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# A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies

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**Scenarios that limit global warming to 1.5 °C describe major transformations in energy supply and ever-rising energy demand. Here, we provide a contrasting perspective by developing a narrative of future change based on observable trends that results in low energy demand. We describe and quantify changes in activity levels and energy intensity in the global North and global South for all major energy services. We project that global final energy demand by 2050 reduces to 245 EJ, around 40% lower than today, despite rises in population, income and activity. Using an integrated assessment modelling framework, we show how changes in the quantity and type of energy services drive structural change in intermediate and upstream supply sectors (energy and land use). Down-sizing the global energy system dramatically improves the feasibility of a low-carbon supply-side transformation. Our scenario meets the 1.5 °C climate target as well as many sustainable development goals, without relying on negative emission technologies.**

The purpose of the global energy system is to provide useful services to end users. End-use demand determines the size of the energy system and so the challenges of mitigating climate change[1]. Rises in energy demand place an ever-larger burden of emission reduction onto supply-side decarbonization. Global mitigation scenarios tend to focus on supply-side solutions[2]. Available emission budgets for a 1.5 °C warming create a need for large-scale negative emission technologies that have been critically assessed in terms of limitations and uncertainty[3,4].

Energy end-use is the least efficient part of the global energy system[5] and has the largest improvement potential. Improving end-use efficiency also leverages proportionally greater reductions in the energy resources needed to provide for human needs[6] (Supplementary Note 1). In this study we describe an energy end-use and efficiency-focused future scenario based on the major trends observable today. Consistent with our scenario narrative, we provide bottom-up quantifications of changes in activity levels, energy intensities and final energy demand to 2050 for all the major energy end-use services and corresponding upstream sectors. Using the global integrated assessment modelling framework MESSAGEix-GLOBIOM (MESSAGE, Model for Energy Supply Strategy Alternatives and their General Environmental Impact; GLOBIOM, Global Biosphere Management Model)[7], we show how an appropriate scaling down of the size of the global energy system creates the necessary space for a feasible supply-side decarbonization within a 1.5 °C emission budget without the need for negative emission technologies and with significant sustainable development co-benefits.

## Scenario narrative of low energy demand

Our global scenario is called Low Energy Demand (LED). The LED scenario narrative has five main drivers of long-term change in energy end-use: quality of life, which is the continued push for higher living standards, clean local environments and widely accessible services and end-use technologies[8]; urbanization, which refers to continued rapid urbanization, particularly in mid-size cities in developing countries[9]; novel energy services, which sees a continued historical trend of end users demanding novel, more accessible, more convenient, cleaner and higher-quality energy services[10]; end-user roles, which means the continued diversification of roles played by end users in the energy system from consumer to producer, trader, citizen, designer and community member[11]; and information innovation, which involves continued rapid improvements in the cost and performance of information and communication technologies (ICTs) that support the drivers' widespread application[12]. Each of these drivers is clearly shown to shape the current energy-related developments (Supplementary Note 2).

These five drivers of change interact to generate five additional elements of the LED scenario narrative: granularity, which refers to the proliferation of small-scale, low-unit-cost technologies that enable experimentation, rapid learning and equitable access[13]; decentralized service provision of energy generation, distribution and end use, with a piecewise expansion or adaptation of a centralized infrastructure[14]; use value from services, which means a move away from the ownership of single-purpose goods to 'usership' with flexible multipurpose services delivered through digital platforms or sharing economies[15]; digitalization of daily life, which describes

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the integration of sensors, processors, wireless communication and control functionality into energy-using technologies and daily routines[16]; and rapid transformation, which is the accelerated improvement demanded by end users in the changing form and quality of energy-service provision as incomes and aspirations rise.

We emphasize four important points of difference between LED and the large body of climate change mitigation scenarios[17]. First, the LED scenario narrative describes rapid social and institutional changes in how energy services are provided and consumed, in addition to technological innovation (Supplementary Note 2). Second, this narrative is significantly less reliant on stringent climate policy than comparable low-emission scenarios (Supplementary Notes 2, 10 and 11). Third, LED is strongly focused on energy end-use and energy services (see below and Supplementary Notes 3–6). Fourth, downstream changes in LED, in turn, drive structural change in the intermediate and upstream sectors (see below and Supplementary Notes 7–9).

## Final energy demand by end-use service

We map the LED scenario narrative onto changes from 2020 to 2050 in the activity levels and intensities of the four main end-use services. LED has been designed to match, and, in most cases, to far exceed the activity levels or amount of energy services provided in comparable scenarios, but with drastically reduced energy inputs.

Highlights of LED for energy end-use are summarized below and in Table 1, which also provides links to extensive further documentation in the Supplementary Information. Figure 1 summarizes the decomposition analysis and changes in final energy demand that resulted (see also Methods).

Thermal comfort in LED is characterized by conditioned and adequate residential floor space that converges globally to $30\,m^2\,capita^{-1}$ by 2050 (the current average in the global North). This is a factor of three higher than the minimum acceptable for a decent standard of living[18]. Energy use per square metre of floor space improves dramatically towards the current best-practice designs for new construction (in the global South) and for building retrofits (global North), in line with recent scenario literature (Supplementary Note 3).

Consumer goods continue to proliferate in line with rises in living standards. By 2050, the number of devices increases by 80% in the global North and almost by a factor of 3 in the global South. Energy efficiency improves significantly per device. The integration of multiple service functions in single devices (particularly smartphones) yields up to a 100-fold potential power savings while in use (Fig. 2). Devices increasingly become 'smart' and interconnected, which opens up potential for controllability, system integration (including load management) and demand response (Supplementary Note 4).

Mobility services (passenger kilometres) delivered in the global South increase by more than 100% by 2050 with the rise in populations, aspirations and living standards. Mobility also grows in the global North, but more modestly, constrained by urbanization and some virtual substitution of physical travel. Energy intensity improves drastically due to the combined effects of electric vehicles and new organizational models of service provision, which include shared mobility (Supplementary Note 5).

Food supply expands by one-third globally to feed a 20% larger population and to eradicate undernourishment and malnutrition. Food supply increases to $3{,}130\,kcal\,capita^{-1}\,day^{-1}$ and diets converge globally towards being healthier and more varied (Supplementary Note 6).

## Energy used in intermediate and upstream sectors

Changes in the type and quantity of energy services consumed by end users have knock-on effects on upstream energy use in commercial buildings, industry (including manufacturing and construction) and freight transportation.

The highlights of LED for upstream energy use are summarized below and in Table 1.

By 2050, commercial and public buildings expand by two-thirds in terms of floor area globally to $23\,m^2\,capita^{-1}$ in the global North and $9\,m^2\,capita^{-1}$ in the global South, where space constraints in dense cities stimulate new construction of flexible-use multipurpose buildings. Energy efficiency improves dramatically in line with thermal comfort trends in residential buildings (Supplementary Note 7).

Industry sees changes both downstream in the quantity and type of material goods, and upstream in the energy and material requirements of production processes (Supplementary Note 8). Industrial-process energy efficiency improves by one-fifth. The aggregate total material output decreases by close to 20% from today, one-third due to dematerialization, and two-thirds due to improvements in material efficiency. 'Dematerialization' describes a lower absolute material use due to increases in asset utilization, for example, shared-car fleets that require fewer cars. 'Material efficiency' includes lightweighting, for example, less material input per car.

Freight transport expands in activity levels (tonne kilometre) in both the global North and the global South, particularly by rail. Further growth is moderated by dematerialization and reduced transport distances in growing urban agglomerations. Modal split changes and vehicle-efficiency improvements combine to yield significant reductions in energy use per tonne kilometre transported (Supplementary Note 9). (International shipping and aviation are reported separately in LED as international bunker fuels to ensure consistency with energy statistics.)

## Summary of global energy demand in LED

Table 2 summarizes the constituents of the 245 EJ total global final energy demand in 2050, relative to reference levels in 2020 (see Methods). This total includes 8 EJ of additional final energy demand as a contingency reserve for the emergence of new energy services and 10 EJ for international bunker fuels used in aviation and shipping. Food calories are excluded from the energy-demand estimates, but energy needs for their production are included in the upstream sectors. Supplementary Note 10 provides extensive documentation per sector, comparisons to the literature and 2020 base year values.

