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

2
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6
7 **Reducing energy demand has become a key mechanism for limiting climate change,**
8 **but practical limitations associated with large energy savings in a growing global**
9 **economy and, importantly, its lower-income parts remain. Using new energy-GDP data,**
10 **we show that adopting the same near-term low-energy growth trajectory in all regions**
11 **in IPCC scenarios limiting global warming to 1.5°C presents an unresolved policy**
12 **challenge. We discuss this challenge of combining energy demand reductions with**
13 **robust income growth for the 6.4 billion people in middle and low income countries in**
14 **light of economic development's reliance on industrialisation. Our results highlight the**
15 **importance of addressing limits to energy demand reduction in integrated assessment**
16 **modelling when regional economic development is powered by industrialisation and**
17 **instead exploring faster energy supply decarbonisation. Insights from development**
18 **economics and other disciplines could help generate plausible assumptions given the**
19 **financial, investment and stability issues involved.**

20
21 Limiting global warming to 2°C or even 1.5°C requires carbon emissions from energy to reach
22 net zero by around mid-century¹. Reducing energy demand is considered a key mechanism
23 for emissions reduction and alleviates the burden on the two other principal measures:
24 decarbonisation of the energy supply, and carbon dioxide removal (CDR)². However, energy
25 is key for the economy. The implications for global and regional economic growth of reducing
26 energy demand are insufficiently explored but central in integrated assessment models
27 (IAMs).

28
29 Scenarios from IAMs synthesized in the IPCC Special Report on Global Warming of 1.5°C
30 assume that absolute decoupling (i.e. reducing energy consumption while growing GDP) is
31 both readily feasible and inexpensive³. The report presents 90 scenarios limiting the
32 temperature increase to 1.5°C by 2100. In the near term, all continue or exceed historically

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33 observed GDP growth rates. However, the scenarios assume declining primary energy (PE)
34 demand in contrast to historical patterns, with median global PE demand falling by 13.6%
35 between 2020 and 2030 to a rate of 507.5EJ/yr or 16.1TW, below the level of 2010. Some of
36 this reduction is achieved by shifting from fossil to more efficient renewable energy sources.
37 The resulting decarbonisation would be insufficient for meeting the 1.5°C constraint, so
38 scenarios also require final energy (FE) demand to fall by a median 8.0% over the same
39 period. Once decarbonisation is sufficiently advanced and/or CDR technologies become cost-
40 competitive after 2040, energy demand is projected to return to its historical growth trend.
41 These patterns are less pronounced, but qualitatively similar, in scenarios limiting temperature
42 rise to 2°C.

43

44 How plausible are these near-term projections? Economic growth-energy trajectories of rich,
45 de-industrialising countries can be argued to decouple, at least from territorial energy
46 demand⁴. But a large majority (84%) of the global population currently lives in low and middle
47 income countries which are still set on a development path paved by industrialisation. Using
48 a new global dataset on national output-energy relationships from 1950 to the present, we
49 discuss why decoupling trends contained in the current scenarios are hard to justify for
50 robustly growing developing countries and explore how the underlying models' explanatory
51 power could be improved. Focusing on the extreme case of the (relatively low-income) Middle
52 East and Africa region, we illustrate that scenario assumptions about decoupling, catching-
53 up, and energy demand (e.g. that per capita FE demand is projected to fall, often below levels
54 deemed critical for decent living standards, while income growth accelerates) imply a near-
55 term mitigation capacity qualitatively similar to that of rich countries and a development path
56 at odds with historical data and insights from development economics. While large efficiency
57 improvements are thermodynamically possible, achieving the projected absolute decoupling
58 alongside successful industrialisation presents an unresolved policy challenge. Growth
59 strategies, financing of investments in capital constrained developing countries, means of
60 technology transfer, and macroeconomic policy could facilitate both. Spelling them out
61 explicitly could clarify lower limits on energy demand in growing economies and help uncover
62 opportunities for modelling faster energy supply decarbonisation.

63

64 **Economic Activity and Energy Demand**

65 The dependence of economic output on energy can be expressed by decomposing GDP per
66 capita (or labour productivity), Y/P , often seen as a measure of affluence, into energy per
67 capita, E/P , and the inverse of energy intensity or energy 'productivity' of output in economists'
68 jargon, Y/E ,

69
$$\frac{Y}{P} = \frac{Y}{E} \frac{E}{P} \quad (1)$$

70 This is an economically-inspired decomposition⁵ related to the widely used Kaya identity.⁶
 71 Labour productivity growth requires either a decline in energy intensity (higher average energy
 72 productivity) or more energy per worker. Because energy enters the economy as primary
 73 energy (PE) and becomes final energy (FE) before acting directly on producing value as useful
 74 energy (UE), (1) can be further decomposed into

75
$$\frac{Y}{P} = \frac{Y}{UE} \frac{UE}{FE} \frac{FE}{PE} \frac{PE}{P} \quad (2)$$

76 where first law conversion efficiencies determine how much PE input is needed for a given
 77 useful energy output. Exergy or second law efficiency imposes upper bounds on these
 78 conversion ratios and thus a lower bound on energy intensity at every level.

