Global Environmental Change 65 (2020) 102168

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Providing decent living with minimum energy: A global scenario

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ARTICLE INFO

Keywords:
Basic needs
Climate change
Demand
Energy
Inequality
Sufficiency

ABSTRACT

It is increasingly clear that averting ecological breakdown will require drastic changes to contemporary human society and the global economy embedded within it. On the other hand, the basic material needs of billions of people across the planet remain unmet. Here, we develop a simple, bottom-up model to estimate a practical minimal threshold for the final energy consumption required to provide decent material livings to the entire global population. We find that global final energy consumption in 2050 could be reduced to the levels of the 1960s, despite a population three times larger. However, such a world requires a massive rollout of advanced technologies across all sectors, as well as radical demand-side changes to reduce consumption – regardless of income – to levels of sufficiency. Sufficiency is, however, far more materially generous in our model than what those opposed to strong reductions in consumption often assume.

1. Introduction

The annual energy use of late-Palaeolithic foragers is estimated to have been around 5 GJ per person annually (Smil, 2017) – the sum of food-energy metabolised plus biomass for cooking. By 1850, after nearly 10,000 years of agriculturally-supported expansion, average global primary energy consumption rose to over 20 GJ/cap (GEA, 2012). Today, after 150 years of fossil-fuelled industrial development, it has reached 80 GJ/cap (IEA, 2019a). In absolute terms, total global primary energy use has risen from around 1 PJ in the late-Palaeolithic to nearly 600,000 PJ today, driving changes in the composition of the atmosphere (warming) and oceans (acidification) leading to dangerous climate change (IPCC, 2018).

Have the massive increases in energy consumption that accompanied the agricultural and industrial revolutions brought about comparable improvements for human well-being? Evidence suggests that for much of the past 10,000 years agriculture led to a declining quality of life for most human populations, compared to their forager predecessors (Larsen, 2006). But recent centuries have seen a rapid reversal of this trend, with improvements in health indicators across the board. However, it is difficult to say whether humans today are better off than ancient foragers (Diamond, 2010), who were far more socially and politically sophisticated than is often assumed (Wengrow and Graeber, 2015). Available data – life expectancy, child mortality, rates of violence seen in some modern foraging societies – can never tell the full story (Harari, 2016).

Regarding the modern era, however, some things can be stated with certainty:

First, current levels of energy use underpin numerous existential threats – ecological crises (Haberl et al., 2011; Steffen et al., 2015), resource scarcity, and the geopolitical instabilities these issues can catalyse, especially in a growth-dependent global economy (Büchs and Koch, 2019). And those most severely impacted tend to be the least well off (Haberl et al., 2011).

Second, while immense improvements in energy efficiency have occurred throughout the industrial revolution, these largely served to boost productivity and enable further growth (Brockway et al., 2017; Sakai et al., 2018; Ayres and Warr, 2010). Global energy use has thus risen consistently (GEA, 2012), with the exception of financial crises – whose effects soon wear off (Geels, 2013) – and global pandemics (Le Quéré et al., 2020) – the long-term impacts of which are yet to be seen. In countries where economic activity appears to have been decoupled from energy-use, this normally turns out to be an artefact of accounting conventions (Arto et al., 2016; Haberl et al., 2020) – namely, production-based methods, which ignore offshoring of production and imported goods (Peters, 2008; Peters et al., 2011).

Finally, the drastic increases in societies' energy use seen in recent decades have, beyond a certain point, had no benefit for the well-being

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https://doi.org/10.1016/j.gloenvcha.2020.102168
Received 23 April 2020; Received in revised form 31 August 2020; Accepted 9 September 2020

of their populations – *social* returns on energy consumption per capita become increasingly marginal (Arto et al., 2016; Steinberger and Roberts, 2010; Steinberger et al., 2012; Martínez and Ebenhack, 2008). Some countries thus achieve high social outcomes with far lower energy consumption than others, but none currently manage to achieve high social outcomes while staying within planetary boundaries (O'Neill et al., 2018).

Estimating the energy requirements of well-being is therefore an important but challenging task. Fortunately, recent advances have been made in both theory (Rao and Baer, 2012; Day et al., 2016; Brand-Correa and Steinberger, 2017) and estimation (Rao et al., 2019; Arto et al., 2016). It has been argued that a finite and universal set of satiable human needs underpin life satisfaction (O'Neill et al., 2018), while the ways they can be satisfied are culturally, historically and technologically varied (Gough, 2015; Brand-Correa et al., 2018). Further, while efficiency improvements have undoubtedly contributed to the decreasing levels of energy associated with human development (Steinberger and Roberts, 2010), other cultural and technological (long- and short-term) trends work counter to this. For example, diffuse contemporary social networks and a globalised economy necessitate high levels of mobility and complex communications technologies to meet basic needs of social and political participation, while infrastructure biased toward private vehicles ensures much of this mobility is car-dependent. A global population in the billions necessitates substantial agricultural activity – the foraging methods of our ancestors were much less energy intense, but could support < 1% of the current world population (Burger and Fristoe, 2018). Moreover, inequality, and especially affluence, are now widely recognised as core drivers of environmental damage (Wiedmann et al., 2020).

Here, we aim to contribute to these debates by estimating minimum *final* energy requirements for decent living standards to be provided to the entire global population in 2050. We build an energy-model upon the existing framework of Rao and Min (2018a), which proposes a list of basic material needs that underpin human well-being, and consider final (as opposed to primary) energy in order to move a step closer to the energy requirements of social life. These material needs are in many ways specific to our time, but can be taken as a reasonable basis for the coming decades. We find that, with a combination of the most efficient technologies available and radical demand-side transformations that reduce excess consumption to sufficiency-levels, the final energy requirements for providing decent living standards to the global population in 2050 could be over 60% lower than consumption today. In countries that are today's highest per-capita consumers, cuts of ~95% appear possible while still providing decent living standards to all.

2. Background and theory

2.1. Two perspectives on human well-being and basic needs

What do we mean by *decent living*, and what is its relationship to well-being? Debates about *the good life* can be traced back millennia to Aristotelian and Buddhist ideas (Gough, 2015) and likely extend back into unwritten (pre)history. The topic is thus vast, but in ecological contexts debates have largely revolved around two types of well-being: *hedonic* and *eudaimonic* (Lamb and Steinberger, 2017; Brand-Correa and Steinberger, 2017; Gough, 2015; O'Neill, 2008).

