirements in DLS_HIGH and DLS_LOW

149   sensitivity scenarios, which capture the high and low bounds of this uncertainty, respectively

150   (See *Supplementary Note 1, Supplementary Figure 7*).

151   Below, we present the results and their implications for energy demand, energy policy and

152   climate change mitigation. The last section presents the methods behind these estimates.

The energy demands of basic human needs

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154   Below we first describe the aggregate energy needs, and the contribution of DLS dimensions.

155   We compare their composition across countries with respect to new construction requirements

156   and operating energy. We then discuss the implications of these findings for national policy,

157   climate equity, and future energy research. Note that construction energy includes the energy to

158   build out and turnover of new capital, including vehicles, appliances, housing and infrastructure.

159   As capital outlays are front-loaded, and reduce to capital turnover in later years, we present the

160   construction energy investment as an average per capita energy requirement per year over the

161   time period 2015-2050. Operating energy includes the economy-side energy required to deliver

162   DLS to all, expressed in GJ per capita per year. We focus on the operating energy post 2030,

163   when DLS is hypothetically achieved.

164   We find, somewhat surprisingly, that operating energy dominates total energy needs, despite the

165   large infrastructure gaps, particularly in India (Figure 2). Between the DLS_ACCEL_LCT and

166   DLS_ACCEL scenarios, total annual operating energy is 10-11 GJ per cap in India, 14-16 GJ per

167   cap in South Africa, and 19-21 GJ per cap in Brazil, in final energy terms, once the infrastructure

168   to provide DLS has been built out (that is, post 2030). In addition, the construction energy over

169   the 2015-2050 period lies between 1.4-2.3 GJ per cap in India, 2.1-3.2 GJ per cap in South

170   Africa, and 1.9-2.9 GJ per cap in Brazil. In the case of India, which has the largest gaps, meeting

171   DLS for all by 2030 (the target for achieving SDGs) would require 23 percent greater capital

172   (and related energy) infusion compared to BAU trends. Notably, these energy requirements are a

173   likely lower bound, as they are based on conservative thresholds.

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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).
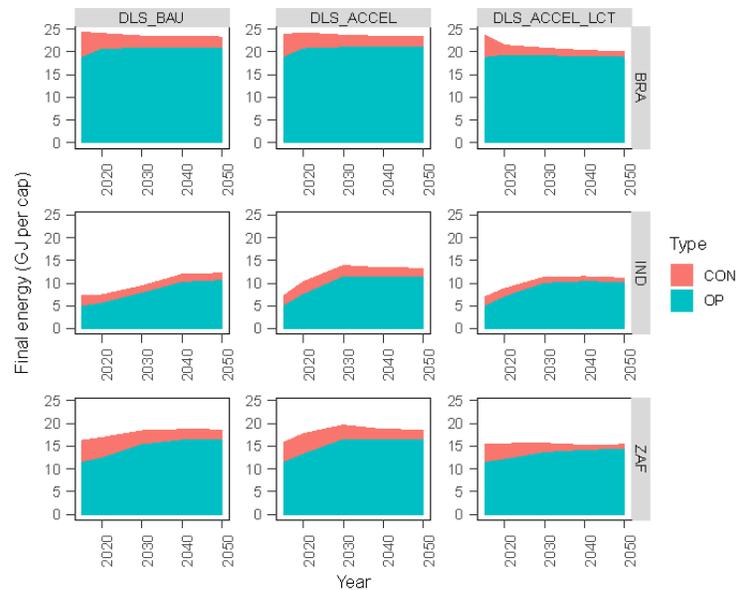
Taking construction and operation together, total DLS energy needs (averaged over the period 2015-2050) lie at the lower end of the 10-100 GJ per capita range in literature, but significantly dependent on context. This is not surprising, considering that most studies estimate global relationships between 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

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193   requirements (basic education and ICT) are of comparable magnitude, at 2-3 percent of the total

194   each.

195   The construction energy requirements per capita are similar across the three countries, even

196   though the gaps in decent living differ so widely between them. This is due to different

197   circumstances related to mobility in each country, which dominates construction energy (45-66

198   percent, across scenarios and countries) (Figure 3). In Brazil, which is reliant on road transport,

199   just the replacement of retiring stock of private vehicles dominates this investment. In India, the

200   overall stock of transport infrastructure has to grow more than in Brazil, but with a higher share

201   of public transit, which is less energy intensive to build. In South Africa, paving unpaved roads

202   in rural areas dominates its construction energy.

