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Supplementary information

Plausible energy demand patterns in a growing global economy with climate policy

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Supplementary Information:
Plausible energy demand patterns in a growing global economy with climate policy

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Supplementary Note 1: Literature on decoupling energy demand from economic growth at the global level

The integrated assessment model literature suggests that projected faster reductions in energy intensity are relatively more feasible compared with most other mitigation challenges[1]. Either economic activity is not affected by different energy trajectories at all, e.g. in the IEA's World Energy Model[2] or PBL's IMAGE model, where GDP is exogenously given, or it has a small negative effect on growth, when carbon prices induce input combinations that substitute other inputs for energy (see also supplementary note 5 and Methods). Yet, while a certain rate of relative decoupling (GDP grows at a faster rate than energy demand) is well established for long-run cross sectional growth rates of large countries[3,4], little is known about the impact of much stronger efforts at restraining (especially final) energy demand on economic growth at the global level. Typically, studies are restricted to higher income countries, where some absolute decoupling actually takes place, sometimes against the backdrop of concerted policy efforts. But as the multiregional input-output literature emphasises, looking only at one part of the world and drawing general conclusions can be misleading, since the parts' behaviours are interdependent[5,6]. Recent results suggest that national level decoupling in rich countries is weaker when taking into account energy embodied in trade[7,8]. Given this limited evidence, simulation results showing near-term absolute decoupling at the global level need to be well explained.

The difficulty of restraining energy demand growth simultaneously in all countries (see also main text figure 1c) has led some to argue that the only way to reduce energy demand in line with climate change mitigation policies is via degrowth[9]. Against this stands the argument that degrowth to sufficiently low levels to achieve climate mitigation targets on a global scale is hard to square with other objectives, and moreover that more energy efficient innovations are more likely to occur in growing economies[10]. Engineering energy efficiency potential is large[11,12], but not necessarily cost effective[13,14]. The debate is complicated by uncertainty about rebound effects, whereby part of the cost savings from energy efficiency cause additional demand for energy, spurred by the *monetary* savings from economising on energy purchases[15]. Global macroeconomic rebound studies are rare and sensitive to parameter choices[16–18]. For the link with growth, a better understanding of this mechanism would be particularly important, as the 'growth effect' component of the macroeconomic rebound effect argues that energy efficiency improvements actually boost economic growth and thereby generate additional demand for energy.

Supplementary Note 2: Additional analysis of historical data

The fit for the main text figure 1a is mostly linear and flattens and worsens at the lower and upper ends, confirming prior findings for a much smaller sample[19]. Flattening at low levels of per capita income and energy use suggests a minimum level of energy use when output is low, due to large parts of the economy operating in non-market subsistence activities or (civil) war, such as during Liberia's (LBR) first civil war. Flattening above USD 75,000 and reversal at UD 133,000 represents mainly small countries that are major oil exporters and to a lesser extent financial centres like Luxembourg, where per capita GDP can be high while energy use is low or high due to specialization in finance, trade, or natural resources. Part of rich countries' energy consumption is invisible due to positive net energy imports embodied in energy intensive commodities produced elsewhere[20,21].

The historical correlations between output and primary energy per capita do not vary qualitatively between variants of calculating GDP either adjusted to account for living standards as in the main text or further adjusted to reflect terms of trade or national accounts growth rates as in the top row of extended data figure 1. They are also invariant to using employment instead of population to better reflect the correlation between different input factors – energy and labour – into production that produce output or limiting the sample to G20 countries as in the bottom row of that figure.

Extended data figure 2 shows the differences between primary and final energy (PE & FE) demand growth rates at the global level. Over most of the period, PE grew slightly faster than FE. After 2010 FE grew faster, which is unsurprising given the fast growth of new renewable power sources with higher primary to final conversion efficiency than fossil electricity generation.

