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Closing decent living gaps in energy and emissions scenarios: introducing DESIRE

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Abstract

Social and environmental agendas are intricately connected and shape the international policy discourse. To support these discussions, we present a framework for interpreting global scenario outcomes on energy demand and supply-side transitions through the lens of societal well-being and minimum resource requirements. We develop and apply a new model called Decent living standards and the Environment in Scenarios considering Inequality and Resource Efficiency (DESIRE) to fill a critical gap in modelling inequality-growth-efficiency interactions. Utilising bottom–up literature on energy inequality and minimum energy requirements, we analyse system-wide changes from integrated assessment models to assess whether levels of energy consumption in pathways can be consistent with providing decent living standards (DLS) for all, covering three sectors in 173 countries. We apply DESIRE to multiple new sustainable development pathways (SDPs). By 2040, the combination of ambitious inequality reductions, service provisioning efficiency, and higher energy services in the SDPs reduces the global residential and commercial energy deprivation—currently over 5 billion people—by at least 90%. Industry energy gaps are closed, but transport gaps remain. In the SDPs, more than half of the global population—including in low-income countries—achieve living standards more than twice as high as the DLS benchmark for the residential and commercial sector. Energy use beyond DLS across all sectors accounts for about two-thirds of total energy use globally. Efficiency improvements reduce global energy requirements 30%–46% by 2040 in the SDPs (across countries from 17–35 GJ cap^{-1} in 2020 to 9–23 GJ cap^{-1}), while climate policies reduce CO_2 emissions related to energy for DLS to almost zero in 2050, keeping cumulative emissions for DLS for all until 2050 close to the size of the remaining carbon budget to 1.5 °C (at 50% probability). This work illustrates the possibility of pathways that deliver DLS for all while meeting the Paris Agreement.

1. Introduction

The Sustainable Development Goals (SDGs) aim to simultaneously achieve objectives related to eradicating poverty, promoting socio-economic development and preserving the natural environment. However, most countries currently fall short of meeting these social and environmental targets concurrently (Fanning *et al* 2022). Therefore, there is a need to create and understand scenarios that simultaneously support human flourishing and meet environmental targets. Energy systems play a major role in this: energy use is directly related to eradicating poverty and reversing ecological degradation, in particular climate change and air pollution. Several frameworks have been suggested to define desirable futures either from an ecological perspective and development perspective or both, such as the 'safe and just Earth system boundaries' (Gupta *et al* 2023, Rockström *et al* 2023), linked to 'doughnut' or 'safe and just operating space' (Raworth 2017, O'Neill *et al* 2018, Fanning *et al* 2022), the 'sustainable development target space' (van Vuuren *et al* 2022), or 'consumption corridors' (Fuchs *et al* 2021) and 'production corridors' (Bärnthaler and Gough 2023). The concept of 'decent living standards' (DLS; Rao and Min 2018a) has gained traction as a lower boundary, or minimum requirement, for supporting human well-being in these concepts (e.g. Schlesier *et al* 2024).

The current consensus is that eradicating extreme income poverty (e.g. Bruckner *et al* 2022, Wollburg *et al* 2023) does not put climate goals at risk (Riahi *et al* 2012, 2022, Van Vuuren *et al* 2015, Rao and Min 2018b). However, such a low, unidimensional international poverty line tracks a 'standard of miserable subsistence' (Alston 2020) and does not track the achievement of DLS (Kikstra *et al* 2021). Integrated assessment models (IAMs) have been used to help understand multidimensional future socioeconomic scenarios with climate and environmental information for decades. Several studies have investigated the simultaneous achievement of multiple dimensions of the UN SDGs (e.g. McCollum *et al* 2018, Soergel *et al* 2021a, p 202, 2021b, Van Vuuren *et al* 2015). However, the representations of SDGs in existing literature is not complete (van Soest *et al* 2019, Orbons *et al* 2024), and models especially struggle to capture the challenges faced by the poor and vulnerable, since social heterogeneity within model regions is lacking (Rao *et al* 2017). Even while many energy access studies exist (e.g. Pachauri *et al* 2013, Poblete-Cazenave *et al* 2021), when studies with IAMs do investigate within-country distributions explicitly (e.g. Soergel *et al* 2021a, Emmerling *et al* 2024), representation of inequalities beyond monetary indicators are often missing.

The concept of DLS aims to provide clarity on the material prerequisites for human well-being (Rao and Min 2018a). Studies that are critical of specific quantifications of sufficientarian thresholds emphasise, for instance, the choice of units of concern and the relative arbitrariness of threshold values (Casal 2007). The DLS approach can be seen as a pragmatic, partial (and thus imperfect; for a discussion on its advantages and limitations, see SI section 9), implementation of the material aspects of a capabilities and human needs approach to human welfare (e.g. Doyal and Gough 1991, Max-Neef 1991, Sen 1993, Nussbaum 2003, Robeyns 2005), ensuring a (multidimensional) minimum for all people to achieve and do what they have reason to value. While DLS are intended to serve as a universal set of services, their energy requirements need to be determined bottom–up, as energy needs are dependent on existing infrastructures and boundary conditions and thus differ widely across countries (e.g. Rao *et al* 2019a, Millward-Hopkins *et al* 2020, Kikstra *et al* 2021). Consequently, planning a sustainable, more efficient system can reduce energy needs for DLS. Importantly, not all activities in countries are used to satisfy basic needs, with significant energy use related to energy excess or luxury consumption. This means that both the purpose of energy use, and importantly the inequality (Oswald *et al* 2020) within countries need to be studied to understand paths towards a just future with DLS for all, separating human needs, prosperity, and excessive use of resources (Pauliuk 2024). Current regional (Jaccard *et al* 2021, Millward-Hopkins and Johnson 2023, Kikstra *et al* 2024) and global (Millward-Hopkins 2022, Millward-Hopkins and Oswald 2023, Schlesier *et al* 2024) analyses provide limited tools to model the energy availability for achieving DLS lacking either dynamics (changes in the energy system and emissions) or spatial and sectoral detail. No tool exists that links multiple sectors of IAMs to energy needs for DLS on a global scale. The Decent living standards and the Environment in Scenarios considering Inequality and Resource Efficiency (DESIRE) model fills this gap by introducing a framework that bridges the bottom–up literature on the energy needs for DLS with more aggregate IAMs. While there is no fundamental reason that prevents the endogenous modelling of DLS achievement in IAMs, its implementation is complex and would need to overcome many data limitations. This work aims to enable a more consistent treatment and assessment of inequality-growth-efficiency interactions, in relation to energy needs. Comprehensive tools for assessing such interactions across multiple sectors in climate mitigation pathways are currently lacking. The purpose here is to assess whether these scenarios can feasibly support DLS for all from an energy perspective, offering insights on the energy requirements of decent living to guide and inform climate mitigation strategies that also support important developmental needs.

2. Data and methods

2.1. Terminology for decent living energy (DLE) and beyond

The following terms, which we illustrate in figure 1, are used throughout the manuscript. *Energy needs*: the minimum energy requirements for meeting DLS, also known as the *DLE threshold*. *Deprivation headcount*: the estimated population consuming less energy than the minimum energy per capita required to provide DLS. *Energy needs gap* (also known as *DLE gap*): the amount of additional energy necessary to lift all those below the minimum up to the DLE threshold (DLET). *Energy headroom*: the energy left after subtracting the DLET from the total energy use. Total energy use can be split between *Energy provided for DLS* and *Energy beyond DLS*.

2.2. The DESIRE model

The DESIRE model permits a consistent and dynamic interpretation of energy inequalities of IAM pathways, thus supporting the creation and evaluation of energy and emission scenarios (section 2.3). DESIRE is primarily targeted at linking with IAMs, and its key inputs are tabular time series data. It is designed to supplement models with structural change in energy systems but without endogenous representations of within-country energy inequality or energy requirements for DLS. This dynamic framework quantifies future changes in country-level final energy consumption (section 2.4), within-country inequality (section 2.6), and service provisioning efficiency (section 2.5), for energy consumption and energy needs to meet DLS related to three sectors; 'Residential and Commercial', 'Industry' (including feedstocks, agriculture, and fishing), and 'Transportation' (including bunker fuels, excluding pipelines). The aggregation of DLS constituents to these three sectors should be seen as a data limitation and is not an indication that the constituents of DLS within these sectors are substitutable. While in this version, the DLS constituents and their thresholds do not change over time, what is changing is *how* they are provided in the IAM pathways, and thus also the amount of (final) energy required to support DLS is changing. For instance, for transport, the modal share changes over time, and the efficiency of cars changes as electric vehicles become more common. For buildings, heat pumps are introduced and building standards change. DESIREv1.0.0 computes outcomes for 173 countries covering over 97% of the global population. An extended model description, including the calculation of model output, is available in the appendix and supplementary material.

2.3. Scenarios

We apply DESIRE to a new set of sustainable development pathways (SDPs) reflecting different societal strategies to pursue the SDGs and the Paris climate target (Soergel *et al* 2024b). These are SDP-EI ('Economy-driven Innovation'—focusing on innovation and technological solutions), SDP-MC ('Managing the Global Commons'—focusing on strong institutions and regulation), and SDP-RC ('Resilient Communities'—focusing on sufficiency and local solutions in a post-growth economy). More detailed descriptions of the scenarios are available in SI section 6, and Soergel *et al* (2024b), which also provides a detailed modelling protocol articulating its implementation in multiple models and compares the scenario quantifications, with policy mix assessments available in Dombrowsky *et al* (2024). We compare the SDPs against two scenarios based on the middle-of-the-road Shared Socioeconomic Pathway 2 (SSP2; see Riahi *et al* 2017), representing a continuation of current trends and policy ambition levels, both with (SSP2-1.5C) and without ambitious climate policies (SSP2-Ref). SSP1 variants are in SI section 10. Throughout this manuscript, we analyse all SDPs, but sometimes place more focus on the SDP-RC scenario (in these cases, results for other SDPs are in the supplementary material), which shows the strongest international and within-country convergence, while also showing the strongest challenges to energy access. The SDP-MC scenario reflects the median position across the full SDP set for many variables.

2.4. Energy consumption growth at the national level

The process-based IAMs models used in this project describe world development for a set of aggregate regions. We downscale the regional final energy pathways to the country level, capturing short-term projections while remaining consistent with long-term IAM trends (Sferra *et al* 2021, Richters *et al* 2023). Especially for countries where historical data is unavailable, or for countries which form only a relatively small part of the modelled IAM region, this downscaling process faces uncertainties (sensitivity analysis in SI section 3). Final energy variables are downscaled for residential and commercial (separately, if available), industry, and transport, for the 12 regions for REMIND-MAgPIE 3.2–4.6 (hereafter REMIND), and the 26 regions for IMAGE 3.3 (hereafter IMAGE). In REMIND, the 2020 model year represents the 2018–2022 average, while the IMAGE model year represents the year itself, both accounting for shocks in energy use. Diagnostic indicators of the energy systems in these IAMs are described in Dekker *et al* (2023). Not all energy consumption is related to providing DLS. Therefore, we adjust energy consumption to align pathways with the DLET. We only count clean residential energy consumption and

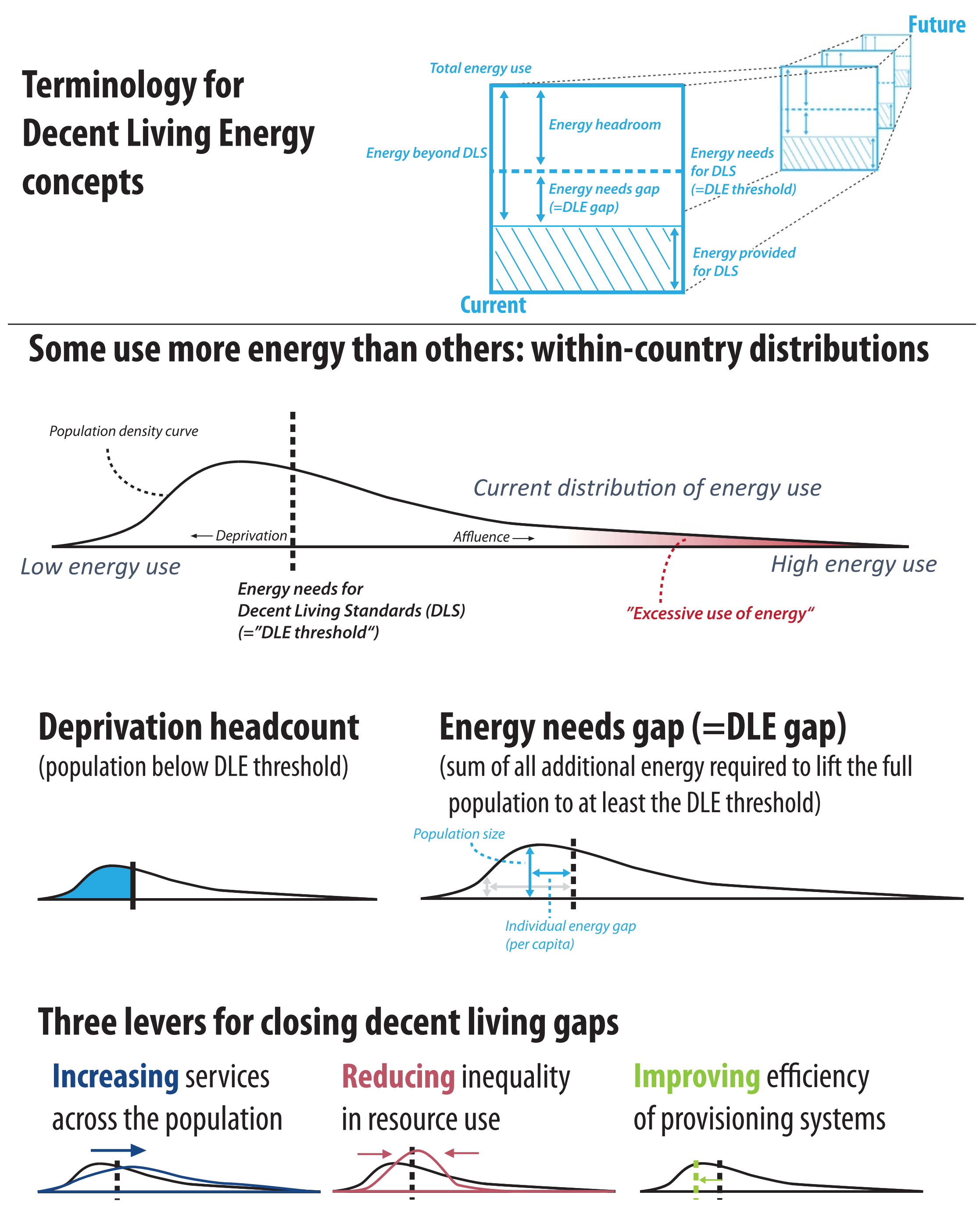

Figure 1. A visual illustration of various concepts for decent living gaps. Top: a terminology for energy requirements and gaps related to decent living standards. Middle: deprivation rate and energy needs gap considering within-country inequality in energy consumption. Bottom: increasing energy availability for end-use services (i.e. growing the pie, shifting the distribution), reducing inequality (i.e. compressing the distribution of consumption), and improving service provisioning efficiency (i.e. lowering the minimum energy requirement for providing decent living standards).