## Supply-side transformation

LED describes a major transformation in the quantity and quality of energy services provided. Higher levels of energy services in absolute terms are provided with improved service efficiencies (for example, higher asset utilization), improved physical capital stock (for example, efficient building designs and retrofits) and granular end-use technologies with diverse applications or economies of scope (for example, batteries or fuel cells in vehicles, homes and grids). This demand-side transformation requires energy carriers with a high versatility or exergy (ability to do work). As a result, LED sees a strong electrification of energy end-use, consistent with the narrative of pervasive digitalization and more versatile end-use technologies that are also non-polluting at the point of use. Over the longer term, hydrogen also increases its share of the final energy demand (in addition to its role for energy storage).

Changes in energy end-use therefore drive supply-side transformation, as has been the case historically[10]. Consistent with the LED scenario narrative, granular energy-supply technologies, such as heat pumps, fuel cells and solar photovoltaics (PVs) proliferate. Granularity, decentralization and variable renewables pose significant challenges for system management and balancing, addressed via 'smart' transformation of physical networks and control systems and scaled-up storage and load-management options.

Figure 3 shows the global final energy demand bbase year and comparable scenarios withy end-use sector and by energy carrier,

**Table 1 | Main assumptions and findings, key references and links to Supplementary Notes, Supplementary Figures and Supplementary Tables**

| LED scenario | | Main assumptions | | Key references | Supplementary Notes | Supplementary Figures | Supplementary Tables |
|---|---|---|---|---|---|---|---|
| Rationale | | Underlying justification for the LED scenario's emphasis on energy services and final energy demand | | [5,6,61] | 1 | 1 | 1 |
| Narrative | | Overview and discussion of five scenario drivers and how these generate five additional elements of scenario narrative | | [9,10,18,32,62,63] | 2 | 2–7 | 2 |
| | | Activity levels | Energy intensity | | | | |
| End-use services | Thermal comfort | Roughly constant in the global North and a 35% increase in the global South converging to a global average of 30 $m^2$ $capita^{-1}$ | High service-efficiency thermal end-use technologies combined with a doubling of retrofit rate (global North) and new-build standards (global South) reduces energy intensity by 75% in the global North to around 160–170 MJ $m^{-2}$ and by 86% in the global South to 40 MJ $m^{-2}$ | [33,35] | 3 | | 3 |
| | Consumer goods | Increases by a factor of 2 in the global North to 42 devices per capita, and by a factor 3 in the global South to 24 devices per capita | Fall in global average electricity intensity, weighted by share of total devices, from 93 to 82 kWh $device^{-1}$, with the strongest reductions in lighting and appliances | [32,63] | 4 | 8 | 4–11 |
| | Mobility | A factor of 2 increase across all modes (particularly flexible route-shared vehicles) in the global South; 20% fall in the global North with larger reductions in road-based modes that offset increases in rail and air | 70% fall in global average energy intensity weighted by modal share, with the strongest reductions in road-based modes, which result from electrification, shared fleets, flexible public transit and active modes | [31,64] | 5 | 9–10 | 12–16 |
| | Food | Increase of food demand by 70–100% globally, combined with the continuation of dietary transition; food availability is solved in the global South, reaching an appropriate calorie intake | Energy-intensity impacts are not quantified in LED | [42,65–67] | 6 | | 17 |

Continued

**Table 1 | Main assumptions and findings, key references and links to Supplementary Notes, Supplementary Figures and Supplementary Tables (Continued).**

| LED scenario | | Main assumptions | | Key references | Supplementary Notes | Supplementary Figures | Supplementary Tables |
|---|---|---|---|---|---|---|---|
| Intermediate and upstream sectors | Commercial and public buildings | 43% increase to 23 $m^2$ $capita^{-1}$ in the global North and a 50% increase to 9 $m^2$ $capita^{-1}$ in the global South | Falls 76% to an average of 139 MJ $m^{-2}$ in the global North and falls 90% to an average of 44 MJ $m^{-2}$ in the global South | [33,35] | 7 | | 18 |
| | Industry | Demand for global commodities (steel, aluminium, cement, paper, petrochemicals and feedstocks) falls by around 15% to 6.4 Gt as a result of dematerialization (one-third) and improvements in material efficiency (two-thirds) | Global average energy intensity, weighted by activity shares of specific manufacturing and construction processes, falls by one-fifth to 16.7 GJ $t^{-1}$ | [32,34,68] | 8 | | 19–20 |
| | Freight transport | Rises by around 20% in the global North to 64 tkm $\times10^{12}$, and by around 70% in the global South to 58 tkm $\times10^{12}$, with stronger increases in rail (and shipping) and some reduction in truck activity | Global average intensity (MJ $tkm^{-1}$) falls by 50% to 0.5–0.7 MJ $tkm^{-1}$ for trucks and by 10% to 0.2 MJ $tkm^{-1}$ for rail; limited potentials for electrification in shipping and aviation, so no significant intensity changes | [64] | 9 | | 21–22 |
| | | **Main findings** | | | | | |
| Total final energy demand | | Compared to similarly ambitious climate-target and low-demand scenarios at both the global and regional levels (global North and global South), LED is identified as the lowest final energy demand scenario | | [17,19,32,60,69] | 10 | 11–12 | 23–27 |
| Supply-side transformation | | Changes in levels and structure of end-use drive supply-side transformation and decarbonization; trends towards electrification and increasing shares of renewables drastically reduce dependence on fossil fuels in end-use and supply; continued productivity increases in agriculture and lessened demand for biofuels allows for reforestation; scenario quantifications in the MESSAGEix-GLOBIOM Integrated Assessment Modelling framework are based on a SSP2 scenario set-up, but adjusted with assumptions derived from the LED scenario narrative | | [46,61] | 11 | 13–22 | 28–32 |
| Implications for SDGs | | Implications of LED on SDG1 (poverty), SDG2 (hunger), SDG3 (health), SDG7 (energy), SDG12 (responsible consumption and production), SDG13 (climate) and SDG14 (ocean) are assessed qualitatively and quantitively; SDG1 is assessed through the decent standards of living framework. SDG3 analysis is assessed using the GAINS model | | [3,4,18,70] | 12 | 23–26 | 33 |