Supplementary Note 3: Detail on low per capita final energy in the MAF region

A few scenarios show particularly low FE/capita in the MAF region in 2030 or 2040. The lowest, the POLES EMF33 “limbio” scenario shows a 56% reduction from 2020 to 2030 to a rate of below 0.5kW/cap. FE/capita demand in MAF drops 48% in WITCH-GLOBIOM 4.4 “CD-LINKS NPi2020_400” from 2020 to 2040, and it drops 43% in IMAGE 3.0.1 “SSP1-19” from 2010 to 2030. While the former two see below median economic growth, the IMAGE scenario shows the sixth highest MAF economic growth rate in the ensemble. The LED scenario also shows very low FE/capita of 0.62kW/cap in 2040 which then drops further to stabilise at 0.55kW/cap for the rest of the century. Note that main text Figure 2b adjusts scenario output so 2010 figures fit historical data. This can lead to differences between the exact levels of energy shown there and mentioned here.

Supplementary Note 4: Scenarios for all regions

Extended data figure 4 reproduces figure 2 from the main text but for other regions than the Middle East & Africa. The IPCC 1.5°C report database holds data for five regions: Asia, Latin America, Middle East and Africa, OECD (1990 members and EU28) and Economies in Transition according to the R5 regional grouping. Two things stand out about historical correlations: First, expect for the Economies in Transition's Slow period and the OECD's 1970s to early 1980s, and Millennium periods, energy demand per capita has risen historically. All exceptions correlate with important regional recessions/depressions: the collapse of planned economies in the Economies of Transition, and in the OECD the 1970s' oil crises and later the 2008-9 Great Recession and its aftermath. Second, periods of faster economic growth per capita, or productivity growth, were associated with faster growth in energy demand. Thus, the findings in the main text carry over to regions.

Exceptions correlate with notable politically motivated production patterns, such as Asia in the 'Gold' period, that included Mao's "Great Leap Forward", and the Latin American "Slow Period", which included the Lost Decade of the 1980s of military dictatorships and the IMF's austerity policies. It's also remarkable that economic growth in the Economies in Transition in the Gold period wasn't faster than that in Millennium. In the former period, a large share of these economies operated under Soviet planning, and the data suggest that this energy-intensive production method was no more conducive to economic growth than the much less energy intensive growth under a more market-oriented setup, at least to the extent that the Material Product System accounting used at the time can be converted reliably to GDP and taking into account that part of the Millennium growth was just a rebound from a deep recession in the 1990s resulting from the transition.

In the IPCC scenarios, all regions display abrupt departures from historical trends in terms of primary and final energy consumption, except the OECD, whose current Millennium trajectory is in the direction of SSP1 and SSP2 scenarios, albeit at a lower GDP growth per capita growth rate than in scenarios. It's remarkable that per capita SSP2 energy demand falls below that in SSP1 for Transition Economies and OECD.

Supplementary Note 5: Economic growth theory used in IAM models

Two key mechanisms are behind the breaks in the GDP-energy demand trajectory, both embedded in an explicit or implicit growth model. First, conventional (or neoclassical) economic production theory describes substitution between different types of inputs, such as capital, labour, and materials, using aggregate production functions that map input combinations to output (GDP) levels. Given a production function specifying possibilities for substitution among different inputs, cost minimization at given input prices determines the level at which each input is employed. In modelling climate change, it is crucial to include energy as an input, along with labour and capital. These production models imply that output can be maintained, even with reduced availability or increased cost of specific types of energy, if other inputs increase sufficiently. For example, the introduction of carbon pricing lowers fossil energy inputs. Constant output would require carbon-free energy inputs to go up or, if these cannot be increased rapidly enough or at sufficiently low cost, capital and labour inputs would have to be increased to compensate. A second mechanism is an increase in factor-specific productivity. For instance, a one percent increase in final energy-specific productivity would shift the production function so that the same level of output could be maintained with only 99% inputs on final energy, leaving other inputs unaffected. However, cost minimisation might lead to a change in input proportions too (this is where the rebound literature enters). The mechanisms remain intact with growth of GDP. To reduce the absolute level of energy inputs when the economy grows at 3%, substitution and productivity effects must reduce fossil fuel inputs by more than 3% (this symmetry is due to assumptions about constant returns to scale).