part of commercial energy (health care and education), while discounting energy for domestic aviation (appendix A.3.1).

2.5. Energy needs and service provisioning efficiency

2.5.1. DLS thresholds

In this work, we focus on understanding the dynamics of energy sectors (this section) and emissions (section 2.7) related to a static set of DLS thresholds. Therefore, we do not consider dynamic changes in thresholds or services making up the DLS basket, but rather follow the thresholds from Kikstra *et al* (2021), with data updates documented in SI sections 1.1 and 11.

2.5.2. Current energy needs at a national level

We build on the service-driven energy accounting model in Kikstra *et al* (2021) to calculate the direct (operational) and indirect (construction) energy use required for delivering each aspect of DLS. These energy services are mapped onto the more aggregate 3-way territorial *Residential and Commercial, Transportation, Industry* sectors available in IAMs (appendix A.3.2). Current energy requirements vary between countries (Rao *et al* 2019a, Millward-Hopkins *et al* 2020, Kikstra *et al* 2021). Global average (5–95th percentile across countries) per capita DLETs (based on the DLS thresholds summarised in table A1) are estimated as 6.7 [4–12] GJ for the residential and commercial sector, 11.8 [10–18] GJ for transportation, and 3.8 [3–7] GJ for industry, making a total of 22.3 [17–35] GJ cap^{-1} yr^{-1} (table 1). National circumstances lead to a considerable variation in energy needs based on for instance the climate and current provisioning systems, with modal shares of passenger transportation being the biggest single factor in explaining differences between countries (Kikstra *et al* 2021).

2.5.3. Future energy needs considering service provisioning efficiency changes

The relationship between energy and the provisioning of DLS is not set in stone—it depends on the service provisioning systems in place. We use the term 'service provisioning efficiency' to capture changes in energy service delivery as a whole, including the energy efficiency of end-use technologies, structural shifts, and fuel-switching. The 2020 national DLETs are adjusted over time by the service provisioning efficiency improvements of each scenario (detailed description and equations in table A2, appendix A.3.2). In version 1.0.0 of DESIRE, effects of climate change on future energy needs for thermal comfort are not modelled.

2.6. Current and projected energy inequality

Within-country inequality in energy consumption is characterised by a derived energy Gini coefficient for each of the three sectors in DESIRE using data from Oswald *et al* (2021), (2020), with missing data imputed by effectively converting income Gini coefficients to energy consumption coefficients using multivariate regression (appendix A.3.3, SI section 2.1). Together with the average energy use per capita, we use these energy Gini coefficients to construct a lognormal distribution of sectoral energy use. We find a lognormal distribution to be a relatively good approximation of clean residential energy use, but note that the scarcity of data results in large uncertainties, potentially underestimating within-country inequality (for an extended discussion, see SI section 2.2). Changes in the energy Gini are modelled as a change proportional to the relative change of the income Gini, meaning that, for instance, a 10% reduction in the income Gini of a country results in a 10% reduction of the sectoral energy Gini (appendix A.3.3). The income inequality projections of the SDPs are described by Min *et al* (2024), while the SSPs follow the inequality projections of Rao *et al* (2019b). Any dynamic effects of efficiency improvements and between- and within-country inequality reduction on aggregate energy demand would need to be captured in the IAM (REMIND or IMAGE; see Soergel *et al* 2024b), not in DESIRE, and are therefore not further discussed here.

2.7. Emissions implied in delivering DLE

Like for energy consumption (section 2.4), we replicate the methodology applied in NGFS Phase 4 (Richters *et al* 2023) to arrive at country-specific emissions implied in delivering DLE. These emissions depend strongly on current and future energy systems, especially in transitions towards net-zero and potentially even net-negative emissions. We divide total CO_2 emissions (excl. Land Use, Land-Use Change and Forestry; LULUCF) by the covered energy consumption to obtain the country-, time-, and scenario-specific CO_2 emissions intensities. Then, we multiply the DLET by the emissions intensity—with both the DLET and the emissions intensity changing over time. We assume the same emissions intensity per unit of energy across different consumption levels (DLS and non-DLS energy). We do not use the term 'Decent Living Emissions' (e.g. Rao and Baer 2012) to avoid suggesting that it is a perpetual material byproduct of providing DLS.

3. Results

3.1. Comparing model output to bottom–up energy and service gap estimates

At the global level, we find that the energy needs gap in DESIRE for 2020 (57–60 EJ; table 1) closely approximates the bottom–up calculated global energy needs gap (57 EJ; table 2). Taking a cross-sectional look at the national level reveals that DESIRE also captures bottom–up cross-sectional gaps while also showing considerable variation in energy gaps depending on the national context and data sources, ranging within ±5 GJ cap^{-1} yr^{-1} (figure B1). In this paper, we group energy gaps by sector. However, we stress that DLS for different services are not substitutable, neither between nor within sectors. Therefore, perfect correlations should not be expected between for instance the aggregate national residential and commercial energy gap and the national lack of access to clean cooking, as they depend on the different national DLS provisioning contexts and energy intensities of the gaps in provisioning. We provide a cross-sectional analysis of DLS and DLE indicators in appendix B.

3.2. Projecting energy growth, inequality, and efficiency

The SDPs seek to eradicate monetary poverty and pursue DLS for all. There is a rapid, strong income inequality reduction in virtually all countries (figure 2(A)). The highest GDP/cap growth rates are in low-income countries, showing the

Table 1. Global energy needs gap estimates and thresholds in DESIREv1.0.0. Using the SDP-RC scenario, in 2020, with ranges indicating the IMAGE and REMIND model-based estimates.

Sector	Energy needs gap in EJ (SDP-RC, 2020)	Share of total energy needs gap (SDP-RC, 2020)	Total global energy consumption in this sector in EJ (SDP-RC, 2020)	DLE threshold (2020) in EJ	DLE threshold (2020) in GJ cap^{-1} (Global average (5–95th range across countries))
Residential and commercial	16.7–17.1	28%–29%	115–123	51.2	6.7 [4–12]
Transportation	38.1–40.4	67%	85–99	90.0	11.8 [10–18]
Industry	1.9–2.9	3%–5%	120–183	28.6	3.8 [3–7]
Sum	57–60	100%	320–405 (out of total final energy consumption: 388–432)	154	22.3 [17–35]

Table 2. Sectoral global energy needs gap estimates, using bottom–up methods following Kikstra *et al* (2021).

Sector	Energy needs gap in EJ	Share of total energy needs gap
Transport	30.2	52.7%
Space and water heating	8.7	15.1%
Health care	8.3	14.5%
Appliances	2.4	4.1%
Education	2.2	3.8%
Sanitation	2.0	3.4%
Shelter	1.8	3.1%
Space cooling	0.8	1.5%
Roads	0.7	1.3%
Nutrition	0.2	0.4%
Water	0.2	0.3%
Sum	57.4	100%

strongest breaks with historical trends. The SDP-RC scenario also sees lower-than-historical growth rates in high-income countries, resulting in strong between-country convergence. These economic patterns are connected to the energy futures of countries (figure 2(B)). In SDP-RC, energy inequality declines everywhere, energy demand grows in lower-income countries, and energy reductions are seen in high-income countries.

Residential and commercial total final energy use reduces not only in high-income countries, but also in low-income countries. In low-income countries, this is a result of very strong efficiency improvements of energy services coming with for instance the phasing out of traditional biomass use (supplementary figure 13) as well as structural changes resulting from electrification (figure 2(C)) counteracting the strong increase in clean energy use (across SDPs increasing 661%–793% for the median low-income country, and 72%–111% for middle-income countries, from 2020 to 2040; supplementary figures 25 and 30). For high-income countries, end-use technology efficiency improvements (e.g. heat pumps) are paired with other energy demand reduction measures, especially in SDP-MC and SDP-RC (−4% to −28% for total final energy demand).

The transportation sector currently has much higher energy inequality than the residential and commercial sector, and sees the largest within-country inequality reduction. A clear income gradient can also be seen in the transportation sector, with high energy growth in low-income countries (across SDPs 85%–150%) and total final energy demand reductions in high-income countries (−46% to −64%), resulting from a combination of more efficient technologies (e.g. electric vehicles), reduced total passenger transport, and transport modal shifts (reduced share of cars), with contributions of different elements depending on the SDP and model implementation. The income gradient is the mirror image of the residential and commercial sector, with high-income countries featuring the strongest efficiency improvements, where the energy intensity of passenger transport is currently highest, due to high modal shares of cars. Industrial energy demand increases most in low-income countries. Total final energy demand in the SDPs in 2040 is lower than in 2020 (IMAGE SDP-EI forms an exception with a small increase, but is still substantially below SSP2-Ref).

3.3. The importance of within-country inequality

In order to understand global inequality, both within-country and between-country inequality is important. One way to look at within-country energy inequality is by using the Palma ratio (dividing the total energy use of the highest 10% of users by the lowest 40% of users). Inequality is largest for the transportation sector (figure 3(A)) and decreases strongly in the SDPs, while inequality across sectors is projected to remain steady in SSP2 scenarios. We show that methods working only with national averages substantially underestimate global energy inequality (figure 3(B) and table 3). Global