203   It is also noteworthy that with sustainable development policies, the construction energy to

204   provide DLS for all can be reduced by over 34 percent for all countries (DLS_ACCEL_LCT

205   scenario vs DLS_ACCEL). In the case of India, such a sustainable path would entail less energy

206   demand than that associated with DLS_BAU — a slower expansion of DLS access and less

207   efficient technology choices. Most of this potential is in transport, and to a lesser extent in

208   housing. In particular, the construction energy for mobility for all countries can be reduced by

209   36-48 percent (the latter in India, where growth is highest) if incremental demand in cities is met

210   by public transportation alone. This would reflect an increase in the share of public transport, rail

211   or bus, in 2050 from 20 to 80 percent in South Africa, from 2 to 26 percent in Brazil, and from

212   63 percent to 78 percent in India. Replacing slums and overcrowded homes with multi-storey

213   housing, and over 30 million sub-standard homes in rural India, and a million in rural South

214   Africa with durable alternatives would require (~0.6-0.9 GJ/cap, 2010-2050), depending on the

215   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).
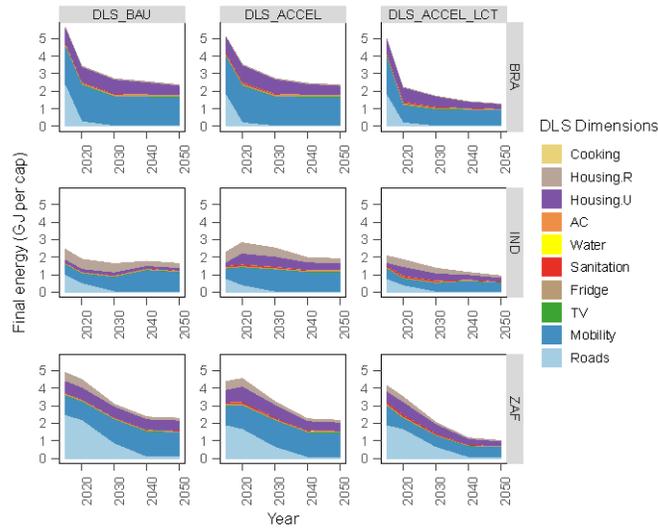
Supporting mobility on an ongoing basis dominates DLS operating energy as well (Figure 4). The energy requirements for mobility depend significantly on existing mode shares, because different transport modes have very different energy intensities. Despite high growth in private vehicles in India, over 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

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234   comparable to India's entire DLS energy needs, even if public buses serve the bulk of future

235   demand growth.

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

237   Operating energy per capita for delivering decent living standards to all in Brazil (BRA), India
238   (IND) and South Africa (ZAF) in three scenarios of progress: left, business as usual, where full
239   access is not achieved by 2030 (DLS_BAU); middle, full achievement by 2030 (DLS_ACCEL);
240   right, full achievement by 2030 with climate-friendly strategies (DLS_ACCEL_LCT).
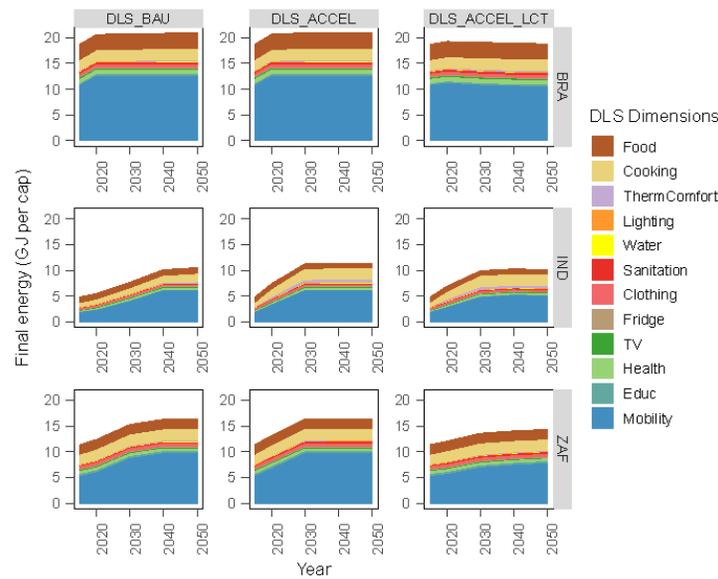
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242   After mobility, the production and preparation of food comprises the largest share of annual