79
 80 Reducing energy demand is different from decarbonising its supply: there is no particular
 81 reason why the economy cannot run on a 100% decarbonised energy mix. However,
 82 thermodynamics explains why a minimum of energy must be involved in all productive human
 83 activity. Primary to final energy conversion efficiencies can be vastly improved when
 84 decarbonising the energy supply, and its magnitude is partly an accounting question.⁷ The
 85 pivot is the final to useful conversion efficiency, for which large theoretical and also significant
 86 technical potentials for improvement exist.^{8,9} The pertinent obstacles in a socio-economic
 87 context however are economic and behavioural, i.e. practical, limits to the rate at which
 88 efficiency improvements can be implemented in growing and developing economies, whose
 89 primary aim is to raise labour productivity and income per capita, not to improve energy
 90 efficiency.

91
 92 **Historical trends**

93 The relationship between economic activity and energy demand has been widely analysed
 94 (see supplementary note 1). Historically, primary to final and useful conversion efficiencies
 95 have improved, but slowly. The useful energy to output ratio has no time trend¹⁰. Therefore,
 96 most labour productivity growth over the past three centuries translated into higher PE
 97 demand¹¹⁻¹⁴. Since the Industrial Revolution humans unlocked the energy stored in fossil fuels
 98 and power increasing amounts of useful labour human workers perform^{15,16}. Labour
 99 productivity rose twentyfold between 1820 and the end of the millennium in Europe and its
 100 Western offshoots¹⁷. Most other countries have since embarked on the same process of
 101 energy-intensive technical change, aspiring to similar increases in labour productivity and the
 102 resulting standards of living. Economic historians mostly track correlations in GDP and primary
 103 energy per capita¹⁶, although recent work tentatively confirms similar patterns for final and
 104 useful energy demand^{10,18,19}.

105

106

[Figure 1 about here]

107

108 The relationship between energy demand and labour productivity is clearly visible in historical
109 data. Figure 1a depicts annual time series for 185 countries over a period 1950-2014,
110 comprising ~99% of global population in most years, on a log-log scale. It reveals a very tight
111 correlation between GDP per capita and PE per capita, with a Spearman rank correlation
112 coefficient of 0.86 for the overall sample. While country-specific differences exist due to
113 geography, climate, institutions, idiosyncratic production and consumption patterns etc.,
114 pooled data show that increases in GDP/capita go in hand with increases in PE/capita, both
115 across countries and time. A flexible regression gives a nearly linear fit in the log-log plot over
116 the interval relevant to today's developing countries. The estimated GDP elasticity of primary
117 energy, i.e. the logarithmic derivative of primary energy divided by that of GDP, is 0.89 over
118 the interval of USD 2,000 to USD 20,000 in 2011 purchasing power parity (a country belongs
119 to the high-income group from a GDP of around USD 12,500 per capita). In other words, a
120 10% increase in GDP/capita corresponds to a 8.9% increase in PE/capita (see Methods), with
121 the difference capturing the gradual reductions of primary energy intensity, PE/GDP, over
122 time²⁰. The regression line flattens at very low levels suggesting a minimum level of energy
123 use even when large parts of the economy operate in non-market subsistence activities or
124 during (civil) war, e.g. the leftmost observations in the plot capture Liberia's first civil war. Data
125 points above USD 130,000 are small oil exporting countries, introducing strong idiosyncrasies
126 to the regression at such income levels. Our findings are robust to relevant subsamples (e.g.
127 only large economies, the G20) and to alternative measures of GDP and population (extended
128 data figure 1, see also supplementary note 2).

129

130 Globally, labour productivity and per capita energy demand have been growing over the
131 complete sample, except for periods of crisis. Figure 1b divides global rates of change of GDP
132 and PE/capita into three subperiods, corresponding to economic growth performance. The
133 fastest global labour productivity growth on record occurred during 1950-73, known as the
134 Golden Age of Capitalism (Gold)¹⁷. Rapid economic expansion was underpinned by an almost
135 equally rapid growth in energy demand in particular for cheap oil and electricity; and rural
136 electrification in many developing countries started virtually from scratch^{21,22}. The Golden Age
137 was followed by a period of crises and slow growth for the rest of the 20th century (Slow).¹⁷
138 Sluggish GDP growth during the 1973 and 1978-9 oil crises preceded the deepest recession
139 in 1981 the world had seen since the Great Depression. Deindustrialisation and productivity
140 slowdown in rich countries combined with the transitions of formerly socialist economies,
141 several of whom went through severe depressions, kept average growth rates lower

142 throughout the 1980s-90s²³. Higher energy prices and supply curtailment set in train energy
143 demand restraint and efficiency-increasing technological change in rich countries. Meanwhile,
144 the economic collapse of the Soviet Union forced a revision of its comparatively low efficiency
145 energy sector and production processes²⁴. China's fast machinery upgrading combined with
146 a shift towards light industry in the 1980s-90s, temporarily slowed its energy demand growth
147 relative to that of GDP²⁵. These one-time shifts produced an almost stagnant PE/capita
148 trajectory. After the millennium, growth in both measures rebounded, driven increasingly by
149 China's return to more energy intensive production, but also 'emerging markets' more
150 generally. Fast growth in both indicators was interrupted by the Great Recession 2008-09.
151 Growth rates subsequently returned to pre-millennium levels. Overall, faster growth in one
152 indicator was positively correlated with faster growth in the other, and PE demand growth was
153 a good proxy also for that of FE (extended data figure 2). And while energy demand in rich
154 countries has been stagnating and even falling, growth is continuing robustly in middle and
155 low income countries (figure 1c).