The former has roots in Bentham's utilitarianism and Epicurean philosophy, and tends towards questions of happiness and subjective well-being; calculus of pleasure and pain (O'Neill, 2008). There has been a tendency within economics for such ideas to be simplified into the notion that more is better, and that individuals can rationally judge what to consume to improve their lives (Gough, 2015). In short, an assumption that rising incomes can consistently raise well-being (Max-Neef, 1995; Easterlin, 2017). Others have used the same ideas to highlight the hedonic-treadmill of consumption, where people constantly adapt to improved material circumstances, so that well-being stagnates despite increasing wealth. From this perspective, true happiness can only be obtained by turning away from the world of positional consumption and insatiable desires (O'Neill, 2008; Jackson, 2005). This 'adaptivity' has also been criticised for its contrary effects: when people adapt to difficult circumstances this can leave subjective well-being measures obscuring systemic injustices (Lamb and Steinberger, 2017). Nonetheless, such adaptivity is a highly desirable characteristic, given how much of the external circumstances of humans' lives are beyond their control, and how fleeting desires can be – things the Buddha taught millennia ago.

Despite the human capacity to adapt to unfortunate circumstances, few argue against the idea that society should be structured such that basic human needs are universally met so far as possible. This is where eudaimonic conceptions of well-being enter, which underpin prominent capabilities- and needs-based-approaches (Fanning and O'neill, 2019; O'Neill, 2008). Broadly, these focus on providing people with the capabilities required for flourishing – physical health and safety; clean air and water and adequate nutrition; social and political participation; autonomy (so far as it's possible; Greene and Cohen, 2004) cultivated through education and cognitive understanding; time and space for imagination and social play (Lamb and Steinberger, 2017; Gough, 2015). The argument that such basic needs are universal and independent of cultural context, rests on the distinction between *needs* and *need satisfiers*. *Needs* are universal; *satisfiers* culturally specific (Doyal and Gough, 1991).

Needs-based approaches along these lines have recently been used as a basis for developing a framework to decouple energy-use from human well-being (Brand-Correa and Steinberger, 2017). But for modelling purposes, these basic human needs must be translated to material requirements. Recently, Rao and Min (2018a) have stepped in to fill this gap by offering an inventory of universal material requirements they suggest are prerequisites for fulfilling basic human needs. In compiling the inventory, they proposed that each material need should (a) satisfy at least one basic need, (b) not impede others' fulfilling their needs and (c) either be the *only satisfier* of a particular need, or currently be *overwhelmingly preferred* by people (globally) among competing satisfiers. They are clear to stress that fulfilment of these material requirements are instrumental to achieving social and physical well-being, *but are by no means sufficient alone.* Their inventory is shown in Table 1, along with an indication of all regional variations that we apply in the model (described in Section 3).

Our contribution is conceptually simple: We aim to estimate the *final energy* needed to provide these material living standards to the full global population. In this process, our intention is to imagine a world that is fundamentally transformed, where state-of-the-art technologies merge with drastic changes in demand to bring energy (and material) consumption as low as possible, while providing decent material conditions and basic services for all. To this end, we take a bottom-up modelling approach.

2.2. Two approaches for estimating minimum energy-use requirements

Modelling attempts to estimate the energy requirements of meeting basic human needs and enabling a high quality of life, tend to take either a top-down or bottom-up approach.

Top-down approaches statistically analyse empirical data to investigate relationships between environmental impacts and social outcomes. Among the former are energy consumption, ecological- or carbon-footprints (Wackernagel and Rees, 1998), and among the latter life expectancy (Dietz et al., 2012; Jorgenson and Dietz, 2015; Givens, 2018), life satisfaction (Knight and Rosa, 2011), composite indicators such as the *Human Development Index* (HDI) (Martínez and Ebenhack, 2008; Steinberger and Roberts, 2010), and baskets of indicators often inspired by the UN's *Sustainable Development Goals* (Lamb, 2016; Lamb and Rao, 2015; O'Neill et al., 2018).

Previous estimates of the energy consumption necessary to achieve,

Table 1

. Inventory of the prerequisites for *Decent Living Standards* (DLS) (Rao and Min, 2018a) broken-down into key material requirements and services. The final column indicates where we implement regional variations in the model, and gives a brief explanation; the Supplementary Materials give full details.

DLS dimension	Material requirements and services	Regional variation
Nutrition	Food	Consumption varies with countries' age structures
	Cooking appliances	*None implemented*
	Cold Storage	*None implemented*
Shelter and living conditions	Sufficient housing space	*None implemented*
	Thermal comfort	Requirements vary with regional HDDs and CDDs
	Illumination	*None implemented*
Hygiene	Water supply	Intensity varies with water scarcity (higher scarcity → higher intensities)
	Water heating	Intensity varies with countries' average temperatures
	Waste management	*None implemented*
Clothing	Clothes	*None implemented*
	Washing facilities	*None implemented*
Healthcare	Hospitals	*None implemented*
Education	Schools	Requirements vary with age structures (more young people → more schools)
Comms' and information	Phones	Requirements vary with age structures (more children < 10yo → less phones)
	Computers	*None implemented*
	Networks + data centres	*None implemented*
Mobility	Vehicle production	Activity levels and mode shares vary with countries' adjusted ('lived') population densities (higher densities → lower activity levels)
	Vehicle's propulsion	
	Transport infrastructure	

for example, a high HDI are wide-ranging – a HDI above 0.8 appears to require 30 to 100 + GJ/cap/yr in primary energy terms (Martínez and Ebenhack, 2008; Steinberger and Roberts, 2010; Smil, 2005; Rao et al., 2019). This range is unsurprising given the diversity of cultural, political, technological and climatic factors at play, however, useful points can still be made: Improvements in social outcomes with rising energy consumption become increasingly marginal, saturating above 100–150 GJ/capita/yr of primary energy (Arto et al., 2016); countries tend to achieve high social outcomes with lower energy use over time (Steinberger and Roberts, 2010; Jorgenson et al., 2014); the energy-consumption of countries with high social outcomes appears higher when a consumption-based perspective is taken, due to offshoring of high-energy industries (Arto et al., 2016); the levels of democracy present appear to have negligible effect on the energy-intensity of well-being (Mayer, 2017).

