**Supplementary Information**

Providing Decent Living with Minimum Energy:

A Global Scenario

*[Author details removed for peer review]*

# Overview

In Part 1 below, we expand upon the methods of our paper by giving details of data sources, calculations and assumptions made while building the model. In Part 2, we present a sensitivity analysis, and Part 3 offers data for *Decent Living Energy* by consumption category across all countries we study. But first, we offer a note on *provisioning and ownership,* and a high-level comparison between our work and two similar studies.

*Provisioning and ownership:* Decent Living Standards (DLS) could, in theory, be provided through a myriad of ways via different ownership structures, economic imperatives, material infrastructures, cultural norms and individual preferences. As an example, washing machines could be owned by all households or accessed through communal facilities, with these facilities themselves collectively or privately owned. Where necessary, we base our assumptions on present day conditions; in this case, assuming a washing machine is owned by each household. However, the structure of the model does not always require such assumptions to be made.

Cars for mobility are an illustrative example. The data we use for the embodied energy of vehicles is scaled in MJ/pkm, rather than MJ/vehicle. This makes is unnecessary to specify in the model whether every person owns a vehicle, or whether all vehicles are accessed via shared ownership

**Table S1:**DLS dimensions and details of the provisioning scale for each material requirement/service.

|  |  |  |  |
| --- | --- | --- | --- |
| **DLS dimensions** | | **Provisioning and ownership** | |
| **Nutrition** | Food | Individual | Food is consumed by individuals (but it could be in collective contexts) |
| Cooking appliances | Household | Appliance ownership at the household level (but eating could be collective) |
| Cold Storage | Household | Appliance ownership at the household level |
| **Shelter**  **& living**  **conditions** | Sufficient housing space | Household | Residential floor space is household level by definition |
| Thermal comfort | Household | Again, household level by definition |
| Illumination | Household |
| **Hygiene** | Water supply | Collective | Supply infrastructure is collective (but consumption is individual/household) |
| Water heating | Household | Water heating occurs at the household level |
| Waste management | Collective | Collective systems collect and manage household waste (sanitary and solids) |
| **Clothing** | Clothes | Individual | Clothing worn individually (but ownership could be collective/household) |
| Washing facilities | Household | Appliance ownership at the household level |
| **Healthcare** | Hospitals | Collective | Hospitals and healthcare systems are collective |
| **Education** | Schools | Collective | Educational institutions systems are collective |
| **Comms’ &**  **information** | Phones | Individual | Phones are owned individually (by those above a certain age) |
| Computers | Household | Laptops are owned at the household level |
| Networks + data centres | Collective | Infrastructure supporting the above technologies is collective |
| **Mobility** | Vehicles | *Various* | Some *could* be owned individually (e.g. cars, bikes), others not (e.g. trains…) |
|  | Vehicles’ propulsion | *Various* | This would vary in-line with vehicle ownership |
|  | Transport infrastructure | Collective | Infrastructure supporting transport is collective |

schemes. The model is thus flexible with respect to ownership levels – we need only assume that all vehicles produced are (i) used to the end of their useful life, (ii) always driven with a particular occupancy rate and (iii) cover a fixed distance annually. Of course, ownership is an essential issue for implementation – individual vehicle ownership could make high occupancy rates and low-activity levels difficult to achieve; collective schemes could be public or private with associated pros and cons. These questions are beyond our scope, but are nonetheless important to bear in mind throughout Part 1. In Table S1, we summarise DLS dimensions along with wider considerations.

*Comparison with similar studies:* We now compare our key assumptions and model outputs with two similar studies, outlining the largest differences we find and likely reasons for them. Specifically, these are (i) that of Rao, Min and Mastrucci (2019)1, which estimates minimum energy requirements for decent living in India, Brazil and South Africa, including analysis of how to get from here to there, given current infrastructure gaps, and (ii) the *Low Energy Demand* Scenario of Grubler et al. (2018)2, which describes a high-tech, low demand scenario consistent with keeping global temperature change to under 1.5 degrees (without negative emissions technologies).

Table S2 shows that across all three studies activity levels for housing and transport are broadly similar. Our assumptions are equal to those of Rao, Min and Mastrucci for average residential floor-space per capita, but Grubler et al. assume twice what we do (15 vs. 30 m2/capita). Our housing energy requirements are thus lower than those of Grubler et al., and similar to Rao, Min and Mastrucci. All three studies assume mobility levels of ~10,000 p-km/capita (our values are slightly lower; Grubler et al.’s slightly higher). However, our ambitious energy intensity improvements bring total energy requirements below both these other studies. For food, our values are close to Rao, Min and Mastrucci, but cannot be compared directly to Grubler et al. Note that Table S2 does not include energy use values for all DLS dimensions, so they do not sum to the total energy requirements listed.

Overall, we estimate per-capita final energy requirements that are similar to those of Rao, Min and Mastrucci (although with a narrower range). In contrast, our estimates are substantially lower than Grubler et al., due, mostly, to our more ambitious, sufficiency-based, demand-side assumptions.

**Table S2:**Key assumptions in the current study compared to values from 1 and 2. **Food** includes production, supply chains, cooking and cold storage; **Transport** includes energy for vehicle production, provision and combustion of fuels, and infrastructure (which includes roads in this study); **Housing** includes both construction of residential buildings and energy for heating & cooling.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  | **This study** | **Rao et al.** | **Grubler et al.** |
| **Average household floor space+** | m2/cap | 15 | 15 | 30 |
| **Housing energy requirements** | GJ/cap | 0.7-1.7 | 0.6-1.1 | 1.2-5\* |
| **Mobility levels** | p-km/cap | 4,900-15,000 | 10,000 | 9,544-17,117 |
| **Mobility energy requirements** | GJ/cap | 2.1-5.4 | 4.5-12 | 1.5-10.7 |
| **Food** | GJ/cap | 3.1-3.3 | 2.5-5.6 | NA\* |
| **Total (final) energy requirements** | GJ/cap | **13-18.4** | **11.4-26** | **20-50** |
| **Geographic scope** |  | Global | IND/BRA/ZAF | Global |
| **Granularity** |  | Country & urban/rural | Country | Global N & S |

**+**This is based upon our average of 4-persons per household.

\*In LED, cooking is included in *Housing*, and food production is not reported separately.

**Part 1** Methods and Data Sources

# Shelter and living conditions

## Household floor space

Our floor-space per capita is a function of the minimum requirements suggested by Rao and Min3, and the average household size that we specify. They suggest 10 m2/capita of living space, plus 20 m2/household for kitchen and bathroom facilities. We assume a household size of four persons on average, thus floor space requirement of 15 m2/capita. This feeds into our thermal comfort, illumination and residential construction calculations. We vary the household size in our scenarios and sensitivity test.

For simplicity, we use the same floor-space per capita in rural and urban areas, even though rural living space could be larger due to lower space restrictions. This is appropriate from a threshold perspective, where the minimum is key. In future work, differentiation of household floor-space based upon urban/rural splits, special physical needs, or other fine-grained parameters could be implemented.

## Household thermal comfort

*Global data:* We start with data from Atalla, Gualdi and Lanza4, who provide heating and cooling degree days (HDD and CDD) for 147 countries. These are calculated from global climate data, aggregated to national values by taking a population-weighted average of the gridded, spatial data across each country. They offer data for different temperature thresholds, and we use a reference temperature of 21.1°C for CDD, and 15.6°C for HDD. In both cases, we take their average 1964-2013 values as a starting point.

*Future climate changes:* We project these national values forward to 2050, using a rough estimation of the impacts of future climate change; *rough*, as we only have projections for European counties from Spinoni et al.5. Spinoni *et al.* explore potential changes in HDD and CDD in Europe to 2100, for two emission representative concentration pathways (RCP4.5 and RCP8.5). They find significant decreases in HDD, especially in northern and colder regions, and increases in CDD that peak over Mediterranean regions. But overall, differences are found to be modest when population weighting is applied.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Table S3:** *Matching of European regions in Spinoni et al. (2018) to four climate zones* | **Climate**  **zones** | **European**  **analogue** | | **RCP4.5** | | **RCP8.5** | |
| **∆HDD** | **∆CDD** | **∆HDD** | **∆CDD** |
| **Tropical** | South Spain; Turkey | | -2 | 5 | -5 | 10 |
| *Average* |  | **-2** | **5** | **-5** | **10** |
| **Subtropical** | Iberian Peninsula | | -2.5 | 1.7 | -4.9 | 4.1 |
| Mediterranean region | | -3.4 | 1.9 | -6.1 | 4.4 |
| South Spain, Turkey… | | -2 | 5 | -5 | 10 |
| *Average* |  | **-2.6** | **2.9** | **-5.3** | **6.2** |
| **Temperate** | British Isles |  | -2.9 | 0.1 | -5.2 | 0.3 |
| France + Benelux | | -3.2 | 0.8 | -6 | 2 |
| Central Europe | | -3.9 | 0.4 | -7.2 | 1.1 |
| Eastern Europe | | -4.4 | 0.7 | -7.9 | 1.7 |
| *Average* |  | **-3.6** | **0.5** | **-6.6** | **1.3** |
| **Cold** | Northern Europe | | -5.7 | 0.1 | -9.4 | 0.3 |
| European Russia | | -6.5 | 0.6 | -10.9 | 1.7 |
|  | *Average* |  | **-6.1** | **0.4** | **-10.2** | **1.0** |

The main issue is matching their European data to our global GTAP countries. This is a crude process, but seems acceptable, given the relatively modest changes, and the discrete format of the building energy use data we introduce later.

We consider all GTAP countries to lie within one of four climate zones: *tropical*, *subtropical*, *temperate*, or *cold*. For comparison, other authors6 have used *tropical*, *desert*, *temperate* and *cold*. For each climate zone, we assume linear yearly changes in HDDs and CDDs out to 2050. Simple linear trends in CDDs and HDDs are reported by Spinoni et al.5 across Europe, and we take European analogues to represent the four climate zones before matching GTAP regions to these climate zones (Table S3). Note that for tropical areas our matching is far from ideal – there are no areas in Europe suitable to use as proxies – thus we take the areas furthest south.

Once HDDs and CDDs are calculated for 2050, we calculate heating and cooling energy demands. We use data from the *Global Building Performance Network* scenarios7 for final energy for both space heating and cooling. This is given in KWh/m2 for geographical regions (*Africa*, *Eastern Europe*, *South Asia*, etc.), urban and rural buildings, various building types (*single-family*, *multi-family*, *hotels*, *educational*, etc.), technology standards (*standard*, *advanced new*, *advanced retrofit*, etc.), and discrete HDD/CDD bands (Table S4). These can readily be combined with the floor space per capita values described above.

We’re interested only in the residential buildings with the greatest possible energy-performance. Accordingly, we focus upon *advanced new* buildings and use only the data for *single-family* buildings for rural areas, and *multi-family* for urban areas; urban *multi-family* buildings have lower energy requirements than urban *single-family* buildings (by ≈8%), but no data is provided for the former for rural areas. GBPN suggest that *advanced retrofit* buildings consume ~20-50% more energy than *advanced new* buildings; we use these data in the sensitivity analysis but not our DLE scenario.

**Table S4:** *Input building energy requirement data, calculated from GBPN (2012)*

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Heating and cooling description** | **Energy use** (KWh/m2) | | **CDD** | | **HDD** | |
| **Urban** | **Rural** | **min** | **max** | **min** | **max** |
| **Only Heating** (Very high demand) | 15.1 | 13.1 | 0 | 1000 | 5000 | 10000 |
| **Only heating** (High demand) | 14.7 | 12.9 | 0 | 1000 | 3000 | 5000 |
| **Only Heating** (Low & moderate demand) | 12.9 | 10.4 | 0 | 1000 | 1000 | 3000 |
| **Heating & Cooling** (V.high heating demand & mostly Low cooling demand) | 19.4 | 17.0 | 1000 | 2000 | 5000 | 10000 |
| **Heating & Cooling** (High heating demand & mostly Moderate cooling demand) | 17.6 | 14.1 | 2000 | 3000 | 3000 | 5000 |
| **Heating & Cooling** (High heating demand & Low cooling demand) | 15.1 | 13.3 | 1000 | 2000 | 3000 | 5000 |
| **Heating & Cooling** (Moderate heating & cooling demand) | 12.2 | 10.6 | 2000 | 3000 | 2000 | 3000 |
| **Heating & Cooling** (Moderate heating demand & Low cooling demand) | 14.0 | 12.0 | 1000 | 2000 | 2000 | 3000 |
| **Heating & Cooling** (Low heating demand & Moderate cooling demand) | 12.8 | 10.7 | 2000 | 3000 | 1000 | 2000 |
| **Heating & Cooling** (Low heating & cooling demand) | 11.8 | 10.5 | 1000 | 2000 | 1000 | 2000 |
| **Only Cooling** (Very high demand) | 15.3 | 11.4 | 5000 | 10000 | 0 | 1000 |
| **Only Cooling** (High demand) | 14.3 | 10.9 | 3000 | 5000 | 0 | 1000 |
| **Only Cooling** (Low & moderate demand) | 14.1 | 10.4 | 1000 | 3000 | 0 | 1000 |
| **Cooling & Dehumidification** (V.high demand) | 13.9 | 10.8 | 5000 | 10000 | 0 | 1000 |
| **Cooling & Dehumidification** (High demand) | 13.8 | 10.7 | 3000 | 5000 | 0 | 1000 |
| **Cooling & Dehumidification** (Low & mod’ demand) | 13.8 | 11.4 | 1000 | 3000 | 0 | 1000 |
| **Heating & Cooling & Dehumidification** | 13.7 | 12.7 | 1000 | 10000 | 1000 | 10000 |

Finally, we average across geographical regions for each HDD/CDD band, as we are interested primarily in how different energy requirements are determined by climate, and hence wish to assume technological deployment is independent of region.

