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Your money or your life? The carbon-development paradox

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Abstract

The relationship between human health and well-being, energy use and carbon emissions is a foremost concern in sustainable development. If past advances in well-being have been accomplished only through increases in energy use, there may be significant trade-offs between achieving universal human development and mitigating climate change. We test the explanatory power of economic, dietary and modern energy factors in accounting for past improvements in life expectancy, using a simple novel method, functional dynamic decomposition. We elucidate the paradox that a strong correlation between emissions and human development at one point in time does not imply that their dynamics are coupled in the long term. Increases in primary energy and carbon emissions can account for only a quarter of improvements in life expectancy, but are closely tied to growth in income. Facing this carbon-development paradox requires prioritizing human well-being over economic growth.

1. Introduction

Over the past decades, most countries have developed along many dimensions at once: economic, demographic, social, political and technological. As populations and economies have grown, individuals within them have achieved longer life expectancies, as well as improvements in other social factors [1]. These developments, in turn, have been accompanied by shifts in the scale and type of biophysical resource dependency, such as minerals and fossil fuel consumption [2, 3]. Currently, countries that attain or surpass multiple social thresholds also transgress multiple planetary boundaries [4, 5, 6].

The UN Sustainable Development Goals (SDGs) reflect the tension between human development and planetary impacts. Overarching social goals such as ‘Good Health and Well-Being’ (SDG 3) are considered alongside ‘Climate Action’ (SDG 13). The SDGs also explicitly include ‘Affordable and Clean Energy’ (SDG 7) and ‘Decent Work and Economic Growth’ (SDG 8). The implication here is that energy access and economic growth are necessary preconditions for good health and well-being, whereas climate change is detrimental.

Historically, energy, economy and human development have evidently progressed alongside each other, and indeed these factors are highly correlated internationally. However, it is far from clear that they are causally linked: that improvements in one depend on improvements in the other. The causal relationship between energy use and economy activity has been explored most comprehensively, with evidence pointing to strong cross-sectional relationships, although no clear unidirectional causal link has been shown [7–9]. The links between economic activity and well-being also show strong cross-sectional correlations, but elusive causality (a phenomenon known as the Easterlin or happiness-income paradox) [10, 11].

The research on the links between human well-being and energy use or emissions is more sparsely researched, and exposes a more complex picture [12]: the relation between energy and well-being has been shown to saturate at moderate levels [13–15], decrease over time [16], and intensify with economic growth [17]. Moreover, there exists great diversity in the drivers of emissions and dynamics of countries who achieve high levels of human development [18, 19], with trade playing a particularly important role [18, 20, 21]. The energy and emissions implications of poverty alleviation

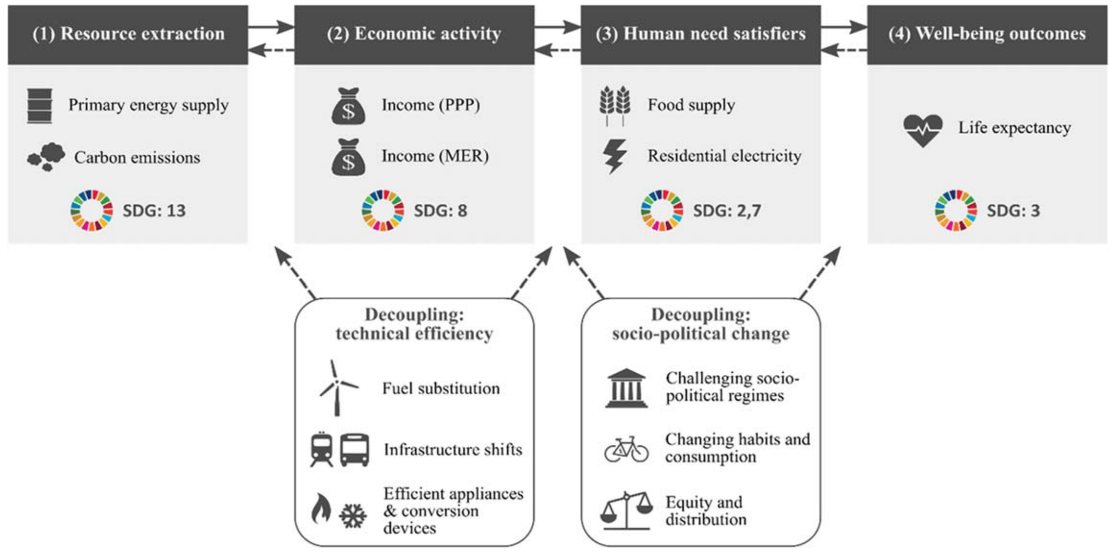


Figure 1. Analytic framework linking resource extraction and human well-being. Income: PPP means purchasing power parity; MER refers to international market exchange rate.

have become a recent focus of research [22–27]. Although some gains are estimated to be possible at low emissions costs [22, 23], others may require more substantial shares of carbon budgets [24, 25].