156

157 **Future Scenarios**

158 Stringent mitigation policy strives to break (some of) these historical trends. Scenarios of the
159 IPCC special report calculate that in order to achieve the 1.5°C goal, a structural break from
160 historical total energy-income relationships is needed in the coming twenty years. To characterize
161 this break, figure 2a combines future projections of GDP and FE/capita with aggregated
162 historical data from figure 1. The historical trend (black in figure 2a) is upwards and rightwards.
163 Extrapolations based on the three historical periods (red in figure 2a) continue in this direction:
164 faster economic growth in the Gold and Millennium periods (further right) is associated with
165 faster increases in energy demand (further up). In contrast, scenario pathways combine robust
166 growth in GDP/capita with an unprecedented sustained reduction in FE/capita, particularly in
167 the 2020s and 2030s. Qualitatively similar results hold for PE and for scenarios limiting
168 warming to 2°C (extended data figure 3).

169

170 **[Figure 2 about here]**

171

172 Four scenario pathways (blue in figure 2a), highlighted as so-called archetype scenarios in
173 the IPCC special report, are based on the shared socioeconomic pathways (SSP) 1, 2, and 5
174 and a 'low energy demand' (LED) scenario, which is also based on SSP2. Significant near-
175 term FE/capita reductions occur in all of them except SSP5, which assumes that current
176 carbon-intensive development is adopted globally and projects faster GDP/capita growth than
177 seen even during the Golden Age. Since other mitigation avenues are assumed to be
178 unavailable and/or exhausted, CDR is cost-effectively deployed to meet meaningful climate

179 targets in SSP5²⁶. In SSP2 past technological, economic and social dynamics are extrapolated
180 and CDR is less cost-effective²⁷. As a result, energy demand has to fall to meet the 1.5°C
181 target, with rates of energy intensity reductions surpassing previous records set in the 1980s-
182 90s. GDP/capita growth is robust, similar to the Millennium period average. The SSP1 “green
183 growth” scenario is optimistic by design and, therefore, least consistent with historical trends,
184 combining historically unobserved high GDP/capita growth rates with a 17% reduction in
185 FE/capita from 2020 to 2030²⁸. The LED is a Goldilocks scenario with the same baseline as
186 SSP2, but with efficiency improvements and demand reductions due to consumer habits
187 following best practice in both the global South and North²⁹. FE/capita falls by 32% from 2020
188 to 2030. This ensemble of scenarios unmistakably illustrates the clean break with past energy
189 drivers of economic growth underlying the 1.5°C and also 2°C targets.

190
191 This structural break extends to the regional level and is particularly striking for regions with
192 lower labour productivity, represented by the *Middle East and Africa* (MAF) region in figure 2b.
193 In this region, median GDP/capita growth and year across scenarios runs at healthy 2.5%
194 during 2020-2050, compared with stagnating 0.1% during 1973-2000 and meagre 1.4% during
195 2000-18. Since 1950, FE/capita has increased continuously in the MAF region, from less than
196 0.4kW/capita to around 1kW/capita. This is low compared to the global average of
197 1.75kW/capita and lower still in some African countries, as the MAF average masks the large
198 variation between Middle Eastern oil exporters and sub-Saharan agrarian economies.
199 However, rather than converging toward the world average and in spite of the evidence that,
200 especially at these low levels, development (including GDP growth) and energy are
201 particularly strongly correlated, almost all scenarios project steep declines in FE demand for
202 the MAF region³⁰. A majority of scenarios even move significantly below the 0.95kW/cap
203 (30GJ/yr/cap) FE identified as tantamount to low levels of development in the SSP literature
204 itself³¹. The most extreme case sees a 56% reduction from 2020 to 2030 to a rate of below
205 0.5kW/cap (supplementary note 3 details). Similar patterns are projected in Asia and to a
206 lesser extent Latin America (extended data figure 4 and supplementary note 4). Put differently,
207 the scenarios rely heavily on final to useful energy efficiency improvements to provide energy
208 services for development.

209

210 **[Figure 3 about here]**

211

212 Mitigation strategies can also be characterized by comparing scenarios with their own
213 baselines in addition to historical evidence³². Figure 3a documents the near-term deviation of
214 growth rates in both baseline and policy scenarios from historical rates. Global archetype
215 baselines (marked by disks) assume faster GDP/capita growth than historically observed in

216 the period to 2030, correlated with faster FE/capita growth in all but the SSP1 baseline. The
217 MAF region is the only region where every archetype scenario baseline assumes FE/capita
218 growth to slow down and economic growth to accelerate, thereby assuming some decoupling
219 already in the baseline. Remarkably, near-term GDP/capita growth accelerates in every single
220 global baseline of successful mitigation scenarios (extended data figure 5). Regions see more
221 variation. A few regional baselines exclusively in Asia and the OECD feature lower economic
222 growth rates, with Asia slowing from fast historical ones. Regional baseline FE/capita often
223 correlates positively with faster economic growth, but sometimes slows already like in the MAF
224 archetypes. In sum, baselines project near-term economic development highly successful by
225 historical standards, often but not always correlated with faster global energy demand growth.
226 Several regions are assumed to decouple already in the baseline.