Overall, our calculations give maximum energy usage for thermal comfort of ~**0.9 GJ/yr/cap** (in rural areas of Canada, Kazakhstan and Scandinavia). In contrast, there are countries in warm (but not extreme) climates – e.g. South Africa and Portugal – where energy demand is < **0.3 GJ/yr/cap**.

## Household illumination

Estimates for household lighting require various assumptions: (i) how much space is illuminated, (ii) for how long each day, (iii) how brightly, and (iv) how efficient the process of converting energy into illumination is6. A simple energy use equation thus reads:

*Energy use* = *t*ill*AE*/*efficacy*,

where *t*illis the time period of illumination (seconds/yr) *A* is the average floor area illuminated during this time (m2), *E* is the *illuminance* (lm/m2) and *efficacy* gives the efficiency in lm/W. Energy use here is thus in J/yr.

For *A*, we take the total residential floor space per person, and assume 33% is normally illuminated, as all rooms of a house need not always be lit. We assume this average illumination is needed for 6 hours/day, while for the remaining 18 hours no lighting is used (irrespective of country). This means *t*ill= 7.9 million seconds (6 x 602 x 365).

For *E,* Cullen, Allwood and Borgstein6 suggest that existing illuminance levels in buildings tend to be higher than lighting code recommendations, which vary from 54 lm/m2 for hallways to 430 lm/m2 for offices. They also highlight that a room need not be uniformly lit; even in offices 430 lm/m2 need only be met in the task area. They thus suggest a value of 125 lm/m2 as a low, practical limit. Finally, the *efficacy* of exceptionally efficient LED lighting currently stands at 150 lm/W. We assume this value isn’t improved upon.

Overall, this gives an energy requirement for lighting of ≈ 33 MJ/cap/yr (≈ 7.9 x 15 x 33% x 125/150). We increase this to **36 MJ/cap/yr**, as lifecycle data suggests that direct energy use only accounts for 90% of the energy use of LED lighting8. We assume the value is independent of geography. Various assumptions here could be approved upon, but given the minor contribution of lighting to total energy use any changes would be negligible.

## Household water use

### Water supply

We calculate separately the energy used to supply water to households and for water heating in the home. For the former, we need the total water use (L/cap/yr) in each country, and the energy intensity of water supply infrastructure (MJ/L). From a basic needs perspective, the former is relatively easy to estimate as widely cited recommendations are available. However, the latter is uncertain and dependent upon water scarcity relative to local population densities, and how this will vary under future climate change.

For direct water use, we use data from Gleick9. They summarise four types of home water use underpinning basic human needs – *drinking*, *sanitation*, *bathing* and *food preparation* – and minimum values per person for each, respectively, of 1-1.5mL/kcal of food, 20L/day, 15L/day and 10L/day. In total this gives ~50L/day/cap – close to the UN range of 50-100L[[1]](#footnote-1). This totals 7,350-7,406 L/cap/yr, with the small range due to variations in average food intake across countries.

Before estimating the energy intensity of water supply, we classify each country on a scale of water stress, using data from the *World Resources Institute* (WRI). WRI offer projections of water stress for 167 countries for 2020, 2030 and 2040. We tried their ‘optimistic’ and ‘pessimistic’ scenario data, which they base upon the IPCC’s RCP4.5 and RCP8.5 pathways, respectively, but to negligible affect (the *pessimistic* scenario data increases DLE global energy use for 2050 by ~0.1%). We thus use the *optimistic* scenario in our DLE calculations.

*WRI* measure water stress on a continuous scale from 0-5, where:

**0-1** is *low stress* (<10% of available water withdrawn),

**1-2** is *low to medium stress* (10-20%),

**2-3** is *medium to high* stress (20-40%),

**3-4** is *high stress* (40-80%),

**4-5** is *extremely high stress* (>80%).

Data shows 70 *low stress* countries in 2020, in regions from Central and Western Africa through Scandinavia to South America. In contrast, only 34 are under *extremely high stress* even by 2040 in the pessimistic scenario, largely in Northern Africa, Central Asia and the Middle East.

The distribution of countries is shown in Figure 1. It can be seen that temporal and inter-scenario variations are quite small. Consequently, we don’t extrapolate to 2050, and assume that the *WRI* 2040 values are also appropriate then.

To each of the five stress levels, we assign five distinct energy intensities of water supply. Estimates for these must include the energy used in (1) extraction and distribution, (2) pre-treatment, (3) waste-water treatment and recovery, and (4) construction of all supporting infrastructure10:

The energy intensity of **extraction and distribution** varies considerably with the availability of water relative to population densities. Where sufficient water reserves are available from nearby rivers or lakes, extraction and distribution may use well under 1 MJ/m3 of water delivered to the home. But where long-distance or deep groundwater pumping is required – as in various highly populated areas of Spain, Mexico, California and Australia – intensities can rise as high as 15 MJ/m3 10, 11.

**Figure 1:** Frequency distributions of countries across the five water stress categories of WRI Aqueduct, in 2020, 2030 and 2040, with *Optimistic* and *Pessimistic* scenarios shown for the latter two.

The energy intensity of **pre-consumption treatment** is relatively low at 0.04-2 MJ/m3. The exception is if desalination is used to bypass problems of freshwater scarcity – this can increase intensities to ≈ 10 MJ/m3 or more10, 12.

**Waste-water treatment** is low intensity relative to desalination or long-distance pumping, but remains significant at 1-2 MJ/m3 in countries from Canada to Taiwan (*ibid*). *Recovery* significantly increases intensities relative to *disposal* (*ibid*), but we assume the former nonetheless.

**Water infrastructure** **construction** and associated maintenance is typically small relative to direct energy use, but it remains significant at ≈ 0.5 MJ/m3 for conventional surface and ground water systems. Further, in cases like rain and storm-water harvesting, building infrastructure can be the dominant use of energy11, 12

Given these wide ranges, we use five different energy intensities, as summarised in Table S5. We use the values from Godskesen et al.12 for our *central* energy intensities, as they are for conventional ground- and surface-water systems *without* desalination or long-distant pumping. These include direct energy use and that embodied in infrastructure. Our *very low* and *very high* values are based on the *low-* and *high-energy* scenarios of Plappally10, both assuming waste-water recovery. We then add the energy embodied in infrastructure (which they omit) using a correction factor based upon our *central* value. Our *low* and *high* estimates are set as (mean) averages to fill the gaps. The assumed water use of 7,350-7,406 L/cap/yr translates to **0.1-0.3 GJ/cap/yr**.

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| **Table S5:** Energy usage assumptions for water supply. *Infrastructure* here refers to the energy used in building the infrastructure. |  | **Energy** *(MJ/m3; KJ/L)* | | | | |
|  | V-Low | Low | Central | High | V-High |
| *Direct energy* | **4.0** | 6.3 | **8.7** | 11.6 | **14.4** |
| *Infrastructure* | **0.8** | 1.3 | **1.8** | 2.4 | **3.0** |
| **Total** | **4.8** | 7.6 | **10.5** | 14.0 | **17.4** |

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| **Table S6:**  *Household consumption of heated water, based upon Gleick (1996)* | **Water use:** | **Demand** (L/cap/day) | **Heated fraction** | **Details** |
| **Bathing** | 15 | 100% | 1 short hot shower daily |
| **Sanitation** | 20 | 25% | Includes flushing toilets |
|  | Total hot water demand: **7,300** L/cap/yr | | |

### Water heating

We assume drinking water doesn’t require heating, and the energy for heating water used in food preparation are included in the *nutrition* section estimates. Here, we only estimate the energy requirements for heating water for bathing and sanitation. We recognise that current consumption of hot drinks is widespread globally, but this is not formally included in the framework of Rao and Min3 so we omit these from our results. Adding 1 L of hot drink/cap/day would increase the below values by around 10%.

Table S6 summarises requirements in volumetric terms. A daily per person usage of 5L of hot water for sanitation and 15L for bathing leads to a total requirement of 7,300 L/cap/yr. This 5 L/day comes from starting with the 20 L/day for *all* sanitation suggested by Gleick9, and assuming only 25% of this is heated; much of the remaining 15 litres is for flushing toilets.

**Figure 2:** Energy use requirements for water heating, and heating together with water supply to the home, plotted against each nations’ (current) average temperature.

Next, the energy use required to heat a given volume of water is needed. This requires the water’s starting and target temperatures (*T*in and *T*out), heat losses in storage and distribution, and heat transfer efficiency. Cullen, Allwood and Borgstein6 use *T*out = 50°c, and highlight that storage and distribution losses can be eliminated by using point-of-use boilers, leading to a simple equation for the energy required to heat a given volume of water:

*Energy use* = Cp*Vρ*(*T*out - *T*in) / *Eff*,

where *V* is the volume of water and *ρ* the density (0.997 kg/L), Cp is the specific heat capacity of water (4,184 J/kg.K) and *Eff* is the heat transfer efficiency of the boiler.

Taking *Eff* = 95%, an intensity of 4.42 MJ/L/K is obtained. To get total annual energy use per capita for each country, this is multiplied by the total hot water demand (7,300 L) and the required change in temperature, 50°c – *T*in. Finally, for each country, we simply take the annual average temperature as *T*in. This gives the values shown in Figure 2, where maximum and minimum energy usage for water heating are **1.6 GJ/yr/cap** (e.g. Canada) and **0.7 GJ/yr/cap** (e.g. Burkina Faso). This appears reasonable, as research suggests water end-use in the home has a much larger carbon footprint than water supply13.

## Housing infrastructure

With residential floor space already estimated, the only further data required to calculate the energy embodied in residential buildings is the energy intensity of construction (GJ/m2built), along with building lifetimes. However, data describing this intensity varies markedly due to a multitude of factors, particularly materially (in)efficient design and choice of materials.

Figure 3 shows data from the review of Ramesh, Prakash and Shukla14, alongside values from Cabeza et al.15 and Nässén et al.16. Ramesh, Prakash and Shukla find residential construction intensities ranging from 35-500 MJ/m2/yr, with some concrete frames at 50 MJ/m2/yr and timber at 33 MJ/m2/yr. These are given annually as they’re normalised by buildings’ lifetimes (40-100 years in the studies they reviewed). Cabeza et al. and Nässén *et al.* offer energy intensities of 90-280 MJ/m2/yr for multi-story residential complexes, with lower values for timber frames, higher for steel, and concrete close (or sometimes lower) than timber.

Timber is widely considered to be an attractive building material with respect to carbon emissions17, 18, 19, 20, but reported energy intensities aren’t substantially lower than for concrete constructions. Further, timber isn’t practical where local availability is poor, as long-distance transport can be intensive for such a bulky material. The recent *Global Status Report* from the Global Alliance for Buildings and Construction21 suggests that timber buildings only dominate residential construction in three world regions: North America, Oceania, and Africa. In Europe, Asia and Latin America, concrete, masonry and steel construction dominate.

Our approach is thus as follows: (1) we consider residential construction in each country to be either *low* or *high* intensity, (2) for *high* intensities, we assume a significant fraction of concrete and non-biomass materials are used, giving construction intensity of 50 MJ/m2/yr (i.e. the low end of Ramesh’s review for these materials, which could likely be obtained with high material efficiency and/or extension of buildings’ lifetimes to 80 yrs), (3) for *low* intensities, we assume timber-framed buildings with an intensity of 30 MJ/m2/yr – again at the low end of Ramesh’s review this material and finally (4) energy intensities are set to *high* in Europe, Asia and Latin America and *low* in North America, Oceania, and Africa. Clearly this is crude – e.g., in various European countries residential buildings are predominantly timber (Scandinavian), even if timber plays a less significant role continent-wide. But this has little impact on the results, especially global totals. Overall we estimate regionally-dependent energy use to be **0.45-0.75 GJ/yr/cap** for residential construction (with a household size of 4).

**Figure 3:** Energy embodied in construction for different buildings and materials, from Ramesh, Prakash and Shukla14 (Ref.1), Cabeza *et al.*15 (Ref.2) and Nässén *et al.*16 (Ref.3).

# Nutrition

## Food production

To gain an aggregate estimate of the energy requirement of food production – all stages of the supply chain ‘up to the farm gate’ – three things are required:

1. An estimate of the average food-energy requirements in a given country (*kcal/person/day*),
2. The average energy intensity of producing different food types (*MJ in/kcal out*),
3. The composition of food types consumed (i.e. average dietary composition).