243   energy needs, albeit to different extents in the three countries. Food production contributes 1.1

244   GJ/cap/yr., 2.1 GJ/cap/yr. and 3.2 GJ/cap/yr. in India, South Africa and Brazil respectively to

245   energy demand. This is explained in large part by the extent of meat consumption,[25] which

246   contributed 12, 35 and 51 grams of protein per day to an average person in the three countries

247   respectively in 2012-13[26]. Actual food-related energy demand in India would likely grow, as

248   meat consumption is on the rise, but previous work shows that nutritional requirements can be

249   met with modest diet changes that reduce energy use.[24] In keeping with our approach to

250   calculating minimum energy needs, we do not count this growth in the DLS energy needs.

251 Energy demand for cooking (including stove and fuel production) would decrease with DLS to

252 ~2 GJ/cap/yr. for all three countries, due to the replacement of inefficient and toxic solid fuel

253 combustion with cleaner and more efficient stoves and fuels such as liquid petroleum gas

254 (LPG)[27]. The energy for conditioning a minimal amount of residential `space at night to a

255 comfortable range of temperature and humidity amounts up to only 0.5 GJ in India per person

256 per year.

Implications for sustainable development policy

258 The lifestyles people adopt as they rise out of poverty will influence their wellbeing and, through

259 their material content, energy demand growth.[28] This study helps relate energy demand growth to

260 aspects of lifestyles associated with basic needs and affluence. Compared to the modest energy

261 needs required to avoid heat stress in homes, more luxurious use of AC can entail energy

262 demand of five times this minimum level[29]. Means of social affiliation, including basic

263 education, and access to broadcast and social media, require just a few gigajoules of energy per

264 capita. In contrast, electronics are a growing and non-trivial share of household energy use in

265 affluent countries[30].

266 For India in particular, the findings reveal the extent to which national energy demand mirrors

267 inequities in living standards. Current final energy use was 17.5 GJ per cap in 2015, of which,

268 given the large gaps in DLS, about 7 GJ/cap of current demand likely serves basic needs.

269 Further, only 12-15 GJ per cap per year would be required to meet DLS for all, and only a small

270 fraction of that to build out the necessary infrastructure. Although this is not a comprehensive

271 estimate of the energy use needed to support an economy, it reveals that the scale of the energy

272 gap to eradicate poverty is comparable to current energy use.

273   These insights also help define policy choices that can support climate mitigation and enhance

274   wellbeing. Over a third of construction energy can be avoided if slums and poor quality rural

275   homes were upgraded with energy-saving housing construction practices,[23] and if public

276   transportation were scaled up to serve future urban mobility demand. Targeting future energy

277   infrastructure expansion and improvement towards newly emerging urban areas, particularly in

278   support of such improved housing and public transit, can be an effective way to dovetail energy-

279   efficient and equitable growth. Expanding access to clean cooking and encouraging healthy diets

280   are already well-known strategies to improve wellbeing and reduce energy demand[31].

281   The analytical framework can also provide stakeholders with insights into the sensitivity of the

282   DLS energy needs to different threshold values of the DLS dimensions, since the final results are

283   a linear combination of these inputs and their respective embodied energy intensities

284   (*Supplementary Tables* 15-18). For instance, one can compare the impact on energy needs of

285   changing the minimum standard of floor space in public housing to that of changing minimum

286   mobility requirements.

287   **Implications for climate equity**

288   Climate agreements have for long expressed in their call to action an intent to protect

289   development rights[32,33]. However, without a concrete articulation, the compatibility of such an

290   entitlement with meeting ambitious climate mitigation has eluded policy debates. The DLS can

291   be a basis to characterize such an entitlement. Its related energy demand is one critical link to the

292   many societal transformations required for climate mitigation. This study shows that the energy

293   demand in global scenarios of $2°C$ can support DLS in the three chosen countries. However, the

294   extent of this compatibility differs across the countries.