227

228 Mitigation is assumed to leave economic growth rates virtually unchanged from baselines
229 while energy demand plummets. Deviations from baselines are an order of magnitude larger
230 for final energy than GDP (figure 3b). This is independent of whether GDP is exogenous or
231 endogenous in the IAM used (extended data figure 6a). The MAF region exhibits the same
232 flexibility for energy demand reductions from baselines as other regions, despite its much
233 lower base level and in addition to the substantial savings already assumed in its baseline
234 scenarios. After 2040 growth rates approach their historical averages across all scenarios. As
235 decarbonisation advances and/or CDR measures come online, energy demand becomes a
236 lesser constraint on emissions. These effects are qualitatively similar but less pronounced in
237 scenarios limiting warming to below 2°C (extended data figures 5, 6b). In sum, scenarios are
238 optimistic in two ways: baselines exhibit an acceleration of income growth, then mitigation
239 assumes a decoupling between energy demand and income. How can this optimism be
240 motivated?

241

242 **Problems with regional absolute decoupling**

243 While models behind the scenarios discussed above vary in their details about future trends,
244 they share the same theoretical approach to economy-energy modelling. Responses to
245 carbon prices are assumed to be efficient, smooth, and in principle arbitrarily large. Except for
246 differences in parameter values, high-, middle- and low-income economies are assumed to
247 follow the same model. Supplementary note 5 critically discusses the economic growth theory
248 behind IAMs.

249

250 Development economics tells a cautionary tale about assuming efficient growth without
251 explaining how it is achieved. The simple idea of “getting the prices right”, by imposing high
252 corrective carbon prices or equivalent policies, must contend with two centuries of economic

253 history. Achieving sustained and fast economic growth from low levels has been far from the
254 norm since the 1950s, and where it has been achieved it was by industrialisation. Industrial
255 production requires higher commercial energy inputs per worker than either (subsistence)
256 farming or services, and industrialisation has historically tended to imply rising, not falling,
257 commercial energy intensity³³⁻³⁵. Yet, in order to realise the robust growth rates projected for
258 the less affluent regions and the world as a whole, some form of industrialisation has to take
259 place. Achieving this industrialisation is difficult. Simultaneously maximising energy
260 conversion efficiency as emphasized in the scenarios above poses an unresolved policy
261 challenge.

262

263 In order to industrialize and adopt 'frontier' technology, developing countries have to import
264 capital goods from rich country producers. This is especially true for the kind of energy-saving
265 industrialisation envisioned by the IPCC scenarios. Industrialising countries face what are
266 known as 'two gap' problems in development economics. The domestic lack of savings
267 hinders investments (gap 1), and excessive trade deficits – e.g. from the need to import high
268 efficiency capital goods – makes these investments even more expensive (gap 2)³⁶. To get
269 around this financing dilemma, less efficient but cheaper and possibly domestically produced
270 machines could be installed. This would however 'lock in' the lower level of efficiency for the
271 machines' lifetimes³⁷. Case studies of tapping vast energy efficiency potentials tend to
272 describe situations where financing is not a constraint³⁸, and how quickly or whether efficiency
273 improvements pay for themselves is context-dependent³⁹.

274

275 The capital constraint is accentuated when recognising the limited domestic resources
276 available in most countries⁴⁰. Incomes reported in purchasing power parity (PPP) inflate lower
277 income countries' resources to reflect relatively cheap domestic purchases. However, to the
278 extent that energy efficient products must be purchased internationally, market exchange
279 rates count. In 2018 - and low-income countries had only 42% the income in terms of US
280 dollars at market exchange rates compared to PPP (USD4,967 vs. USD11,769 per capita).
281 Borrowing internationally and in foreign currency to finance these investments is risky and
282 costly, as a predominance of international finance can have destabilising effects.^{41,42} Shrewd
283 macroeconomic policy in developing countries could help with improving economic conditions
284 and enabling the financing. It must also stabilise economies that are disrupted by high carbon
285 prices.

286

287 Abrupt and unanticipated changes in prices (energy or otherwise) have caused recessions
288 with high unemployment by upending the original production structure based on a different set
289 of prices. The aftermath of the 1978-79 oil crisis is one example of this. It also helped cause

290 debt defaults in Latin American countries when their foreign debts denominated in dollars
291 became more expensive in the wake of the US' hike in interest rates (Volcker shock) to deal
292 with US price changes. Additionally, disruptions from price-focussed climate policy could
293 cause asset stranding, default on debts, and a destabilisation of the financial system via these
294 'transition risks', another area that needs a macroeconomic policy response^{43,44}. IAMs,
295 originally designed for long-term analysis, assume smooth paths of adjustment given any
296 price. Yet, as the short-term assumes crucial importance for ambitious mitigation, the question
297 of how financing and macroeconomic stability in developing countries constrains model
298 pathways requires scrutiny and insights from short-term (development) macroeconomics
299 could inform assumptions about feasible industrial and stabilization policy^{45,46}.

300

301 **Research Directions**

302 Economists have historically tended to be more bullish than other disciplines about the
303 economy's ability to overcome resource constraints via substitution^{47,48}. Yet, the smooth
304 substitution in developing countries of vastly more energy efficient technologies over the next
305 couple of decades alongside successful development implied by current climate policy
306 scenarios in IAMs is challenging also by these standards. None of this even addresses
307 rebound effects, which are poorly understood at the macroeconomic level but could be
308 substantial⁴⁹, additional consumption at the extensive margin, such as first-time purchase of
309 white goods⁵⁰, or increased air-conditioning in a warming climate⁵¹. Historical evidence and
310 development economics strongly suggest saving energy cannot play the role it is currently
311 assigned in scenarios.