**Food-energy intake:** Estimating (1) is straightforward. We start with daily calories requirements per person from the *Dietary Guidelines for Americans: 2015-2020[[2]](#footnote-2)*, for 30 different age bands (from 2 to 76+ years of age), three different activity levels, and separately for females and males. We focus on the central *moderately active* data, and then aggregate this to six age bands, as in Table S7. We then average across females and males, partially as sex ratios across nations are generally close to 50-50, and partially as energy requirements for each sex may become more similar if divisions of labour are

reduced. Using these sex-independent, age-dependent data, we calculate calorie requirements per capita for each nation from weighted averages utilising each nation’s total population by age group. Population data is from the *UN World Population Prospects 2019*. We obtain fairly similar daily average food requirements across all nations; from ~2,000 to 2,150 kcal/person.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Table S7:** Daily food requirements (kcal/cap) for six age bands (from the *Dietary Guidelines for Americans: 2015-2020*) |  | **Age** | | | | | |
|  | **0-4** | **5-9** | **10-14** | **15-19** | **20-49** | **50+** |
| Males | 1,267 | 1,600 | 2,120 | 2,760 | 2,600 | 2,300 |
| Females | 1,200 | 1,520 | 1,920 | 2,040 | 2,033 | 1,800 |
| **Averages** | **1,233** | **1,560** | **2,020** | **2,400** | **2,317** | **2,050** |

**Energy intensity of food production:** Estimating (2) is particularly uncertain, and a decision must be made as to whether to include solar energy fixed by the sun. We do *not*: we include only industrial energy inputs for food production itself.

For plant-based products, we begin with data from Pellegrini and Fernández22. They estimate *Energy Use Efficiency* (EUE) of various crops, globally, from 1961 to 2014, with EUE defined as the ratio of energy fixed by crops to the energy embedded in all human inputs in the food production process. These human inputs are include: fertilizer, fuels and machinery. They show that while EUE varied dramatically across the globe 50 years ago, it is now quite homogeneous due to standardised farming practices. Current values lie between 3 and 4 (note, for crops EUE > 1 consistently). As they expect further improvements in EUE over the coming decades, we take a global value of EUE = 5. This means that for every 1 MJ (239 kcal) of food produced, we assume 0.2 GJ of energy inputs are required for production, in all countries (see Table S8). Note that this matches the data of Woods et al.23 for UK-produced wheat, potatoes, and soy.

For animal-based foods, we also use data from Woods *et al.*23. They estimate the energy inputs required in the UK to produce a tonne of various foods, including milk, eggs, beef and poultry. Using the FAO’s *Food Balance Sheets[[3]](#footnote-3)*, these can be converted to the energy input required per food-energy output (EUE-1). The resulting plant- and animal-based food data are recorded in Table S8. Again, we use these same values globally.

|  |  |  |
| --- | --- | --- |
| **Table S8:** Ratio of the required industrial energy inputs for food production to the edible food-energy output. Note, values are assumed to be applicable globally. Data modified from Pellegrini and Fernández22 and Woods *et al.*23. |  | Energy in / energy out |
| **Crops**1 | 0.2 |
| **Milk**2 | 1.3 |
| **Eggs**2 | 2.1 |
| **Beef**2 | 4.8 |
| **Poultry**2 | 2.2 |

**Dietary composition:**  Regarding (3), there is of course huge variation in the diets that people consume within and across nations. Culture plays the critical role here, with low-meat consumption stemming from religious beliefs in countries like India, and high-meat consumption cultivated by secular dogma, among other things, in countries like the USA. However, we do not wish to capture such cultural influences, as we aim to consider only whether nutritional needs are met. That said, we recognise that the basic need of social participation can be hindered when one’s diet differs significantly from the norm – something many vegetarians and vegans are all too aware of. But this is not a factor we consider here.

Accordingly, we use a fixed composition of food consumption across nations, chosen to meet nutritional needs and minimise energy use[[4]](#footnote-4). We start with data from Springmann *et al.*24, which corresponds closely to that of the recent *Food in the Anthropocene* report by the *Lancet*25. Springmann et al. give recommended daily intakes (g/day) of different food types for omnivores, based upon established healthy-eating guidelines (see Table S9) and world averages for 2005-2007. They also offer food intakes for vegetarian and vegan diets, but we don’t include these in Table S9.

From the perspective of meeting nutritional needs, it’s reasonable for us to use a composition of foods in our scenario by starting with the recommendations of Springmann et al.24 for omnivores, but further reducing consumption of animal products. We thus first convert their recommended values to a percentage contribution to energy intake of each food type (again using the FAO’s *Food Balance Sheets*). We then reduce consumption of animal-based products by ~50% (rounding to one significant figure). This gives the model inputs shown in Table S9. Note that plant-based foods are all considered to have the energy intensity of *crops*, so further disaggregation is unnecessary. Combined with the values of Table S8 above, we estimate that *up to the farm gate*, an average of 0.23 GJ of input energy is required to produce 1 GJ of human-edible food. Across countries, this gives **0.8-0.9 GJ/cap/yr**.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Table S9:** The composition of the average global diet in years 2005-07, alongside a recommended omnivore diet, and the composition (on an energy-content basis) of foods assumed in our model inputs |  | **World average 2005-07** | **Recommended** | | **Model input** |
|  | g/day | g/day | Composition (energy basis) | Composition (energy basis) |
| **Animal-based** | **334** | **369** | **13%** | **7%** |
| Red meat | 66 | 33 | 2.2% | 1% |
| Poultry | 31 | 50 | 4.1% | 2% |
| Dairy | 215 | 260 | 5.6% | 3% |
| Eggs | 22 | 26 | 1.6% | 0.8% |
| **Plant-based** | **902** | **987** | **87%** | **93%** |
| Fruit & Veg | 341 | 492 | 11.0% | - |
| Sugar | 59 | 45 | 8.0% | - |
| Oils | 32 | 43 | 17.3% | - |
| Pulses | 17 | 16 | 2.4% | - |
| Staples | 453 | 391 | 58.2% | - |

We recognise that a diet completely free of animal-products can be nutritionally acceptable; that technologies like lab-grown meat may drastically reduce the energy- and carbon-intensity of meat production as well as its various other substantial ecological impacts; and that we could have included fish in our dietary composition. However, there remains too little known about the future of lab-grown meat, and fish is not particularly low-energy so its inclusion would have little benefit for overall energy-use26 (not to mention that it can bring fresh ecological concerns). Further, our assumptions reduce current meat consumption substantially, to under 15kg/yr/person – a reduction of 85% in countries like the USA and Australia, and well under half the current global average. Nonetheless, the assumption is conservative for a ‘lowest energy-demand’ scenario, and thus we consider fully plant-based diets in the sensitivity test later.

## Food processing, transportation and distribution

In the supply chains of higher-GDP countries, the FAO27 suggest that energy used in processing, transportation, distribution (including packaging and retail) and cooking and preparation in the home together is typically 3-4 times more than that used up-to-the-farm-gate. (Note that this is exclusive of the energy used for cooking in the home, which we consider in a separate section below.) Pelletier *et al.*28 offer similar estimates, suggesting that food production in the USA accounts for only 13% of food system energy use, with 40% used in processing, transport and distribution, and the remaining 47% accounted for by home preparation and eating outside the home (restaurants, etc.). The consensus is that transport energy use itself contributes only a small amount to the energy use of the food system (<5%), although it remains significant relative to primary production.

We use the more disaggregated estimates of Pelletier *et al.*28 to compile our inputs. They suggest that the energy used in processing, transport and distribution are ~130%, ~20% and ~150%, respectively, of that used in food production (see their Figure 1). We start with these values, but reduce the former two (distribution could likely be reduced, too, but we found no clear rationale to do so). The FAO27 suggest that the energy intensity of food processing stages can be reduced by 20-30% with *medium cost investments*, so we reduce the 130% to 100% – perhaps conservatively relative to our estimates for other sectors. We then assume a reduction in demand for processed food, and some localisation of food supply. In the absence of a more rigorous approach, we simply half each intensity, then test the model’s sensitivity later.

In summary, this means we assume that the energy used in food processing, transport and distribution is 50%, 10% and 150%, respectively, of that used in food production. In other words, the energy use of the food supply chain beyond-the-farm-gate is a factor of 2.1 greater than food production alone. In practical terms, this means that we assume 0.49 GJ of energy are required in the beyond-farm-gate supply chain to deliver food with 1 GJ of human-edible energy.

Adding this to the up-to-the-farm-gate value above, gives a total supply chain energy requirement of 0.72 GJ to produce and deliver 1 GJof food; equivalent to **2.25-2.39 GJ/cap/yr**, depending on the countries average per capita food-calorie requirements.

Finally, we assume there’s some unavoidable waste. Food waste is a complex subject: losses occur at stages from harvesting through distribution to household consumption; some losses are considered avoidable and others not; and where along the supply chain the most significant losses occur strongly depends upon the level of economic development and centralisation of food production29, 30. Estimates suggest that overall food waste levels in different nations can be anything from 10-50%; the lower end of this range is populated by energy-based measurements (*ibid*). In wealthier countries, losses tend to become concentrated in the household consumption stage31 and studies from *WRAP*[[5]](#footnote-5) suggest the majority of this is avoidable. More specifically, WRAP suggest that about 25% of UK food is wasted post-farm-gate, and 30% of this is unavoidable (2019 data). This means that, overall, about 7.5% of food is unavoidably wasted. We thus take 15% as the unavoidable food waste along the full supply chain, which allows for the same amount of waste in production stages. This increases the 2.25-2.39 GJ estimate above to **2.65-2.81 GJ/cap/yr**.

## Cooking and Cold storage

Currently, energy use for cooking varies dramatically between lower- and higher-GDP countries, with the former typically relying upon open, generally inefficient cook-stoves. In countries where cooking appliances are the norm, the FAO suggest typical energy use is currently 5-7MJ/kg of food27. Assuming a nominal value of 150kcal/100g for cooked food, this translates to ~4kJ/kcal. Cullen, Allwood and Borgstein6 suggest that, with practical measures, the energy intensity of cooking could be reduced 80% below these levels, which implies ~0.8kJ/kcal. Finally, in the absence of a more objective or rigorous estimate, we assume that 50% of food calories are cooked. We thus assume that for every kcal of food consumed, 0.4kJ of energy is required, irrespective of nation. Combining this with total kcal intake per capita for each nation, gives energy use for cooking between **0.30 and 0.31 GJ/capita/yr**.

For cold storage in the home, we also use values from Cullen, Allwood and Borgstein6. They suggest that 80-90% energy savings above current levels for cold storage are feasible. This is similar to the efficiency of the most efficient household refrigerator in production, which requires only 120 kWh/yr; an 80% reduction on current averages. We thus assume one of these current-best-performing appliances per household, which results in cold-storage requirements of **0.11 GJ/yr/cap**, with a household size of four.

Finally, we add embodied energy for producing and distributing these high-efficiency appliances. For cold storage, we use the values from Ma *et al.*32 for eco-design of refrigerators. For the model they study, 81% of the total lifetime energy use is account for by direct energy use, with the remaining 19%, or 2 GJ, involved in production and distribution. We assume the same energy is required for producing a household freezer, thus giving 4 GJ/household. With the 14 year lifespan they use, this is brought down to 0.28 GJ/yr, or for a household of four **70 MJ/yr/cap**. For cookers the calculations are the same, but we start with the estimate of Pina *et al.*33 who find the embodied energy in various induction cookers to be approximately 1 GJ; lower than cold-storage. Cookers’ lifetimes are also suggested to be longer at 20 years34. We thus obtain a value of **13 MJ/yr/cap**.

Note that we’ve used values currently reported in the literature for embodied energy of cookers and cold storage, and these are *not* necessarily absolute best-practice values like we’ve used for other aspects of consumption. This potentially makes these values overestimates, given the spirt of our model. However, the values are smaller enough for this to be a negligible issue overall.

# Mobility

## Total mobility requirements

Grubler *et al.*2 cautiously suggest 7,000 km/capita/year as a minimum for the total mobility people require, as this level was found in Japan in the late 1980s (when the nation was already well developed). For comparison, the IEA’s *2DS* (*Two Degrees Scenario*) 35projects average annual mobility levels in 2025 ranging from <5,000 km/cap in India to >20,000 km/cap in the USA (Figure 4). Moving forward from 2025, *2DS* mobility levels in the USA remain broadly similar, but mobility in India rises to nearly 10,000 km/cap, leaving levels in Mexico the lowest at ~7,000 km/cap. The world average annual mobility rises from a current ~7,000 km/cap in 2014 to ~10,000 km/cap by 2060.

Given these trends, we take 7,000 and 10,000 km/cap as base estimates of mobility requirements in urban and rural areas, respectively (each termed *MOB*base). We then modify these to reflect nations’ population densities, using a number of assumptions:

1. A proportion of mobility (*f*fixed) is *independent* of region, consisting of travel that does not depend upon local population density;
2. The remainder (*f*variable) is inversely proportional to population density in the nation;
3. Population density is better captured by removing land that’s mostly uninhabited to give a *lived density* (*LD*), which better represents that encountered by people in their daily lives[[6]](#footnote-6).

We combine these assumptions in the following equation:

*MOB*n = *MOB*base × (*f*fixed + *f*variable × *LD*base/*LD*n),

 **Figure 4:** Annual average mobility in the main regions of the IEA’s *Energy Technology Perspectives* 2017, for the central *2DS* projections.

where the subscript *n* references a particular nation. For the base lived density we use the median of our data – 189 persons/km2. We assume a value for *f*variable of 50%, making *f*fixed also 50%. The model has little sensitivity to these relatively arbitrary assumptions.