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295 The gap between countries' DLS energy requirements and IAMs' projected energy demand

296 pathways in a 2°C world (Figure 5) reflects the energy demand associated with affluence, above a

297 DLS. India, as the poorest country with the largest DLS gap (Figure 1), has the least 'headroom'

298 under the IAM trajectories, despite already having lower average demand of DLS. This implies

299 that India's future affluence from income growth would have to be achieved with relatively less

300 growth in energy demand or have to bear a higher carbon price tag than elsewhere. International

301 cooperation on technology transfer and diffusion in future negotiations have to address such

302 inequities if countries like India are expected to pursue ambitious mitigation. These questions

303 require exploration in the broader context of greenhouse gas emissions and not just energy, but

304 the DLS framework offers a common foundation for such a discussion.

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

307 Comparison of energy demand scenarios for decent living standards (DLS_ACCEL,
308 DLS_ACCEL_LCT) to national projections from two IAMs (IMAGE, GCAM) under available
309 socioeconomic futures (Shared Socioeconomic Pathways SSPs 1, 2, 4) that all achieve climate
310 stabilization at 2.6W/m^2 (2°C) (SSP-2.6). Variability of DLS pathways to socioeconomic futures
311 is relatively small. See *Supplementary Note 1*. Note: DLS for all achieved only in 2030.
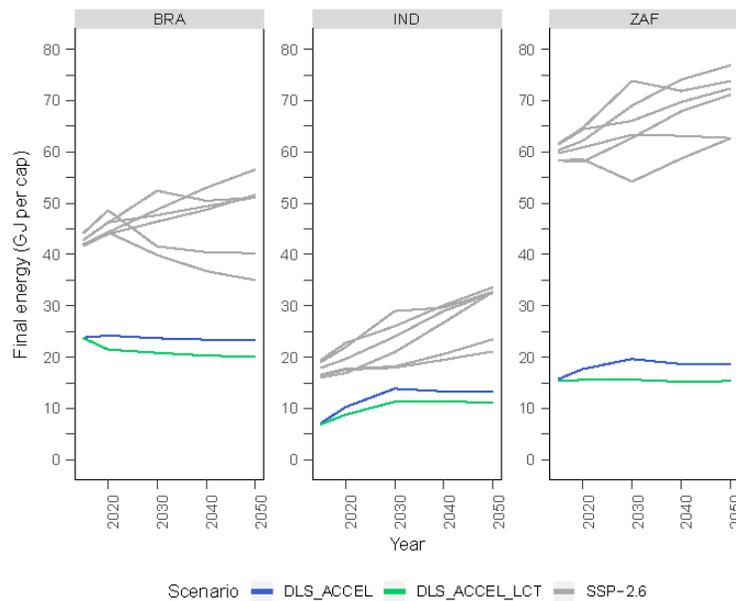
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313   Questions about fair efforts and technology transfer have immediate practical significance for

314   countries' Nationally Determined Contributions (NDCs) under the Paris Agreement. Current

315   pledges fall well short of what is required to meet the targets. Many stakeholders believe that

316   equitable efforts-sharing is central to ratcheting up ambition[34-36]. The global stock stake, starting

317   in 2023, obligates parties to develop more ambitious plans for mitigation, adaptation and means

318   of implementation, which include technology transfer and climate finance. The energy needs and

319   climate impacts of providing DLS can be one lens through which subsequent NDC pledges are

320   viewed. Its underlying components provide a concrete basis to debate comparability of countries'

321   demand-side climate mitigation efforts. For instance, India's significantly lower energy demand

322   for the same DLS compared to Brazil raises questions about convergence. What factors justify

323   these differences? How should path dependence and the maturity of Brazil's transport

324   infrastructure be considered against its higher income and transport energy intensity? Similar

325   questions can be asked of food and culture, or housing characteristics and climate, among others.