312

313 IAMs were designed to produce consistent long-run projections of the climate and the
314 economy. With climate change accelerating and policy lagging behind, model scenarios are
315 push the limits of feasibility in multiple domains to achieve stringent mitigation targets. Hence,
316 such scenarios have to be interpreted as conditional explorations. However, we argue that
317 various IAM scenarios ignore important institutional constraints, which we believe to be
318 binding due to historical evidence. Since IAMs cannot test their results against data that is not
319 yet generated, they must convince with strong explanatory power that their pathways are
320 plausible^{32,52}. Our analysis of the development of energy demand alongside robust economic
321 growth across regions suggests that the details of near-term "development without energy"
322 need to be better understood for making plausible assumptions.⁵³

323

324 Key details would involve clarifying developing country growth strategies (particularly
325 industrialisation) and their energy implications, as well as problems of financing and
326 stabilization in the short-term. Taking industrialisation as a growth strategy seriously may

327 challenge some of the assumptions about low energy growth as we argued here. But more
328 attention to explicit modelling of investment and its financing may loosen other constraints.
329 While daunting challenges also exist in decarbonising developing countries' energy mix,⁴⁰
330 robust investment-price decline relationships could highlight opportunities for faster energy
331 supply decarbonisation⁵⁴, where IAMs have been shown to depict slow rates of change relative
332 to historical figures⁵⁵⁻⁵⁷.

333

334 First attempts to quantify global investments within IAMs⁴⁶ and independent studies^{41,58,59} are
335 promising, and financing and risks to stability are also starting to be considered⁶⁰. Research
336 on the political feasibility of such investments and potential trade-offs between different
337 mitigation policies has not yet produced robust evidence, but suggests that barriers may
338 exist^{61,62}. With their rapid break from past patterns of growth in economic output and energy
339 inputs, the scenarios show just how difficult the challenge for a concerted policy effort is to
340 simultaneously sustain economic growth, redirect investments towards low-carbon
341 alternatives, improve policy cooperation and prevent rebound effects with price policies that
342 must nonetheless not be regressive. Detailing the process by which this happens would make
343 them even more helpful tools in the design and analysis of climate change mitigation.

344

345

346

347

348 **ENDNOTES**

349 **Correspondence and requests for materials** should be addressed to GS.

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492 Methods:

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495 Historical Country Data

496 The historical analysis builds on a newly compiled dataset for annual national total primary
497 energy supply from 1950 to 2014 with nearly global coverage of 186 countries. Total primary
498 energy supply from the International Energy Agency Energy Balances⁶³ (starting in 1960 for
499 most OECD countries, and 1971 or later for other countries) was combined with Energy
500 Balances constructed from the United Nations Energy Statistics⁶⁴ that start in 1950. IEA data
501 was converted to direct equivalent accounting for compatibility with UN data and IPCC
502 scenarios, all of which use that accounting method. Where both datasets were available, IEA
503 data was used; however, besides wide coverage back to 1950, the UN data covers several
504 countries not included in the IEA data. Databases were spliced and adjusted to the IEA level
505 if necessary. To address the problem of missing non-commercial energy data (most often
506 reported only from 1970 by the UN), non-commercial energy demand in most areas of the
507 world in 1949 was taken from a unique 1952 study by the UN⁶⁵. The share of non-commercial
508 energy in the mix in 1949 and 1970 or the earliest available year was calculated and the share
509 in each year in the interval interpolated. Then total primary energy supply was calculated by
510 adding the non-commercial energy demand implied by the interpolated share to the known
511 commercial energy supply. GDP and population are from the Penn World Table⁶⁶ and, where
512 unavailable, from the Maddison Project⁶⁷. Supplementary figure 1 shows the resulting
513 population and country coverage. The 1950s cover upwards of 91% of population, and this
514 coverage reaches almost 98% in the 1960s and stays above 99% from 1971 onwards.
515 Between 1969 and 1971 many additional countries report data, but most of the 1990 additions
516 are due to accounting switching from the former Soviet Union and Yugoslavia to altogether 20
517 successor states. Detail about the dataset construction, in particular the construction of non-
518 commercial energy time series and treatment of dissolving or unifying countries is in the
519 accompanying data article⁶⁸.

520 Historical Regional Data

521 Historical world and regional primary and final energy, GDP and population data are from the
522 IEA Energy Balances and Indicators from 1971 through 2017. Countries were assigned to
523 regions according to the IPCC's R5 definition⁶⁹. Data for the world for 2018 are from IEA's
524 2019 World Energy Outlook⁷⁰ and the World Bank Open Data. Primary energy was converted
525 to direct equivalent accounting for comparability with IPCC scenarios. For 1950-1970 regional
526 data and global energy data is from the PFU database¹⁹, global population data is from the
527 UN, GDP data for 1960-1971 is from the World Bank and for 1950-1960 from the Maddison
528 Project. These data were spliced and adjusted to the level of the later time series where
529 necessary.

530

531 **Historical Correlation and Regression Analysis**

532 The correlation coefficient calculated for historical data is Spearman's rank-based
 533 coefficient. Figure 1 in the main text displays a local polynomial regression, loess, which
 534 does not impose a particular parametric global model, but estimates a fit based on segments
 535 of the data using a quadratic polynomial. For each observation $j=1, \dots, n$, we estimate an
 536 equation system of $k = 0.8 \times n$ dimensions

$$537 \quad \frac{E_i}{P_i} = \alpha + \beta_1 \frac{Y_i}{P_i} + \beta_2 \left(\frac{Y_i}{P_i} \right)^2 + \varepsilon_i, \quad \text{for } i = 1, \dots, k$$

538 using least squares, and including observation j and its argument's $k-1$ nearest neighbours,
 539 that are weighted in the least squares calculation using the tricubic function $w = (1 - |d|^3)^3$
 540 and where d is a metric distance between observation j and its neighbours. This gives n fits.