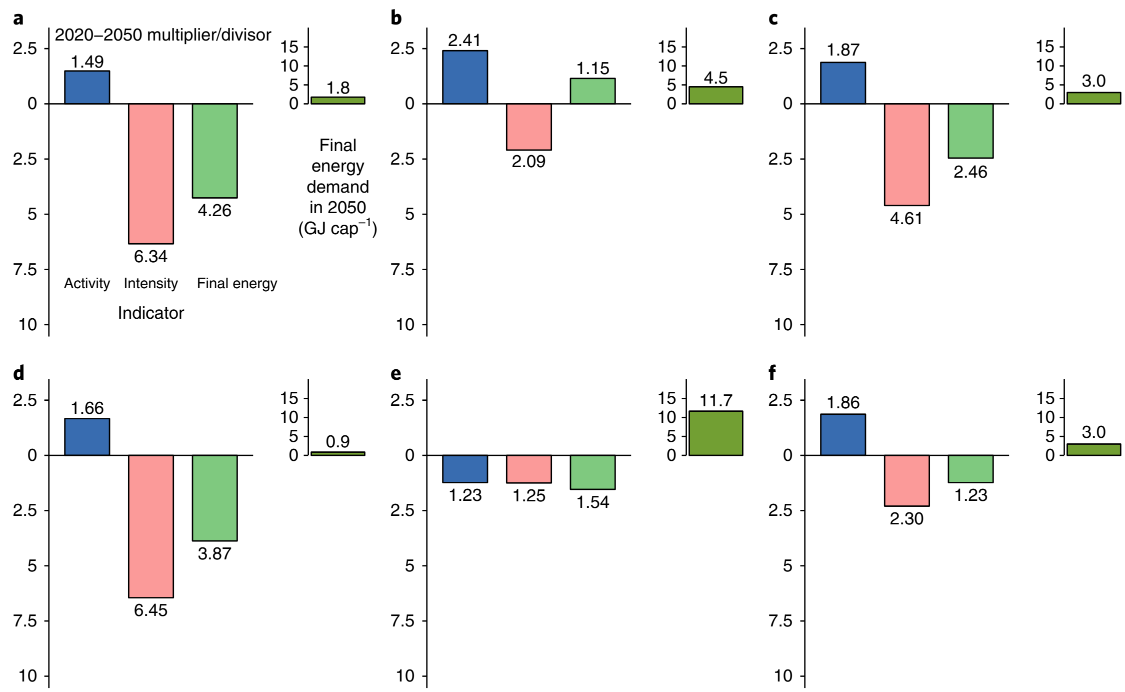


**Fig. 1 | Decomposition analysis of determinants of LED final global energy demand for end-use services and upstream sectors.** Changes in 2020–2050 in total global activity, energy intensity and final energy demand (left chart in each panel; variable multiplier above the *x* axis, divisor below) and resulting per capita final energy demand (GJ capita$^{-1}$) (right chart in each panel). Decomposition is represented by variable multipliers or divisors with the direction of change also shown. These are multiplicative and not additive, with the final energy change being the product of the activity and intensity changes between 2020 and 2050. **a**–**c**, End-use services for thermal comfort (**a**), consumer goods (**b**) and mobility (**c**). **d**–**f**, Upstream sectors for commercial and public buildings (**d**), industry (**e**) and freight transport (**f**). Regionally disaggregated results are given in Supplementary Note 10.

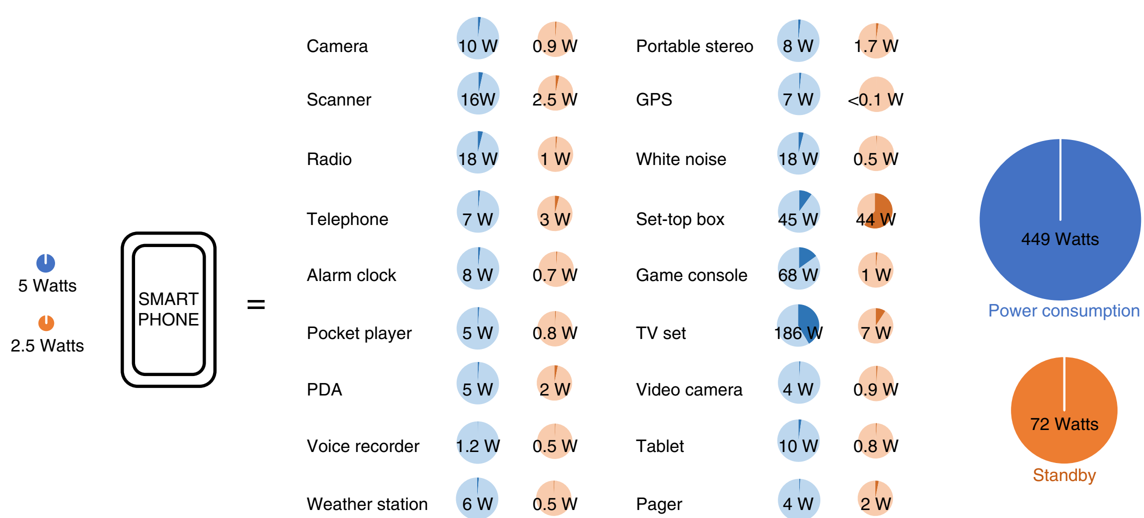


**Fig. 2 | Example of reduced energy demand through digitalization and device convergence.** A smartphone with 5 W of power and 2.5 W of standby-energy use provides a single integrated digital platform, which potentially substitutes for over 15 different end-use devices. The reductions in power that result (load (blue)) are close to a factor of 100, and reductions in standby-energy use (orange) are close to a factor of 30 (Supplementary Table 4). The wedges in each graph represent the share of the respective device in total power consumption (blue) and in total standby power (orange); for example, the load of 186 W for a TV set is over a third of the estimated total power consumption of substituted devices (449 W). Tupy[59] gives a pictorial representation. PDA, personal digital assistant; GPS, global positioning system, a navigation system that substitutes a map.

and the implications this has for the primary energy supply (Supplementary Note 11 gives a regional disaggregation). The results are shown to 2100 though LED is primarily concerned with the period to 2050. Historical context is also provided[19]. Energy demand is shown in absolute terms for the key years at the top of each panel and compared to other modelling projections for 2050 on the ruler (Fig. 3d).

LED's historical energy shares by sector remain broadly consistent into the future (Fig. 3a). In contrast, LED shows a significant structural change in end-use technologies and fuels (Fig. 3b) and

**Table 2 | Impact of the LED scenario on final energy demand in 2050**

| | | Region | % change in activity levels (2020–2050) | % change in energy demand (2020–2050) | Activity levels in 2050 | Energy demand in 2050 (EJ) | Total energy demand in 2050 (EJ) (GJ capita⁻¹) |
|---|---|---|---|---|---|---|---|
| End-use services | Thermal comfort | North | 6 | −74 | $47\times10^9$ m$^2$ | 8 | 16 (1.8) |
| | | South | 63 | −79 | $218\times10^9$ m$^2$ | 8 | |
| | Consumer goods | North | 79 | −25 | $67\times10^9$ units | 13 | 41 (4.5) |
| | | South | 175 | 54 | $186\times10^9$ units | 28 | |
| | Mobility | North | 29 | −60 | $25\times10^{12}$ passenger km | 16 | 27 (3.0) |
| | | South | 122 | −59 | $73\times10^{12}$ passenger km | 12 | |
| | Contingency reserve | | | | | | 8 |
| Upstream | Public and commercial buildings | North | 49 | −64 | $35\times10^9$ m$^2$ | 5 | 8 (0.9) |
| | | South | 77 | −82 | $68\times10^9$ m$^2$ | 3 | |
| | Industry | North | −42 | −57 | $1.0\times10^9$ t | 26 | 107 (11.7) |
| | | South | −12 | −23 | $5.4\times10^9$ t | 82 | |
| | Freight transport | North | 109 | −28 | $31\times10^{12}$ tkm | 11 | 27 (3.0) |
| | | South | 75 | −12 | $51\times10^{12}$ tkm | 17 | |
| | International aviation and shipping (bunker fuels) | | | | | | 10 |
| Total | | North[a] | | −53 | | 82 | 245 |
| | | South[a] | | −32 | | 153 | |

All sub-totals and totals are rounded (lower integer at numerical values <0.5, to upper integer ≥0.5). [a]Contingency reserve of 8 EJ is allocated equally to the global North and global South. Bunker fuels are reported at the global level only, consistent with current energy balances and emission accounting frameworks.

the upstream conversion that results (Fig. 3c). By 2050, close to 60% of global final energy is delivered by electricity and hydrogen. The rest of the final energy is provided by a diverse portfolio of energy carriers, which include gases, liquids and some district heat. Solids (coal and traditional biomass) are practically phased out. This structure of final energy demand allows a greater flexibility in the portfolio of supply options (Fig. 3c). Single-purpose fuel-supply chains (for example, from crude oil to refineries to gasoline to cars) are substituted by 'general purpose' electricity and hydrogen supplied by a variety of low-carbon resources: solar PV, wind, biomass, hydro and nuclear (in decreasing order of final energy supplied in 2050). Fossil fuels are increasingly phased out. Carbon capture and storage (CCS) for fossil or bioenergy is explicitly excluded in LED (Supplementary Note 11).

The final energy demand of 245 EJ by 2050 in LED is significantly below current values and also below comparable scenarios in the mitigation literature (Fig. 3d), including the lowest scenario of all those reviewed in the IPCC Fifth Assessment Report (274 EJ in 2050[17]).