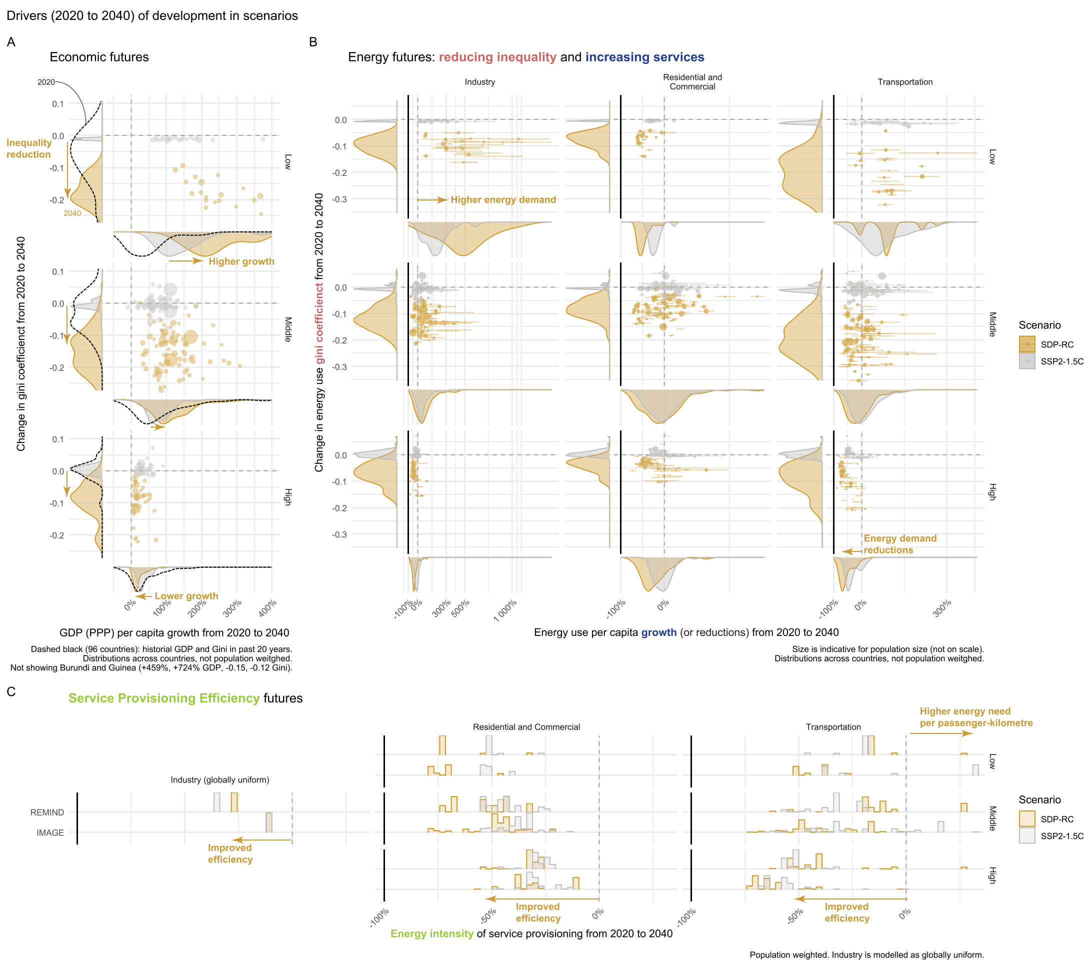

Figure 2. An overview of country-level scenario drivers for the Resilient Communities SDP (SDP-RC, goldenrod) and the SSP2-based mitigation pathway (SSP2-1.5C, grey), for 2020–2040, split by low-, middle-, and high-income country groupings. Panel (A): national GDP (PPP) per capita growth and income inequality reductions. Dashed black marginals are historical trends, for 96 countries where historical data is available, with GDP per capita data from the World Bank from 2000 to 2019 and income Gini coefficient from 1994–2002 to 2014–2022 from the World Bank Poverty and Inequality Platform. Distributions across countries are not population weighted. Outliers excluded for visualisation in projections are Burundi (+459% GDP, −0.15 Gini) and Guinea (+724% GDP, −0.12 Gini).
Panel (B): national final energy per capita consumption and energy distribution inequality reductions, per sector, ranges across models.
Panel (C): population-weighted distributions of service provisioning efficiency improvements, per model and sector. For industry, a global scaling is used and therefore there are no differences between country groupings.

energy Gini coefficient estimates in 2020 in DESIRE for residential and commercial, transportation, and industry are 0.47, 0.67, and 0.58 (table 3). Under SDP-RC, this is reduced to 0.37, 0.47, and 0.35.

Characterising within-country inequality beyond between-country inequality is crucial, too. By comparing downscaled country-level averages-only with additionally estimate within-country inequality, we show steeper falls in future global inequality in the SDPs when considering within-country inequality, but less progress towards inequality for transport under SSP2-Ref, where within-country inequality increases (figures 3(B) and (C)). We show that the contribution of within-country energy inequality to global energy inequality in 2020 is largest in transport (41%), and smallest in residential and commercial (24%). In line with a previous modelling study that focuses on income inequality (Emmerling *et al* 2024), in our scenarios within-country inequality is expected to more strongly determine global inequality in the second half of the century than it does today (supplementary figure 32). This is due to a reduction in between-country inequality in line with the assumed strong convergence in GDP per capita. The SDPs, however, also see rapid within-country inequality reductions especially in the first two decades (figure 3(C); Min *et al* 2024). Subsequently, in SDP-RC, the share of global inequality in total final energy use attributable to within-country inequality does not change much in the first decades, with the 2040 share of within-country inequality accounting for only 18% of global inequality in residential and commercial, and 47% in transport.

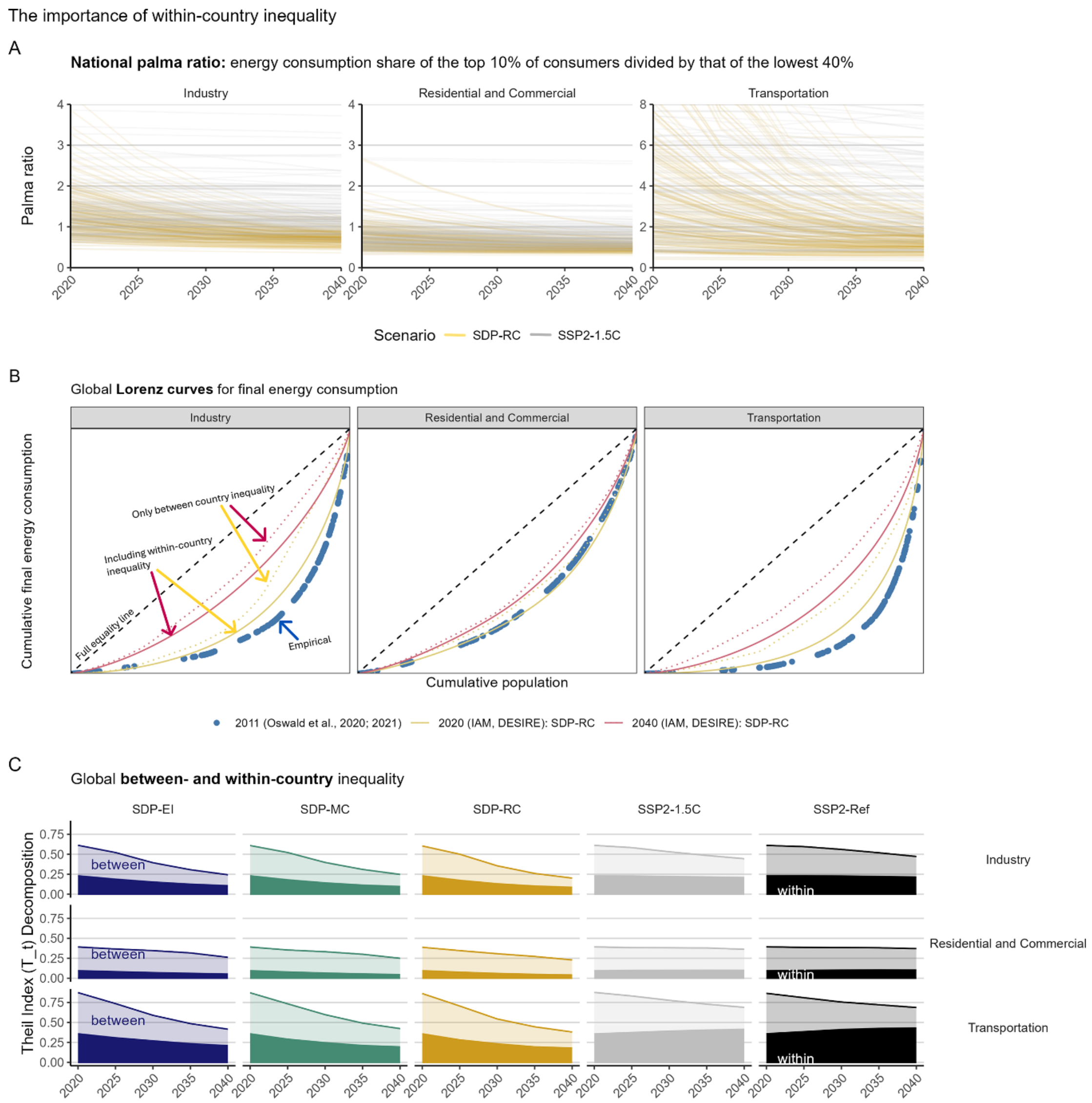

Figure 3. The importance of within-country inequality in emissions and energy.
Panel (A): national Palma ratios for sectoral energy consumption per capita. The Palma ratio is calculated as the total energy consumption of the top 10% of energy consumers divided by the total energy consumption of the bottom 40% of energy consumers.
Panel (B): global Lorenz curves for energy consumption distributions for three energy consumption sectors, comparing different methods. 'Only between country inequality' means that only the region-to-country downscaling of IAM scenario data has been performed, while 'Including within-country inequality' means that, in addition to the downscaling, a sample of 10 000 has been drawn from the assumed within-country distribution. 'Empirical' refers to the data from Oswald *et al* (2021), (2020), which includes fewer countries than DESIRE.
Panel (C): global Theil's T index decomposition of within and between country contributions to inequality.

3.4. Sustainable development and climate policies lead to a major reduction in energy requirements for decent living

Under the SDPs, the global average DLE energy needs are reduced by 30%–46% of the current energy requirement by 2040, going from 22 GJ cap^{-1} in 2020 to 12–16 GJ cap^{-1} (figure 4(A)), with SSP2-1.5C falling within that range. These improvements are due to the combination of different factors, including efficiency improvements related to energy conservation (e.g. insulation), electrification (e.g. in transport and heat pumps), a switch towards clean fuels and technologies and sufficiency-oriented structural changes (see section 3.2 and supplementary figure 11). There are differences across countries. The average energy needs in low-income countries declines from 18 to 10–15 in 2040 (range across model and SDP and SSP2-1.5C scenarios), for lower-middle income countries from 17 to 9–14, for upper-middle from 24 to 13–18, and for high-income from 35 to 17–22 (more results, including by sector, in SI section 1.2). Across models, scenarios, and countries, the 5–95th percentile 2020 DLET range of 17–35 GJ cap^{-1} (section 2.3.1) is reduced to 10–22 GJ cap^{-1} in 2040. In absence of climate policies (SSP2-Ref), the DLET remains much higher and declines only moderately (to 19–20 GJ cap^{-1}, range across countries 15–28 GJ cap^{-1}, in 2040). This is due to the lack of deep

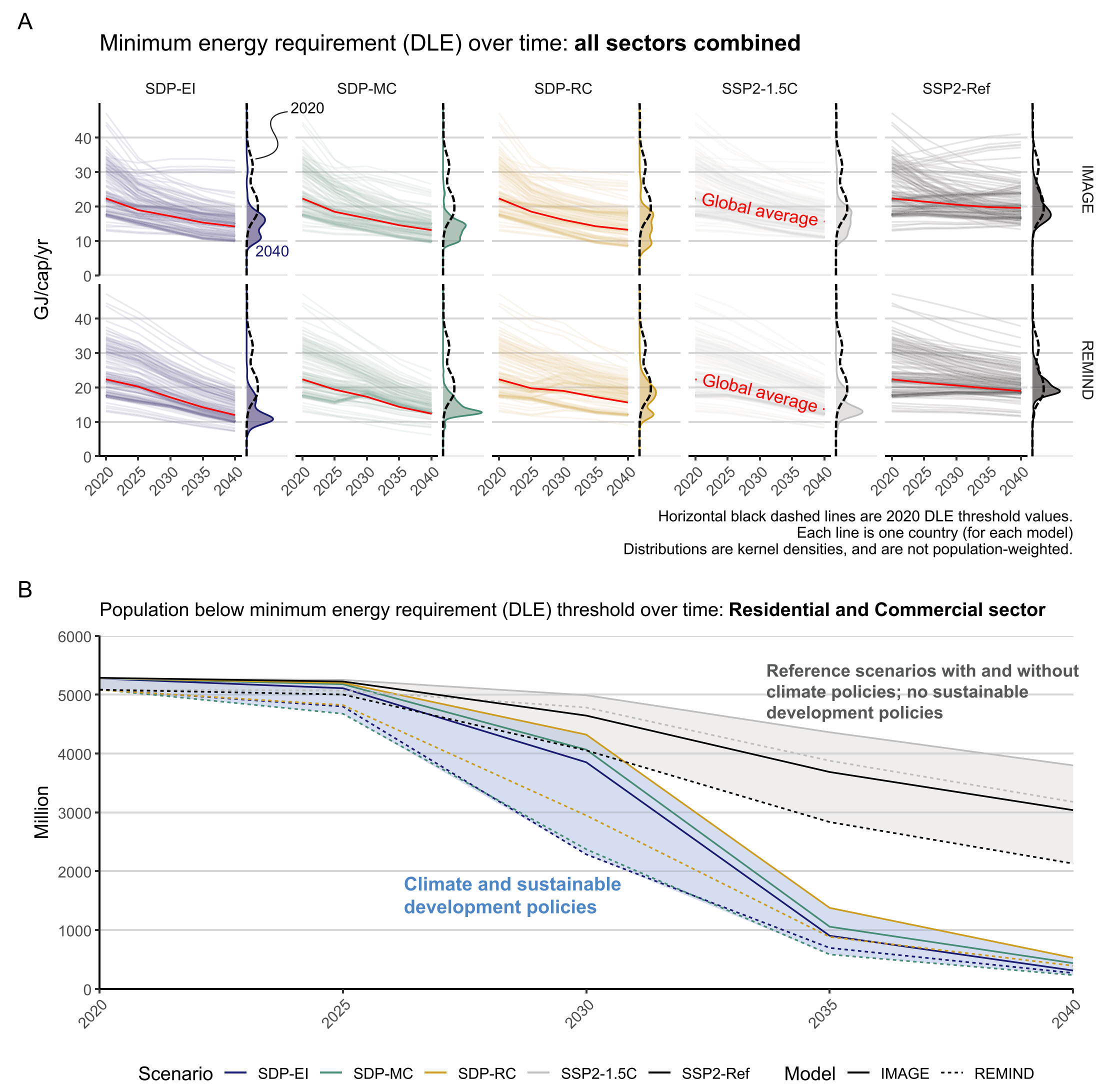

Figure 4. Decent living energy thresholds and deprivation headcounts over time.
Panel (A): total DLE threshold per capita for all countries, with distributions in 2020 (dashed vertically plotted distribution black line) and 2040 (coloured vertically plotted distribution) visualised, not population-weighted, per model and scenario. The globally averaged DLE threshold (population-weighted) is plotted as a red line. In some cases, several groups of countries share a very similar pathway, leading to what looks like a (coloured) thick line, but this is simply a result of overlapping lines.
Panel (B): total global population (in millions) consuming less than the energy requirement for residential and commercial services, per model and scenario.

structural changes in the energy system (e.g. continued use of private cars) and generally slower service provisioning efficiency improvements (supplementary figure 31).