Studies exploring the ecological-intensity of well-being via other means – e.g. by relating greenhouse gas emissions or ecological footprint to well-being – offer both consistent and additional findings. Again, the ecological-intensity of well-being appears to be falling over time (Jorgenson, 2014), but it's higher for higher incomes (Jorgenson and Dietz, 2015; Jorgenson and Givens, 2015). Further, the relationship between inequality and carbon emissions is complex. Some suggest that inequality increases the carbon-intensity of well-being (Jorgenson, 2015), particularly inequalities *between* countries (Rao and Min, 2018b). Others suggest that *reducing* inequality within countries is likely to *increase* total carbon footprints in low-middle income countries (Grunewald et al., 2017); the opposite relationship may exist in high-income countries (Hubacek et al., 2017), but this is not yet well understood. Finally, although many countries provide good basic services (e.g. widespread sanitation services) and achieve some social outcomes (life expectancy) with low emissions per capita (Lamb et al., 2014), it's rare to find countries achieving good social outcomes across the board with relatively low emissions (Lamb, 2016). Indeed, none do so while remaining within planetary boundaries more broadly (O'Neill et al., 2018).

The issue with top-down approaches, however, is they assume that relationships between social outcomes and ecological impacts will remain broadly similar to those currently existing. Current socio-political organisation, economic provisioning systems, and the highly unequal wealth and income distributions that exist, all influence the efficiency with which energy- and resource-use supports human well-being; inefficiencies in the system tend to become embedded within the conclusions of top-down modelling studies. Only rarely do studies look into reducing *social inefficiencies* that stem from consumption that doesn't satisfy human needs, or even inhibits need satisfaction (Max-Neef, 1995; Lamb and Steinberger, 2017; Jackson and Marks, 1999). Far from cultivating well-being, consumption is often driven by factors such as private profit; intensive and locked-in social practices; employment-related stress and poor mental health; conspicuous- or luxury-consumption; or simply over-consumption in numerous forms (Gough, 2017).

Indeed, demand-side studies in general are rare (Creutzig et al., 2018). In contrast, it is common for researchers to focus on the production-side by analysing the ecological benefits of increasing technological efficiencies. Seemingly positive solutions are often found, but technological trends are notoriously difficult to forecast. The emergence of game-changing innovations are hard to predict and, crucially, may work either for or against sustainability. For example, despite steady improvements in engine efficiency, passenger aircraft in the 2000s were only as efficient as those of the 1950s, due to the invention of jet engines in the interim and their widespread substitution for propeller-driven aircraft (Peeters et al., 2005).

Bottom-up approaches largely avoid these limitations. They work by compiling consumption inventories that include all that considered essential for humans' to live good lives, and estimating the ecological impacts of providing these. When building such models, the implicit influence of current socio-political configurations can be minimised; if one really wants to study, say, inequality or overconsumption, they must be explicitly built in. The flip-side is that such models tend towards underestimates. Essential goods or services are more likely to be omitted than double counted, and the ecological impacts of supply chains more likely to be truncated than incorrectly elongated (Fry et al., 2018).

An early bottom-up estimate was made by Goldemberg et al. (1985). They compiled an inventory of activities across *residential* (cooking, food storage, etc.), *commercial* (floor space), *transportation* (private, public and freight), *manufacturing* (steel, cement, etc.) and *agricultural* (food) sectors. Together these were suggested to provide *'basic needs and much more'*, for only 30 GJ/cap/yr of *final energy* consumption annually. Most recently, Rao et al. (2019) estimated that 12–24 GJ/cap of final energy consumption annually would be required to provide decent material living standards in India, Brazil and South Africa. They used a similar inventory to Goldemberg et al., but included modern communication and information technologies, education, healthcare and water provision (among other things) and, in addition, made robust estimates of indirect energy use. Another recent estimate by Grubler et al. (2018) offered values for a global *Low-Energy Demand* scenario, which lie within the range of the above. Similar studies have looked into carbon emissions (Mundaca et al., 2019; Akenji et al., 2019). By taking a bottom-up approach here, our work builds upon the tradition pioneered by Goldemberg et al.

2.3. Two types of energy

Our choice to consider final energy is novel but essential: final energy better reflects the energy requirements of society and economic activity (Alessio et al., 2020). Primary energy assumes a portfolio of existing energy sources, whose losses during conversion into final energy – e.g. coal into electricity, or oil into gasoline – are included in total consumption. However, renewable energy sources like solar or wind have no primary energy equivalent, and this means arbitrary assumptions are often made when comparing them to fossil fuels. Such misleading comparisons can leave fossil fuels appearing to outperform renewables (Brockway et al., 2019). These issues are avoided by focusing on final energy.

However, a discussion of final and primary energy leads to another important point, namely, that final energy is still a means to an end – one stage in the *energy cascade* (Kalt et al., 2019). Final energy can provide *energy services* – such as heating or mobility – which themselves provide *benefits* – such as comfort and social participation. These benefits may then satisfy different aspects of human well-being. Final energy is thus closer than primary energy to the services that can satisfy basic needs.

This leads us to our last crucial point: In the results herein, if a country's current energy footprint is greater than what we estimate is required for decent living standards, this *does not* imply that decent living standards are being met throughout the population. How efficiently each country's current final energy use is being transformed into energy services, how aligned these services are with benefits that satisfy human needs, and how (un)equally benefits are distributed among populations, are questions beyond the scope of our work – despite their importance.

3. Methods and data

3.1. Approach

Our bottom-up modelling approach involves combining activity-levels and associated energy intensities for each material requirement or service, and then summing across all DLS dimensions to obtain estimates of total final energy consumption. Activity-levels are such things as meters squared of housing per person, lumens of lighting per household per day, kilograms of new clothing per person per year, litres of hot water per person per day. By deriving energy intensities in the same units, we can then perform simple upscaling to obtain energy use for each DLS dimension. For example, we have the direct energy intensity of heating and cooling, as well as for the embodied energy of construction, both recorded in MJ/m^2 of residential floor-space; these can simply be multiplied by the m^2/person activity-levels to obtain per capita energy requirements.