However, from a historical perspective the structural change observed in LED is 'dynamics as usual'. Figure 4 shows the consistent dynamic of substitution from carbon to hydrogen to electrons in final energy, as energy resources and carriers shifted from fuelwood to coal to oil to gas and to electricity over the past 70 or so years. This dynamic has stalled over the past two decades; LED sees it restarted and continued out to 2050.

The rapid supply-side transformation in LED is enabled by its low final energy demand (Fig. 5). A lowered demand (Fig. 5a), via efficiency gains and changing end-use technologies and services, leads to pervasive electrification (Fig. 5b) and the diffusion of granular, decentralized energy-supply technologies, which include solar PVs. This results in a strong expansion of low-carbon energy resources in general (Fig. 5c,d), and of non-biomass renewables specifically (Fig. 5e,f). Annual growth rates by 2050 are about 3% and 5%, respectively. These are at or below comparable growth rates in other 1.5 °C scenarios. However, as LED scales down the whole energy system, these growth rates lead to much higher market shares: 80% and 55% of primary energy from low-carbon resources and non-biomass renewables, respectively (Fig. 5d,f).

A low energy demand also implies less need for biofuels, which reduces the adverse impacts on food security (Fig. 6g). Combined with continued agricultural yield increases and changing diets (Supplementary Note 6), cropland areas remain roughly constant, whereas forest cover expands from 4,000 to 4,300 million hectares (Fig. 6h). These changes in both energy and land-use systems have diverse benefits for biodiversity, health, poverty alleviation and climate (including a cumulative 168 Gt of carbon dioxide ($CO_2$) absorbed by forest sinks between 2020 and 2100).

## Implications of LED for sustainable development goals

LED outcomes translate into important benefits for many of the 17 United Nations sustainable development goals (SDGs), especially when compared to other mitigation scenarios. Figure 6 demonstrates important positive outcomes of LED for SDG2 (hunger (Fig. 6a)), SDG3 (health (Fig. 6b,c)), SDG7 (energy (Fig. 6d)), SDG13 (climate (Fig. 6e,f)), SDG14 (oceans (Fig. 6f)) and SDG15 (land (Fig. 6g,h)). However, it is important to note that SDG indicators are complex and have important distributional aspects not analysed here (Supplementary Note 12 gives a fuller discussion).

## Discussion and conclusions

Scenarios are possible futures based on a coherent and internally consistent set of assumptions about the driving forces of change[20]. The LED scenario is one such possible future. It comprises (1) a detailed narrative of future social, institutional and technological changes based on observable trends; (2) bottom-up estimates of activity, intensity and final energy demand in 2050 for four end-use services and five upstream sectors, consistent with the narrative, and (3) quantitative energy and land-use transformation pathways to 2050, with (4) resulting impacts on emissions and sustainable development.

LED is the lowest global energy demand scenario available. Its main findings are in stark contrast to much of the growing literature on energy and climate mitigation.

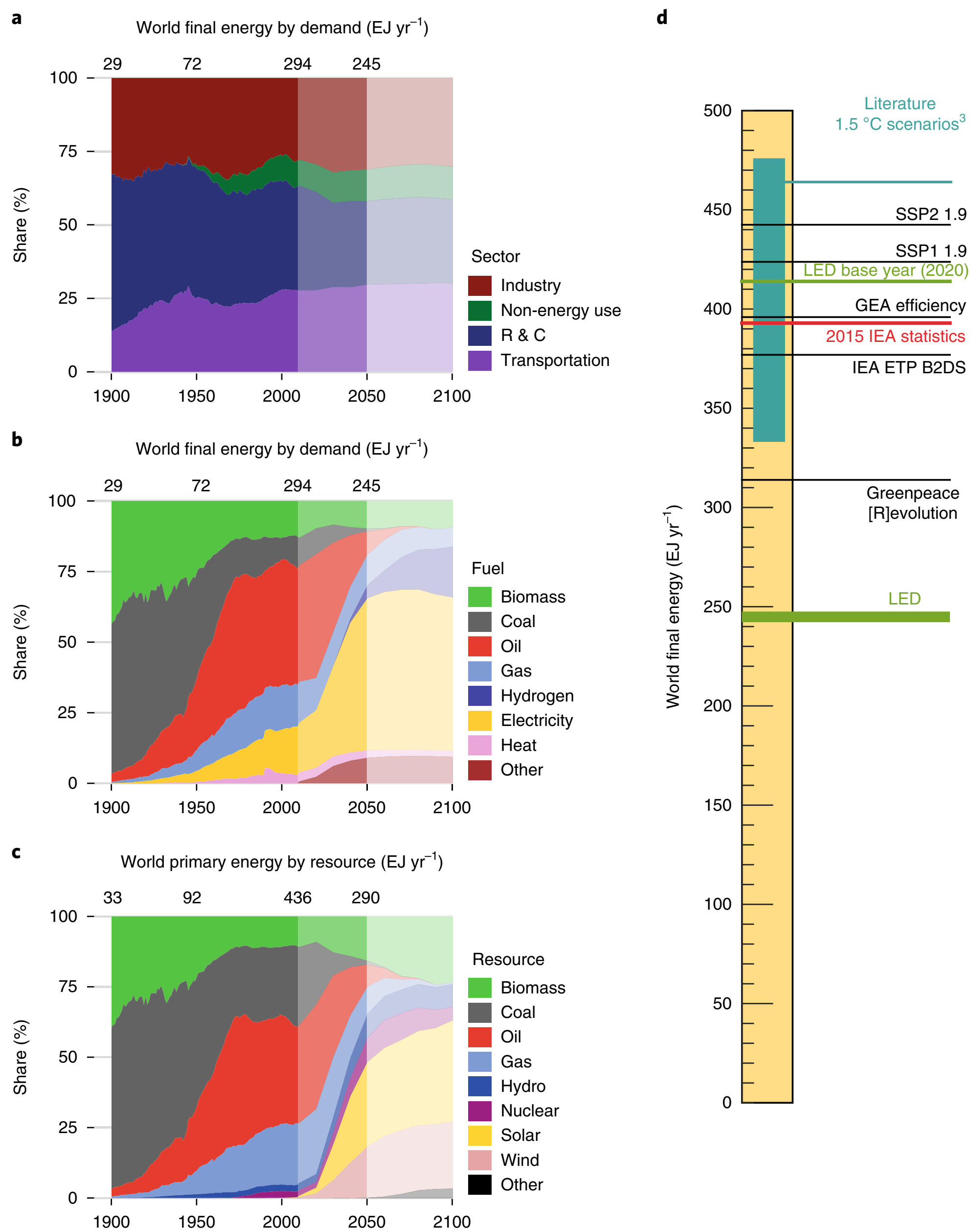


**Fig. 3 | LED scenario in historical context and in comparison to the literature. a–c**, Structural changes in world final energy shares by sector (**a**), final energy shares by fuel (**b**) and primary energy shares by resource (**c**): historical data to 2014 (darkest tint), the LED scenario to 2050 (lighter tint) and simplified scenario extension post-2050 (lightest tint) used for calculating climate change outcomes. The absolute levels of historical final and primary energy are indicated for key years on top of **a**, **b** and **c**. **d**, Final energy demand (EJ) for LED compared to 2015 statistics, LED 2020 base year and comparable scenarios with stringent climate mitigation for the year 2050, which include the SSP1 and SSP2 1.9 W m$^{-2}$ scenarios[7], other literature on 1.5 °C scenarios[3], the IEA Energy Technology Perspectives Beyond 2 Degree (B2DS) scenario[32] and the Greenpeace [R]evolution scenario[60]. The GEA Efficiency scenario that provided the starting point for LED is also shown. Note that the primary energy of non-combustible energy carriers is counted as the direct equivalent of secondary energy output. R & C, residential and commercial sector.

LED shows that improving energy-service efficiency is the key to achieving a range of climate and development goals synergistically. A lower demand results in greater flexibility and speed of both end-use and supply-side decarbonization, lowers pollution and reduces systems costs, as also found in previous scenario studies[21] that focused on lowering energy demand, although not to the extent of LED (Fig. 3d). LED also goes significantly further in showing that the 1.5 °C mitigation target can be achieved without relying on controversial and uncertain negative emission technologies.