To calculate lived densities for each country, we use standard population density figures and modify them by assuming only agricultural and urban land is significantly inhabited. Specifically, we take population density from the World Bank databank, and add a correction factor that removes land that is neither urban nor agricultural (values for which are also available from the World Bank):

*LD* = *Population* *Density* × *Total land area* / *Inhabited land area*,

*Inhabited land area* = *Agricultural land area* + *Urban land area*.

A final assumption we make is to give *LD* an upper limit, so as not to create outliers in nations with very low densities. We allow mobility to rise to 150% of the base values of 7,000 and 10,000 km/cap. At the other end of the scale, the lowest calculated values of *LD* lie at ≈\70% of the base values (in the high-density city-states of Hong Kong and Singapore). This 70% to 150% range is very similar to that existing in 2060 across the IEA’s regions, if the outlying USA values are discounted (69% to 157%, as shown in Figure 4).

In summary, these calculations give annual mobility requirements in each nation ranging from 4,900 to the upper limit of 15,000 km/capita (Figure 5). Roughly the same number of countries are found at the maximum level as at the minimum (23 and 22, respectively) which leaves 74 countries with mobility levels in between. The total, global average mobility calculated using 2050 population data comes out at just over 10,000 km/capita – almost identical to the IEA 2050 global average, but the distribution in our model reflects needs, not pre-existing patterns of demand, thus is more equal.

**Figure 5:** Annual mobility requirements for all nations, shown for urban and rural regions, and plotted against ‘lived’ population density. The black line is the probability density function of lived densities for all 119 regions. Note: Data for Hong Kong, Taiwan and Singapore are not shown: their lived densities are exceptionally high at 7,000-8,000 persons/km2 (but their mobility remains at the specified minimums).

## Mode share assumptions

With total mobility levels estimated, it is then necessary to specify the mode share and the energy intensity of each mode. Below we describe both of these steps, for each mode in turn. We describe non-motorised and air transport first, as we assume the distance travelled per capita via these is independent of lived density (and hence of nation), and equal in urban and rural areas.

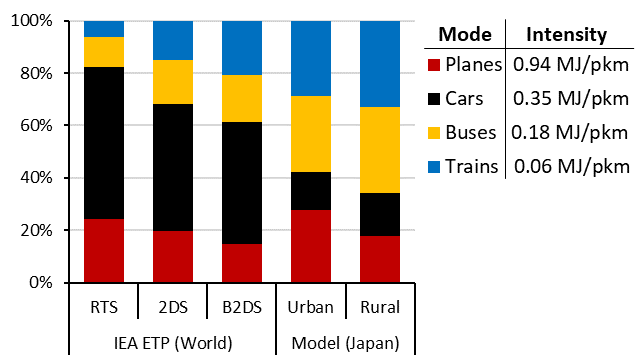
**Non-motorised transport:** The mostlow-energy modes of transport are non-motorised forms, i.e. walking and cycling. We assume an average non-motorised distance travelled of 4km/capita/day, which equates to just over **1,000 km/capita** annually.

**Air transport:** At the other end of the scale is air-transport – the most energy-intensive means of travel. Nonetheless, we retain some flying in our scenarios. Short-haul flights are normally considered to be those <1,000 miles, and medium-haul 1,000-3,000 miles. We thus assume roughly one short- to medium-haul return flight every three years per person, i.e. two 1,000 mile flights, or just over **1,000 km/capita** annually (i.e. 2 × 1,000 × 1.6 / 3).

**Rail transport:** After non-motorised and air transport are subtracted from total mobility levels, we distribute remaining mobility to three modes of surface transport. We assume 40% of *remaining* pkm are accounted for by trains (21% to 34% of *all* pkm, depending upon nation and rural/urban type). This is generally higher than the IEA’s most ambitious *Beyond 2 Degrees* scenario (*B2DS*), where rail accounts for 21% of pkm in 2060 (see Figure 6). We obtain values ranging from **1,000 to 5,100 km/capita** annually in high density urban areas to low density rural ones.

**Road transport – buses:** We assume that buses make the same (40%) contribution to remaining mobility as trains, in all nations. Again, this is higher than in the IEA’s scenarios, where buses only account for 18% of pkm by 2060 in the *B2DS*. The values are the same as for rail, at **1,000 to 5,100 km/capita** annually.

**Road transport – cars:** We assume all remaining mobility is accounted for by cars. This fraction is lower than in the *B2DS*, thus balancing out the higher share of bus and rail. Values range from 5**00 to 2,500 km/capita** annually.

**Figure 6:** Mode-shares of pkm between motorised transport in (i) the three scenarios of the IEA, globally, in 2060 and (ii) the current work for urban and rural Japan – the central cases for mobility. Energy intensities by mode are shown in the legend.

## Direct energy intensities

The IEA suggest that current energy intensities of aviation are 1.75-1.85 MJ/pkm, with rail transport at 0.1-0.35 MJ/pkm, *heavy road* transport at 0.45-0.86 MJ/pkm (0.56 MJ/pkm globally), and *light road* transport at 1.1-2.4 MJ/pkm. Lower values are consistently found in *non-OECD* areas. We use these lower values as a starting point and reduce them further using the practical energy savings that Cullen, Allwood and Borgstein6 estimate:

For **aviation**, they suggest 46% reductions in energy intensity would be feasible with ambitious, but realistic improvements to aerodynamics, propulsion efficiency, and vehicle weight, which reduces the IEA’s lower value to **0.94 MJ/pkm**.

For **trains**, they suggest 41% as a (conservative) practical energy reduction, achievable via maximising aerodynamic efficiency, but retaining modest average speeds, thus giving **0.06 MJ/pkm**.

For **buses**, we make a slight modification to their analysis for *heavy road* transport. They suggest that 54% energy savings on current levels would be feasible for heavy duty vehicles through reducing drag (aerodynamic and rolling resistance) and light-weighting. However, their estimate is averaged across various sizes of freight vehicles as well as coaches, and due to the latter, their light-weighting estimates are conservative. We thus assume more significant weight reductions that further reduce rolling resistance and thrust requirements, increasing the 54% reduction to a 60% reduction. This then gives **0.18 MJ/pkm**.

For **cars**, we again modify their estimate, which is that 91% energy savings on current levels would be feasible through reducing drag (aerodynamic and rolling resistance) and light-weighting. However, they assume exceptionally light vehicles (200kg vehicle + 100kg of passengers) with accordingly low thrust requirements and drag. We thus assume a much larger vehicle weight in order to maintain high vehicle capacity. We increase their assumed weight to 1t (inclusive of passengers), thus reducing energy savings to ≈ 70% and giving **0.35 MJ/pkm**.

Finally, we assume **non-motorised transport** uses no direct energy – or, at least, the energy is assumed to be already provided for by normal food intake.

## Embodied energy

### Vehicles

To estimate the energy embodied in vehicles, we use data from Chester and Horvath36 and Chester *et al.*37. They give estimates of energy requirements (MJ/pkm) for *direct fuel use*, *vehicle manufacture* and *infrastructure provision*, for various modes of transport and alternate scenarios (their analysis is focused upon the USA, but we apply the values globally):

Formanufacturing **cars**, averaged embodied energy values of 0.37 MJ/pkm36 and 0.38 MJ/pkm37 are offered for conventional sedans of weight ~1.4t, assuming occupancy rates of 1.6-1.7. We thus cut this value down to the lighter-weight vehicles we’ve assumed, then further for a higher occupancy rate of 3 people. Finally we assume a more efficient manufacturing process, cutting the embodied energy a further 33%, which is the potential energy intensity reduction for steel production suggested feasible by Allwood *et al.*38; we use this material as a proxy for the whole car. This brings the 0.37 MJ/pkm down to **0.10 MJ/pkm**.

Formanufacturing **buses**, averaged embodied energy values of 0.07-0.15 MJ/pkm are offered36, 37, assuming peak-occupancy rates. The lower value is part of a *long-term* forecast for an advanced bus rapid transport system in Los Angeles. As for cars, we assume more efficient manufacturing and thus cut this value down 33%. This brings the 0.07 MJ/pkm down to **0.04 MJ/pkm**.

For manufacturing **trains**, averaged embodied energy values as low as 0.01 MJ/pkm are offered36, 37. Again this assumes high occupancy rates and a *long-term* forecast for an advanced rail transport system. We again cut this value down 33% for manufacturing improvements, giving **0.007 MJ/pkm**.

Formanufacturing **planes**, Chester and Horvath36 offer values for large, medium and small aircraft, and we use the former (lowest) value, namely 0.13 MJ/pkm. Again we cut this down 33% for manufacturing improvements, to give 0.09 MJ/pkm. We also add their estimates for the embodied energy of fuel provision, namely 0.14 MJ/pkm, but we reduce this to 0.09 MJ/pkm to be consistent with the efficiency increases in direct energy that we‘ve assumed for planes. (Note, as described later, we assume surface transport is electrified, thus the energy embodied in is included below in *Power Supply*.) This gives **0.18 MJ/pkm** for the combined energy embodied in planes and their fuel.

Finally, we assume the embodied energy in any **non-motorised transport** equipment is negligible.

### Infrastructure

To estimate the energy embodied in infrastructure supporting the mobility requirements outlined above, we again use data from Chester and Horvath36 and Chester *et al.*37. They offer the embodied energy of infrastructure in the same format – and for the same transport networks – as they do for vehicle manufacture (averaged to MJ/pkm values). Their values for conventional cars range from 0.11-0.4 MJ/pkm, for buses 0.02-0.37 MJ/pkm, for rail transport 0.16-0.76 MJ/pkm, and for air transport 0.06-0.07 MJ/pkm.

For **cars**, we take the average as our starting point, 0.25 MJ/pkm. We then reduce this to account for higher occupancy rates (3 people per vehicle, as opposed to ~1.6) and more efficient production. For the latter, we take the potential 2050 improvements in cement production efficiency as a proxy for road transport infrastructure in general, namely a 22% improvement from Millward-Hopkins *et al.*39. This gives a final input value of **0.11 MJ/pkm**. This infrastructure is assumed to be sufficient to support **non-motorised travel** as well.

For **buses**, we take a value towards the lower end of the range as our starting point, specifically 0.07 MJ/pkm (the higher values assume low occupancy). This is the *long-term* estimate of Chester *et al.*37 for Bus Rapid Transport in Los Angeles, and assumes high occupancy rates. We reduce this to account for more efficient production, using the same 22% reduction as for car infrastructure, giving a final input value of **0.05 MJ/pkm**.

For **rail transport**, we again take a value towards the lower end of the range as our starting point, specifically 0.33 MJ/pkm, which lies in the middle of the estimates of Chester and Horvath36 and Chester *et al.*37 that use high occupancy rates. We then reduce this by 33% to account for more efficient production, now using steel as the proxy material, thus giving **0.22 MJ/pkm**.

For **air transport**, we start with the narrow range of estimates of Chester and Horvath36, 0.06-0.07 MJ/pkm40. As they already use high occupancy rates, we reduce them further only to account for more efficient production – again by 22%, with cement as the proxy material. This gives a final input value of **0.05 MJ/pkm**.

Overall, adding direct and indirect and infrastructure-related emissions for mobility gives values ranging from **2.1-4.0 GJ/cap/yr** in urban areas and **2.8-5.4 GJ/cap/yr** in rural areas.

# Communication and information

## Phones

Rao and Min3 suggest one phone per adult is required for decent living, given the demands of contemporary social participation. We assume this applies only to those over the age of 10 yrs, thus obtaining average values of 0.75 to 0.94 phones/cap, depending upon the age distribution of a nation. We then calculate energy requirements for *use* and *production* *and distribution* – provision of service networks is estimated separately below in *networks and infrastructure*.

As Grubler *et al.*2 point out, smart phones can replace many other electronic gadgets – cameras, radios, GPS, etc. – by streamlining functionality. This potentially reduces both the material and energy requirements of electronic goods. In use, Grubler *et al.*2 offer a value for smartphone electricity use of 5W at full power and 1W in standby (or 7-32kWh/yr, assuming 8hrs of total shutdown a day). Others suggest lower values, specifically 2.8, 3.9 and 7.7 kWh/yr for *light*, *representative* and *high* users, respectively41. And LCA data for the *Fairphone* suggests 4.9 kWh/yr42, consistent with the above41. We take the *high use* value of Ercan *et al.*41, given that phones are assumed by Grubler *et al.*2 to replace various other electronics’ functionality. This converts to 27.7 MJ/phone.

For embodied energy in the manufacturing supply chain, we start with the datafor the *Fairphone*42. This is reported to be 232 MJ/phone (including transport) in a refurbishment scenario intended to capture the repairs necessary to extend product life to 5yrs. We then decrease this based upon a recent review43. Energy requirements aren’t summarised in this review, but comparison of GHGs shows the *Fairphone* to be relatively average in terms of manufacturing intensity (45 kg.CO2e). Smartphones from *Nokia* and *HTC* are suggested to be produced with much lower emissions (17-30 kg.CO2e) than the *Fairphone*. This is only partially explained by refurbishment of the latter, thus we take the embodied energy for the *Fairphone* and reduce this by 50% to obtain a production intensity for our model of 110 MJ/phone.

Spreading production impacts over the 5yr lifetime gives 22 MJ. Adding this to in-use energy and multiplying by the number of phones per capita gives nationally-averaged values of **37-47 MJ/cap/yr**, depending upon the fraction of the population that’s over 10yrs old.