Obtaining appropriate activity-levels and energy intensities requires harvesting and assimilating a diversity of data, and we offer a high-level summary of our values in Table 2. For energy intensities, we draw upon a broad range of data from (among other things) life cycle assessment, input–output analysis, industrial ecology and state-of-the-art engineering work to derived values representative of the most efficient technologies available. For activity-levels, we aim to determine what is appropriate for *sufficiency* – what consumption is required for decent living, but no more. Rao and Min (2018a) suggest first approximations for each DLS category, but these aren't intended to input directly into an energy model – they aren't always in quantitative form nor suitably fine-grained when they are. We thus make various modifications and add further details where necessary. For example, Rao and Min offer an estimate of total mobility requirements per person (7000 km/year), but we must disaggregate this into various modes of transport. They also state requirements for healthcare and education in terms of minimum expenditures and physicians and teachers per 1000 persons; from this, we determine the floor-space of hospitals and schools each country requires, then estimate the direct and embodied energy use of these buildings and all related equipment and activities. An additional assumption we make is that the average household size is four persons for all countries; this feeds into calculations where activity levels are defined relative to the number of households, e.g. our assumption of one laptop per household.

For both activity-levels and energy intensities, we implement regional variations where this is appropriate and we have data sufficient to do so. For example, daily food-calorie requirements vary with age, peaking in a person's early twenties, so we make countries' average per-capita food requirements vary with age composition. Similarly, we make educational floor-space requirements dependent upon the fraction of a countries population that is 5–19 years of age (but note that our energy intensities are not influenced by variations in activity-levels). Other aspects of our modelling of regional-variation are particularly novel:

- For *mobility*, rather than using a fixed activity-level across all countries, we make passenger kilometres/capita a function of *adjusted* population densities – national population densities scaled up by considering what fraction of land is populated. These therefore better represent the densities that people experience. Adjusted densities also feed into our mode share calculations, which include an (ambitious) combination of non-motorised transport, public transport, and limited private vehicle use and air travel.
- For *thermal comfort*, the amount of floor space per person is fixed across all countries. For energy intensities, however, we integrate (i) data describing direct energy requirements per unit floor space, which vary with the number of cooling (CCD) and heating (HDD) degree days experienced, with (ii) national, population-weighted data for CCD and HDD, and forecasts of how these may vary under future climate change. We do this for residential, healthcare and public buildings.
- For *water supply*, we begin with current energy intensities of water supply infrastructure – the MJ required per litre supplied to households – and estimate regional variability by considering current water scarcity. We then use forecasts of climate change- and population growth-induced water stress to estimate how these intensities of water supply may change in different countries.

As mentioned, our aim is to consider the theoretical situation of radically lowered demand and state-of-the-art technologies. Data for the latter are derived from numerous sources, but they must sometimes be modified to be consistent with activity-levels. For example, for the energy intensity of private transport, we begin with energy intensities for highly advanced vehicles, based on what Cullen et al. (2011) suggest is practically achievable in the long-term. Then, however, we slightly retreat upon these assumptions to allow for the larger vehicles needed to achieve the high occupancy rates we assume. Note, 'achievable' here refers to engineering considerations – we say nothing of the affordability of such technologies and, within the current economic paradigm, there are serious barriers that would require major technological transfer programmes from the Global North (among numerous other things). Further, the unjust distributional impacts that accompany the rollout of high-tech, ecological solutions are well known. For example, hybrid cars and rooftop solar technologies are typically only accessible to wealthier citizens, who are thus the ones that benefit from any associated tax breaks and subsidies.

When presenting the results, we show for comparison recently published estimates of final energy consumption in 2011 derived from

Table 2

. Inventory of the prerequisites for *Decent Living Standards* (DLS) (Rao and Min, 2018a) alongside activity levels and direct and indirect energy intensities of products, supply chains and infrastructure. Numbers are rounded and presented as ranges where there are variations between countries or sub-activities (e.g. different transport modes). *Approximate* percentage increases for *Higher Demand* (HD) and *Less Advanced Technology* (LAT) scenarios are included where possible, but these cannot always be summarised in this high-level format. Full details can be found in the Supplementary materials.

DLS dimensions & services	Activity levels		Energy Intensities		
	Default levels	HD	Default (direct)	Default (indirect)	LAT
Nutrition					
Food	2000–2150 kcal/cap/day	15%	–	3 KJ/kilocalorie	30%
Cooking appliances	1 cooker/household	–	0.8 KJ/kilocalorie	1 GJ/app$^+$	50%
Cold Storage	1 fridge-freezer/household	–	0.44 GJ/app$^+$/yr	4 GJ/app$^+$	–
Shelter & living conditions					
Household size	4 persons/household	−25%	–	–	–
Sufficient space	15 meters^2 floor-space/cap*	80%	–	2–4 GJ/m^2	100%
Thermal comfort	15 meters^2 floor-space/cap*	80%	20–60 MJ/m^2/yr	–	300%
Illumination	2500 lm/house; 6 hrs/day	100%	150 lm/W	14 MJ/house/yr	–
Hygiene					
Water supply	50 Litres/cap/day	100%	–	5–17 KJ/L	–
Water heating	20 Litres/cap/day	100%	96–220 KJ/L	–	50%
Waste management	*Provided to all households***	–	–	180 MJ/cap/yr	200%
Clothing					
Clothes	4 kg of new clothing/year	33%	–	100 MJ/kg	–
Washing facilities	80 kg of washing/year	33%	2.4 MJ/kg	2 GJ/app$^+$	–
Healthcare Hospitals	200 meters^2 floor-space/bed	50%	410–560 MJ/m^2/yr	14–23 GJ/m^2	130%
Education Schools	10 meters^2 floor-space/pupil	50%	100–130 MJ/m^2/yr	4.5–7.5 GJ/m^2	150%
Communication & information					
Phones	1 phone/person over 10yrs old	–	28 MJ/phone/yr	110 MJ/phone	30%
Computers	1 laptop/household	–	220 MJ/laptop/yr	3 GJ/laptop	30%
Networks & data	*High***	100%	–	~0.4 GJ/cap/yr	–
Mobility					
Vehicle production	*Consistent with pkm travelled***	–	–	0.1–0.3 MJ/pkm	50%
Vehicle propulsion	5000–15,000 pkm/cap/year	3–10%	0.2–1.9 MJ/pkm^{++}	–	100%
Infrastructure	*Consistent with pkm travelled***	–	–	0.1–0.3 MJ/pkm	–

* Assuming 10 m^2 of living space/capita plus 20 m^2 of communal space/house; with the latter divided by four, we get 15 m^2/capita overall.

** Activity levels here are not straightforward to define.

$^+$ 'App' refers to 'appliance'.