Energy-service efficiency is the product of energy-conversion efficiency and 'use efficiency'. Enormous scope remains to improve conversion efficiencies through technological change and public policy, particularly envelope-pushing standards for buildings and appliances. Use efficiency is a more complex outcome of the organizational, institutional and infrastructural forms of energy-service provision. These effects are not commonly resolved in global scenario and modelling analysis. LED shows how an energy-service lens opens up new vistas for progressive action on global challenges.

This, in turn, opens many new avenues for further research. We highlight three in particular: economic implications, modelling, and implementation and policy.

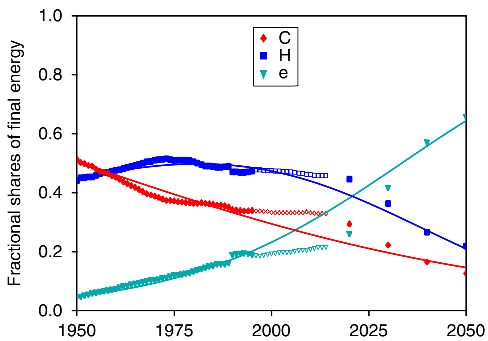


**Fig. 4 | Dynamics of change in global final energy structure historically and in the LED scenario.** Fractional shares of final energy provided by the (oxidation of) carbon (C), hydrogen (H) and electrons (e; electricity also includes direct uses of heat) analysed with a model of competing technologies or products. Hydrocarbon fuels are allocated to the respective carbon and hydrogen fractions of fuels based on their specific stoichiometric hydrogen–carbon ratios (for example, 1:4 in the case of methane, $CH_4$) applied to fuel energy contents using lower heating values. Symbols represent the historical (1950–2015) and LED data (2020, 2030, 2040 and 2050). Lines represent logistic substitution curves fitted to the combined historical data and to the 2020–2050 LED scenario data (filled symbols) with the 1995–2015 stagnation (open symbols) in the observable structural change omitted.

The aim of LED was to examine how changing forms of energy-service provision could potentially transform both the demand and the supply sides of the global energy system. Clearly, this has implications for commodity prices, economic growth, patterns of trade in energy technologies and resources, and other economic factors. We have not explored these in any detail, with the exceptions of the costs of supply-side investment and of carbon shadow prices. In both cases, LED compares favourably with other mitigation scenarios (Supplementary Note 11). For example, energy-supply investments in LED are 2–3 times lower than those in other 1.5 °C scenarios. However, this is a one-sided story without analogous quantifications of the demand-side investments and costs for which current data are mostly unavailable (Supplementary Note 11 gives a discussion).

However, the big economic 'elephant in the room' is the rebound effect. Historically, cheaper and more-efficient energy services have led inexorably to demand growth and welfare gains from higher consumption[22]. Could this be different in a LED future? First, compared to the past, there is increasing evidence of demand saturation in activity levels (along the well-established Engel curve for food demand)[23,24]. Examples include ever-fewer drivers' licences held by successive younger generations[25], indications of 'peak travel' or 'peak car travel'[26] and the decline observed in aggregate energy-use indicators, such as per capita electricity consumption in economies like California[27]. Second, rebound is not inevitable and can be managed by policy, for example, by adjusting taxation levels to offset efficiency improvements and so hold energy-service prices roughly constant (though this might be difficult to implement).

Model sensitivity analyses performed for LED show that its main conclusions (staying below 1.5 °C global warming without negative emission technologies) remain robust even if demand increases by up to +50% (Supplementary Note 11). This leaves a sufficient buffer to absorb potential rebound effects. Ultimately, LED's low energy demand outcomes depend on social and institutional changes that reverse the historical trajectory of ever-rising demand. How these can be endogenously represented in modelling studies remains a critical, multidisciplinary research agenda[28].

Policy also plays a critical role to drive and enable the change depicted by LED. First, strict and tightening efficiency standards are needed for building retrofits in the global North, for new construction in the global South and for appliances and equipment globally. Forward-looking standardization is also needed to reduce the transaction costs of technology and network integration. Second, rapid innovation, cost reductions and performance improvements from the widespread diffusion of granular end-use and low-carbon supply technologies require sustained innovation policies aligned to credible efforts to stimulate market demand[29]. Third, regulators need to ensure that space is opened up for new business models, digital integration and distributed service provision to overcome incumbents' vested interests to slow structural change[30]. These are important, but not insuperable, challenges towards a cleaner, cooler, healthier world in which high-quality living standards are enjoyed by all.

## Methods

**Scenario demand-development methodology.** We carried out a bottom-up assessment of activity, intensity and energy demand for four end-use services (thermal comfort, consumer goods, mobility and food) and five intermediate and upstream sectors (public and commercial buildings, industry, freight transport, energy supply, agriculture and land use) with the Global Energy Assessment (GEA) Efficiency scenario[1] as a starting reference point (Supplementary Note 2).

We mapped our LED scenario narrative down onto each end-use service and upstream sector by varying the GEA Efficiency assumptions about activity levels and energy intensities from 2020 to 2050 (Table 1). This included upward revisions to the amount of energy services provided in the global South to ensure rises in living standards in line with the LED scenario narrative. We then examined how these high levels of energy services could be provided with lower energy (and material) inputs than in GEA Efficiency, which focused more narrowly on technical improvements in energy-conversion efficiencies.

We used 2020 as a base year to ensure consistency with the decadal output reported by the integrated assessment model used to assess supply-side transformation. We adjusted 2020 data from GEA Efficiency if it deviated from either recently available observations or near-term projections (for example, activity levels for mobility in the global South are based on the International Transport Forum[31] and the International Energy Agency (IEA)[32], and thermal comfort provision in buildings data are based on ref. [33]). We provide detailed comparisons between our 2020 estimates and recent data for each end-use sector in Supplementary Note 10. Where necessary, we also enriched the GEA Efficiency data with further detail and analysis (for example, the dematerialization impacts on industrial production processes[34]).

Changes to the activity and energy intensity from 2020 to 2050 relative to GEA Efficiency combine to provide estimates of the final energy demand in 2050 (Table 1). We focused on a 2050 timeframe over which the major end-use and supply transformations of the LED scenario need to take place to meet the SDGs. To assess longer-term climate change implications, we extended the LED scenario to 2100 based on simplified assumptions (stationary energy demand), but we emphasize that the LED's analytical focus is on the period to 2050.

**Bottom-up assessments of energy demand.** Table 1 summarizes the headline changes to activity levels and energy intensities in the global North and global South over the period 2020–2050. Here, we explain the main underlying assumptions derived from relevant elements of the LED scenario narrative (further detail is provided in the relevant Supplementary Notes, with all the relevant links shown in Table 1).

*Thermal comfort.* Thermal comfort improves through strong end-user demand for higher living standards and an improved quality of life. Activity levels in the global South (approximated by floor space) rise to around 30 $m^2$ $capita^{-1}$, particularly in multifamily dwellings, given a pervasive urbanization and densification. In line with recent scenario studies[33,35], floor space in the global North converges downwards to a similar level as trends towards suburban single-family dwellings revert to urban living in cleaner, less congested, more amenable cities.

In the global North, retrofit rates double to around 3% of the housing stock per year stimulated by low-cost, low-hassle techniques to install prefabricated building shells that combine external wall insulation with solar PV and air-source heat-pump units (for example, by Energiesprong Foundation[36]). Offsite manufacture reduces costs for high-performance retrofits through standardization, economies of scale and controlled manufacturing. In the global South, increased cooling demands in new-build homes lead to a ratcheting up of the efficiency and indoor air-quality standards and improve building quality through best-practice design (for example, Passivhaus standards with forced ventilation and advanced regenerative room-conditioning systems).