3.5. Reduced energy deprivation headcounts for residential and commercial energy consumption

Currently, over 5 billion people consume less energy than the national residential and commercial DLET. The SDPs show trajectories to reducing this to 0.2–0.5 billion in 2040, a reduction of 90% or more for all SDPs (figure 4(B)). Taking the average between models, of the countries that currently face a deprivation rate of >90% in 2020, most countries (64% for SDP-RC, 70% for SDP-MC, and 70% for SDP-EI) see the deprivation rate fall below 1% by 2040. For each of the SDPs, 1–3 countries stay behind with deprivation rates of >50%, compared to 45–58 without sustainable development policies (SSP2-Ref and SSP2-1.5C) (supplementary figures 33 and 34). Global energy deprivation headcounts in 2040 for transportation are much larger across the board at 4.4–6.9 billion people for the SDPs, as compared to 5.6–5.8 billion in 2020 (supplementary figure 35).

As to differences across countries, we find that the energy consumption of the entire population of, for instance, India and Nigeria is well above the residential and commercial DLET in 2040 across all SDPs, while about 5%–8% of the population in China uses less (figure 5). The mean across models and SDPs, for China, India, Nigeria respectively, shows that this is an outcome of a combination of growth of clean energy per capita (1.2×, 3.4×, 8.0×), service provisioning efficiency improvements (48%, 54%, 77%)

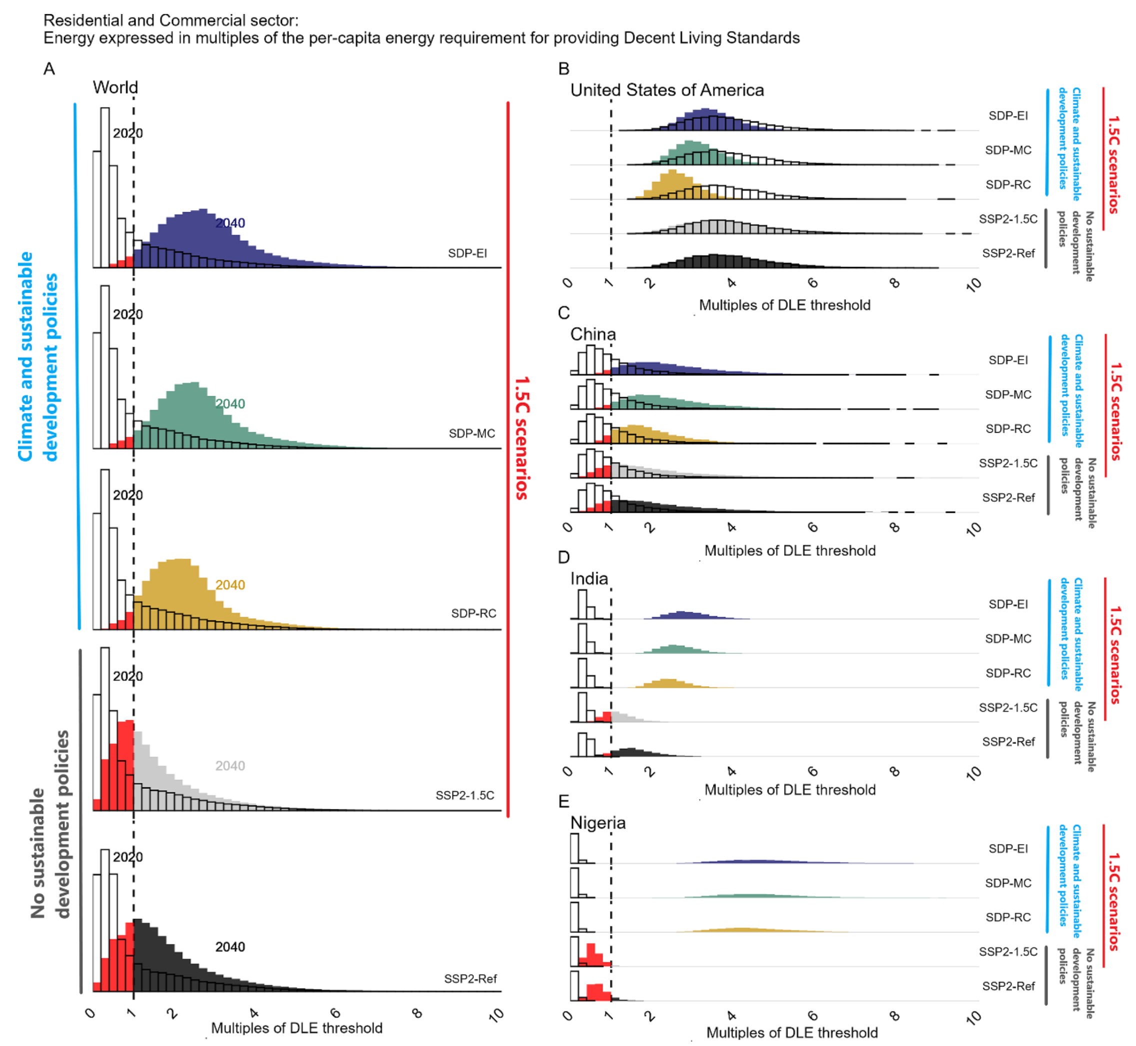

Figure 5. Energy per capita of clean, DLE-related residential and commercial consumption distributions, relative to national-level DLE thresholds. Comparing 2020 and 2040 distributions.
Panel (A): all countries pooled into a global distribution, with all countries rescaled to their respective DLE thresholds.
Panel (B)–E: national distributions for four selected countries, dashed line referring to the national DLE threshold.

and inequality reduction (energy Gini −0.13, −0.04, −0.06). Policies in the SDPs reduce the excessively high energy consumption in parts of the population of for instance the USA, while under SSP2-Ref and SSP2-1.5C energy consumption distributions relative to the DLET hardly change. In the SDPs in 2040, for the residential and commercial sector, 64%–76% of the global population use more than two times their national minimum energy requirement. Grouping across low (65%–74%), lower-middle (58%–66%), upper-middle (61%–70%), and high (74%–93%) income countries we always find the majority of the population using more than double the minimum energy requirement.

3.6. Sectoral energy needs gaps

In figure 6, we visualise the energy needs gap (ENG) for ten world regions. Africa and Southern Asia account for the majority of the current energy deprivation, at 17 EJ (29%) and 15 EJ (25%) of the 58 EJ global energy needs gap (figure 6(B)). In each region, the biggest energy gap is in transportation, which has a high energy intensity and the largest deprivation rates. Southern Asia undergoes an industrialisation phase with increasing manufacturing capacity and thus has a relatively small industry energy gap. However, at the same time it suffers from a relatively high residential and commercial energy gap. Africa has the largest per-capita energy gaps across all regions, with the energy gap being as big as 68% of its total energy consumption. In the future, under the SDPs, the total ENG decreases but a transportation gap persists. For instance, in Africa, the per capita ENG decreases from 13 GJ cap^{-1} to 4–5 GJ cap^{-1} by 2040 (table 4). Globally, in the SDPs the energy gap per capita is more than halved, from currently 6 GJ cap^{-1} to 2–3 GJ cap^{-1} in 2040.

3.7. Energy beyond DLS and convergence in energy headroom

Energy use in the scenarios is split up in energy provided for DLS and energy beyond DLS, with the

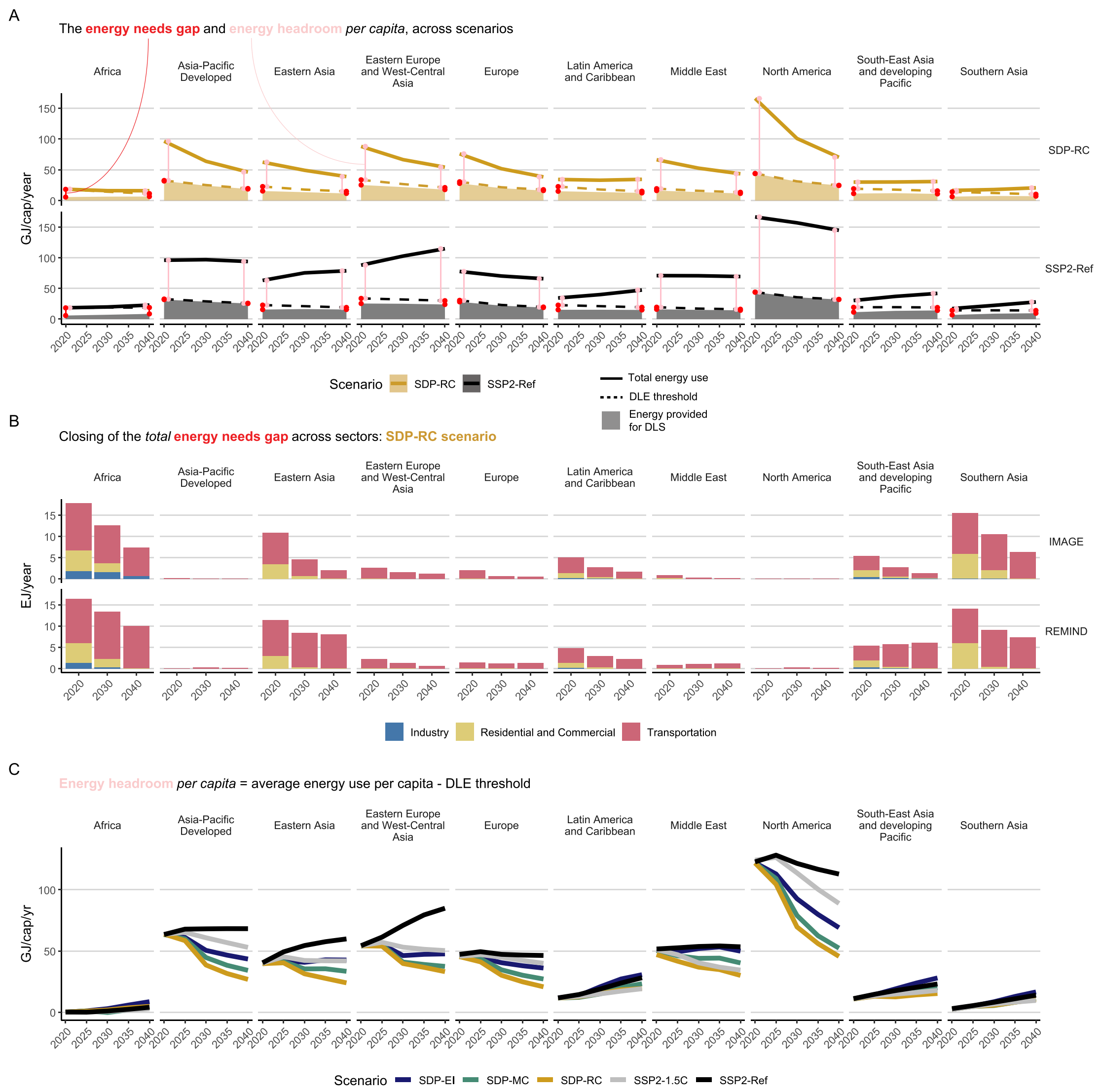

Figure 6. Energy needs gap in the context of affluence.
Panel (A): the total energy per capita (solid line), DLE threshold (dashed line), and implied energy used to support the provisioning of decent living standards (filled area) together show the energy needs gap (red vertical line) and energy not used for decent living standards (pink vertical line), visualised for 2020 and 2040, averaged across models, aggregated to 10 regions.
Panel (B): total energy gap per sector, aggregated to 10 regions, per model, for the SDP-RC scenario.
Panel (C): average energy headroom per capita, with ranges and lines indicating averages and ranges across models, per scenario, aggregated to 10 regions.

energy headroom being the energy left after subtracting the DLET from the total energy use. The energy provided for DLS as a share of total energy use is roughly the same in 2040 as in 2020 (31%), with SDP-RC increasing to 35% and SDP-EI declining to 26%. For SDP-RC this share increases in the US from 26% to 35% and in Africa from 31% to 41%. Energy beyond DLS thus accounts for 69% of global energy use in 2020, and ranges from 65% to 74% under the SDPs in 2040.

Across the SDPs, we show (figure 6(C)) strong convergence and a varying level of contraction (SDP-RC) or expansion (SDP-EI) of the energy headroom. The modelled 2020 energy headroom ranges from 0 GJ cap^{-1} in Africa (indicating average energy consumption around the DLET) and 2 GJ cap^{-1} in Southern Asia, to 122 GJ cap^{-1} in North America (which is itself almost 3 times the DLET level, indicating the presence of excessive energy use). SDP-RC sees the strongest energy headroom reduction and convergence across regions, to 5–46 GJ cap^{-1} in 2040. In contrast, the SSP2-Ref scenario sees a continued wide disparity across regions in the energy headroom (4–113 GJ cap^{-1}) and a thus a high inequality in the availability and use of energy beyond DLS.