$^{++}$ Large range as this covers different modes (public transport to passenger flights).

the input–output data of the Global Trade Analysis Project (GTAP), for 119 countries (Oswald et al., 2020). This gives an indication of current energy use as compared to the minimum our model suggests is possible while still providing decent living, but the disclaimer given in Section 2.3 must again be noted.

3.2. Infrastructure timescales

How we incorporate long-term infrastructure requires clarification. Our assumption of state-of-the-art technologies raises the question of how to account for currently built infrastructures that have lifetimes extending beyond 2050, and when such infrastructures should be replaced prematurely by more efficient ones. Housing is a salient example. Much current housing has a lifetime beyond 2050, so retrofitting is more likely than replacement with advanced new buildings, despite the latter having lower direct-energy requirements. However, estimating what fraction of housing in each country would be more appropriate to retrofit than rebuild would be an enormous task; this would require estimating the remaining lifetimes of buildings and applying a time-threshold to this to determine when, from a full lifecycle perspective, retrofitting is most appropriate, and forecasting all of this for 2050. We thus assume the global housing stock is fully replaced via a worldwide deployment of advanced new buildings with very low heating and cooling energy requirements – and we make the same assumption for other buildings (educational, healthcare and commercial). This implies that a significant amount of infrastructure is replaced prematurely, which could be considered unrealistic. However, we account for all the energy embodied in these new infrastructures, distributing it over buildings' lifetimes (note also that we account for energy relating to lighting and appliances separately). And we show below that had we assumed advanced retrofits instead the results would change only negligibly. Our results thus offer a steady-state picture of future energy-consumption for 2050 in a world where advanced technologies are fully deployed and replaced when necessary. There remains a valid concern that if the entire global building stock were somehow replaced over a period of two or three years, there would be a huge spike in energy use and carbon emissions. However, these temporal dynamics are beyond our current scope.

To demonstrate the difference between new and retrofit housing, a back-of-the-envelope calculation is insightful. With full deployment of advanced buildings, we calculate global annual energy use for thermal comfort in residential buildings to be ~5 EJ; equal to the indirect energy used in their construction. Data from GBPN (2012) suggests that direct energy use for thermal comfort in *advanced retrofit* buildings is ~40% higher than in the *advanced new* buildings we assume. Retrofitting would thus lead to a ~2 EJ increase in direct energy annually, but if it also reduced indirect energy use in construction by, say, 80%, this would mean ~4 EJ less indirect energy – a net decrease of ~2 EJ. This equates to < 2% reduction in total global energy use, implying that the effects of assuming advanced new builds rather than advanced retrofits is negligible.

3.3. Scenarios

We are most interested in our lowest energy-consumption scenario *(Decent Living Energy; DLE)*, but also consider three others: one with increased (but still relatively low) demand (*Higher Demand*; *HD*), one without the same technological ambition (*Less Advanced Technology*; *LAT*) and one with these rolled-back assumptions combined (*HD-LAT*). Our wording here is chosen carefully: all of these scenarios, HD-LAT included, can be considered to be ambitious.

An indication of the percentage increases in activity-levels and energy intensities across DLS dimensions in the scenarios is given in Table 2, but it should be emphasised that these are only indicative, as the changes are not readily summarised at this high-level. For example, one aspect of the HD scenario is a decrease in average household size (from 4 to 3 people), which has impacts across numerous consumption sectors – appliance and computer ownership levels, residential floor area and hence energy related to thermal comfort, lighting and construction. In other cases, the model is changed at a relatively low level in multiple ways, which combine to affect one DLS aspect. For example, in the HD scenario, we increase the consumption of animal products and the quantity of food waste generated, which together modify the energy input per kilocalorie of food consumed. Full details are given in the Supplementary Materials.

4. Results

4.1. Global energy use for decent living

When we compare current final energy consumption across the 119 GTAP countries with our estimates of final energy for decent living (DLE), we find the vast majority (~100) of countries are living in surplus (Fig. 1). Those living in deficit all have a GDP/cap less than $6000 PPP. The range of DLE thresholds is small at 13–18.4 GJ/cap/yr of final energy consumption across all 119 countries, while current consumption ranges from under 5 GJ/cap/yr to over 200 GJ/cap/yr – a level of inequality that mirrors environmental pressures more broadly (Teixido-Figueras et al., 2016). Current consumption increases with GDP, while DLE (unsurprisingly) bears no relationship – it's instead determined by climatic and demographic factors (heating & cooling degree days, age profiles, living densities, etc). More specifically, regional variations in activity levels (mostly mobility levels) and energy intensities (mostly thermal comfort and water heating in residential buildings) make roughly equal contributions to the overall range of our DLE values. Where GDP/cap > $15,000, current energy consumption is ~2 to ~15 times larger than DLE. However, note again that this *doesn't* imply decent living standards in these places are currently being provided to everyone.

In comparison to other studies estimating future final energy demand, our DLE estimates are remarkably low, with global final energy consumption at 149 EJ in 2050 (Fig. 2; or 15.3 GJ/cap/yr). This is over 60% lower than current consumption (despite the 2050 population being ~30% larger than the present day); 75% below the *International Energy Agency*'s 2050 *Stated Policies* estimate – the expected trajectory if todays' commitments are met and maintained – and 60% below their most ambitious *Sustainable Development Scenario* (IEA, 2019b); and around 40% lower than 2050 consumption in the *Low Energy Demand* scenario of Grubler et al. (2018) (245 EJ).

Note, however, that none of these studies attempt – as we do – to minimise energy-use without sacrificing decent living. In the IEA's *Sustainable Development Scenario*, for example, the focus is on fulfilling the United Nations *Sustainable Development Goals* by increasing things like electricity access and availability of clean cooking stoves to 100%, globally; this effectively puts a floor on consumption, but the IEA do not consider capping the energy use of the wealthiest global consumers. This is a primary reason for their 2050 SDS final energy consumption being douple ours – and, incidentally, it leaves the 10th Sustainable Development Goal of reducing inequality unchecked.