## Computers

Rao and Min3 suggest one ICT system per household for decent living. We thus calculate energy requirements for *use* and *production* *and distribution* for providing a laptop in each home, again with service networks accounted for separately in the infrastructure section.

The estimate is made uncertain by the rapid change that characterises computer technologies, which makes it difficult to estimate what a *sufficient* level of computing technology could be. For computers, as with most technologies, increases in the efficiency of production have been negated by producing more complex goods, such that a typical computer processor in 2006 required roughly the same energy to produce as one in 199544. We thus use current best practice for in-use- and production-energy requirements. As with phones, the majority of energy use for a computer is in production, rather than use44, although the difference is reduced via lifetime extension.

We use values from Deng, Babbitt and Williams45 for use and production, and for distribution. They suggest a range of 3,000-4,300 MJ/laptop for production and distribution, of which we take the lower value. For use, they suggest 62 kWh/yr, or 220 MJ/yr. Compared to our estimates for smartphones, these are a factor of ~27 and ~8 larger for production and use, respectively, which passes a sense check given their relative masses. We assume the lifetime of a laptop is 10 years (twice that of a phone) given the lack of daily transportation and lowered wear and tear. Overall, we obtain a value of 520 MJ/household (i.e. 3,000/10 + 220) or **130 MJ/cap/yr**.

## Networks and infrastructure

As mentioned above, energy use in producing electronic gadgets tends to be higher than direct energy use over their lifetimes. But higher still is the energy used by, and embodied within, the networks and data centres that form the backbone of modern communication and information systems46, 47, 48.

Ercan *et al.*41 offer estimates of the energy use of Wi-Fi networks and data centres to go alongside their estimates for production of smartphones and their use. The give 28.7, 33.3 and 49 kWh/phone/yr for *low*, *representative* and *high* users as before. We take the *high* value to be consistent with our in-use estimates above, which converts to 176 MJ/phone/yr – a factor of 3.5 larger than smartphone production and use combined. We assume that laptops require 5× as much network and data centre usage, giving a value of 880 MJ/laptop/yr. Overall, this gives an energy requirement of **0.35-0.39 GJ/cap/yr** for information and communication infrastructure – just over two times larger than that required for production of smartphones and laptops and their use.

As a sense check, the widely cited forecast of Andrae and Edler46 suggests that, by 2030, global ICT systems could require over 8,000 TWh/yr of energy to support direct energy usage of consumer electronics, production of these electronics, and network infrastructure and data centres. This is equivalent to a global average of ≈ 3.5 GJ/cap/yr. Further, their forecast shows the energy use of networks and data centres to be 4× larger than production of consumer electronics and their use. Note that this is a business-as-usual forecast, and includes far more consumer electronics than smartphones and a laptop per house alone. For comparison, we have values of ~0.65-0.7 GJ/cap/yr for the entire information and communication sector – 80% lower than their estimate. Given ours is a minimum-energy-use scenario, this seems reasonable.

# Clothing

For clothing, we assume a standard wardrobe across regions – clearly a crude assumption, given climatic variation and hence requirements for more (or less) warm clothes. However, clothing makes a small contribution to overall DLE, and at least some of the error cancels – hotter climates may require less clothes, but these may be washed more frequently for hygiene reasons. Nonetheless, these assumptions could clearly be improved.

We compile a list of basic clothing items with weights, lifetimes in days worn, average days worn per wash, current embodied energy use in the full supply chain, and potential supply-chain energy savings. Data are summarised in Table S10, with the various sources detailed. The assumptions regarding energy savings are worth elaborating upon, as these a relatively crude.

In the absence of a detailed estimate of technical limits to production efficiency, we consider the ratio of the current average- to best-practice energy efficiencies for producing three key clothing materials: *cotton*, *wool* and *rubber*. We take these from the latest *ICE Database*49, which show the lowest UK values for the energy efficiency of cotton production to be 76% below UK averages, with analogues of 44% and 58% for wool and rubber, respectively. We make a heuristic assumption, applying reductions relating to single-materials to the full embodied energy estimates for each clothing item, matching the most appropriate material to each item. From here, embodied energy estimates can easily be obtained by calculating how many times each item must be replaced in a year, multiplying by the embodied energies, applying potential energy savings, and finally summing over all clothing items. For example, for *Tops*, the embodied energy is: 365/112.5 × 62 × (100%-76%) = 48 MJ/yr/capita. Summing over all items gives 0.32 GJ/capita/yr.

Now we must also add the direct energy used for washing and drying, and the embodied energy of washing appliances themselves. For the former, we start with values from Steinberger *et al.*50, which suggest ≈ 10 MJ of final energy is required for washing and drying 1kg of clothes. We then reduce this by the average practical energy savings (75%) suggested by Cullen, Allwood and Borgstein6 for washing (91%) and drying (60%). This gives 2.4 MJ/kg, which can be multiplied by the total weight of washing required per year (≈ 78kg; from the days/wash values) to give an annual direct energy requirement of 0.19 GJ/capita. For the embodied energy of washing machines, we apply a simply scaling with the direct energy of use. For highly efficient washing machines, the lifecycle impacts of appliance production are approximately 30% of those of the use phase, when averaged to annual values51. We thus simply take the energy embodied in washing machines to be 56 MJ/cap/yr (i.e. 0.19 GJ × 30%). Assuming an 8-15 yr lifetime, this is equivalent to 1.8-3.4 GJ/machine, so it passes a sense check by laying in between our estimates of 1 GJ and 4 GJ for cookers and refrigerators, respectively.

Finally, we increase all direct and embodied emissions by 20% to approximate the requirements of non-clothing items like towels and bedding. This gives a total energy requirement of **0.67 GJ/cap/yr**.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Table S10:** Standard array of clothes assumed to be worn, along with weights, lifetimes, washing frequencies, and supply chain emissions. |  | **Weight** (kg)a | **Lifetime** (yrs)b | **Days/** **wash**c | **Embodied energy** *(MJ)*d | **Potential energy savings**e |
| **Tops** | 0.25 | 112.5 | 3 | 62 | 76% (*cotton*) |
| **Bottoms** | 0.5 | 300 | 15 | 172 | 76% (*cotton*) |
| **Jackets** | 0.5 | 562.5 | 25 | 111 | 44% (*wool*) |
| **Jumpers** | 0.5 | 337.5 | 15 | 172 | 44% (*wool*) |
| **Underwear** | 0.05 | 125 | 1.5 | 12 | 76% (*cotton*) |
| **Shoes** | 0.6 | 365 | 60 | 133 | 58% *(rubber)* |

a Weights for *Tops*, *Jackets* and *Jumpers* are directly from WRAP’s *Benefits of Reuse* report52. For other items, common-sense estimates are made.

b Lifetimes are based upon WRAP’s *Longevity Protocol53*, with additional assumptions: *Bottoms* are taken as *Jeans*; *Jackets* are assumed to last *5x* as many days as *Tops*, as they are typically worn for a fraction of the day; *Jumpers* are assumed to last 3x as many days as *Tops* for the same reason; *Shoes* are assumed to last a year if worn daily.

c Days of wear per wash are based upon the values in Steinberger *et al.*50, who assume two days of wear per wash for t-shirts, and ≈17 days per wash for jackets. We assume approximately 50% longer wear between washes, and makes reasonable assumptions to extrapolate to other clothes types.

d Values for production are also based upon those in50 for t-shirts, jackets and from report52 for jumpers, and mass-based extrapolations for other items.

e Potential energy savings, using the savings for a single material (shown in brackets) to estimate those possible for the full supply chains. From49; see text for details.

# Public and Commercial Services

## Education and healthcare

### Direct energy

For educational services, our calculations are based upon (i) assumed floor-space requirement per pupil, (ii) energy intensities of this floor space, and (iii) the proportion of the country’s population in education. Our floor-space assumptions are simple: We assume that pupils need as much floor-space when at school as living space at home (10m2/pupil).

For direct energy intensities, we use the same approach that we did for thermal comfort in homes. First, we use data estimating average CDD and HDD in each country. Then we use this data to select climate-dependent energy requirements for space heating and cooling intensity from those offered by the *Global Building Performance Network*7. Again, we use data for *Advanced New Buildings*, this time for educational buildings, which suggest intensities of 14-19 kWh/m2. We estimate that *total* building energy use in schools is double that of heating and cooling, at 28-38 kWh/m2. Finally, we assume children from 5-19 are in school, which equates to ~10%-30% of the population depending upon the age profile of the country.

Overall, this gives annual direct energy requirements in educational buildings (averaged across *whole* national populations) of **0.11-0.43 GJ/cap/yr**.

For healthcare, our calculations are based upon (i) assumed floor-space requirement per hospital bed, (ii) the average number of hospital beds per capita, (iii) the energy intensity of this floor space and (iv) a simple upscaling to account for energy use beyond hospitals themselves.

A widespread rule-of-thumb for hospital floor-space is that one bed requires 2,500 square feet of floor-space (~180 m2) when all facilities are taken into account[[7]](#footnote-7). The US government energy efficiency guidelines give a similar value of 0.46 beds per 1000 square feet of floor space[[8]](#footnote-8), which converts to ~200m2 per bed – we use this value.

We translate this into total, average per capita terms by specifying how many hospital beds there are for each member of the population. Currently, World Bank data shows ratios reaching over 10 beds/1,000 people in various countries, but much lower ratios are also found even in countries with good health outcomes. Indeed, countries that have high ratios of physicians to citizens often have average ratios of hospital beds to citizens; Scandinavian countries tend to have 4 or less beds per 1,000 people, but some of the highest ratios of doctors to citizens. We thus assume a generous level of beds relative to this, specifically 8/1,000 citizens, which accounts for a large part of healthcare not being accessed at hospitals. This gives healthcare floor space of 1.6m2/capita.

For energy intensity, the calculations follow those for educational buildings, but using the GBPN data for space heating and cooling in *Hospitals* instead. We assume that this is only 50% of total hospital energy use, given the extent of specialist equipment beyond heating and cooling (which is a reasonable value in the UK[[9]](#footnote-9)). Finally, we scale this up by factor of three, as recent studies suggest hospitals themselves are currently only around 1/3rd of the healthcare sector’s footprint54. This effectively gives 114-155 kWh/m2, or when scaled up, **0.66-0.89 GJ/yr/cap**.

### Infrastructure and equipment

With floor-space requirements for educational and healthcare buildings already specified, estimating the energy embodied in infrastructure requires only the energy intensity of construction (GJ/m2) for each type of building. To estimate these, we use the process we did for residential construction, assuming either *Low* or *High* intensities, regionally dependent as before, and with *Low* intensities 40% lower than *High*, assuming some lower-energy, timber construction. However, for both educational and healthcare buildings, we assume higher energy intensities than for residential construction.

For educational buildings, we start with the residential values above (30 and 50 MJ/m2/yr) and increase them by a factor of three to 90 and 150 MJ/m2/yr. This assumes schools are more similar to offices than houses, based upon the data of Ramesh, Prakash and Shukla14 in Figure 3, which suggests a lower limit for the intensity of offices around three times larger than for houses. Overall, this gives values of **0.13-0.38 GJ/yr/cap** for educational buildings – the range arising from variations in populations’ age structure.

For healthcare, we start with the construction intensities for educational buildings, and increase these as hospital infrastructure includes a large amount of specialist equipment, besides the building. Recent analysis suggests that building structures themselves only account for about 1/3rd of the embodied carbon footprint of fixed capital used by the *health and social care* sector55[[10]](#footnote-10). Assuming educational and healthcare building structures have the same energy intensity as educational ones (90 and 150 MJ/m2/yr; for *low* and *high*), and that embodied carbon is a good proxy for embodied energy, the total energy intensity of healthcare infrastructure can be estimated to be 3 times that of educational buildings, i.e. 270 and 450 MJ/m2/yr. This gives **0.44-0.73 GJ/yr/cap** for healthcare infrastructure.The scaling up means these estimates are uncertain, however, the values account for <5% of total energy demand.

## Commercial buildings and freight

### Direct energy

Much of the LCA data we use to estimate the embodied energy in goods and infrastructure accounts for transport of materials and products, as well as a degree of commercial/retail activity. But some necessary freight and retail activity is potentially missed. We thus add further energy use to make up for this, while being aware that we may be double counting to some degree.

For retail and freight, we use the activities levels suggested by Goldemberg et al.56 in their estimate of energy for basic needs: **5.4 m2/cap** for commercial floor area; **2,295 tkm/cap** for freight (1,495 by road and 800 by rail). The former can be combined with energy intensities from GBPN in the same way as was done for other buildings above, obtaining intensities of 12-17kWh/m2. This gives values of **0.24-0.31 GJ/cap/yr** across countries for commercial buildings’ direct energy use. For freight, we calculate energy intensities the same way we did for mobility, using data from the IEA and Cullen, Allwood and Borgstein6. This gives 0.48 and 0.08 MJ/t-km for road and rail, respectively. Combining with activity levels gives national totals of **0.78 GJ/cap/yr**.

### Infrastructure

To estimate the energy use in constructing the commercial floor area assumed above, we need only the intensity of construction. We use the same intensities we did for educational buildings, based themselves upon the intensities of constructing office buildings (see Figure 3). Specifically, we have floor space of 5.4 m2/cap and intensities of 90 and 150 MJ/m2/yr, thus giving **0.49-0.81 GJ/cap/yr**.