Looking at the SDPs in 2040, we note that despite the existence of a persistent ENG, Africa's total energy consumption is slightly higher than the minimum energy requirement, with a 27%–45% headroom (table 4). For all other regions, the energy headroom percentages are higher, between 49% and 82%. Globally, the headroom is more than half of the total energy use (55%–69%).

Table 3. Global energy Gini coefficients. 'Based on national average energy use' is derived from IAM results after downscaling final energy, while 'With within-country distributions' is after downscaling and sampling within-country inequality. Sample size of within-country distributions is 10 000 samples per country.

Scenario	Energy sector	Year	Based on national average energy use	With within-country distributions	Oswald *et al* (2021), (2020) (GTAP9 + GCD + IEA)
Historical	Residential and commercial	2011			0.45
Historical (SDP-RC)	Residential and commercial	2020	0.41	0.47	
SDP-RC	Residential and commercial	2040	0.34	0.37	
Historical	Transportation	2011			0.75
Historical (SDP-RC)	Transportation	2020	0.53	0.67	
SDP-RC	Transportation	2040	0.34	0.47	
Historical	Industry	2011			0.65
Historical (SDP-RC)	Industry	2020	0.47	0.58	
SDP-RC	Industry	2040	0.26	0.35	

3.8. Emissions and carbon budgets

The emissions for achieving DLS for all depend strongly on the energy system of the country and its future climate policies. The global average CO_2 emissions for DLS based on the global energy system in 2020 is about 2 tCO_2 per capita per year. The 5–95th percentile across countries currently ranges from 0.3 to 3.8 tCO_2 per capita. This range declines to 0.1–0.8 tCO_2 per capita in 2050 (global 0.4 tCO_2 per capita) across the SDPs (for all countries, see SI section 8). For instance, current low emissions for DLS for all are found in Ethiopia—a country with a medium-low DLET and currently low emissions in the energy system (due to very high bioenergy use, and to a smaller extent hydropower). The USA has high emissions for DLS for all due to a high DLET and a fossil-fuel dominated energy system, but this goes down to levels similar to those of Ethiopia in 2050 in SDP-RC (figure 7(A)).

The scenarios with stringent climate mitigation policies reduce emissions of energy and industrial processes to near-zero, implying near-zero emissions for delivering DLS as well. About three quarters of the total CO_2 emissions (excl. LULUCF) required to deliver energy to support DLS for all until 2050 can be allocated to Global South countries (figure 7(B), for SDP-RC, other scenarios and timeframes in SI section 4).

Without decarbonization (SSP2-Ref), the emissions to achieve DLS for all will vastly exceed the remaining carbon budget (RCB) associated with a 50% chance of staying below the 1.5 °C global warming threshold (Forster *et al* 2024), and break the Paris Agreement. With decarbonization and sustainable development policies in place, however, emissions related to DLS for all are close to the size of 1.5 °C RCB. Emissions to support DLS for all are 179–206 $GtCO_2$ between 2024 and 2050 in the SDPs, equivalent to 89%–103% of the RCB (figure 7(C) for SDP-RC, other scenarios in SI section 4). Global mean temperature outcomes for each scenario are shown in supplementary figure 49.

4. Discussion and conclusions

4.1. Conclusions

To understand justice and fairness implications of proposed climate solutions, it is necessary to explicitly represent energy inequalities and how they may develop into the future. For this purpose, we have operationalized the concept of energy for decent living in energy-economic mitigation scenarios, and introduced a new methodological framework that permits us to develop internally consistent projections of energy needs gaps and deprivation headcounts.

Analysing a set of scenarios implemented by two IAMs, we show under which circumstances mitigation and development pathways are consistent with providing DLS for all while meeting temperature goals. Without sustainable development policies (SSP2-Ref and SSP2-1.5C), billions are left consuming too little energy to provide DLS by 2040. Holistic policies pursuing concerted climate action and human development are needed and can reduce residential and commercial energy deprivation headcounts by over 90% by 2040. The SDPs show similar deprivation headcounts in 2040, but the level of convergence and amount of energy headroom varies. If, by 2040, DLS (all sectors) were to be provided to 100% of the population, well over half (55%–69%) of global energy consumption would still be available for other services beyond DLS, under sustainable development policies. Emissions attributable to delivering DLS for all between 2023 and 2050 in SDPs are close to the RCB for 1.5 °C warming. Without decarbonisation, providing DLS for all is at odds with the Paris Agreement.

All levers for closing decent living gaps are important. Deep energy efficiency improvements in

Table 4. DLE thresholds combining all sectors, divided by the current total energy use, and energy needs gaps, by region, for 2020 and 2040 under different future scenarios.

Region	Current (SDP-RC, 2020)			SDPs (2040)		SSP2-1.5C (2040)		SSP2-Ref (2040)	
	Energy per capita consumption (GJ cap^{-1})	DLE threshold (% of total energy use in region)	Energy gap per capita (GJ cap^{-1})	DLE threshold (% of total energy use in region)	Energy gap per capita (GJ cap^{-1})	DLE threshold (% of total energy use in region)	Energy gap per capita (GJ cap^{-1})	DLE threshold (% of total energy use in region)	Energy gap per capita (GJ cap^{-1})
Africa	19	99%	13	55%–73%	4–5	82%	7	82%	11
Asia-Pacific Developed	96	34%	1	29%–42%	0–1	27%	0	27%	0
Eastern Asia	65	36%	8	24%–38%	1–4	26%	3	24%	3
Eastern Europe and West-Central Asia	88	38%	8	30%–39%	2–3	31%	5	26%	6
Europe	80	40%	3	31%–46%	0–2	31%	1	30%	1
Latin America and Caribbean	37	66%	8	29%–44%	1–3	43%	3	41%	5
Middle East	84	29%	4	18%–31%	1–2	25%	2	23%	2
North America	166	27%	0	24%–35%	0	21%	0	22%	0
South-East Asia and developing Pacific	30	64%	8	32%–51%	2–5	44%	3	45%	5
Southern Asia	16	89%	8	38%–50%	2–3	54%	4	50%	5
Global	48	47%	8	31%–45%	2–3	37%	4	36%	5

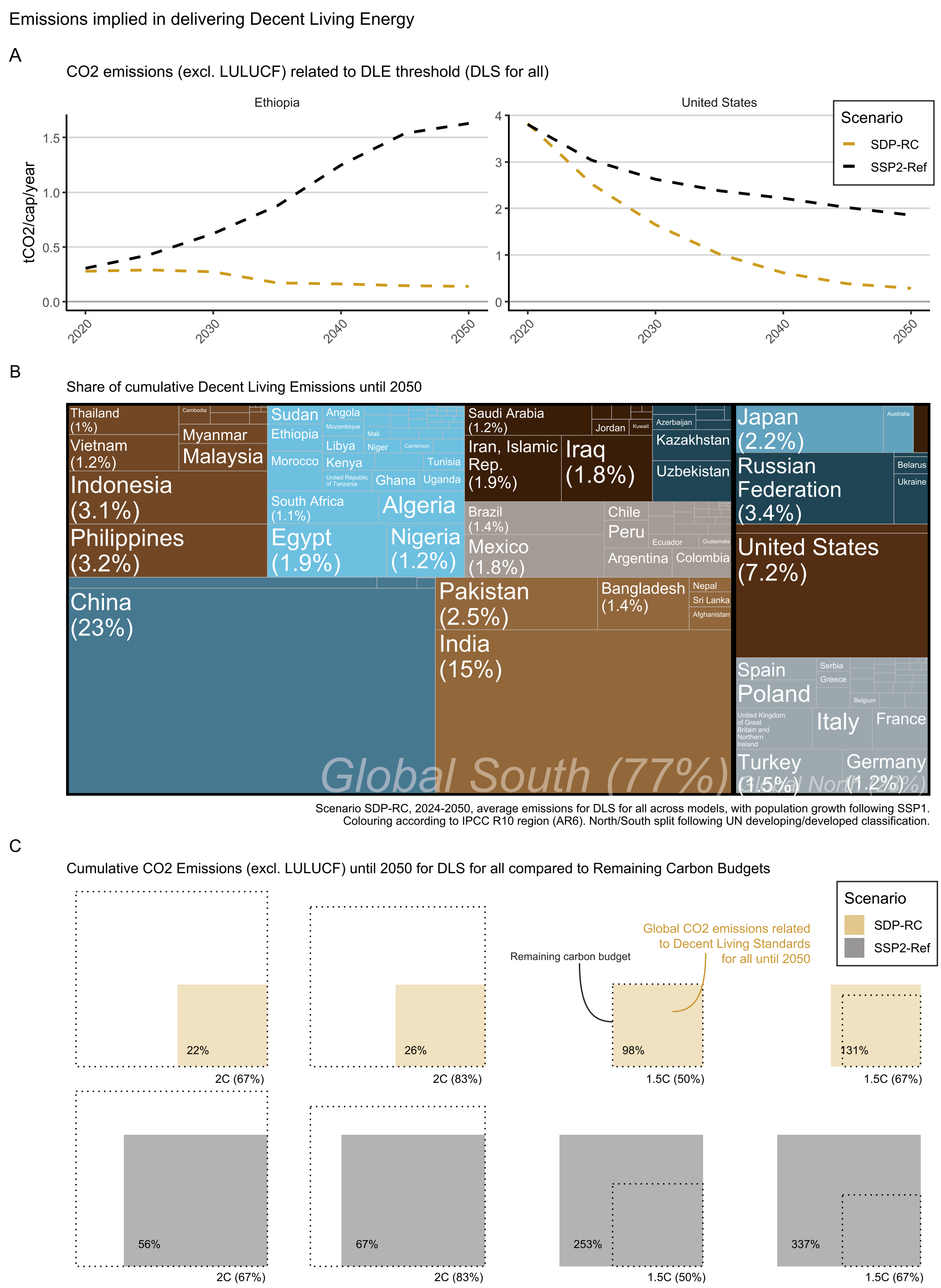

Figure 7. Emissions implied in delivering decent living energy.
Panel (A): emissions related to DLS for all (dashed line), for Ethiopia and the United States of America.
Panel (B): country shares of global cumulative CO_2 emissions (emissions threshold related to DLS for all) from 2024 to 2050.
Panel (C): comparing the cumulative global CO_2 emissions (emissions threshold related to DLS for all) from 2024 to 2050 to remaining carbon budget estimates, with averaged value across models.

providing DLS for all are key while moving towards zero-carbon energy sources fast enough. This is in addition to strong clean energy growth in countries currently seeing the largest gaps, and inequality reductions across all countries. Relative and absolute importance of the levers does vary with the national context. For instance, while high-income countries see transportation energy demand halving, low-income countries see clean residential and commercial energy use grow 7–8 times over. Similarly, the rate of potential energy efficiency improvements depends on the structures in place currently, and the same holds for levels of inequality reductions. Special attention should be given both to countries that still show deprivation levels under the SDPs as well as to countries where the SDPs suggest major cuts in energy use of excessive and energy-intensive patterns to improve equity. The results thus hold crucial country-level insights for the relative importance of growth, technological and service provisioning efficiency, and inequality reduction as prerequisites for successfully implementing just transitions.

4.2. Discussion

Matters of equity, including reducing unequal access to clean energy services for meeting basic needs, should be central to devising globally just transition strategies. However, till now no methods were available to provide a comprehensive analysis showing to what extent climate and energy scenarios are consistent with providing DLS for all. In this manuscript we presented and applied the DESIRE model, which can provide a rapid assessment of the decent living gaps in energy and emissions scenarios. The key strengths of DESIRE include its relatively simple and modular design, coverage of multiple sectors, and analytical form. Its global coverage with national-level detail allows for country- and region-specific information to be analysed, which is required for international policy discussions. Similarly, our work highlights a scenario where the most energy-intensive, high-consuming countries see large cuts in energy use, improving equity alongside energy growth in countries with current high deprivations.

With this tool, scenarios can be designed that focus on meeting DLS. In this manuscript, we focused on describing how existing scenarios can be analysed. Future work could analyse a larger set of scenarios, across more IAMs. DESIRE can also be used in the scenario-making process to define energy targets that can be used in iterative scenario design processes (figure A1), and explore alternative climate mitigation pathways with varying DLS thresholds and levels of DLS achievement. The methods presented here open the way for intentionally exploring multiple patterns of justice, including sufficientarian (e.g. DLS for all), limitarian (reducing the consumption of the highest percentiles) and beyond (see e.g. Zimm *et al* 2024).

Limitations of the analysis presented here point towards new areas of research, including better understanding certain DLS thresholds, improved data availability, and additional model dynamics. The range of justifiable DLS thresholds is yet to be explored systematically. For instance, the passenger transportation threshold could be explored more robustly by a combination of a strong theory-based definition with novel empirical spatio-temporal and survey-based analysis (Fu and Zimm 2024). Moreover, conceptions of what services should be included in DLS may change—most likely expand, not contract—over time, which could be explored in future work. While DLS thresholds aim to be independent of individual situations, energy needs are location-dependent, and significant differences on subnational spatial scales are possible. The calculation of DLETs relies on life cycle analysis and input–output tables, which are constrained by scaling assumptions and uncertain country-specific sectoral energy intensity factors, respectively. Combining multiple methods innovatively could help reduce these uncertainties. Regarding within-country energy inequality estimates, the current data situation is dire. There is a critical need for updated consumption accounts with higher resolution within countries. Moreover, the lack of time series data for such accounts further hampers our understanding of how energy inequality evolves over time. Whilst energy inequality data is unavailable, refinements to the scenario driver of within-country inequality are also possible, for instance by modelling wealth inequality for scenarios alongside income inequality. Developments of IAMs may include the endogenous modelling of income and energy use distributions (e.g. Sampedro *et al* 2024), which could be compared with, or potentially replace, the energy inequality projection module of DESIRE, and look into fuel-specific inequalities (appendix A.3.3).