4.2. Energy use by decent living-sector

Globally, the major contributors to DLE are *nutrition* and *mobility* at ~3 GJ/cap/yr each (Fig. 3). Nutrition itself is mostly comprised of food production and supply (we don't include the energy contained in food itself), with only 0.5 GJ/cap/yr involved in cooking and cold storage. For mobility-related energy use, 70% is for manufacturing and powering vehicles, with the remaining 30% used for producing transport networks' infrastructure (e.g. railways, roads). *Shelter & living conditions*, *healthcare* and *hygiene* make contributions of ~1.5 GJ/cap/yr each, globally. For the former, the contributions of constructing houses and thermal comfort are roughly equal, while energy used for lighting is

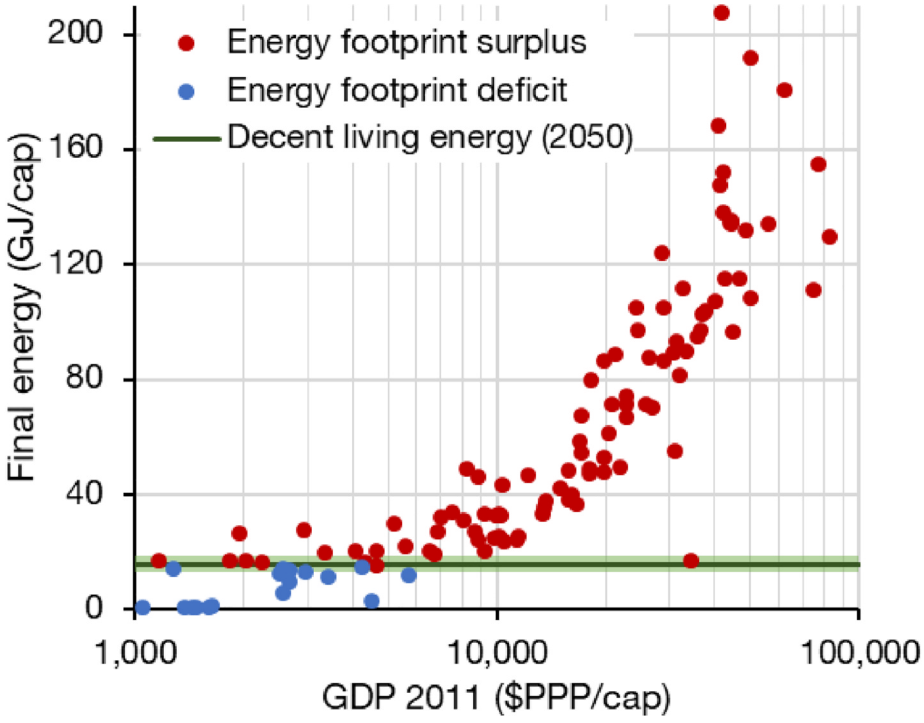

Fig. 1. . Final energy consumption for 119 countries in the GTAP database calculated using input–output analysis, for 2011. For the same countries, *decent living energy* estimates are shown. Visually, there is little variation: DLE estimates all lie within the narrow green band, where the dark line is the global mean. Note the logarithmic scaling on the *x*-axis *only*. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

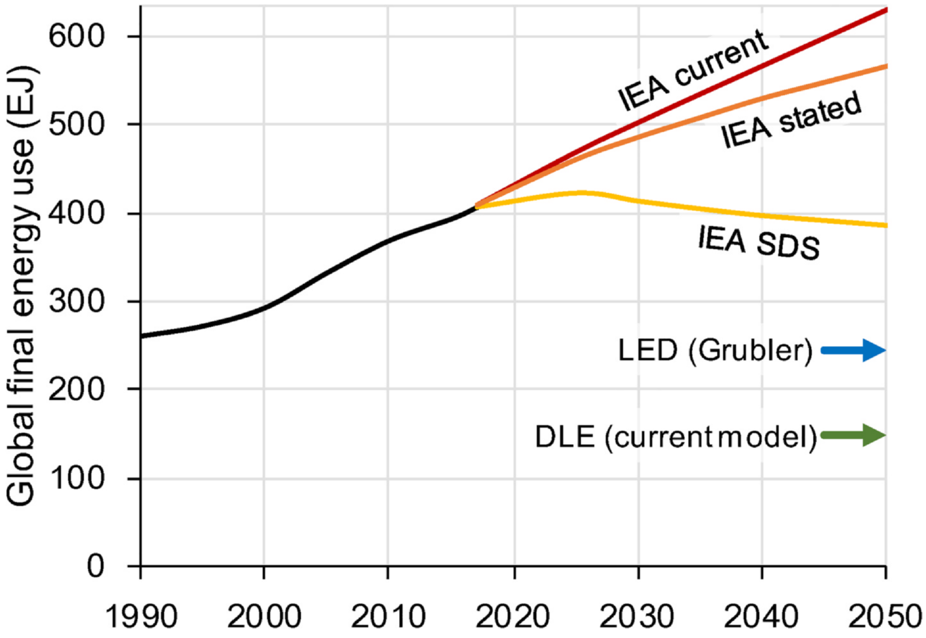

Fig. 2. . Global final energy consumption, including: historical data and projections from the IEA's *Current Policies*, *Stated Policies* and *Sustainable Development* (SDS) scenarios; the *Low Energy Demand* estimate of Grubler et al. for 2050; and the current DLE estimate for 2050.

comparatively negligible. *Healthcare* includes construction of, and services provided by, hospitals, along with broader activities like medications and emergency transport. For *hygiene*, household water heating dominates, accounting for 1 GJ/cap/yr, with the remaining 0.5 GJ/cap/yr split equally between household water supply and waste management (i.e. all the energy used by these sectors, including construction of infrastructure). The energy use associated with *clothing* (both production and washing of clothes), *education* (construction of and energy used by schools) and *communication & information* (phones, laptops and the infrastructure requires for networks and data centre operations) together comes to a global average of nearly 2 GJ/cap/yr. The remaining 3 GJ/cap/yr (shown as *other*) is associated with power supply infrastructure and retail and freight activities, which have not been allocated to consumption categories.

Sector-breakdowns of DLE are also shown for Rwanda, where the regional specificity of our model estimates low mobility and thermal-comfort requirements; Uruguay, where mobility requirements are high and thermal comfort requirements average; and Kyrgyzstan, where both mobility and thermal comfort requirements are high. Accordingly, the DLE threshold for Rwanda is estimated to be 13.5 GJ/cap/yr, with Uruguay at 16 GJ/cap/yr and Kyrgyzstan at 18.4 GJ/cap/yr. Inter-country variations are found in various other categories besides mobility and thermal comfort, due to factors like population age structures, which affects educational requirements and food-intakes; the assumed availability of low-energy building materials (i.e. timber as an alternative to steel); and the energy-intensity of water supply, which we assume depends upon scarcity (or abundance) of local supply. However, the influence of these factors is generally small or negligible overall.