326

327   **Implications for future research**

328   The analytical approach pursued here builds on a new direction of research that bridges between

329   IAM and industrial ecology research. This link has been recognized as a way to formally assess

330   climate policy alongside other sustainability impacts of a changing industrial system[37,38]. This

331   study extends this link to consumption and its contribution to wellbeing. Future sustainability

332   research can assess trade-offs and impacts between policies that influence consumption,

333   materials and energy system changes against environmental and social objectives. We create a

334   common point of comparison through energy demand, which we relate to consumption through

335   IE and to climate impacts through IAM. Future work can derive other sustainability impacts of

336   DLS from IE and relate these to climate mitigation goals.

337   **Methods**

338   This study utilizes a service-driven energy accounting model (SEAM) to map countries' progress

339   in living standards to their energy use (*Supplementary Figure 1*). SEAM builds on a foundation

340   of previous studies, particularly for the definition and justification of DLS[16] and the simulation

341   of building construction and operation[29]. SEAM calculates embodied energy intensities of DLS

342   dimensions using standard methods in industrial ecology[39], including multi-regional input-output

343   (using the EXIOBASE MRIO[40]) and life cycle assessment (LCA)[41,42]. The MRIO is linked to

344   household consumption and expenditure surveys for the three countries so that embodied energy

345   intensities can be calculated for all household consumption categories[43]. We use this household

346   footprinting approach for calculating, by country, the embodied energy for food, clothing, health

347   and education. The LCA tools are used primarily to calculate the embodied energy of

348   construction and manufacturing, for appliances, buildings and infrastructure. In both methods,

349   we track final energy use (instead of primary energy) through the supply chain, in order to

350   capture actual energy demand, so as to remove the dependence of the results on the fuel mix of

351   the respective countries and thereby enable legitimate comparisons of energy needs across

352   countries. The quantification process involves several similar steps for each DLS dimension.

353   First, based on normative thresholds quantities for DLS dimensions, supported by academic

354   literature[16] and prevailing regulations and standards, estimate shortfalls in DLS from household

355   survey and other national data (*Supplementary Methods, Supplementary Note 4*). Second, using

356   statistical or simulation techniques, where needed, to determine the material satisfiers that best

357   relate to the chosen DLS dimension. For instance, for cold storage and adequate shelter the

358   material satisfiers are straightforward – refrigerators and buildings. The chosen material basis for

359   health and education standards – national expenditure – is less obvious but was found to best

360   correlate to outcomes compared to other physical indicators, such as hospitals or schools. Third,

361   we use MRIO and LCA, as appropriate, to estimate the embodied energy intensity of the chosen

362   material satisfiers. MRIO was used for food, health, education and clothing, while LCA was used

363   for buildings, appliances, vehicles and infrastructure. The choice was based on the specificity of

364   material requirements and their alignment with sector or product definitions in each method.

365   Fourth, we estimate pathways of progress for the DLS dimensions under the chosen scenarios of

366   development and climate policies. In the DLS_BAU scenarios we extrapolate historical rates of

367   progress/growth in each DLS dimension; in DLS_ACCEL we accelerate growth to fill all gaps in

368   DLS by 2030, in line with the SDGs. In the DLS_ACCEL_LCT scenario, different measures are

369   adopted in each dimension, which are described later. We operationalize these choices in a

370   simple capital stock and flow model to represent the material stock that deliver DLS and their

371   operational characteristics. Capital is replaced in accordance with the assumed lifetimes of

372   durables.

373   The rest of this section first briefly summarizes the principles underlying the estimation

374   approach, and then presents how the above steps were operationalized for each dimension. The

375   full details of the material stocks, operating assumptions and the resulting energy demands can

376   be found in the *Supplementary Tables 14-18.*

377   With foundations in theories of basic capabilities and basic needs, the DLS identifies a common

378   universal set of material prerequisites, or 'satisfiers', for attaining physical and social wellbeing

379   in modern society[16]. Everyone ought to have adequate nutrition, shelter, health care and

380   education, decent living conditions, and the opportunity to participate in society. The DLS

381 operationalizes these universal satisfiers into context-dependent material and energy

382 requirements. The use of industrial ecology tools allows us to comprehensively capture the

383 hierarchy of material dependence, and therefore, the full extent of the built environment, needed

384 to provide DLS. The threshold quantities of individual satisfiers, where relevant (e.g. daily

385 allowance for micronutrients, or floor space), are based on prevailing international and national

386 standards or global trends and translated to actual material consumption based on local

387 conditions. For instance, in all countries a universal floor space threshold ($10m^2$ per person) and

388 range of thermal comfort is used, but country-specific building types (e.g. urban multi-storey vs

389 rural single-storey), local construction materials and prevailing efficiency standards, determine

390 the housing and space conditioning energy requirements. Adequate nutrition translates to

391 different daily calorie and micronutrient requirements based on the bioavailability of available

392 foods, which in turn translate to different foods based on prevailing diet choices.