Future analysis could also involve more detailed differentiation in future energy needs and emissions intensity changes for DLS services and non-DLS services separately, and should model climate impacts on energy needs and energy supply systems. If within-country inequality accounts for other resources like water consumption and materials use become available, extending DESIRE beyond energy would allow for dynamically linking to more planetary boundaries beyond climate. Future research could also identify DLS deprivation clusters in households across the globe to enhance understanding of multidimensional gaps in DLS. This exploration could facilitate the examination of intersectoral linkages and high consumers across consumption categories with DESIRE. Lastly, we want to note that our manuscript focuses on energy availability and does not holistically consider elements of affordability, which are included in the narratives and IAM quantifications of the SDPs (see e.g. (Dombrowsky *et al* 2024, Hernandez *et al* 2024, Min *et al* 2024, Weindl *et al* 2024, Soergel *et al* 2024b)).

A large research agenda thus remains. This paper takes a first step towards quantifying resource needs and deprivations for DLS along sustainable development and ambitious climate mitigation scenarios. This may help pave the way for analysing what it takes to ensure individual-level basic needs while creating or retaining societal-level prosperity in a world that fights to address ecological challenges.

Data and code availability

The DESIREv1.0.0 model code is available at https://doi.org/10.5281/zenodo.15034643, with reproduction material for the figures and tables in this manuscript available at https://doi.org/10.5281/zenodo.15031718. Future versions of DLS and DLE data produced with DESIRE will be made available at https://doi.org/10.5281/zenodo.15032219. IAM scenario data used in this paper is released in an online scenario explorer tool (Soergel *et al* 2024a) for the SHAPE (Sustainable development pathways achieving Human well-being while safeguarding the climate And Planet Earth) project, accompanying the publication of this work and other papers from this special issue. For documentation of the assumptions underpinning the SDPs, see the Supplementary Modelling Protocol of Soergel *et al* (2024b). The authors encourage re-use of the scenario data for future research, as well as implementation of the SHAPE SDPs by other models. Other data and code has been referred to in the manuscript and supplementary material.

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Author contributions

J S K conceived the research, wrote the manuscript, produced the figures and tables, produced and analysed the results, and developed the DESIRE model (with coding support from H L and Jonas van Laere, and expert input from J M on Input-Output tables, and A M for the buildings sector). V D was the main developer of the IMAGE scenarios. B S and S R were the main developers of the REMIND-MAgPIE scenarios. F S, B v R, K R and J S K discussed and designed the downscaling setup, which was developed and carried out by F S Supervision of the implementation and interpretation of this research was provided by J R, K R, B v R, and S P All authors contributed to the writing and reviewing of the manuscript.

Conflict of interest

The authors declare that they have no conflict of interest.

Appendix A. Model description DESIRE

A.1. Statement of need

To understand whether future scenarios are consistent with providing DLS, a consistent treatment is required of how inequality, growth, and efficiency interact. Such a methodology also needs to acknowledge different national contexts and respective energy needs, and recognise that different regions will have different pathways and contributions towards global net-zero. Doing so requires linking literature on energy needs, energy inequality, and energy transition pathways. A model for this does not yet exist.

The key methodological advancement of this study is to introduce such a model, taking climate mitigation pathways with detailed energy transition pathways from IAMs, projecting plausible energy distributions along these transitions starting from current within-country inequality in energy consumption, and aligning and comparing these energy demands with a minimum energy requirement for DLS. We call it the DESIRE model. While version 1.0.0 only deals with energy demands, this name acknowledges that other resources requirements (for DLS provisioning) and environmental objectives (e.g. following IAM objectives and constraints) could be integrated with a similar logic in future versions, if data availability improves—especially for current within-country inequality of resource use.

DESIRE aims to provide an internally consistent picture of energy needs gaps given the overall energy system changes projected in an IAM scenario, accounting for national and regional scale improvements in the system of energy provisioning and their impact on the DLET and the number of people below that threshold. We show in the paper that the introduction of within-country energy distributions is at least as important as the regional averages (or downscaled country-level averages) reported in IAM studies for understanding inequalities (see section 3.3 and figure 3).

The model in its current form can be used in multiple ways. In this manuscript, we focus on illustrating how it can be used for *scenario analysis*, to provide additional information alongside existing scenarios, by adding information about the implied needs satisfaction (figure A1). However, the tool can also be used by *scenario creators* during the scenario construction process, by devising energy targets for the first setup of scenarios and providing quick calculations on the outcomes of preliminary outputs that can be used in iterative scenario design processes.

A.2. Model inputs

Key inputs to DESIREv1.0.0 are: (i) final energy consumption pathways, at the national, sectoral level, from downscaled IAM results; (ii) national DLET estimates with current technology; (iii) sector service provisioning efficiency scalers over time for each IAM scenario derived from scenario data, at the regional level; (iv) an account of current energy consumption inequality, by sector; (v) (income) inequality projections for each country. Inputs (i), (iii), and (v) are scenario-dependent, while inputs (ii) and (iv) are approximating currently existing patterns. The variables used from IAM scenario runs are shown in figure A1.

A.3. Description of modules

A.3.1. Energy demand

Downscaling final energy demand to the country-level. IAMs provide pathways at the regional level, aggregating multiple countries, rather than computing pathways for every country. Historically, this has been a result of a combination of data availability, computing power, and parsimony. However, for understanding poverty, high spatial heterogeneity is key, recognising as much as possible varying local contexts. Therefore, we use a new tool that 'downscales' regional IAM final energy pathways to the country level (Sferra *et al* 2021, Richters *et al* 2023). The design of the tool aims to produce national pathways that reflect near-term trends consistent with past national developments while also maintaining strong compatibility with the regional pathways that are being downscaled. Methods are summarised in SI sections 3.1–3.3. As this process does introduce new parameters of variation, we provide a sensitivity analysis in SI section 3.4.

Adjusting energy demand to align with DLETs. To compare total final energy demand per capita with DLETs, it is useful to first adjust the energy demand based on available energy to align it with the bottom–up assumptions underlying DLET estimates (SI section 1.4). Firstly, for residential energy consumption DLE, we only count clean fuels. Therefore, we discount the use of traditional biomass (used e.g. for heating and cooking). As only the IMAGE model reports these variables, we use the traditional biomass use shares derived from each IMAGE scenario to the REMIND residential and commercial energy pathways. Secondly, bottom–up estimated DLETs typically do not include a large commercial energy footprint. We use the 2018 US Commercial Buildings Energy Consumption Survey to estimate the share of commercial energy used for decent living services at 21% based on the energy consumption for health care and education (for further discussion, see SI section 1.4.3). Domestic aviation is not included in the use DLS threshold and thus subtracted from the IAM transportation energy demand. Industrial energy consumption is not adjusted.

A.3.2. DLE

DLS thresholds. To calculate the energy requirements for providing DLS around the world, we follow the definitions used in Kikstra *et al* (2021), which are summarised in table A1. Other publications (e.g. Millward-Hopkins *et al* 2020, Vélez-Henao and Pauliuk 2023, Schlesier *et al* 2024) have used slight deviations of these definitions. We use the definition from Kikstra *et al* (2021) because it allows for a direct comparison with the decent living gaps reported in that publication.

DLETs (current). DLET calculations also follow the methods in Kikstra *et al* (2021), with a major input data update for transport passenger-kilometre and modal shares based on Edelenbosch *et al* (2017) and Van Vuuren *et al* (2021), and minor data updates across the board where new data was available, including for all appliances, education, health care, hot water, nutrition, and roads (for a comparison, see SI section 11). The construction energy here does not include estimates for new infrastructure, but estimates the amount of energy for *maintaining* existing

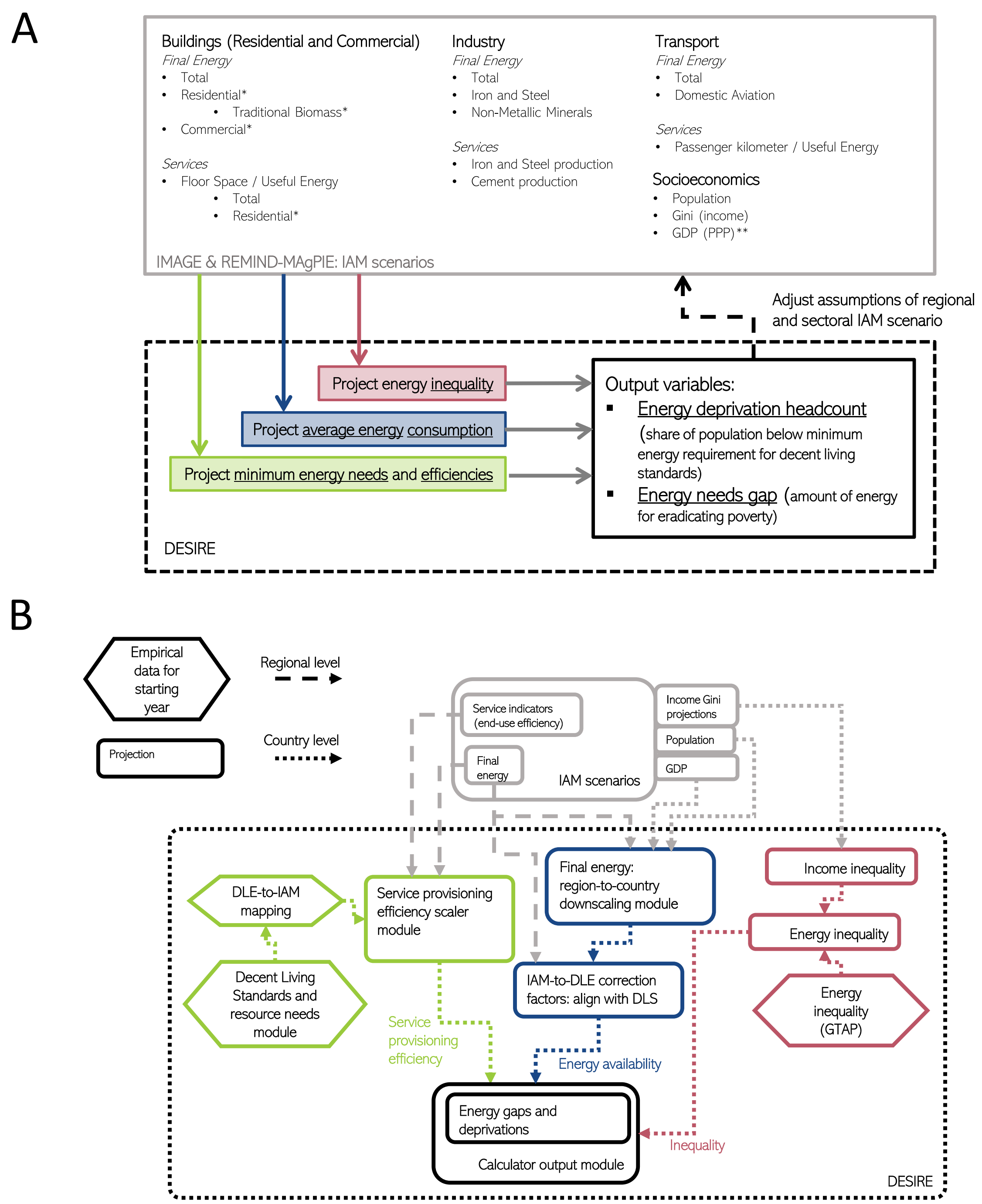

Figure A1. Model design of DESIRE v1.0.0 and its application in this study.
Panel (A): the role of the DESIRE model in the development of the SDPs in this special issue, including the IAM variables used as input to the model.
Panel (B): flow chart design of the DESIRE model, including other sources of data input, where the 'decent living standards and resource needs' module builds on Kikstra *et al* (2021).

DLS-related stocks—meaning that, during the transition phase, this will be an underestimate.

Mapping DLE to IAM. The energy demands for DLS are a consumption-based perspective, while the accounting in IAMs are sectoral. For many demands the mapping is clear, especially when it comes to operational energy demands. When allocating energy for construction, the majority of energy is consumed in industry, but a small part needs to be allocated to transportation energy demand. These shares are derived from life cycle analysis for most dimensions. For the energy calculations where we have used an environmentally extended multi-regional input–output table EXIOBASE3, we use that same table to allocate energy uses to sectoral definitions use in IAMs. Because we are creating an energy requirement level, we allocate all energy use domestically instead of allocating energy across border based on cur-

Table A1. Decent living standards by dimension, similar to Kikstra *et al* (2021).