Similarly, for freight, we’ve specified the activity levels in t-km, so all that’s needed is an estimate of the embodied energy in infrastructure *and* vehicles, scalable in the same units (i.e. embodied energy per t-km). As a starting point, we use our estimates for the embodied energy in infrastructure and vehicles for passenger trains and buses (see the *mobility* section above). We also have direct energy use for passenger rail and buses (0.06 and 0.18 MJ/pkm, respectively), and comparable direct energy use for rail and road freight (0.08 and 0.48 MJ/tkm, respectively). The ratios of direct energy for rail and road are thus 1.35 and 2.6, respectively; these can be taken as ratios of t-km to pkm. Using these to scale up the embodied energies of passenger *vehicles*, we obtain 0.01 and 0.11 MJ/tkm for the embodied energies in rail and road freight vehicles, respectively. Analogous calculations give 0.29 and 0.14 MJ/tkm for infrastructure. Multiplying by the activity levels then gives a total of **0.45 GJ/cap/yr** (0.23 and 0.22 GJ for rail and road, respectively).

## Waste Management

For waste management our estimates are particularly crude. This is justified as consumption in our scenario is considerably different to anything currently existing, thus current energy use data for waste management systems cannot be applied in any meaningful way. We thus make a simple assumption that waste management requires the same energy per capita as the average (*central*) values for water supply described above. We thus *don’t* assume any regional variation; each country is assigned an energy intensity of **0.18 GJ/cap/yr**.

# Power Supply

All of the consumption sectors described above require significant energy use, and the infrastructure required to supply this requires significant energy to build. To estimate this, we assume the energy embodied in power supply infrastructure scales with power demand. Consequently, we only need to estimate total final demand for each country, along with a scaling factor specifying the embodied energy in infrastructure per unit of *final energy delivered*. Note, we do not distinguish between types of power – electricity, heat, etc. – rather, we consider only total energy demand.

Total final demand falls immediately out of our other calculations – it’s the sum of energy used for: household heating, cooling, water heating, illumination, cooking and cold storage; washing clothes; phone and computer operation; education and healthcare buildings’; and all transport besides air travel (which we assume are electrified). This gives values of 4.2-7.2 GJ/cap/yr for each country. Note that industrial energy used in producing cookers, fridges, phones, etc. is included in the LCA data used to calculate the embodied energy of these goods.

To scale this and estimate the embodied energy of the power network, we use a value based on data from Hertwich *et al.*57. They compare the lifecycle impacts of various low-carbon and fossil-based energy sources. Overall, they find the energy embodied in renewable energy infrastructure (wind, solar and hydro) to be 0.1-0.25 kWh per KWh of electricity produced – larger than for fossil-based power infrastructure. Other studies suggest nuclear energy has impacts towards the lower end of that of renewable energy infrastructures58. We thus use a value of 0.15, which is slightly towards the lower end of the range of Hertwich *et al.*57, and could be considered to include a mix of low-carbon technologies, including nuclear. When combined with the direct energy use estimates, this gives **0.63-1.1 GJ/cap/yr** across countries.

**Part 2** Sensitivity Analysis

It’s no exaggeration to say that all models are wrong, and the current work is no exception. Building the model has been an inherently uncertain process, involving assumptions ranging from robust to arbitrary. However, a formal uncertainty analysis such as a Monte Carlo analysis would be relatively meaningless as, for the majority of our assumptions, we lack any robust statistical measure of the uncertainty in our chosen input values (i.e. the type of distribution they follow and/or the spread). It would also be overindulgent, as the mathematics of the model are straightforward – there are no significant interactions in between parameters, nor any complex nonlinearities.

We therefore perform a simple sensitivity analysis instead. This involves (i) selecting a list of key parameters, (ii) perturbing each individually, by a magnitude based either upon literature, or specified using the authors’ judgement, and (iii) finally, for each decent living sector, applying all perturbations together. Typically, we only shift the parameters in one direction, i.e. that which increases energy use; this is because parameters in our model are already set to be a low as seems reasonable, given our intention to estimate minimal energy use for decent living. Specific details of parameters changes are detailed in Table S11, and results shown in Figure 7.

One of the first things that can be gathered from Figure 7 is that total final energy use has very little sensitivity to parameter changes in either the *clothing* and *communication* or *information* sectors. The significant perturbations we make to energy intensities of the latter, and clothing lifetimes and washing frequencies for the former, have very little effect on overall final energy use – for the simple reason that these sectors contribute little to total energy use. Similarly – and for the same reason – total energy use has little sensitivity to the energy intensity of *power supply* infrastructure.

Across the remaining four sectors – *shelter and living*, *nutrition*, *mobility* and *public and commercial services­* – the model’s sensitivity to the key individual parameters is broadly similar, with three exceptions: *lighting*, the fraction of *food intake cooked*, and the energy intensity of *waste management*. Significant perturbations to the parameters in these three cases changes total final energy use by only 1-2%.

With respect to overall decent living sectors, the model appears most sensitive to changes in the *shelter and living* and *public and commercial services­* sectors. Cumulatively, total global final energy use increases to 26-27 GJ/cap, in both cases, while for *nutrition* and *mobility*, it increases to 21-23 GJ/cap. There are two main reasons for this:

1. Within the *shelter and living* and *public and commercial services­* sectors, the key parameters we test for sensitivity have various multiplicative affects, e.g. when we simultaneously increase the energy intensity of both heating and cooling and floor space per capita, and also decrease household size, the increases in energy use are much more than a simple sum of the effects of each individual change. This is not to say there are no multiplicative interactions between the key parameters tested in the *nutrition* and *mobility* sectors, only that there are fewer of them.
2. Relatedly, we increase activity-levels in the sensitivity test more significantly for the *shelter and living* and *public and commercial services­* sectors, than for the *nutrition* and *mobility* sectors. This is because activity levels for the latter two are, arguably, more satiable – if someone’s income were to increase five-fold, it’s conceivable that they’d move into a house five times larger, but they’d be very unlikely to increase their calorie intake to 12,500 kcal/day.

It is difficult to draw further specific conclusions from this sensitivity analysis – the interested reader will have to carefully examine Figure 7 and our assumptions detailed in Table S11, and make of this what they will. However, we can say that the main conclusions of our work appear sound. If it turned out that we’d been optimistic with our central DLE assumptions, we could shift *every* one of the inputs detailed in Table S11 halfway towards the high-energy values and global final energy consumption in 2050 would remain under 300 EJ. This is a significant change, no doubt. Yet it still implies that global energy use in 2050 could be reduced to below 2000 levels – thus well under even the most optimistic mitigation scenario of the IEA – while providing decent living standards universally to a population of nearly 10 billion people across the world. Avoiding ecological collapse and alleviating global poverty are not, it seems, incompatible aspirations (at least, in theory).



**Figure 7:**  Global final energy use per capita in 2050, with parameter perturbations applied individually, and then together sector-by-sector (named *all applied* in each case).

**Table S11:** List of parameters that are tested in the sensitivity analysis, with their default (DLE) values, low values (where applicable), and high values.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Input parameters** | | | **Details** |
|  | *Central* | *Low-energy* | *High-energy* |  | |
| **Shelter & living conditions** |  |  |  |  | |
| Household size | 4 persons/hh | - | 2 persons/hh |  | |
| Floor space | 10 m2 | - | 20 m2 | An arbitrary 100% increase from the default | |
| Building standards | *Advanced new* | - | *New modern/deep retrofit* | These are the GBPN categories used | |
| Construction intensity | 30-50 MJ/m2/yr | - | 120-200 MJ/m2/yr | Cabeza et al. (2014) (Ref.2) and Nässén et al. (2012) suggest ~100 to ~200 MJ/m2/yr | |
| Water consumption | 50 L/cap/day | - | 100 L/cap/day | This reflects the range offered by the UN, mentioned above in the *water supply* section | |
| Water heating temperature | 50°c | - | 65°c | 65°c is a typical current value according to Cullen et al. (2011) | |
| Lighting intensity and coverage | *Default* | - | *400%* | This assumes twice as many lights are used for twice the time | |
| **Nutrition** |  |  |  |  | |
| Consumption of animal-products | 7% | 0% | 14% | Percentage contributions on a calorie intake basis (rather than weight) | |
| Supply-chain intensity | 210% | 150% | 270% | Percentages are relative to food-production energy: 270% is a current FAO estimate | |
| Total food-energy intake | *Default* | - | *125%* | So intake is ~2,000-3,000 kcal/capita, depending upon age | |
| Food-waste | 15% | 7.5% | 30% | 30% is approaching current levels | |
| Food intake cooked | 50% | 33% | 75% | An arbitrary 50% increase and decrease from the default | |
| **Mobility** |  |  |  |  | |
| Mode-share | *Default* | *No flying* | *More driving & flying* | *High energy:* Car use increases 20%**→**50%; buses & rail decrease 40%**→**25%; 1 flight per 2 yrs | |
| Activity-levels | *Default* | 75% | *150%* | A 50% increase brings mobility levels up to the higher end of the IEA's (2017) assumptions | |
| Direct & embodied energy intensities | *Default* | - | *200%* | This keeps the values within the ranges of Chester and Horvath (2009) and Chester et al. (2013) | |
| **Communication & information** |  |  |  |  | |
| Phone ownership age | 10 yrs | 15 yrs | 5 yrs | Minimum age at which a person owns a mobile phone | |
| Embodied energy intensities | *Default* | - | *150%* | Based upon higher estimates from Deng et al. (2011) and Proske et al. (2016) | |
| Network energy for computers | *Default* | - | *200%* | An arbitrary 100% increase from the default | |
| **Clothing** |  |  |  |  | |
| Lifetimes | *Default* | - | *75%* | This matches WRAP data for current UK clothes lifetimes | |
| Days worn per wash | *Default* | - | *75%* | Set equal to the above | |
| **Public & commercial services** |  |  |  |  | |
| Public buildings floor space | *Default* | *67%* | *150%* | An arbitrary 50% increase and decrease from the default | |
| Building standards | *Advanced new* | - | *New modern/deep retrofit* | These are the GBPN categories used | |
| Construction intensity | 90-450 MJ/m2/yr | - | 180-900 MJ/m2/yr | An arbitrary 100% increase from the default | |
| Healthcare/education *other* energy | *Default* | - | *200%* | This is direct energy use that is *not* for heating and cooling | |
| Waste management energy use | Default | 50% | 300% | An arbitrary 50% decrease and 200% increase from the default | |
| **Power supply** |  |  |  |  | |
| Energy intensity of infrastructure | 0.15 MJ/MJ | 0.1 MJ/MJ | 0.25 MJ/MJ | This covers the range offered by Hertwich et al. (2015) | |