541 In the plot, each dot is the predicted value $\widehat{\frac{E_i}{P_i}}$ at argument $\frac{Y_i}{P_i}$ of the i^{th} fit. Loess is introduced
 542 in Cleveland⁷¹ and for computation we use the R language implementation *loess()*⁷². The
 543 extended data fit to G20 countries uses a polynomial of degree one to account for the lower
 544 number of observations.

545

546 An elasticity of y with respect to x , $\eta_{y,x}$, is defined as the percent change in y for a one
 547 percent change in x or the ratio of the logarithmic derivatives, $\eta_{y,x} = \frac{\partial \log y}{\partial \log x}$. We approximate
 548 elasticities of primary energy per capita with respect to output per capita by taking two
 549 arguments and their respective predicted values from the local polynomial regression and
 550 dividing the rates of change in both variables through each other

551

$$552 \quad \eta_{\frac{E}{P}, \frac{Y}{P}} = \frac{\left(\frac{\widehat{E}_2}{\widehat{P}_2} - \frac{\widehat{E}_1}{\widehat{P}_1} \right) / \frac{\widehat{E}_1}{\widehat{P}_1}}{\left(\frac{\widehat{Y}_2}{\widehat{P}_2} - \frac{\widehat{Y}_1}{\widehat{P}_1} \right) / \frac{\widehat{Y}_1}{\widehat{P}_1}}$$

553

554

555

556 **IPCC scenario data and analysis**

557 Data for the scenarios of the future pathways were downloaded on October 19, 2019 from
 558 the database behind the IPCC Special Report on Global Warming of 1.5°C, version
 559 *iamc15_scenario_data_all_regions_r2.0*⁷³. The database was supplemented first with
 560 baselines for the 'PEP' suite of scenarios⁴⁵ calculated with REMIND-MAgPIE 1.7-3.0, which
 561 are not included in the special report dataset. The PEP modelling team kindly shared the
 562 PEP baseline data upon request. Second, the database was supplemented with regional
 563 data for the Low Energy Demand (LED) scenario²⁹, which were not yet available at the time

564 of the 1.5°C Warming IPCC report from 2018, and have been kindly made available by the
565 LED modelling team upon request. In the resulting dataset, 90 scenarios achieve 1.5°C
566 average global warming above preindustrial levels by 2100 with a 50% chance. Scenarios
567 are further subdivided by their probability of temporarily overshooting this temperature during
568 the 21st century. 9 scenarios have a 50-66% chance not to overshoot in the 21st century; 44
569 scenarios overshoot with a 50-67% (low) chance; the remainder have a high probability
570 greater than 67% of overshoot³. Not all scenarios report both GDP and primary and final
571 energy. None of the five C-ROADS-5.005 scenarios report primary and final energy figures.
572 The only MERGE ETL 6.0 scenario and four REMIND 1.5 scenarios do not report GDP. This
573 leaves 80 scenarios, based on 7 models (which can have several versions), as depicted in
574 the supplementary table 1, with more than half of all scenarios supplied by two models. 79
575 scenarios report data on all indicators for MAF and REF regions, and ten of these, all from
576 the POLES model in the scenario family EMF33 do not report data for other regions, leaving
577 69 models with full regional coverage. The table also shows how GDP is calculated. For
578 further information see the IPCC report's supplementary material, which also states the
579 historical period that the report used for validation of energy-GDP trajectories to be 1971-
580 2015⁷⁴. This period can differ from the periods used when individual scenarios were
581 published. E.g. the MESSAGE SSP2 archetype uses 1970-2010²⁷ and the SSP energy
582 sector overview considers 1980-2010³¹.

583 The database also contains 119 scenarios limiting warming to 2°C and 185 scenarios,
584 including but not limited to baseline scenarios where global warming is above 2°C in 2100.
585 To these correspond 109 and 179 scenarios with at least some regional details. These
586 scenarios form the ensemble of the scenarios investigated here.

587 To compare historical levels with those in the scenarios in the main text's figure 2, all
588 scenarios were adjusted so that the GDP and energy per capita levels in 2010 were equal to
589 those of the historical data. Where actual energy demand levels are mentioned in the text,
590 these are taken from the original scenario data, not from the adjusted series.

591

592 **Data availability**

593 The data that support the national and regional historical energy series are from the United
594 Nations (UN) and the International Energy Agency (IEA) but restrictions apply to the
595 availability of these data, which were used under licence for the current study, and so are
596 not publicly available. National historical data are however deposited with the UK Data
597 Service⁶⁸ with access conditional on case-by-case permission by the IEA:
598 <https://www.ukdataservice.ac.uk/get-data.aspx>. All other historical data is publicly available
599 from the Penn World Table, Maddison Project, the World Bank and the PFU database. The
600 data that support the future scenarios are derived exclusively from the IAMC 1.5°C Scenario

601 Explorer and Data and are available for free at: [https://data.ene.iiasa.ac.at/iamc-1.5c-](https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/)
 602 [explorer/](https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/).