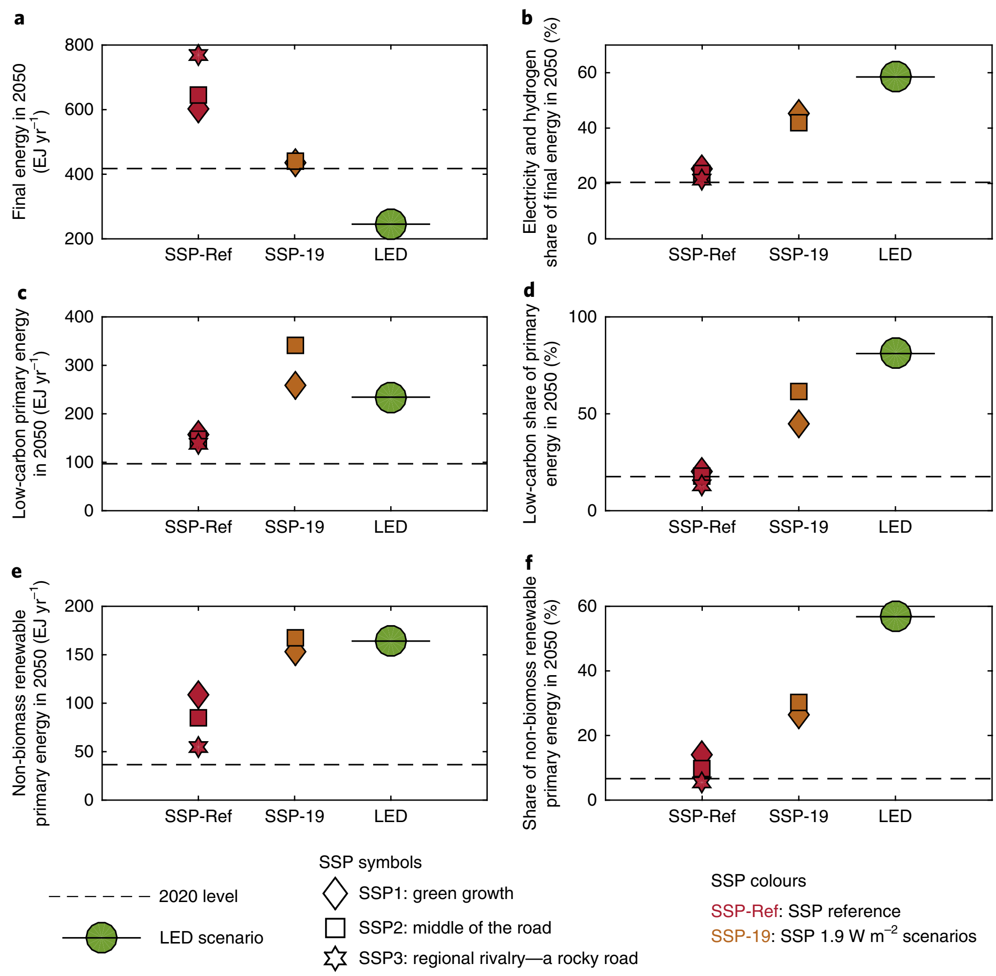


**Fig. 5 | Projected global final energy, low-carbon supply and non-biomass renewables in the LED scenario. a–d**, Global energy system in terms of final energy (EJ) in 2050 (**a**), share of electricity and hydrogen in final energy (**b**), annual deployment rate (EJ $yr^{-1}$) of all low-carbon resources in 2050 (**c**), and the resulting share (%) of all the low-carbon resources in global primary energy in 2050 (**d**). Low-carbon resources comprise solar, wind, hydro, geothermal, biomass and nuclear. **e**,**f**, The same data for non-biomass renewables only. All the panels compare the LED scenario with scenarios developed under the SSP framework, which include three SSP baseline scenarios with no climate constraints[44] (SSP1, SSP2 and SSP3) and two SSP 1.9 W $m^{-2}$ scenarios (SSP1 and SSP2; no 1.9 W $m^{-2}$ SSP3 scenario is available)[46] interpreted by the MESSAGEix-GLOBIOM model in separate studies.

Diversifying end-user roles within an increasingly decentralized energy system stimulates the diffusion of granular end-use technologies, which include heat pumps and fuel cells. Economies of scope (heating, cooling and hot water) create gains in energy-service efficiency relative to the traditional single-purpose systems (gas boilers and air-conditioning units).

*Consumer goods.* Consumer goods are not an end-use service per se, but provide for cooking, lighting, hygiene, entertainment, communication and other useful services principally within the home. In an energy-demand analysis, consumer goods tend to be bundled into 'specific electricity consumption' within the buildings end-use sector. As they are an important determinant of material well-being and living standards, we separate them out.

In the LED scenario, activity levels approximated by numbers of devices see increases by a factor of 2 in the global North and by a factor of 3 in the global South pulled by an increase in incomes and living standards (cooking and lighting). ICTs continue to diffuse and diversify to provide new and improved energy services. In the global North, activity growth is more constrained by increasing economies of scope as multiple functions converge into single devices (for example, smartphones).

The digitalization of devices and appliances accelerates. Low-cost distributed sensors, processors and wireless communication become ubiquitous. Connected and responsive 'smart' devices improve controllability and help reduce passive losses (for example, lighting unoccupied rooms). Cloud-based services disseminate operating improvements (as software patches) and allow for a rapid energy-performance optimization. Online platforms also enable peer-to-peer and commercial exchange of surplus capacity, which increases utilization rates of physical goods. Coupled with an increased uptake of shared mobility, 'usership' starts to weaken cultural norms of 'must-have' ownership. Consumers demand service quality, variety, flexibility, convenience and low life-cycle costs.

*Mobility.* Mobility-related activity levels (passenger kilometres) in the global South double as populations, incomes, work and leisure opportunities rise. Further activity growth is constrained by dense cities, shared modes and some substitution of physical mobility by telepresence as improving quality of life demands stringent action on air pollution and congestion. The same constraints reduce activity in the global North and stimulate vehicle and mode shifts away from private cars. The rapid market diffusion of electric vehicles with a factor of 3 improvement in power-train efficiency is enabled by the short useful life of vehicles, especially when compared to infrastructures. Real-time information via mobile devices support shared vehicle fleets (including autonomous vehicles) and flexible transit systems, which rationalize vehicle usage and reduce congestion[31,37]. Increasing vehicle occupancy by 25% and vehicle usage per day by 75% delivers the same intra-urban mobility with 50% of the vehicle fleet. By 2050, the total vehicle numbers halve to around 850 million light-duty vehicles.

Fewer vehicles allows the existing road infrastructure to be repurposed for walking, cycling and recreation. New forms of mobility as a service are characterized by ease of use, flexibility and variety of choice. High-frequency, high-capacity public transport routes emphasize the use of existing infrastructure (for example, rapid-transit buses) rather than lumpy new infrastructure with high sunk costs (for example, trams and trains). Electrified rail remains the mode of choice for long-distance inter-urban mobility.