393 The results obviously depend on the chosen thresholds, whose determination involves some level

394 of subjectivity, and ought to, in principle, be driven by policy. We have selected values with the

395 intent of capturing a basic minimum, and provide results that scale proportionately with

396 alternative threshold values. We describe each dimension and its related content next.

397 Food requirements and nourishment are conventionally characterized as average calories per day,

398 which masks and understates the extent of malnourishment in the form of deficiencies in micro-

399 nutrients, such as iron, zinc and vitamins[44]. We estimate these deficiencies with reference to

400 national standards for nutritional adequacy. The diet composition for the countries are based on

401 weighted averages from national (representative) household surveys for Brazil and South Africa

402 in all scenarios. In previous work, we use optimization methods to find regional diets in India

403 that meet these nutritional constraints and energy use while minimizing deviations from existing

404   diets[24]. The DLS_ACCEL and DLS_ACCEL_LCT scenarios for India adopt this nutritionally

405   optimal (low-rice) diet. In the cases of Brazil and South Africa, the same granularity on

406   household diets and their nutritional content was not available. We instead assess DLS in terms

407   of total calorie requirements. We calculate the embodied energy of DLS diets using the MRIO-

408   based household footprinting tool described above (*Supplementary Methods* for further details).

409   Food preparation inside homes has a significant effect on well-being due to emission of harmful

410   pollutants from solid and liquid fuel based cook stoves. Thus, DLS require that households have

411   gas or electric stoves, which do not emit these pollutants. We calculate the embodied energy in

412   manufacturing and using stoves based on typical usage in middle-income households in India.

413   We find support for a minimum space requirement of 10 m^2 per person, above a minimum home

414   size of 30 m^2 (for up to three persons), in several national standards for public housing. For

415   instance, populated regions such as Hong Kong and Taiwan, have regulations for minimum

416   living space between 8-13 m^2 per capita[16]. To avoid heat stress, maximum indoor temperature is

417   restricted to 26°C and 60 percent humidity[19,29]. The material requirements, the embodied energy

418   intensities of construction and the cooling energy are calculated using a building simulation

419   model developed elsewhere that uses multi-storey and single-storey building archetypes for

420   urban and rural areas respectively[29]. This model uses the *EnergyPlus* software to simulate space

421   conditioning and an LCA engine to calculate the embodied energy in materials. For the

422   DLS_ACCEL_LCT scenario, we deploy aerated earth blocks for construction and energy

423   efficient materials and cooling equipment, which previous work shows reduces both construction

424   energy and cooling energy requirements relative to conventional masonry[23].

425   For clothing, we find a robust relationship, using linear regression, between quantity of clothing

426   (from household surveys) and climate. We accordingly determine minimum clothing

427 requirements for the three countries using population-weighted climate index (a variation of

428 Heating Degree-Days HDD, see *Supplementary Methods*), and combining with their respective

429 embodied energy intensities from the MRIO. We keep the clothing requirements fixed over time

430 and across scenarios.

431 Decent standards for water supply and sanitation entail in-house access to a minimum quantity of

432 clean water per person per day to support drinking needs, basic ablutions and in-house toilets.

433 Energy for water use in agriculture and industry is accounted for in the indirect energy

434 accounting for other DLS dimensions. The embodied energy for constructing the infrastructure

435 and supplying water are drawn from the LCA literature. Both quantities and intensities are

436 invariant in all scenarios.

437 Households are equipped with basic appliances to meet the needs for cold storage and

438 connectivity to society, including a television, based on the most widely prevalent technology

439 and size options in each respective country[45]. In the DLS_ACCEL_LCT scenario, we assume

440 full penetration of the best available technologies, as modeled in previous work.