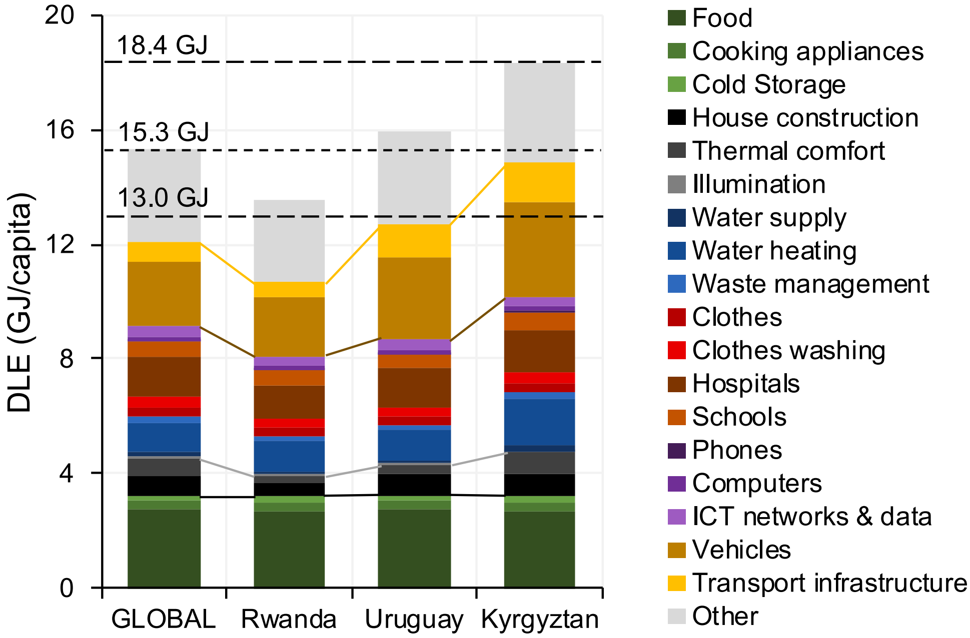

Fig. 3. . Decent living energy per capita (in final energy), broken down into consumption categories and subcategories detailed in Table 1. Our global average is shown alongside data for Rwanda, Uruguay and Kyrgyzstan. Dashed lines indicating our global mean, minimum and maximum are also shown (15.3, 13.0, and 18.4 GJ/cap/yr, respectively).

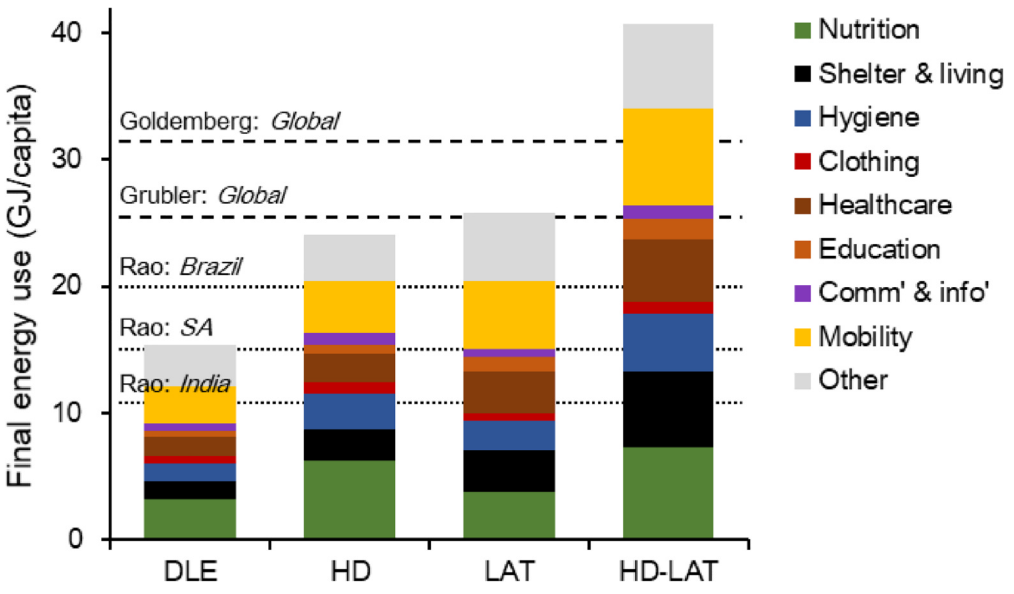

Fig. 4. . Globally averaged *decent living energy* per capita in 2050 and three scenarios with rolled-back ambition, i.e. *higher demand* (HD), *less advanced technologies* (LAT), and *higher demand and less advanced technologies* together (HD-LAT). Thresholds for energy use from other scenarios are also shown, as described in the text. Note, SA = South Africa.

4.3. *Higher energy-use scenarios*

Finally, we consider the impacts of rolling-back the ambitions assumed in calculating our DLE thresholds (Fig. 4) to levels that are still relatively ambitious, but less so than the DLE case. In the *Higher Demand* scenario, energy use jumps 40% – from ~15 GJ/cap to ~24 GJ/cap – due to relaxation of various DLE assumptions. These include, among other things, a decrease in average household size (from 4 to 3); increased consumption of water and animal-based foods; more food waste; greater floor-space per capita in all building types; increased flying as well as a shift in mobility away from public and active transport towards private vehicles; decreased clothing lifetimes; and increased ICT network activity. The consumption-sector undergoing the largest increase is nutrition, due largely to both increased waste and consumption of animal-products (despite the latter still contributing < 20% to food intake on a kcal basis). In relative terms, the energy use associated with all other categories also increases significantly, normally by 50–100%, although the increases in mobility-related energy are slightly lower, at ~30%.

In the *Less Advanced Technology* scenario, globally-averaged energy use rises a similar amount above the DLE case, this time to 26 GJ/cap (Fig. 4). This is due to our increasing energy intensities in various parts of the model, e.g., for both in-use and construction-related energy for all types of buildings; household water-heating systems; food supply chains and processing facilities; vehicles' direct energy use and that required for production of vehicles and transport infrastructure; and for the energy intensity of producing renewable energy infrastructure. The sectors contributing the most to this rise above DLE levels are mobility, residential buildings and healthcare. Rises in other sectors are less significant in absolute terms.