Not all models in the IPCC charting 1.5°C scenarios determine GDP endogenously (see also Table 1 below for an overview and extended data figure 6 for a comparison in energy demand reduction). Those that do all use a particular parametrisation to describe technology, a constant-elasticity-of-substitution (CES) production function.[e] In particular all three models underpinning archetype pathways use one (the LED scenario does not vary GDP). Elasticities of substitution between final energy and capital or labour inputs vary from 0.25 to 0.5. That is, final energy demand falls on average by 1% relative to other inputs for every 4% increase in the relative price of energy in MESSAGE-GLOBIOM, the model on which S2 and LED are based[22].[f] It falls by 1% for every 2.5% relative energy price increase in the AIM/CGE model

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[e] But even those models where GDP is exogenous receive their GDP time series from a CES production function model. For instance IMAGE's exogenous GDP comes from the OECD's ENV model.

[f] MESSAGE-GLOBIOM assumes an elasticity of substitution of 0.3 in the OECD, 0.25 in transition economies, and 0.2 in other regions. The example uses the unweighted average.

underpinning the S1 scenario, and a 1% drop for every 2% relative price increase in the S5's model: REMIND-MagPIE[23,24]. As this elasticity is invariant across the range of input ratios, the upshot is that a sharp deviation from observed trends in the energy-growth relation is assumed to be feasible as a response to almost arbitrarily large relative price changes. Given high enough carbon prices, economic growth can be combined with widely varying energy per capita ratios in these scenarios, as long as the elasticity of substitution does not tend toward zero.[25] An appendix to this section has more technical detail.

This theoretical monoculture is problematic. The use of CES production functions to depict factor substitutability is not further justified except with reference to convention. Production functions such as the CES are usually expressed as weighted harmonic means of the inputs, with scant justification apart from econometric tractability. Capital-energy substitutability is a matter of long standing, and unresolved, dispute[26–28]. Moreover, no empirical evidence can supply parametrisations at the global or regional level that would apply to the very strong reduction in energy demand envisaged. In this context it is apt to mention that alternative growth theories exist which typically do not assume substitutability but regulate input use completely via technological change, which also responds to price signals.[29,30] A recent contribution with such 'Leontief' production functions also includes energy inputs.[31]

Factor-specific productivity increases are discussed at length in the main manuscript. Their depiction in IAMs is less straightforward to summarise. While the values of the elasticity of substitutions used are typically mentioned in a model's documentation, the factor specific increases are not thus revealed. Within models, they differ across scenarios that make different assumptions about technological progress.

Appendix: CES aggregate production functions

An aggregate production function in economic theory is a function, f, that maps a vector of input combinations, $\vec{X}$, into an index of aggregate output, Y, such as gross domestic product,

$$Y = f(\vec{X}) \qquad (1)$$

With factor input prices, p_{X_i}, cost minimisation implies that at a given level of output $\bar{Y}$, for any two inputs X indexed by i and j $p_{X_i}dX_i + p_{X_j}dX_j = 0$. The partial first derivative of Y with respect to input factor X_i, f_{X_i}, determines that input's 'marginal product' which conventional economic theory assumes equal to that factor's input price. Therefore

$$\frac{dX_j}{dX_i} = -\frac{f_{X_i}}{f_{X_j}} = \frac{p_{X_i}}{p_{X_j}}$$

Constant elasticity of substitution (CES) functions, introduced by Arrow et al.[32], are a widely used concave parametrization of the general map in (1), and in the integrated assessment literature take the nested form

$$Y = f(K, L, E_1, \dots E_m) = \left[a_0 \big(g(K, L)\big)^{\frac{\sigma-1}{\sigma}} + \sum_{m=1}^{M} a_m (e_m E_m)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} \qquad (2)$$

where g(K,L) can be a CES or other production function, σ is the elasticity of substitution, K is capital, L labour and E_m one of M energy inputs, e_m is the energy input-specific efficiency parameter and a_m is a weight.[g] In the case of (2), some algebra shows that for any two inputs including the capital labor composite g(K,L)

$$\frac{dX_j}{dX_i} = -\frac{a_i}{a_i}\left(\frac{X_j}{X_i}\right)^{\frac{1}{\sigma}} = \frac{p_{X_i}}{p_{X_j}}$$

Letting X_j stand for the energy input E_1, the efficiency parameter, e_1, enters as

$$\frac{dE_1}{dX_i} = -\frac{a_i}{a_1}\left(\frac{e_1^{1-\sigma} E_1}{X_i}\right)^{\frac{1}{\sigma}} = \frac{p_{X_i}}{p_{E_1}}$$

so that the elasticity parameter σ regulates the extent to which price changes translate into factor substitution while the efficiency parameter reduces the units of E_1 required for substitution.