441 The provision of health care and education is through shared facilities (e.g. hospitals and

442 schools). The literature reveals that indicators of good health (life expectancy and infant

443 mortality) and education completion correlate well with national per capita health and education

444 expenditures respectively, and stronger than other physical indicators such as the number of

445 hospitals or schools[16,46]. These minimum expenditures were combined with embodied energy

446 intensities from MRIO to yield energy requirements for health and education.

447 **Uncertainty analysis**

448   We characterize uncertainty in our results following the types of uncertainty identified by the

449   IPCC[47]: unpredictability in behavior related to society and institutions; value uncertainty, related

450   to data inputs; and structural uncertainty in models related to the underlying energy intensity

451   calculations. Note that we already illustrate policy uncertainty through the scenario design. We

452   describe how we represent each type of uncertainty below.

453   We represent two types of societal uncertainty: socioeconomic futures, and institutional

454   conditions. We select key influential variables in each, and combine them, for ease of

455   presentation, to show the outer bounds of energy needs, using two scenarios, DLS_HIGH and

456   DLS_LOW. The socioeconomic uncertainty influence primarily the DLS gap, and the latter the

457   characteristics of new capital required to fill this gap. We use population, income and

458   urbanization projections from available socioeconomic futures from the climate literature

459   (Shared Socioeconomic Pathways, or SSPs)[48]. Population influences the overall gap; income

460   influences the secular uptake of appliances (TV, cell phone and AC); and urbanization influences

461   the share of urban and rural housing requirements, which have different archetypes, and

462   therefore different energy use for the same comfort thresholds. in the DLS gaps. We use the DLS

463   gap most closely related to current trends (SSP2) for the main results (DLS_ACCEL and

464   DLS_ACCES_LCT scenarios), and use SSP1 and SSP3 for the DLS_LOW and DLS_HIGH

465   variations respectively, because they yield the most contrasting values for the DLS gaps.

466   The lifetime of capital, particularly housing, vehicles and roads, and the share of two-wheelers

467   and four-wheelers in India, constitute the most influential institutional uncertainties. In addition,

468   we incorporate uncertainty in the health care sector expenditures that would be required to

469   achieve DLS.

470   Regarding value uncertainty, several data inputs go into the embodied energy intensity

471   calculations. As described below, the literature does not typically offer a logical basis to estimate

472   ranges for these inputs. Instead, we present a sensitivity analysis of the main results to key input

473   parameters. The input data fall into two categories: threshold material requirements in DLS; and

474   the technical parameters in the energy intensity calculations. The threshold quantities of DLS

475   dimensions are a normative input representing consumption levels, which, as mentioned earlier,

476   have been chosen conservatively to develop a lower bound on energy needs for DLS. As the

477   final result is a linear combination of these quantities and their respective embodied energy

478   intensities, the individual components scale proportionately with different threshold values.

479   Regarding energy intensities, aside from our simulations, we have drawn many estimates of

480   embodied energy intensity of products from the LCA and IO literature, for which authors

481   typically do not provide sensitivities. For convenience, we have tabulated the sensitivity of the

482   overall result to a 10 percent change in every threshold value and input parameter that influence

483   these embodied energy intensities (*Supplementary Figure 7*).

484   The primary structural uncertainties lie in the LCA and IO inventories and databases that we rely

485   on in our calculations. However, these uncertainties are only known generally in the field, not for

486   the specific studies and databases from which we draw. Nevertheless, we quantify the extent of

487   this uncertainty (See *Supplementary Note 1*). A comparison of the main results to the uncertainty

488   scenarios can be found in *Supplementary Table 25*.

489   **Data Availability Statement**

490   The data that support the plots within this paper and other findings of this study are available

491   from the corresponding author upon reasonable request. Publicly available data used in the

492   analysis include nationally representative household consumption expenditure surveys in India[49],

493 Brazil[50] and South Africa[51], and the Ecoinvent 3[52] and EXIOBASE 3[40] databases. Further details

494 available in *Supplementary Note 4.*

495 **Code Availability Statement**

496 The code used to manipulate the data and generate the results are available from the

497 corresponding author upon reasonable request.

500 **Contributions**

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

502 **Financial and non-financial competing interests**

503 The authors declare no competing interests.

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