When the assumptions of the HD and LAT scenarios are applied together in a single model run (HD-LAT), globally-averaged energy use rises to ~40 GJ/cap, thus exceeding the 32 GJ/cap calculated by Goldemberg et al. (1985). However, even this rolled-back scenario gives just under 400 EJ of final energy use globally in 2050 – equal to the IEA's *Sustainable Development Scenario* (Fig. 2).

Note that the results of these scenarios are similar to those in the sensitivity test we present in the Supplementary Materials. There, perturbing our activity-level assumptions – by increasing residential and public buildings' floor space (by 100% and 50%, respectively), consumption of animal products, and overall mobility levels (by 50%) while decreasing the share of public transport, etc. – leaves DLE at around the same level as the HD scenario. Similarly, perturbing our intensity assumptions raises DLE to a similar level as the LAT scenario. We refer the reader to the Supplementary Materials for information upon the sensitivity to individual parameters.

5. Discussion and conclusions

What can be made from these results? First, we can reiterate what has been suggested by countless other authors: high-quality, low-energy housing, widespread public transport, and diets low in animal-based foods are globally important issues for sustainability ambitions. In other words, demand-side solutions are an essential part of staying within planetary boundaries (Creutzig et al., 2018). However, the perspective of the current work is a global, big-picture one, and it focuses exclusively on final energy consumption. The results are thus of limited use for guiding specific local and national actions to reduce ecological impacts effectively and holistically. Consequently, further work applying bottom-up modelling to specific local contexts – following Rao et al. (2019) – would be valuable. To suggest where consumption can be reduced most effectively, it would then be useful to take current energy consumption data and distinguish so far as is possible luxury, wasteful, and sufficiency based consumption (Gough, 2017; Shue, 1993) – disaggregating the latter to needs-based consumption categories, and considering trade-offs and synergies between dimensions of social and ecological sustainability.

What the current work does offer are answers to broader questions. To avoid catastrophic ecological collapse, it is clear that drastic and challenging societal transformations must occur at all levels, from the individual to institutional, and from supply through to demand. From an energy-use perspective, the current work suggests that meeting these challenges does not, in theory, preclude extending decent living standards, universally, to a population of ~10 billion. Decent living is of course a subjective concept in public discourse. However, the current work offers a response to the clichéd populist objection that environmentalists are proposing that we return to living in caves. With tongue firmly in cheek, the response roughly goes 'Yes, perhaps, but these caves have highly-efficient facilities for cooking, storing food and washing clothes; low-energy lighting throughout; 50 L of clean water supplied per day per person, with 15 L heated to a comfortable bathing temperature; they maintain an air temperature of around 20 °C throughout the year, irrespective of geography; have a computer with access to global ICT networks; are linked to extensive transport networks providing ~5000–15,000 km of mobility per person each year via various modes; and are also served by substantially larger caves where universal healthcare is available and others that provide education for everyone between 5 and 19 years old.' And at the same time, it is possible that the amount of people's lives that must be spent working would be substantially reduced.

However, the current work has entirely avoided the most difficult question: how could we get from the current global situation of vast inequalities, excess and inefficient energy-use to one where decent living standards are provided universally and efficiently (Pirgmaier, 2020)? The current work has little to say here in the way of specifics, but there are some things that can be said with more certainty. Although technological progress and individual-level change are essential parts of a solution to ecological breakdown, incrementalist propositions along the lines of green growth and green consumerism are inadequate (Bailey et al., 2011; WEBB, 2012). The ideals of sufficiency, material thresholds and economic equality that underpin the current modelling are incompatible with the economic norms of the present, where unemployment and vast inequalities are systematic requirements, waste is often considered economically efficient (due to brand-protection, planned obsolescence, etc.) and the indefinite pursuit of economic growth is necessary for political and economic stability.

The challenges of changing this trajectory shouldn't be understated (Semieniuk and Yakovenko, 2020). In the Global North, the trends towards sufficiency-levels of consumption that exist – such as *Transition Towns* and the *minimalism* movement – are notoriously middle class and white, and are the exception rather than the norm (Aiken, 2012). In the Global South, consumption of the upper-classes has leapt well beyond sufficiency levels, while hundreds of millions remain left in poverty. This leaves crucial questions for future researchers to address: What sort of political-economy could create a world with both low throughput and high livings standards and the levels of equality that achieving these requires? What sort of culture would accept and support the necessary policies and institutions? Where, from the individual- to institutional-level, are potential leverage points for moving towards such changes (Pirgmaier, 2020; Brand-Correa et al., 2020)?

All this is not to mention that provision of the material living standards we have considered *does not guarantee* that every person will live a good life. Many other factors can adversely and unavoidably affect physical and mental health; as philosophers have pointed out for millennia – back to the Buddha and beyond – even when material living standards are high, human well-being can be elusive.

To finish more positively, however, a comparison of our estimate of the energy required for decent living with projections of the energy supplied by non-fossil sources offers grounds for optimism. Currently, only 17% of global final energy consumption is from non-fossil fuel sources (IEA, 2019a). But in absolute terms this is nearly 70 EJ, and hence nearly 50% of our DLE estimate for 2050 of 149 EJ. Indeed, by 2050, even in the IEA's *Stated Policies* scenario, ~130 EJ of final energy is provided by non-fossil-based sources – very close to the DLE requirement of 149 EJ. That non-fossil energy sources could meet our DLE requirements, even under business-as-usual, is highly significant.

Overall then, the present work is consistent with long-standing arguments that the economic and socio-political changes necessary to address the magnitude of present ecological challenges are enormous, while the technological solutions already exist. What we add is that the material sacrifices are, in theory, far smaller than many popular narratives imply. And quite the opposite is true for the ~4 billion currently living in poverty (that is, on less than $7.40 PPP per day), for whom life could, conceivably, be substantially improved.

CRediT authorship contribution statement

Joel Millward-Hopkins: Conceptualization, Methodology, Software, Formal analysis, Writing - original draft. **Julia K. Steinberger:** Conceptualization, Methodology, Writing - review & editing. **Narasimha D. Rao:** Conceptualization, Methodology, Writing - review & editing. **Yannick Oswald:** Methodology, Software, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

JMH, YO and JKS were supported by the Leverhulme Trust's Research Leadership Award to Julia Steinberger's "Living Well Within Limits (LiLi) project (RL2016-048). We thank the rest of the team and in particular Ian Gough for invaluable discussions, as well as the feedback of anonymous reviewers."

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2020.102168.

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