DLS dimension	Decent living standards thresholds and proxies
Transport	Land-based transportation of 8527 motorised passenger-kilometres per year, with public transport infrastructure relative to the p-km required based on current modal share estimates. Road network needs are calculated based on maintaining current infrastructures and a threshold of 1.5 km of paved road per square kilometre of arable land.
Space and water heating	Space heating up to 20 °C, and 30 l per capita per day of hot water.
Health care	Sufficient and accessible preventive and curative health care facilities. For energy calculations, this is proxied by high enough (government) expenditure ($1024 per person per year) to sustain an average healthy life expectancy (HALE) of more than 65 years.
Appliances	Clean cookstove and fuel, mobile telephone, refrigerator, and television per household
Sanitation	Safely managed sanitation services for all.
Shelter	Durable permanent housing for all, with a minimum apartment size of 30 m^2, increasing with 10 m^2 per person at household sizes above three, resulting in national minimum levels of 10–15 m^2.
Space cooling	Space cooling down to 26 °C.
Education	Adequate schooling with adequate facilities and staff. For energy calculations, this is proxied by high enough (government) expenditure ($1400 and $2843 per year per student for primary and lower secondary education, respectively) to sustain good completion rates.
Nutrition	Sufficiently healthy and nutritious diets, proxied by minimum dietary energy requirements.
Clothing	Sufficient footwear and clothing. For energy calculations, this is proxied by weight and expenditures (footwear: 0.9 kg cap^{-1} yr^{-1} at $15/kg, clothing: 1.3–2.43 kg cap^{-1} yr^{-1} at $51 kg^{-1})
Water	Safely managed clean water supply of 65 l per capita per day.

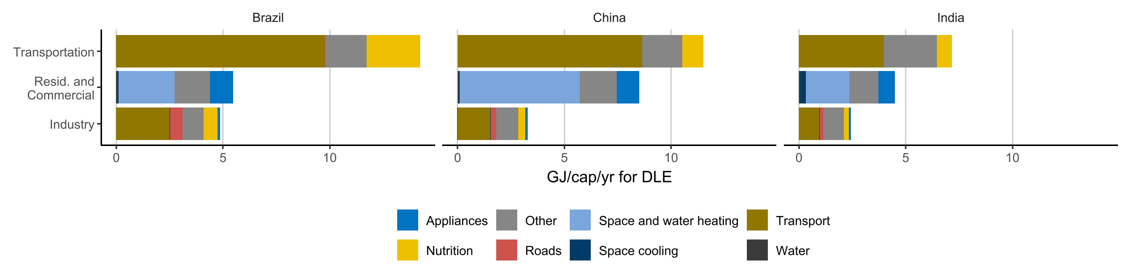

Figure A2. Service-driven accounting of DLE threshold energy requirements of direct and indirect energy requirements (bottom) mapped onto three IAM sectors of direct energy consumption (left), for 2020, for a selected group of countries, based on current technologies.

rent trading patterns. In other words, indirect industrial energy requirements are allocated following a consumption perspective, i.e. not in the country where the energy is currently used for production, but where it becomes part of the service provided. Figure A2 shows the results and provides an indication for a select grouping of countries. More detail on the full mapping is found in SI section 1.2.1.

Tracking efficiency improvements. In DESIRE, the aim is to capture structural changes in scenarios to dynamically scale the DLET by sector over time. For each model and sector, we construct a simple service provisioning efficiency factor (SEF, table A2). We then change the DLETs over time (t), for each country, depending on the change in the SEF in the relevant IAM region, following:

$$\begin{aligned} \mathrm{DLET}_{t,s,r=\mathrm{country}} = \mathrm{DLET}_{t=2020,s,r=\mathrm{country}} \\ \times 1/\left(\left(\mathrm{SEF}_{t,s,r=\mathrm{region(country)}}\right)/\right. \\ \left.\times\left(\mathrm{SEF}_{t=2020,s,r=\mathrm{region(country)}}\right)\right). \end{aligned}$$

For the buildings sector, we use total residential floor space as the service indicator for IMAGE, and useful energy consumption in the buildings sector for REMIND. For transportation, we track total passenger kilometres delivered and energy consumed for

Table A2. Service provisioning efficiency factors applied in this study.

Sector	Service provisioning efficiency factor
Residential and Commercial	REMIND: 'Useful Energy|Residential and Commercial'/ 'Final Energy|Residential and Commercial' IMAGE: 'Energy Service|Residential|Floor Space'/'Final Energy|Residential'
Industry	REMIND & IMAGE (global): ('Production|Non-Metallic Minerals|Cement|Volume'/ 'Final Energy|Industry|Non-Metallic Minerals') $*$ 0.22+ ('Production|Iron and Steel|Volume'/ 'Final Energy|Industry|Iron and Steel') $*$ 0.78
Transportation	REMIND & IMAGE: 'Energy Service|Transportation|Passenger'/ 'Final Energy|Transportation'

transportation. Both are implemented at the regional level, and specific to each IAM implementation of each scenario. For industry, we scale the DLET using a global trend, based on cement and steel production and energy consumption. We provide more discussion on the SEFs in SI section 1.2.2.

A.3.3. Energy inequality

Constructing within-country energy demand distributions. To construct a lognormal distribution ($Lognormal(\mu, \sigma^2)$), we need to define two parameters: μ and σ. We first derive the Gini coefficient of energy consumption accounts for each sector for 87 countries covering the majority of the global population. For countries with no data, we specify a regression model to fill in the missing energy Gini coefficients, infilling missing countries based on the relationship with the income Gini coefficient and the World Bank income level grouping, effectively converting income Gini coefficients to energy consumption coefficients using multivariate regression (SI section 2). The properties of a lognormal distributions allow for writing *sigma* as a function of the Gini coefficient, namely:

$$\sigma = \sqrt{2} \cdot \text{invcdf}(\text{normal}(), \\ \times (\text{energy\_gini\_coefficient} + 1)/2).$$

Then, μ can be written as:

$$\mu = \ln(\text{energy\_per\_capita}) - (\sigma^2)/2$$

where energy per capita comes from the downscaled IAM results. The resulting energy distributions capture the dynamic present in the historical energy consumption accounts (figure A3). In constructing aggregate sectoral energy inequality distributions building on Oswald *et al* (2021), (2020), we do not account for specific fuels. Future work could explore modelling fuel-sector dynamics, by expanding upon past work to construct fuel-sector specific energy Gini coefficients, and explore going beyond an electricity/non-electricity split for DLE estimates in this work, utilising the information already available from the downscaled IAM results (a split of electricity, gases, heat, hydrogen, liquids, and solids).

Projecting changes in energy inequality. Acknowledging limitations in available data on within-country energy inequality over time, we use a simple rule to project energy inequality alongside the income inequality pathways described in Min *et al* (2024)—for the SDPs—and Rao *et al* (2019b)—for the SSP-based scenarios. By specifying that a society with fully equal (unequal) income per capita also has fully equal (unequal) energy consumption inequality, we can draw pathways from current levels of energy and income inequality per country and sector (figure A4). This results in energy Gini coefficients in residential and commercial energy consumption changing fewer points than for transportation—while their relative change is the same (for a sensitivity analysis, see SI section 1.3.2). From 2020 to 2040, the income Gini coefficient of countries is assumed to decline between 0.03 and 0.23 (5–95th percentile, 0–1 scale) in SDP-RC.

While GDP information is not used in DESIRE, it is an additional quantification available for each scenario (Min *et al* 2024). SDP-RC pairs its strong within-country inequality reduction across virtually all countries with median GDP per capita (PPP) growth rates in low-income countries (following World Bank classification, see SI section 5) more than six times higher than historical (2000–2019) rates and about two times higher than for SSP2 (figure 2(A)). In SDP-RC the median (across countries) of GDP per capita growth rate (1.2%/year) in high-income countries is about half of historical economic growth (median: 2.3%/year), while growth in SDP-MC (2.5%/year) and SDP-EI (3.2%/year) is faster than historical (supplementary figure 28).

A.4. Model outputs

Defining and calculating model outputs. The core outputs of DESIRE are the energy consumption per capita related to DLS provisioning, the energy Gini, and the DLET. By integrating over the lognormal probability density function $p(x)$ from zero until the DLET, we obtain the deprivation rate. Multiplying by population yields the deprivation headcount. The 'depth-of-deficit', or the average per capita energy gap of the population under the threshold, is obtained by

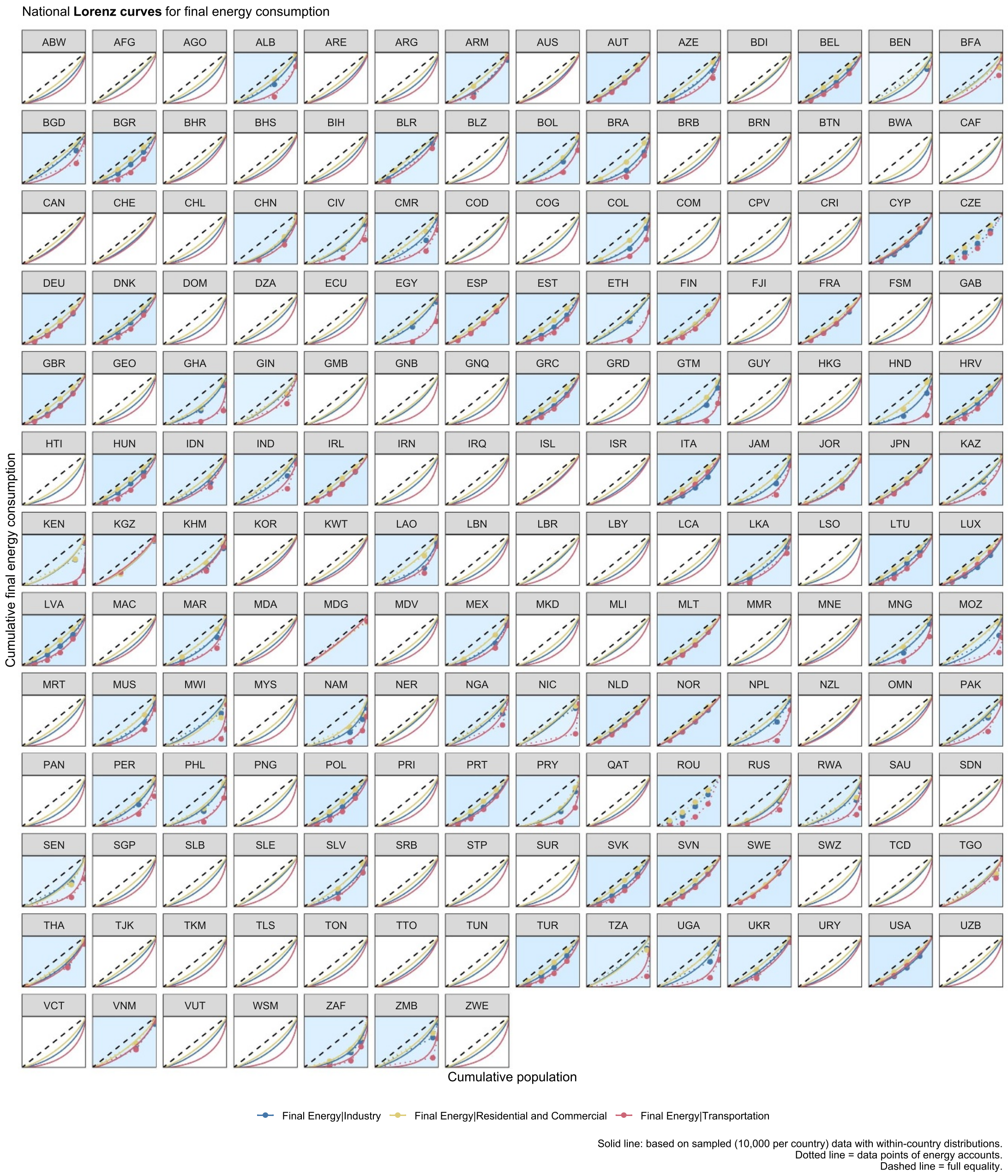

Figure A3. Model starting point energy consumption distributions for each sector in each country, compared to energy account data (Oswald *et al* 2020, 2021) where available (highlighted in blue).

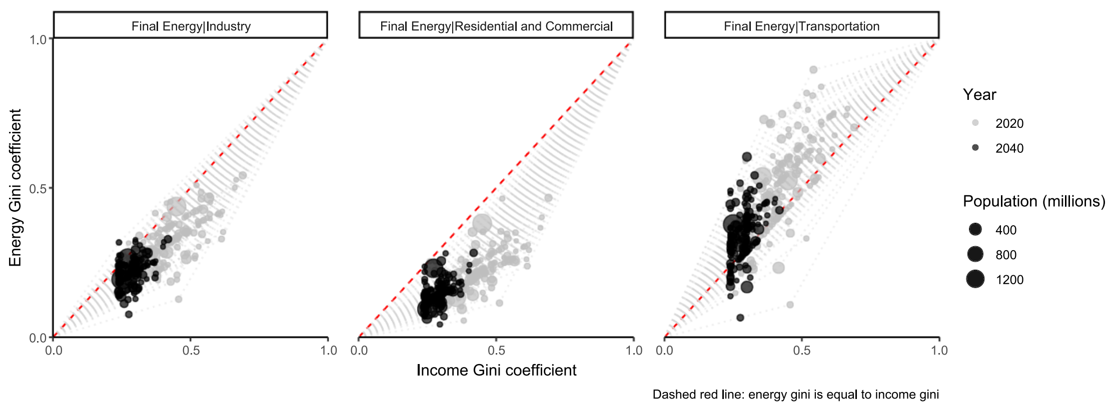

Figure A4. An illustration, using SDP-RC, of how changes in the income Gini relate to changes in the energy Gini.

integrating x from zero to the threshold over $x \cdot p(x)$. The energy needs gap is calculated as the deprivation headcount multiplied by the depth-of-deficit.