603

604 **Code availability.**

605 The code for curating the future scenario data once downloaded and for generating all the
 606 figures in the paper is available with the authors on reasonable request. It is coded in R.

607

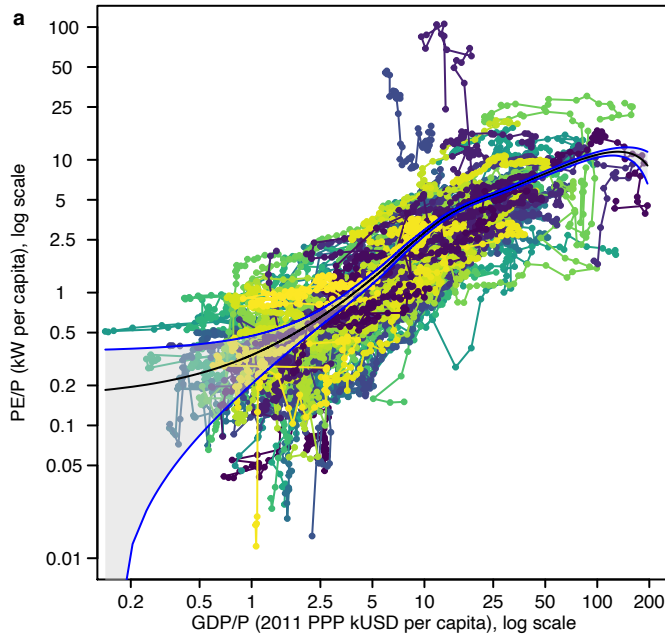
608 **References**

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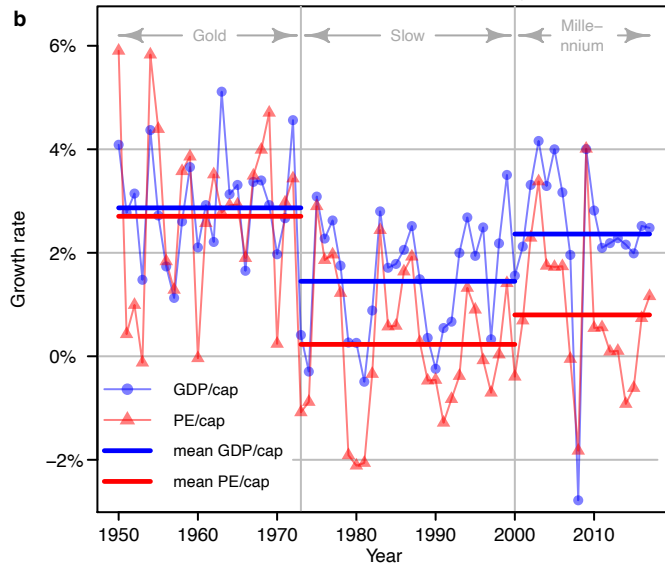
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 636 *strengthening the global response to the threat of climate change*, (eds. Masson-
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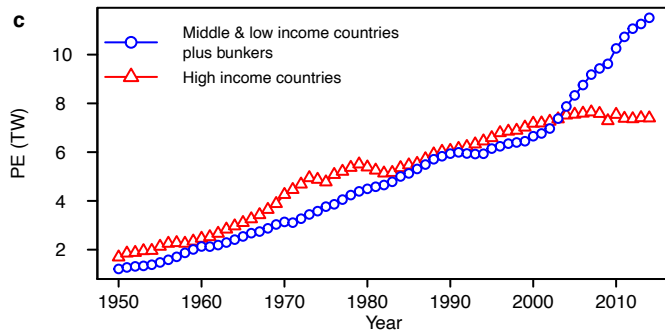
639 **Figure 1 | Historical output and energy per capita relation: (a)** Annual GDP per capita in
 640 2011 kiloUSD at purchasing power parity (PPP) and direct equivalent primary energy
 641 including non-commercial sources per capita in kilowatt for 185 countries 1950-2014
 642 (unbalanced). Every colour represents a country time series. The black line is a loess fit with
 643 the blue lines 1.96 standard deviations. **(b)** Global annual and average growth rates during
 644 three historical periods. **(c)** Rate of energy flow in countries grouped by GDP/capita, 1950-
 645 2014. Sources: see Methods.