**Part 3** Decent Living Energy by country

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ***Decent living energy; GJ/capita*** | | | **Nutrition** | | | **Shelter & living conditions** | | | **Hygiene** | | | **Clothing** | | **Healthcare** | **Education** | **Communication and information** | | | **Mobility** | | **Other** |
| **Country** | | **Region** | Food | Cooking appliances | Cold Storage | House construction | Thermal comfort | Illumination | Water supply | Water heating | Waste management | Clothes | Clothes washing | Phones | Computers | ICT networks & data | Vehicles | Transport infrastructure |
| AUS | Australia | Oceania | 2.7 | 0.3 | 0.2 | 0.5 | 0.3 | 0.0 | 0.2 | 0.9 | 0.2 | 0.3 | 0.3 | 1.1 | 0.3 | 0.0 | 0.1 | 0.4 | 2.9 | 1.2 | 2.9 |
| NZL | New Zealand | Oceania | 2.7 | 0.3 | 0.2 | 0.5 | 0.3 | 0.0 | 0.1 | 1.3 | 0.1 | 0.3 | 0.3 | 1.1 | 0.3 | 0.0 | 0.1 | 0.4 | 2.9 | 1.2 | 3.0 |
| CHN | China | East Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 1.4 | 0.2 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 2.1 | 0.6 | 3.3 |
| HKG | Hong Kong | East Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.2 | 0.9 | 0.2 | 0.3 | 0.3 | 1.6 | 0.3 | 0.0 | 0.1 | 0.4 | 1.7 | 0.4 | 3.3 |
| JPN | Japan | East Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 1.3 | 0.2 | 0.3 | 0.3 | 1.4 | 0.3 | 0.0 | 0.1 | 0.4 | 1.7 | 0.4 | 3.2 |
| KOR | Korea | East Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 1.2 | 0.2 | 0.3 | 0.3 | 1.4 | 0.3 | 0.0 | 0.1 | 0.4 | 1.8 | 0.4 | 3.2 |
| MNG | Mongolia | East Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.2 | 1.6 | 0.2 | 0.3 | 0.3 | 1.5 | 0.6 | 0.0 | 0.1 | 0.4 | 3.1 | 1.2 | 3.5 |
| TWN | Taiwan | East Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 0.8 | 0.2 | 0.3 | 0.3 | 1.6 | 0.3 | 0.0 | 0.1 | 0.4 | 1.8 | 0.4 | 3.3 |
| BRN | Brunei Darussalam | Southeast Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.1 | 0.7 | 0.1 | 0.3 | 0.3 | 1.6 | 0.4 | 0.0 | 0.1 | 0.4 | 1.9 | 0.5 | 3.3 |
| KHM | Cambodia | Southeast Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.6 | 0.0 | 0.1 | 0.7 | 0.1 | 0.3 | 0.3 | 1.6 | 0.6 | 0.0 | 0.1 | 0.4 | 2.3 | 0.7 | 3.3 |
| IDN | Indonesia | Southeast Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 0.8 | 0.2 | 0.3 | 0.3 | 1.6 | 0.6 | 0.0 | 0.1 | 0.4 | 1.9 | 0.5 | 3.3 |
| LAO | Lao PDR | Southeast Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.1 | 0.9 | 0.1 | 0.3 | 0.3 | 1.6 | 0.6 | 0.0 | 0.1 | 0.4 | 2.2 | 0.7 | 3.3 |
| MYS | Malaysia | Southeast Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 0.8 | 0.2 | 0.3 | 0.3 | 1.6 | 0.5 | 0.0 | 0.1 | 0.4 | 1.9 | 0.5 | 3.3 |
| PHL | Philippines | Southeast Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 0.8 | 0.2 | 0.3 | 0.3 | 1.6 | 0.6 | 0.0 | 0.1 | 0.4 | 1.9 | 0.5 | 3.3 |
| SGP | Singapore | Southeast Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.2 | 0.8 | 0.2 | 0.3 | 0.3 | 1.6 | 0.3 | 0.0 | 0.1 | 0.4 | 1.7 | 0.4 | 3.2 |
| THA | Thailand | Southeast Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 0.8 | 0.2 | 0.3 | 0.3 | 1.6 | 0.4 | 0.0 | 0.1 | 0.4 | 2.1 | 0.6 | 3.3 |
| VNM | Viet Nam | Southeast Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.1 | 0.8 | 0.1 | 0.3 | 0.3 | 1.6 | 0.5 | 0.0 | 0.1 | 0.4 | 1.9 | 0.5 | 3.3 |
| BGD | Bangladesh | South Asia | 2.8 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.1 | 0.8 | 0.1 | 0.3 | 0.3 | 1.6 | 0.5 | 0.0 | 0.1 | 0.4 | 1.9 | 0.5 | 3.3 |
| IND | India | South Asia | 2.8 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 0.8 | 0.2 | 0.3 | 0.3 | 1.6 | 0.5 | 0.0 | 0.1 | 0.4 | 1.9 | 0.5 | 3.3 |
| NPL | Nepal | South Asia | 2.8 | 0.3 | 0.2 | 0.8 | 0.6 | 0.0 | 0.2 | 1.4 | 0.2 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 2.0 | 0.5 | 3.3 |
| PAK | Pakistan | South Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 1.0 | 0.2 | 0.3 | 0.3 | 1.6 | 0.7 | 0.0 | 0.1 | 0.4 | 1.9 | 0.5 | 3.3 |
| LKA | Sri Lanka | South Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.6 | 0.0 | 0.2 | 0.7 | 0.2 | 0.3 | 0.3 | 1.6 | 0.5 | 0.0 | 0.1 | 0.4 | 2.0 | 0.5 | 3.3 |
| CAN | Canada | North America | 2.7 | 0.3 | 0.2 | 0.5 | 0.8 | 0.0 | 0.2 | 1.6 | 0.2 | 0.3 | 0.3 | 1.2 | 0.3 | 0.0 | 0.1 | 0.4 | 3.0 | 1.2 | 3.1 |
| USA | United States | North America | 2.7 | 0.3 | 0.2 | 0.5 | 0.7 | 0.0 | 0.2 | 1.3 | 0.2 | 0.3 | 0.3 | 1.2 | 0.3 | 0.0 | 0.1 | 0.4 | 3.0 | 1.2 | 3.1 |
| MEX | Mexico | North America | 2.7 | 0.3 | 0.2 | 0.5 | 0.3 | 0.0 | 0.2 | 0.9 | 0.2 | 0.3 | 0.3 | 1.1 | 0.4 | 0.0 | 0.1 | 0.4 | 2.9 | 1.2 | 2.9 |
| ARG | Argentina | South America | 2.7 | 0.3 | 0.2 | 0.8 | 0.3 | 0.0 | 0.2 | 1.1 | 0.2 | 0.3 | 0.3 | 1.4 | 0.5 | 0.0 | 0.1 | 0.4 | 2.9 | 1.2 | 3.3 |
| BOL | Bolivia | South America | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.1 | 0.9 | 0.1 | 0.3 | 0.3 | 1.4 | 0.6 | 0.0 | 0.1 | 0.4 | 3.0 | 1.2 | 3.3 |
| BRA | Brazil | South America | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.1 | 0.8 | 0.1 | 0.3 | 0.3 | 1.6 | 0.4 | 0.0 | 0.1 | 0.4 | 2.9 | 1.2 | 3.4 |
| CHL | Chile | South America | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 1.3 | 0.2 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 2.8 | 1.1 | 3.4 |
| COL | Colombia | South America | 2.7 | 0.3 | 0.2 | 0.8 | 0.3 | 0.0 | 0.1 | 0.8 | 0.1 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 2.9 | 1.1 | 3.2 |
| ECU | Ecuador | South America | 2.7 | 0.3 | 0.2 | 0.8 | 0.3 | 0.0 | 0.2 | 0.9 | 0.2 | 0.3 | 0.3 | 1.4 | 0.5 | 0.0 | 0.1 | 0.4 | 2.4 | 0.8 | 3.2 |
| PRY | Paraguay | South America | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.1 | 0.9 | 0.1 | 0.3 | 0.3 | 1.6 | 0.6 | 0.0 | 0.1 | 0.4 | 3.1 | 1.3 | 3.4 |
| PER | Peru | South America | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 1.0 | 0.2 | 0.3 | 0.3 | 1.4 | 0.5 | 0.0 | 0.1 | 0.4 | 2.7 | 1.0 | 3.3 |
| URY | Uruguay | South America | 2.7 | 0.3 | 0.2 | 0.8 | 0.3 | 0.0 | 0.1 | 1.0 | 0.1 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 2.9 | 1.1 | 3.3 |
| VEN | Venezuela | South America | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 0.8 | 0.2 | 0.3 | 0.3 | 1.6 | 0.6 | 0.0 | 0.1 | 0.4 | 2.7 | 1.0 | 3.4 |
| CRI | Costa Rica | Central America | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.1 | 0.8 | 0.1 | 0.3 | 0.3 | 1.6 | 0.4 | 0.0 | 0.1 | 0.4 | 2.1 | 0.7 | 3.3 |
| GTM | Guatemala | Central America | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 0.9 | 0.2 | 0.3 | 0.3 | 1.6 | 0.6 | 0.0 | 0.1 | 0.4 | 2.0 | 0.5 | 3.3 |
| HND | Honduras | Central America | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 0.9 | 0.2 | 0.3 | 0.3 | 1.6 | 0.6 | 0.0 | 0.1 | 0.4 | 2.2 | 0.7 | 3.3 |
| NIC | Nicaragua | Central America | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.1 | 0.8 | 0.1 | 0.3 | 0.3 | 1.6 | 0.6 | 0.0 | 0.1 | 0.4 | 2.9 | 1.1 | 3.4 |
| PAN | Panama | Central America | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.1 | 0.8 | 0.1 | 0.3 | 0.3 | 1.6 | 0.6 | 0.0 | 0.1 | 0.4 | 2.5 | 0.9 | 3.4 |
| SLV | El Salvador | Central America | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 0.8 | 0.2 | 0.3 | 0.3 | 1.6 | 0.5 | 0.0 | 0.1 | 0.4 | 1.9 | 0.5 | 3.3 |
| DOM | Dominican Repub’ | Caribbean | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 0.8 | 0.2 | 0.3 | 0.3 | 1.6 | 0.5 | 0.0 | 0.1 | 0.4 | 1.9 | 0.5 | 3.3 |
| JAM | Jamaica | Caribbean | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 0.8 | 0.2 | 0.3 | 0.3 | 1.6 | 0.5 | 0.0 | 0.1 | 0.4 | 1.9 | 0.5 | 3.3 |
| PRI | Puerto Rico | Caribbean | 2.8 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.2 | 0.8 | 0.2 | 0.3 | 0.3 | 1.6 | 0.3 | 0.0 | 0.1 | 0.4 | 1.8 | 0.5 | 3.3 |
| TTO | Trinidad & Tobago | Caribbean | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 0.8 | 0.2 | 0.3 | 0.3 | 1.6 | 0.4 | 0.0 | 0.1 | 0.4 | 1.9 | 0.5 | 3.3 |
| AUT | Austria | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.1 | 1.4 | 0.1 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 2.0 | 0.6 | 3.3 |
| BEL | Belgium | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 1.3 | 0.2 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 1.8 | 0.4 | 3.2 |
| CYP | Cyprus | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 1.0 | 0.2 | 0.3 | 0.3 | 1.6 | 0.4 | 0.0 | 0.1 | 0.4 | 2.0 | 0.5 | 3.3 |
| CZE | Czech Republic | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.2 | 1.4 | 0.2 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 2.1 | 0.6 | 3.3 |
| DNK | Denmark | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.1 | 1.4 | 0.1 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 2.3 | 0.8 | 3.3 |
| EST | Estonia | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.2 | 1.4 | 0.2 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 2.8 | 1.1 | 3.4 |
| FIN | Finland | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.2 | 1.6 | 0.2 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 2.6 | 0.9 | 3.4 |
| FRA | France | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 1.3 | 0.2 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 2.3 | 0.7 | 3.3 |
| DEU | Germany | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 1.3 | 0.2 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 1.9 | 0.5 | 3.3 |
| GRC | Greece | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 1.1 | 0.2 | 0.3 | 0.3 | 1.4 | 0.3 | 0.0 | 0.1 | 0.4 | 2.7 | 1.0 | 3.3 |
| HUN | Hungary | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.1 | 1.3 | 0.1 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 2.3 | 0.7 | 3.3 |
| IRL | Ireland | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 1.3 | 0.2 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 3.1 | 1.3 | 3.4 |
| ITA | Italy | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 1.2 | 0.2 | 0.3 | 0.3 | 1.4 | 0.3 | 0.0 | 0.1 | 0.4 | 2.0 | 0.6 | 3.2 |
| LVA | Latvia | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.1 | 1.4 | 0.1 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 3.0 | 1.2 | 3.4 |
| LTU | Lithuania | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.2 | 1.4 | 0.2 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 3.0 | 1.2 | 3.4 |
| LUX | Luxembourg | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 1.3 | 0.2 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 2.0 | 0.6 | 3.3 |
| MLT | Malta | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.2 | 1.0 | 0.2 | 0.3 | 0.3 | 1.6 | 0.4 | 0.0 | 0.1 | 0.4 | 1.7 | 0.4 | 3.3 |
| NLD | Netherlands | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 1.3 | 0.2 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 1.7 | 0.4 | 3.2 |
| POL | Poland | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.2 | 1.4 | 0.2 | 0.3 | 0.3 | 1.4 | 0.3 | 0.0 | 0.1 | 0.4 | 2.2 | 0.7 | 3.3 |
| PRT | Portugal | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.3 | 0.0 | 0.2 | 1.1 | 0.2 | 0.3 | 0.3 | 1.4 | 0.3 | 0.0 | 0.1 | 0.4 | 2.2 | 0.7 | 3.2 |
| SVK | Slovakia | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.1 | 1.4 | 0.1 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 2.1 | 0.6 | 3.3 |
| SVN | Slovenia | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.1 | 1.3 | 0.1 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 2.2 | 0.7 | 3.3 |
| ESP | Spain | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 1.2 | 0.2 | 0.3 | 0.3 | 1.4 | 0.3 | 0.0 | 0.1 | 0.4 | 2.5 | 0.9 | 3.3 |
| SWE | Sweden | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.2 | 1.5 | 0.2 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 2.4 | 0.8 | 3.4 |
| GBR | United Kingdom | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 1.3 | 0.2 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 2.0 | 0.6 | 3.3 |
| CHE | Switzerland | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.2 | 1.4 | 0.2 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 1.9 | 0.5 | 3.3 |
| NOR | Norway | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.1 | 1.6 | 0.1 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 2.3 | 0.8 | 3.4 |
| ALB | Albania | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 1.2 | 0.2 | 0.3 | 0.3 | 1.4 | 0.3 | 0.0 | 0.1 | 0.4 | 2.2 | 0.7 | 3.3 |
| BGR | Bulgaria | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 1.3 | 0.2 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 2.6 | 0.9 | 3.3 |
| BLR | Belarus | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.2 | 1.4 | 0.2 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 2.9 | 1.2 | 3.4 |
| HRV | Croatia | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.1 | 1.3 | 0.1 | 0.3 | 0.3 | 1.4 | 0.3 | 0.0 | 0.1 | 0.4 | 2.2 | 0.7 | 3.3 |
| ROU | Romania | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 1.3 | 0.2 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 2.7 | 1.0 | 3.4 |
| RUS | Russia | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.2 | 1.6 | 0.2 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 3.0 | 1.2 | 3.5 |
| UKR | Ukraine | Europe | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.2 | 1.3 | 0.2 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 2.9 | 1.2 | 3.4 |
| KAZ | Kazakhstan | Central Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.2 | 1.4 | 0.2 | 0.3 | 0.3 | 1.4 | 0.6 | 0.0 | 0.1 | 0.4 | 3.1 | 1.3 | 3.5 |
| KGZ | Kyrgyztan | Central Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.2 | 1.6 | 0.2 | 0.3 | 0.3 | 1.5 | 0.6 | 0.0 | 0.1 | 0.4 | 3.3 | 1.4 | 3.5 |
| ARM | Armenia | Western Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.2 | 1.4 | 0.2 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 2.4 | 0.8 | 3.3 |
| AZE | Azerbaijan | Western Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.2 | 1.2 | 0.2 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 2.3 | 0.8 | 3.3 |
| GEO | Georgia | Western Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.2 | 1.4 | 0.2 | 0.3 | 0.3 | 1.4 | 0.5 | 0.0 | 0.1 | 0.4 | 2.4 | 0.8 | 3.3 |
| BHR | Bahrain | Western Asia | 2.8 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 0.7 | 0.2 | 0.3 | 0.3 | 1.6 | 0.4 | 0.0 | 0.1 | 0.4 | 1.7 | 0.4 | 3.2 |
| IRN | Iran | Western Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 1.1 | 0.2 | 0.3 | 0.3 | 1.4 | 0.5 | 0.0 | 0.1 | 0.4 | 2.5 | 0.9 | 3.3 |
| ISR | Israel | Western Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.2 | 1.0 | 0.2 | 0.3 | 0.3 | 1.6 | 0.6 | 0.0 | 0.1 | 0.4 | 1.7 | 0.4 | 3.3 |
| JOR | Jordan | Western Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.2 | 1.0 | 0.2 | 0.3 | 0.3 | 1.6 | 0.6 | 0.0 | 0.1 | 0.4 | 1.7 | 0.4 | 3.3 |
| KWT | Kuwait | Western Asia | 2.8 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.2 | 0.8 | 0.2 | 0.3 | 0.3 | 1.6 | 0.5 | 0.0 | 0.1 | 0.4 | 1.7 | 0.4 | 3.3 |
| OMN | Oman | Western Asia | 2.8 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.2 | 0.8 | 0.2 | 0.3 | 0.3 | 1.6 | 0.4 | 0.0 | 0.1 | 0.4 | 2.4 | 0.8 | 3.3 |
| QAT | Qatar | Western Asia | 2.8 | 0.3 | 0.2 | 0.8 | 0.8 | 0.0 | 0.2 | 0.7 | 0.2 | 0.3 | 0.3 | 1.6 | 0.3 | 0.0 | 0.1 | 0.4 | 1.7 | 0.4 | 3.2 |
| SAU | Saudi Arabia | Western Asia | 2.8 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 0.8 | 0.2 | 0.3 | 0.3 | 1.6 | 0.5 | 0.0 | 0.1 | 0.4 | 2.9 | 1.2 | 3.4 |
| TUR | Turkey | Western Asia | 2.7 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 1.3 | 0.2 | 0.3 | 0.3 | 1.4 | 0.4 | 0.0 | 0.1 | 0.4 | 2.3 | 0.8 | 3.3 |
| ARE | UAE | Western Asia | 2.8 | 0.3 | 0.2 | 0.8 | 0.7 | 0.0 | 0.2 | 0.7 | 0.2 | 0.3 | 0.3 | 1.6 | 0.4 | 0.0 | 0.1 | 0.4 | 1.7 | 0.4 | 3.3 |
| EGY | Egypt | North Africa | 2.7 | 0.3 | 0.2 | 0.5 | 0.7 | 0.0 | 0.2 | 0.9 | 0.2 | 0.3 | 0.3 | 1.3 | 0.6 | 0.0 | 0.1 | 0.4 | 1.9 | 0.5 | 3.0 |
| MAR | Morocco | North Africa | 2.7 | 0.3 | 0.2 | 0.5 | 0.7 | 0.0 | 0.2 | 1.1 | 0.2 | 0.3 | 0.3 | 1.3 | 0.4 | 0.0 | 0.1 | 0.4 | 2.9 | 1.2 | 3.1 |
| TUN | Tunisia | North Africa | 2.7 | 0.3 | 0.2 | 0.5 | 0.7 | 0.0 | 0.2 | 1.0 | 0.2 | 0.3 | 0.3 | 1.3 | 0.4 | 0.0 | 0.1 | 0.4 | 3.0 | 1.2 | 3.1 |
| BEN | Benin | Western Africa | 2.7 | 0.3 | 0.2 | 0.5 | 0.7 | 0.0 | 0.1 | 0.7 | 0.1 | 0.3 | 0.3 | 1.3 | 0.7 | 0.0 | 0.1 | 0.4 | 2.1 | 0.6 | 3.0 |
| BFA | Burkina Faso | Western Africa | 2.7 | 0.3 | 0.2 | 0.5 | 0.7 | 0.0 | 0.1 | 0.7 | 0.1 | 0.3 | 0.3 | 1.3 | 0.7 | 0.0 | 0.1 | 0.4 | 2.8 | 1.1 | 3.1 |
| CMR | Cameroon | Western Africa | 2.7 | 0.3 | 0.2 | 0.5 | 0.7 | 0.0 | 0.1 | 0.8 | 0.1 | 0.3 | 0.3 | 1.3 | 0.7 | 0.0 | 0.1 | 0.4 | 2.3 | 0.7 | 3.0 |
| CIV | Côte d'Ivoire | Western Africa | 2.7 | 0.3 | 0.2 | 0.5 | 0.7 | 0.0 | 0.1 | 0.8 | 0.1 | 0.3 | 0.3 | 1.3 | 0.7 | 0.0 | 0.1 | 0.4 | 3.1 | 1.3 | 3.1 |
| GHA | Ghana | Western Africa | 2.7 | 0.3 | 0.2 | 0.5 | 0.7 | 0.0 | 0.1 | 0.7 | 0.1 | 0.3 | 0.3 | 1.3 | 0.6 | 0.0 | 0.1 | 0.4 | 2.5 | 0.9 | 3.0 |
| GIN | Guinea | Western Africa | 2.7 | 0.3 | 0.2 | 0.5 | 0.7 | 0.0 | 0.1 | 0.8 | 0.1 | 0.3 | 0.3 | 1.3 | 0.7 | 0.0 | 0.1 | 0.4 | 3.3 | 1.4 | 3.1 |
| NGA | Nigeria | Western Africa | 2.7 | 0.3 | 0.2 | 0.5 | 0.7 | 0.0 | 0.1 | 0.7 | 0.1 | 0.3 | 0.3 | 1.3 | 0.7 | 0.0 | 0.1 | 0.4 | 2.2 | 0.7 | 3.0 |
| SEN | Senegal | Western Africa | 2.7 | 0.3 | 0.2 | 0.5 | 0.7 | 0.0 | 0.1 | 0.7 | 0.1 | 0.3 | 0.3 | 1.3 | 0.7 | 0.0 | 0.1 | 0.4 | 2.7 | 1.0 | 3.1 |
| TGO | Togo | Western Africa | 2.7 | 0.3 | 0.2 | 0.5 | 0.7 | 0.0 | 0.1 | 0.7 | 0.1 | 0.3 | 0.3 | 1.3 | 0.7 | 0.0 | 0.1 | 0.4 | 2.5 | 0.9 | 3.0 |
| ETH | Ethiopia | Eastern Africa | 2.7 | 0.3 | 0.2 | 0.5 | 0.3 | 0.0 | 0.1 | 0.9 | 0.1 | 0.3 | 0.3 | 1.1 | 0.5 | 0.0 | 0.1 | 0.4 | 2.3 | 0.7 | 2.9 |
| KEN | Kenya | Eastern Africa | 2.7 | 0.3 | 0.2 | 0.5 | 0.3 | 0.0 | 0.1 | 0.8 | 0.1 | 0.3 | 0.3 | 1.1 | 0.5 | 0.0 | 0.1 | 0.4 | 2.7 | 1.0 | 2.9 |
| MDG | Madagascar | Eastern Africa | 2.7 | 0.3 | 0.2 | 0.5 | 0.3 | 0.0 | 0.1 | 0.9 | 0.1 | 0.3 | 0.3 | 1.1 | 0.6 | 0.0 | 0.1 | 0.4 | 3.2 | 1.4 | 3.0 |
| MWI | Malawi | Eastern Africa | 2.7 | 0.3 | 0.2 | 0.5 | 0.6 | 0.0 | 0.1 | 0.9 | 0.1 | 0.3 | 0.3 | 1.3 | 0.7 | 0.0 | 0.1 | 0.4 | 2.3 | 0.8 | 3.0 |
| MUS | Mauritius | Eastern Africa | 2.8 | 0.3 | 0.2 | 0.5 | 0.3 | 0.0 | 0.1 | 0.9 | 0.1 | 0.3 | 0.3 | 1.1 | 0.3 | 0.0 | 0.1 | 0.4 | 1.9 | 0.5 | 2.8 |
| MOZ | Mozambique | Eastern Africa | 2.7 | 0.3 | 0.2 | 0.5 | 0.7 | 0.0 | 0.1 | 0.8 | 0.1 | 0.3 | 0.3 | 1.3 | 0.7 | 0.0 | 0.1 | 0.4 | 3.3 | 1.4 | 3.1 |
| RWA | Rwanda | Eastern Africa | 2.7 | 0.3 | 0.2 | 0.5 | 0.3 | 0.0 | 0.1 | 1.0 | 0.1 | 0.3 | 0.3 | 1.1 | 0.5 | 0.0 | 0.1 | 0.4 | 2.0 | 0.5 | 2.8 |
| TZA | Tanzania | Eastern Africa | 2.6 | 0.3 | 0.2 | 0.5 | 0.3 | 0.0 | 0.1 | 0.9 | 0.1 | 0.3 | 0.3 | 1.1 | 0.6 | 0.0 | 0.1 | 0.4 | 2.9 | 1.2 | 2.9 |
| UGA | Uganda | Eastern Africa | 2.7 | 0.3 | 0.2 | 0.5 | 0.3 | 0.0 | 0.1 | 0.9 | 0.1 | 0.3 | 0.3 | 1.1 | 0.6 | 0.0 | 0.1 | 0.4 | 2.3 | 0.8 | 2.9 |
| ZMB | Zambia | Eastern Africa | 2.7 | 0.3 | 0.2 | 0.5 | 0.7 | 0.0 | 0.1 | 0.9 | 0.1 | 0.3 | 0.3 | 1.3 | 0.7 | 0.0 | 0.1 | 0.4 | 3.2 | 1.3 | 3.2 |
| ZWE | Zimbabwe | Eastern Africa | 2.7 | 0.3 | 0.2 | 0.5 | 0.7 | 0.0 | 0.2 | 0.9 | 0.2 | 0.3 | 0.3 | 1.3 | 0.6 | 0.0 | 0.1 | 0.4 | 3.3 | 1.4 | 3.2 |
| BWA | Botswana | South Africa | 2.7 | 0.3 | 0.2 | 0.5 | 0.7 | 0.0 | 0.2 | 0.9 | 0.2 | 0.3 | 0.3 | 1.3 | 0.5 | 0.0 | 0.1 | 0.4 | 3.0 | 1.2 | 3.1 |
| NAM | Namibia | South Africa | 2.7 | 0.3 | 0.2 | 0.5 | 0.7 | 0.0 | 0.2 | 1.0 | 0.2 | 0.3 | 0.3 | 1.3 | 0.6 | 0.0 | 0.1 | 0.4 | 3.1 | 1.3 | 3.1 |
| ZAF | South Africa | South Africa | 2.7 | 0.3 | 0.2 | 0.5 | 0.3 | 0.0 | 0.2 | 1.0 | 0.2 | 0.3 | 0.3 | 1.1 | 0.4 | 0.0 | 0.1 | 0.4 | 3.0 | 1.2 | 3.0 |