*Food.* Food is an important determinant of human health and capabilities, but is not an energy end-use per se. We include it here because dietary preferences affect

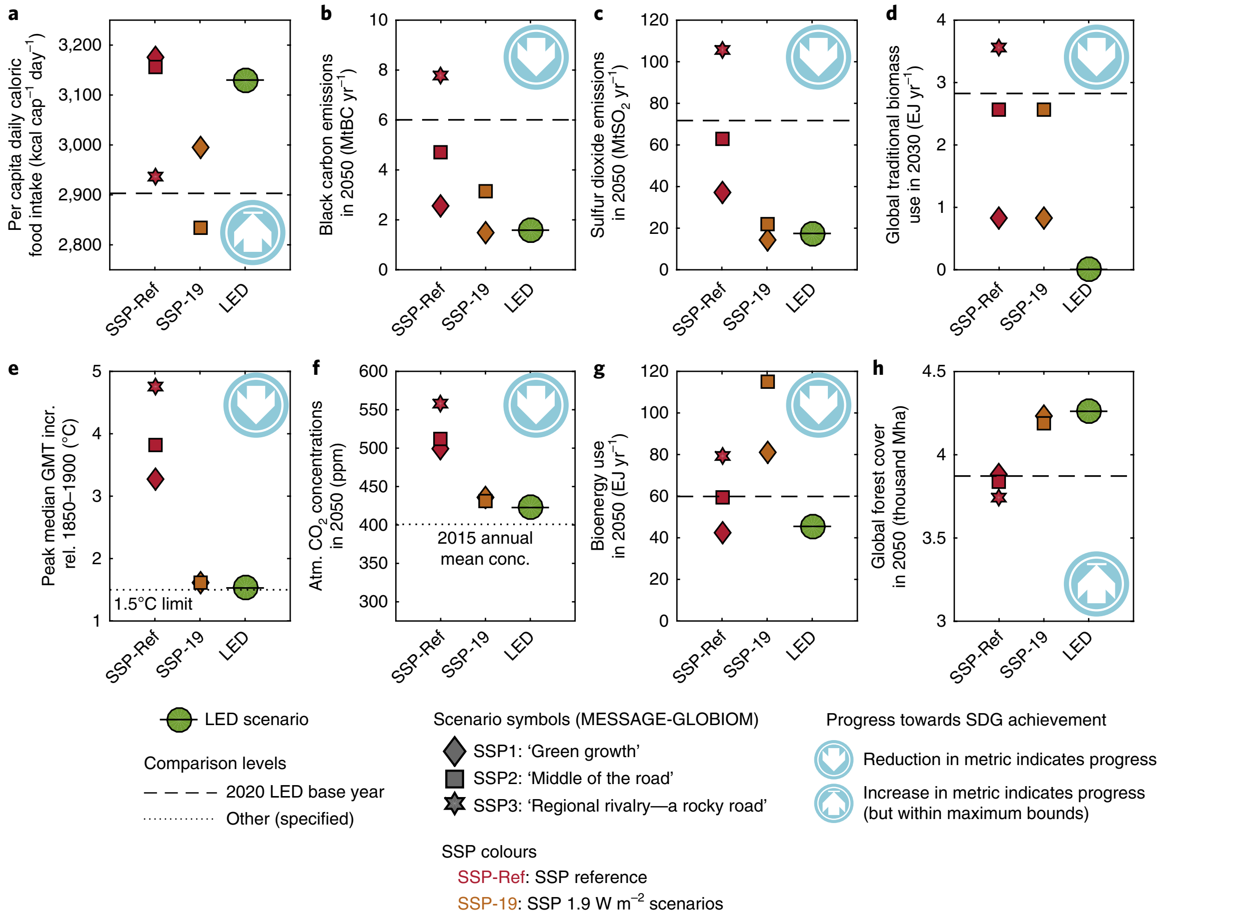


**Fig. 6 | Global SDG benefits of the LED scenario.** Panels show how the LED scenario results in multiple benefits across different SDGs. **a**, SDG2 (the risk of hunger is reduced by increased food availability). **b**,**c**, SDG3 (health is improved by reduced air pollution from black carbon (**b**) and sulfur (**c**)). **d**, SDG7 (less traditional biomass use indicates improved energy access to modern energy forms). **e**, SDG13 (reduced temperature change positively impacts climate). **f**, SDG14 (reduced $CO_2$ concentration reduces ocean acidification). **g**,**h**, SDG15 (less biomass use for energy (**g**) and larger forest areas (**h**) benefits biodiversity). All the panels compare the LED scenario with SSP scenarios, which include three SSP baselines with no climate constraints[44] (SSP1, SSP2 and SSP3) and two SSP 1.9 W m$^{-2}$ scenarios (SSP1 and SSP2; no 1.9 W m$^{-2}$ SSP3 scenario is available). Progress towards the achievement of SDG goals is denoted by circled arrow symbols (increase or decrease of the indicator). The arrows in the circles denote the direction of change to achieve positive SDG benefits, which in some cases can be achieved only within bounds (capped arrows, for example, simply maximizing forest cover would jeopardize cropland availability for food production and hence SDG2). Dashed lines show 2020 values or other target levels for comparison. atm, atmospheric; GMT, global mean temperature; incr. rel., increase relative to.

land-use change and greenhouse gas emissions from agricultural production. In the LED scenario, global food production increases sharply to provide a growing population with adequate calorific intake (including for the 800 million people currently undernourished[38]) and with adequate micronutrients (including for the 2 billion people currently at risk of one or more mineral, vitamin or other deficiency[39]). Growing concerns for healthy living also induce dietary shifts away from excessive calorific intake and red-meat consumption. In the global North, daily intake does not exceed 3,500 kcal in 2050, and meat consumption stays relatively constant despite an increase in prosperity.

Sustainable intensification dominates agricultural production, but diversifying end-user roles combined with rapid urbanization also lead to proliferating decentralized food production. Small-scale (granular) non-meat production systems become more common and include urban farms, vertical farms, hydroponic and aquaponic systems, and roof-top greenhouses that use waste heat from buildings. These trends are consistent with end users that play more active and heterogeneous roles in the final service provision, but make little impact on the aggregate global food production.

*Commercial and public buildings.* Commercial and public buildings range from offices and shopping centres to hospitals and schools. Drivers of change in the LED scenario are similar to those in residential buildings for thermal comfort (heating and cooling) and consumer goods (electricity-using devices and appliances). Activity levels increase in the global South. Space constraints in dense cities stimulate new construction of flexible-use multipurpose buildings. Economies of scope combine with digital exchange platforms to reduce surplus unused capacity. Thermal performance improves markedly through retrofit in the global North, and standards and best-practice designs in the global South. The conversion efficiency of end-use devices similarly improves through standards, digitalization, economies of scope and the reduction of passive losses.

*Industry.* Industry includes consumer-goods manufacturing, raw-materials processing and buildings and infrastructure construction. Energy use in industry is determined by downstream changes in the quantity and type of material goods required ('dematerialization'[40]), and the energy and material requirements of the industrial production processes ('material efficiency'[34]).

Activity levels (approximated by the weight of industrial output) grow significantly in the global South with increases in living standards and development aspirations for improved material well-being. Physical capital stocks and material standards of living in the global North are closer to saturation. Emphasis shifts to repurposing and optimizing the use of existing goods and infrastructure, and the quality of useful services provided. Consumer shifts away from ownership (with preferences for low upfront costs) towards 'usership' (with preferences for high-quality services) are supported by service-based and sharing-economy business models, enabled by pervasive digitalization. Service provision benefits from lower maintenance, longer-lived, higher-quality products, which lead to both lightweighting (lower materials use for same functional performance) and lifetime extensions (reduction in materials needed for replacements). One-off material inputs increase relative to low-quality 'throw away' designs, which reduces resource use overall as turnover rates fall and reuse rates increase. Multiple drivers of change in the LED scenario thus interact to dematerialize end-use services. Halving the private vehicle stock (see above) by 2050 reduces the global demand for steel by 14 Mt and saves around 3 EJ of industrial energy use. Consumer preferences for service quality in clean urban environments reduce the chemical substances in once-through use plastics, which reduces global demand for petrochemical and feedstock materials by 600 Mt and saves around 17 EJ of industrial energy use. Building lifetimes extended by 25% reduce cement use by around 20% (ref. [34]) and energy use by up to 2 EJ.

*Freight transport.* Freight transport in the LED scenario is strongly influenced by changing end-use demand for goods, and upstream changes in manufacturing and construction. As with passenger mobility, the rise in populations and incomes see the total activity, measured in tonne kilometres, rise strongly (+140%) in the global South. However, a combination of dematerialization, product life extension and urban-space constraints slow further demand growth for the movement of goods. The energy intensity of freight transport is shaped by similar drivers to those that affect passenger mobility, and include electrification and increased vehicle and transit utilization.

International statistics report energy and emissions data from international aviation and shipping separately. Following the same drivers of change in passenger mobility and freight transportation, we include an additional 10 EJ of energy use by international aviation and shipping (bunker fuels), which is roughly a 25% increase from current values. Limited potentials for electrification in shipping and aviation result in no significant intensity changes.