Appendix B. Comparing historical DLE and DLS data

Validating model behaviour for future scenarios is notoriously difficult, especially in the absence of high-quality historical time series data. It is however possible to show how the output from DESIRE compares to bottom–up calculated decent living gap indicators. First, we compare the energy gap from DESIRE with bottom–up constructed energy gaps (following methods in Kikstra *et al* 2021) in figure B1.

Next, we explore how residential and commercial energy needs gaps relate to DLS deprivations. First, we calculate the relative service and relative energy needs gaps. We put all indicators on the same scale, scaling from zero service or energy consumption to the service or energy threshold of each DLS dimension. This means we look at the *relative DLS gap* (DLS met/ DLS for all) and *relative DLE gap* (DLE needs met/DLE for all). Sectoral relative DLE gaps are not expected to be equal to relative DLS gaps. The key reason for this is that sectoral energy demands are related to multiple services, and each service may relate to more than one energy sector. In addition, there is also the difference in methods, where between bottom–up constructed DLS gap indicators capture within-country differences in DLS provisioning better than DESIRE output which does not capture subnational variation in the DLET.

To understand what the modelled energy indicators tell us about the level of DLS provisioning in a country, we look at a cross-section of the 2015 national relative DLS gaps and compare it to the most relevant relative DLE gap obtained from DESIRE output in 2020 (figure B2 panel (A). The use of different years is pragmatic, limited by data availability, and introduces some additional unknown inaccuracy in the comparison. Notwithstanding considerable country-specific variation, we find that the relative DLE gap for residential and commercial needs is typically higher than individual DLS gaps, due to the former being the sum of many decent living services. This effect generally outweighs the effect of country-specific difficulties in delivering services even in cases of high enough energy availability. Part of the variation is likely also attributable to DESIREv1.0.0 not capturing within-country differentiation of energy needs, and the difference in years. A correlation between housing and the residential and commercial energy gap is clearly discernible, although some countries have non-negligible populations living in slums not captured in the energy gap. The cooling gap has a unique pattern, reflecting the disproportionately high cooling gap. Low-income countries with high transportation gaps typically have higher modal shares of public transport, yielding relatively lower energy gaps. The opposite dynamic is observed for high-income countries with high shares of energy intensive transport (car use).

Lastly, noting the dimension-specific correlations, we also compare aggregate residential and commercial indicators for deprivation headcounts (figure B2 panel (B) and relative gaps (figure B2 panel (C). Even while DLS are non-substitutable, and energy gaps depend strongly on the varying energy intensity of the existing gaps in each country, we find some very limited correlations between the aggregate DLE and DLS indicators, implying that energy indicators still explain a proportion of the variance in aggregate DLS gaps, and may capture similar development trends. Patterns across services between the residential and commercial services and energy deprivation headcounts are similar to the patterns observed for the relative gaps. While the mean and maximum aggregations carry some information, aggregating using the minimum DLS gap (which is dominated by telecommunication access) is not informative.

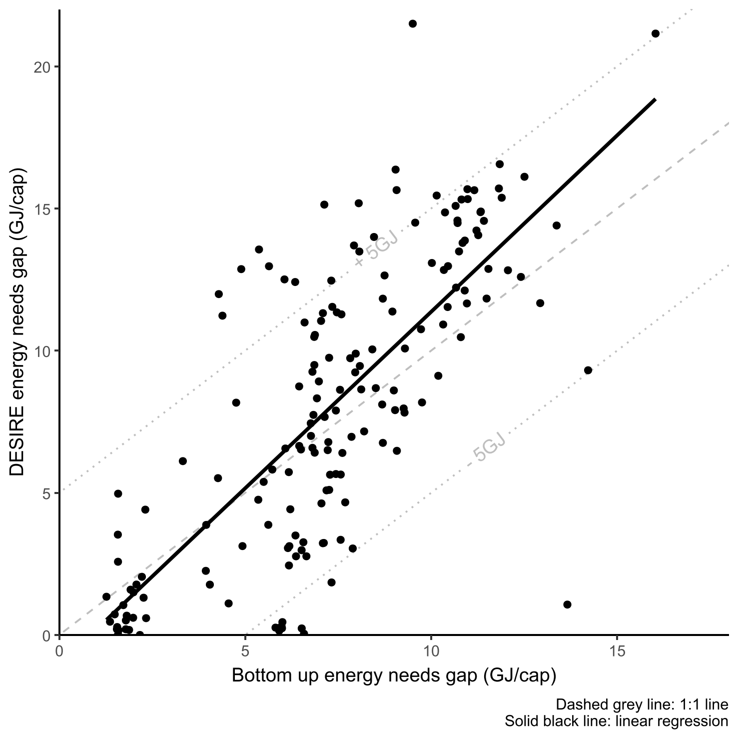

Figure B1. 2020 energy gaps in DESIRE v1.0.0 compared to bottom–up energy gaps.

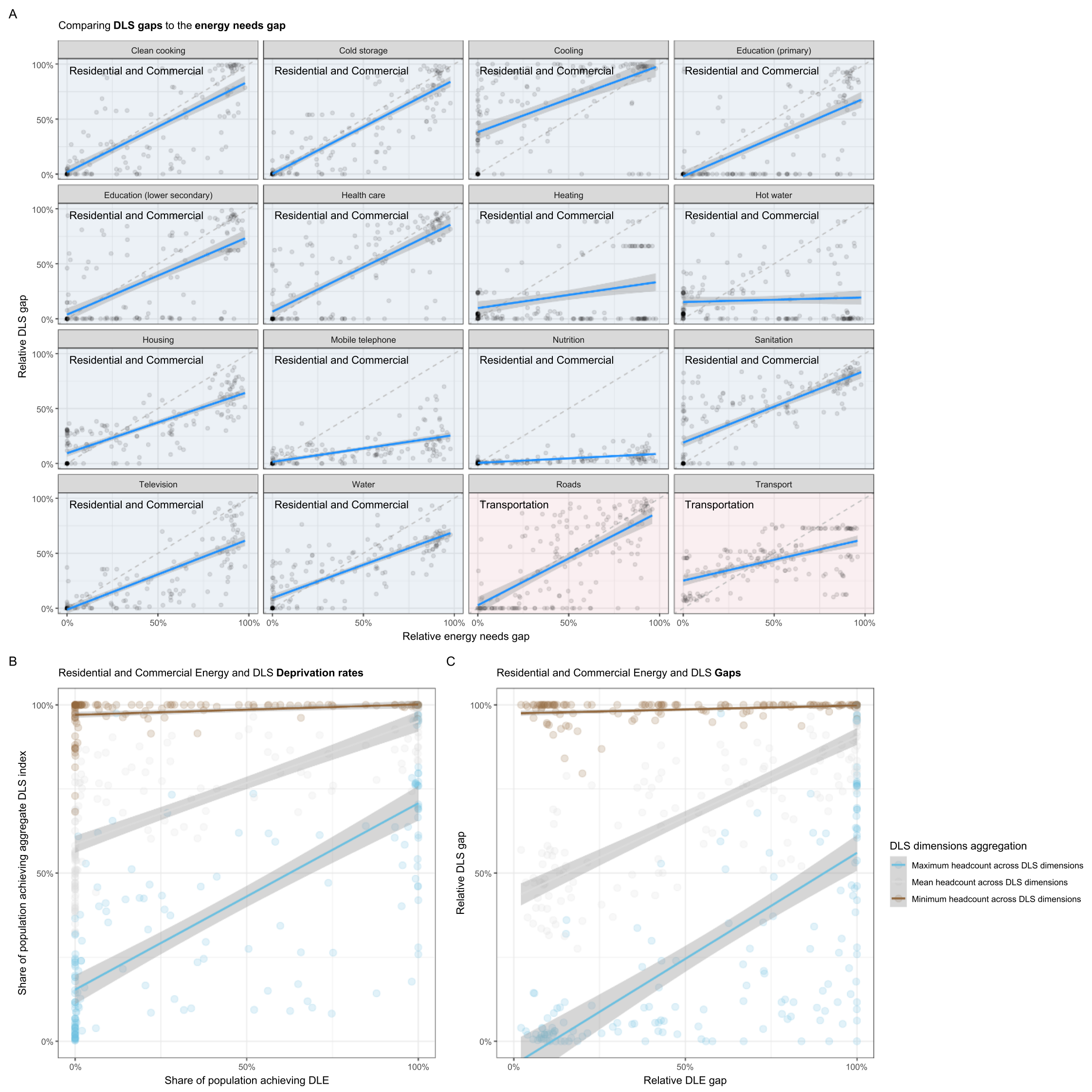

Figure B2. Cross-sectional relationships between relative energy needs gaps and decent living standards (DLS) gaps. Panel (A): comparing energy needs gaps to DLS deprivations, across DLS dimensions. Panel (B) and C: residential and commercial energy deprivation rates (B) and gaps (C) compared to the minimum, mean, and maximum DLS deprivation (B) and DLS gap (C) for each country in our dataset.

Appendix C. Decent Living deprivation rates and GDP per capita

In our analysis of energy gaps, we do not use GDP data. We note that the link between GDP (PPP) per capita and the decent living deprivation rate per country changes drastically in the SDPs, especially for the residential and commercial sector, for all SDPs (figure C1). While GDP per capita levels across countries correlated with the percentage of population consuming less energy than the national DLET in 2020, this relationship is virtually gone in 2040 when most countries meet basic energy needs in the buildings sector. In other words, this indicates that using only GDP per capita levels in the SDPs does not provide much information regarding the achievement of absolute basic needs for the residential sector covering many of the DLS dimensions. The picture is different for transportation, where the relationship continues to exist in 2040, as the SDPs do not prioritise providing high levels of motorised passenger transportation to all as much as they prioritise access to residential basic needs.

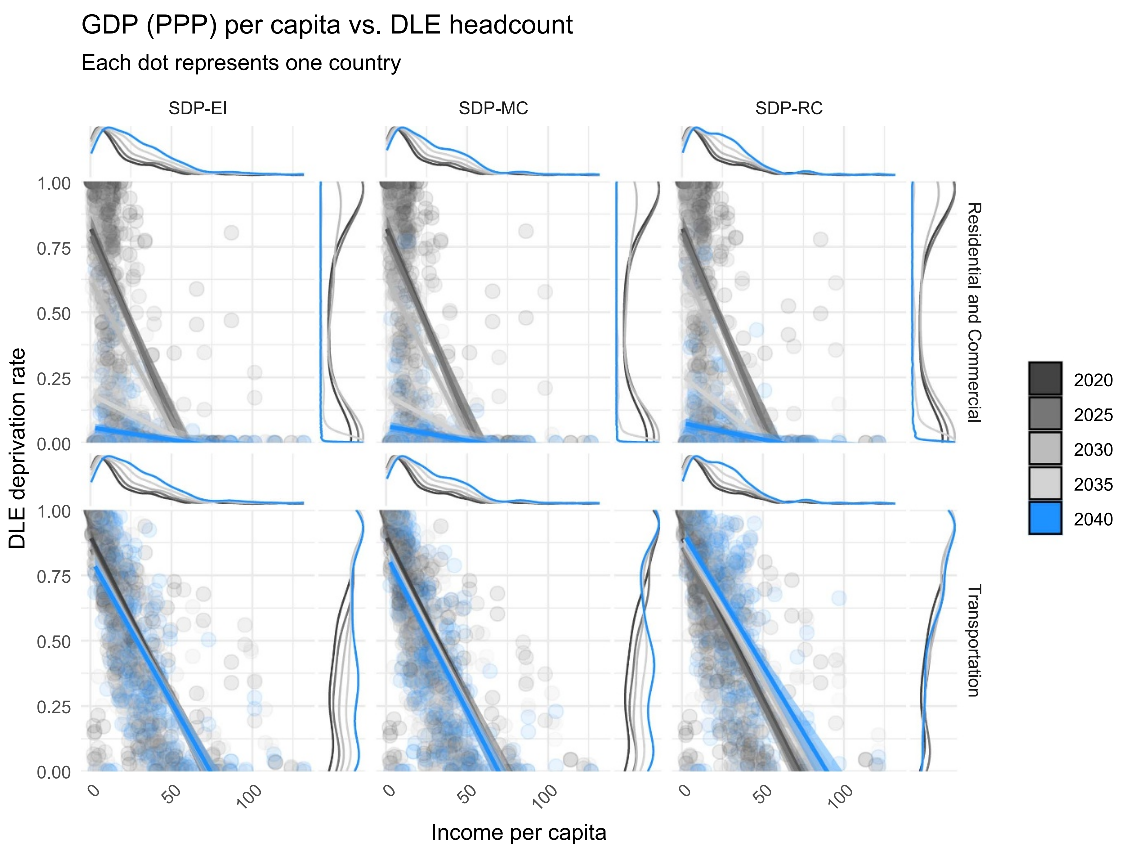

Figure C1. Visualising the change in the cross-sectional relationships (linear regressions) between the sectoral decent living deprivation rate and per capita GDP from 2020 until 2040 in the sustainable development pathways (SDPs).

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