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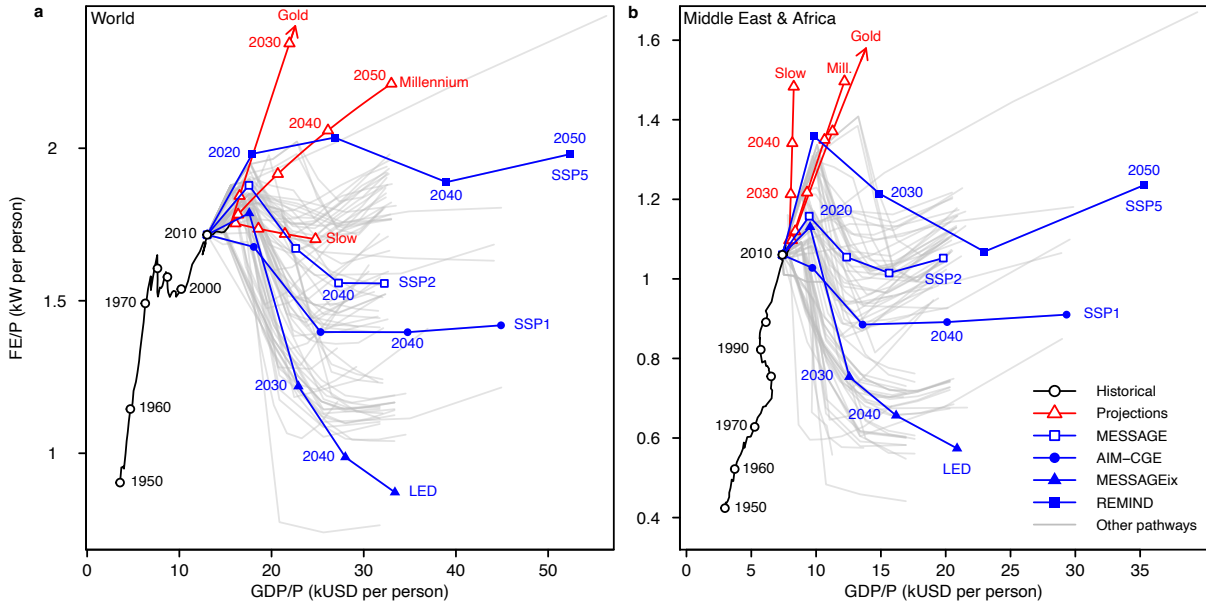


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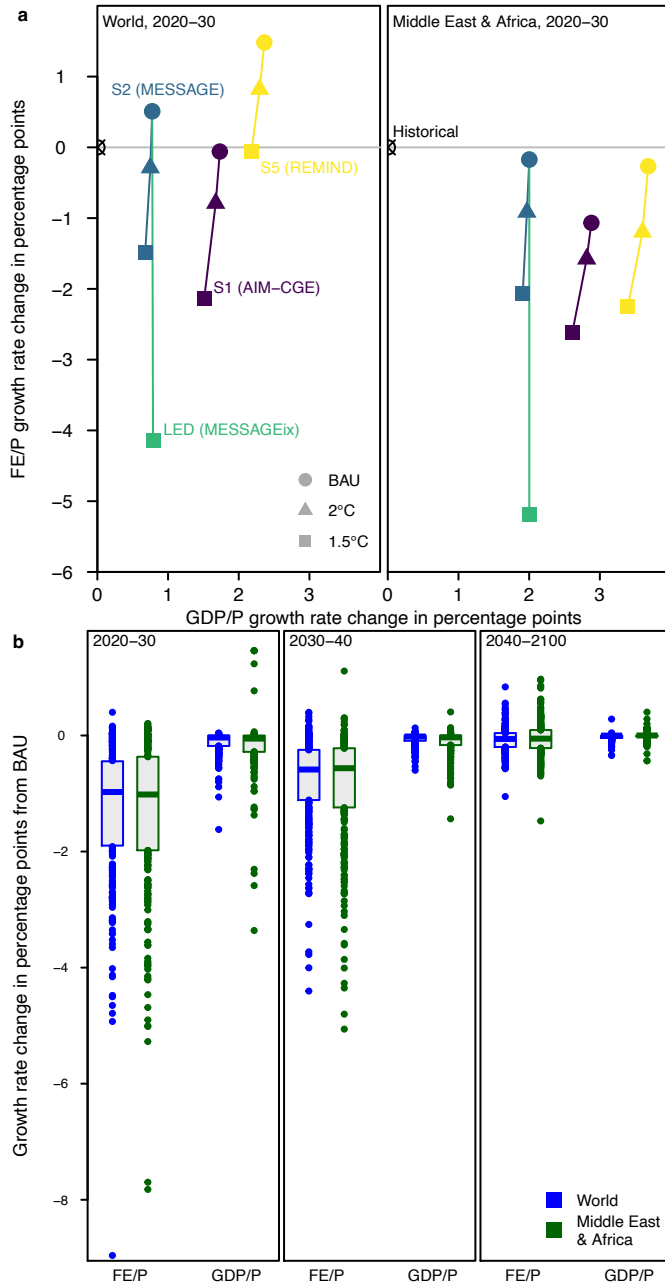
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651 **Figure 2 | Projections of output and final energy per capita relation until 2050: (a)**
 652 Global income per capita and final energy per capita projections of 1.5°C scenarios to 2050
 653 in grey. Archetype scenarios are in blue, others in grey. Scenario values have been
 654 normalised to start at the same historical level in 2010. Markers indicate decades. The
 655 historical trajectory is in black and the red lines extrapolate 1950-73 (Gold), 1973-2000
 656 (Slow) and 2000-18 (Millennium) growth rates. The Gold extrapolation is truncated after
 657 2030 to avoid extending the y-axis. (b) Same as (a) but for Middle East & Africa region.
 658 Sources: see methods.
 659



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662 **Figure 3 | Baseline and policy scenario growth rate deviations from historical rates:**
 663 **(a)** Growth rate deviation in percentage points in scenarios in 2020-30 relative to the 1970-
 664 2015 historical average for the World and Middle East & Africa in baselines (BAU) and
 665 successive mitigation scenarios, 2°C and 1.5°C of the four SSP ‘archetype’ scenarios.
 666 GDP/capita deviation is on the x-axis, FE/capita is on the y-axis. **(b)** Deviations in
 667 percentage points from BAU growth rates in all scenarios mitigating to 1.5°C in three periods
 668 for the World and Middle East & Africa. Boxes encompass the interquartile range with a
 669 horizontal line for the median, and have no whiskers.
 670



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