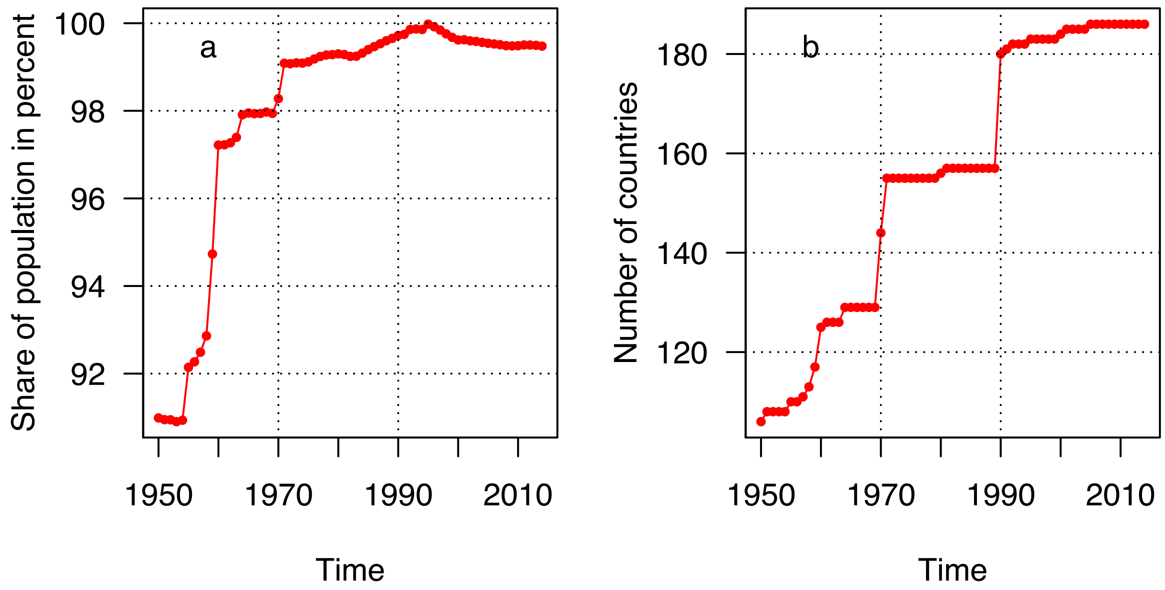
Supplementary Table 1 shows that 4 out of 7 models that underpin the scenario ensemble have endogenous growth models. All use CES production functions. The remaining three models have a simpler, largely exogenous presentation of production, that may however be indirectly informed by an external economic growth model with a CES production function. For instance, the IMAGE and POLES models' GDP relies on projections from the OECD's ENV-Growth model; however, changes in energy demand do not feedback into GDP growth in IMAGE trajectories.

[g] This formulation eschews other efficiency parameters for clarity of exposition.

Supplementary Methods

Supplementary Figure 1 | Historical data coverage

(a) Share of global population covered in each year of the historical data. **(b)** Number of countries covered in each year of the historical data.



Supplementary Table 1 | Overview of scenarios reaching 1.5°C.

Model	# of scenarios	# with (full) regional data	GDP calculation
AIM/CGE	7	7	Computable general equilibrium
GCAM	3	3	Exogenous
IMAGE	11	11	Exogenous (from OECD ENV-Model)
MESSAGE-GLOBIOM	12	12	Intertemporal optimisation single sector
POLES	16	15 (5)	Exogenous (from OECD ENV-Model)
REMIND	26	26	Intertemporal optimisation single sector
WITCH-GLOBIOM	5	5	Intertemporal optimisation single sector
Count	80	79 (69)	
Memo: Models with incomplete data (excluded)			
REMIND 1.5	4	0	Intertemporal optimisation single sector
MERGE-ETL	1	0	Computable general equilibrium
C-ROADS	5	0	None.

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