**System modelling of supply-side transformations in energy and land use.** The detailed bottom-up assessment of the quantity and type of end-use services (with corresponding changes in upstream sectors) provides us with a disaggregated final energy demand over the period 2020–2050. We assess how this impacts energy supply and land use with the MESSAGEix-GLOBIOM integrated assessment modelling framework[7]. This framework couples MESSAGE, an energy-supply model[41], with GLOBIOM, a land-use model that includes agriculture and forestry[42] using IIASA's ix integrated modelling platform.

*Energy supply.* The energy-supply impacts of the LED scenario were calculated using MESSAGE, which is a linear programming energy engineering model[43]. With its intertemporal optimization solution framework, MESSAGE minimizes the total discounted energy-system costs for a range of scenario-specific parameters (which include energy demands, resource availability and technology costs) subject to technical constraints (for example, demand–supply balancing) as well as scenario-specific constraints (for example, carbon emission budgets). For the LED scenario, target final energy demands from the bottom-up assessments were formulated at the level of final energy disaggregated to two regions (the global North and global South) and then downscaled to the 11 MESSAGE regions in proportion to their respective regional shares in the SSP2 scenario (see below)[44].

We ran MESSAGE by imposing three types of constraint. First, bottom-up assessments of the final energy demand per sector had to be met (Table 1). Second, the portfolio of available technology options had to exclude CCS and all negative emission technologies, such as bioenergy with CCS and the direct air capture of $CO_2$ (noting that afforestation calculated by the GLOBIOM model is not affected by this technology constraint). Third, cumulative carbon emissions had to fall within the budget of 390 Gt $CO_2$ between 2020 and 2100 to limit global warming to the 1.5 °C target by the end of the twenty-first century.

*Shared Socioeconomic Pathways (SSPs).* The SSP2 scenario[44] set-up provided the base parameterizations of our MESSAGE model runs in terms of resource availability, technology costs and efficiencies. We assumed a 3% discount rate for the intertemporal optimization. The SSPs are part of a new scenario framework established by the climate change research community to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation and mitigation.

Within the SSPs, SSP2 depicts a central, middle-of-the road pathway that describes a development consistent with intermediate challenges for both adaptation and mitigation[7]. The SSP2 storyline is described in O'Neill et al.[45]. It has also been interpreted with the MESSAGEix-GLOBIOM modelling framework. The quantitative results and the underlying modelling assumptions are summarized in detail in Fricko et al.[7]. In addition to the SSP2 baseline (with no climate constraints), alternative climate change mitigation scenarios with a target of 6.0–1.9 W m$^{-2}$ by 2100 have been developed[7,46]. SSP2-1.9 (SSP2 with 1.9 W m$^{-2}$ radiative forcing) is comparable to the LED scenario in its climate outcomes and consistent with limiting global warming to 1.5 °C.

In SSP2, global population growth is moderate and levels off in the second half of the century[47]. Gross domestic product (GDP) follows historical trends[48]. The availability of fossil energy resources (based on various sources[1,49]) reflects the intermediate characteristics of the SSP2 storyline[7]. Renewable energy resource potentials for solar and wind follow a central path and are classified according to resource quality (annual capacity factor) based on Pietzcker et al.[50] and Eurek et al.[51]. The resource quality curves are implemented in the MESSAGEix-GLOBIOM model[7] with regionally specific capacity factors for solar PV, concentrating solar power and onshore and offshore wind[52]. To account for the variability of solar and wind energy, MESSAGE incorporates renewable integration constraints[53].

Technological costs vary regionally; costs start out lower in the developing world, and are assumed to converge to those of present-day industrialized countries as the former becomes richer. Estimates for present-day and mature technology costs are from the GEA[1] and World Energy Outlook[54]. Assumptions for granular technologies, which include solar PV, small-scale hydrogen production, fuel cells and heat pumps, and distributed energy storage, such as batteries or fuel cells, were updated from SSP2 to reflect the more dynamic storyline of the LED scenario (Supplementary Table 28). For all other technology assumptions, the original SSP2 specifications were retained.

*Agricultural and land-use impacts.* The agricultural and land-use impacts of the LED scenario were assessed by feeding carbon prices and biomass demand for energy use from MESSAGE into GLOBIOM using the ix integrated modeling platform (hence the coupled models are refered to as MESSAGEix-GLOBIOM). GLOBIOM is a partial equilibrium model of the global agricultural and forestry sectors[42]. GLOBIOM represents major GHG emissions from agricultural production, forestry and other land use. Changes in socioeconomic and technological conditions, such as economic growth, population changes and technological progress, lead to adjustments in the production mix and the use of land and other productive resources. By solving the model in a recursive dynamic manner for 10 yr time steps, decadal trajectories are generated for variables related to supply, demand, prices, emissions and land use.

For the LED scenario, a food security constraint was imposed in GLOBIOM to avoid trade-offs with food security. The constraint ensures that the increased populations in the global South are not worse off in terms of animal and vegetal calorie intake as a result of climate mitigation efforts based on land use (for example, the expansion of bioenergy crops). In the global North, a minimum calorie-intake threshold was imposed up to which countries could reduce their consumption levels.

**Evaluating the impacts of LED scenario outcomes on a range of SDGs.** The quantitative outcomes of the LED scenario from MESSAGEix-GLOBIOM were evaluated against relevant SDGs (Supplementary Note 12). Poverty-eradication impacts were assessed through consistency checks with quantitative literature on the minimum acceptable thresholds for activity levels and energy demand per capita to ensure 'decent living standards'[18]. Air-quality and health impacts were quantified by linking MESSAGEix-GLOBIOM with the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model. GAINS projects emissions of air pollutants while considering air-pollution policies and standards, and computes the ambient concentrations of fine particles and associated premature mortality rates[55]. GAINS calculates emissions globally, whereas ambient concentration calculations focus on specific geographical areas that cover two-thirds of the world population. Climate change implications were assessed with the MAGICC (Model for the Assessment of Greenhouse Gas Induced Climate Change) reduced complexity carbon cycle and climate model[7,56] in a probabilistic set-up constrained by historical observations of hemispheric temperatures and uptake of heat by the ocean[57]. The model set-up is consistent with the latest assessment by the Intergovernmental Panel on Climate Change (IPCC) with regard to equilibrium climate sensitivity and transient climate response[58]. A similar set-up was used for the most recent climate assessment of emissions scenarios by IPCC Working Group III[17].

**Data availability.** Extensive documentation of LED scenario data, assumptions and bottom-up assessments are provided in Supplementary Information (Table 1 gives the relevant links). Data that describe the LED scenario from integrated assessment model outputs are publicly available in the LED database at https://db1.ene.iiasa.ac.at/LEDDB/. Analogous data for the SSP scenarios are publicly available in the SSP database at https://tntcat.iiasa.ac.at/SspDb/. The MESSAGEix modeling framework, that is, the software underpinning MESSAGEix-GLOBIOM, is available under an APACHE 2.0 open-source license at http://github.com/iiasa/message_ix. The documentation is available at https://MESSAGEix.iiasa.ac.at/.

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## Author Contributions

A.G. coordinated the project. A.G. and C.W. co-designed the study and co-wrote the initial draft manuscript and Methods. A.G., C.W., N.B., B.B.-K., V.K., D.M., N.D.R., K.R., J.R. and S.D.S. performed technical analyses of energy demand by sector, and contributed to sections of the manuscript, Methods and Supplementary Information. J.C. contributed to the technical analysis of the industry sector and to the Supplementary Information. K.R. coordinated the MESSAGE model runs performed by D.M. and V.K. with support from O.F., F.G., M.G. and D.H. P.H. coordinated the GLOBIOM model runs performed by P.H., S.F., and H.V. G.K., P.R. and W.S. contributed the air pollution and health impact quantifications. The figures were drafted by J.R., S.D.S. and C.W. All the authors contributed to analysing and interpreting the scenario results and commented on the manuscript, Methods and Supplementary Information.

## Competing interests

The authors declare no competing interests.

## Additional information

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