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2. See <https://health.gov/dietaryguidelines/2015/> (accessed 23/9/2019) [↑](#footnote-ref-2)
3. See <http://www.fao.org/3/X9892E/X9892e05.htm#P8217_125315> (accessed 26/9/2019) [↑](#footnote-ref-3)
4. Note: by ‘minimise’, we do not mean ‘optimise’ in any rigorous mathematical sense [↑](#footnote-ref-4)
5. See *Food surplus and waste in the UK – key facts* updated annually at <http://www.wrap.org.uk/food-drink> [↑](#footnote-ref-5)
6. See Alasdair Rae’s article at *The Conversation* (<https://theconversation.com/think-your-country-is-crowded-these-maps-reveal-the-truth-about-population-density-across-europe-90345>; accessed 02/10/2019) [↑](#footnote-ref-6)
7. See: <https://www.healthcaredesignmagazine.com/trends/research-theory/8-considerations-benchmarking/> [↑](#footnote-ref-7)
8. See: <https://www.energystar.gov/ia/business/tools_resources/target_finder/help/Space_Use_Information.htm> [↑](#footnote-ref-8)
9. See: [www.carbontrust.com/resources/guides/sector-based-advice/healthcare/](http://www.carbontrust.com/resources/guides/sector-based-advice/healthcare/) [↑](#footnote-ref-9)
10. Note that these calculations essentially label much hospital equipment as *infrastructure* rather than adding the associated embodied energy to the consumption sector *public services*, which would be more consistent with how other consumption sectors are treated. This is, however, only an issue for presentation of results and has no effect on the calculated total energy requirements. [↑](#footnote-ref-10)