We now know that averting severe and dangerous climate change without new unproven technologies requires immediate and large reductions in energy use [5, 28]: this has been demonstrated in the recent IPCC report on achieving 1.5 degrees. However, the effect of reducing energy demand on human development has not been adequately studied to date. A more nuanced analytic framework is thus necessary to understand the links between biophysical means and well-being ends, with relevance for modelling efforts, climate action and sustainable development policies.

Our research questions are the following: How much of the significant increase in international life expectancy, over the past decades, can be attributed to contemporaneous growth in carbon emissions, diverse forms of energy, income or food supply? And, in contrast, how much of the growth in income at an international scale can be attributed to energy use or carbon emissions?

By applying a novel functional dynamic decomposition method (FDD), we demonstrate that recent improvements in life expectancy are only weakly coupled to increases in primary energy or carbon emissions, whereas these are tightly coupled to growth in GDP per capita measured in internationally traded dollars.

2. Methods

2.1. Analytical framework for linking well-being and carbon emissions

Our analytic framework draws categorical distinctions between resource extraction (primary energy, carbon emissions), economic activity (GDP per capita), satisfiers of human needs (such as food supply, or household electricity), and well-being outcomes (life expectancy). In figure 1, we connect these categories (and their relevant variables) according to our hypothesized, or pre-analytic, structure of potential causation. In this section, we explain our rationale for this hypothesized structure of potential causation.

Starting from the right of figure 1, we separate human need satisfiers from well-being outcomes. In doing so, we build upon several decades of well-being research in the 'eudaimonic' or Aristotelian tradition, which suggests that a wide variety of instrumental good and services (economic, cultural, and political) are critical to realizing well-being outcomes [29–32]. Satisfiers of human needs are hypothesized to include final energy (rather than primary extracted energy), as the closest indicator of energy services available [33]. Next, we represent economic activity as a *means* to deliver satisfiers of human needs, rather than an end in itself. This perspective reflects well-known critiques of GDP as an indicator of social progress [34]. Finally, we thus include primary energy at the resource extraction stage, as a hypothesized precondition for economic activity. We believe such analytic separations, especially between well-being, satisfiers and economic activity, are an important step in uncovering hypothesized material and energy dependencies of human well-being [26, 33, 35], and are critical for designing appropriate social and political responses [32, 36–38].

What are the opportunities for decoupling resource extraction and well-being outcomes? The categorization in figure 1 indicates several opportunities. First, technology efficiency and fuel substitution approaches, for example through the diffusion of renewable energy technologies, are key to decoupling resource extraction (1) and economic activity (2). The

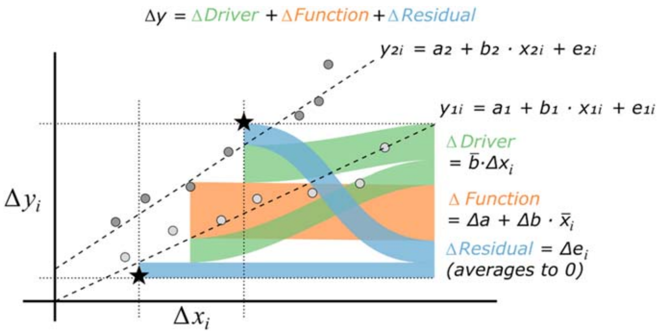


Figure 2. Schematic of functional dynamic decomposition FDD. The change in dependent variable *y* between times 1 and 2, shown for one particular point *i*, is decomposed into its functional, driver and residual change components.

precipitous decline of renewable energy costs in recent years are key to this strategy [39]. However, evidence for complete substitution of biophysical resources, as well as absolute (rather than relative) decoupling, remains elusive [40, 41]. Moreover, these strategies on their own will not be rapid enough to avert catastrophic climate breakdown [28, 42].

Another avenue for decoupling lies on the demand-side, between economic activity (2) and human need satisfiers (3). Technical options such as improving appliance efficiency or switching to alternative conversion devices (e.g. from incandescent to LED lights) offer immense potential for reducing energy throughput [43]. Further gains can be realized by shifting consumption patterns, although this is a strategy that necessitates confronting the socio-political regimes that sustain present habits, incentives and infrastructures [32, 38, 44, 45].

Finally, there are opportunities to improve the linkages between human need satisfiers (3) and well-being outcomes themselves (4). From the perspective of energy policy, these options are most often overlooked, as they would require embracing policies (and politics) that aim to remedy deep social and economic disparities, particularly targeting the extreme divide between luxury and subsistence consumption [25, 38, 46]. However, since SDG 10 explicitly mentions 'Reduced Inequality,' these options are clearly of central interest to the sustainable development agenda.

2.2. Functional dynamic decomposition

In order to elucidate the statistical relationships between the analytical categories in figure 1, we develop a method called FDD. This method estimates the relationship between a dependent variable (life expectancy, for example, or y in figure 2) and its hypothesized driver (the independent variable x in figure 2, which could be carbon emissions or income) over time.

FDD is a novel two-step method consisting in linear regressions at different points in time, followed by decomposition. This method was inspired by Preston (2007) [47]. It decomposes the change in the dependent variable (y) over time by considering the change in the independent variable (x) and the change in the functional relation between the two, as illustrated in figure 2 and in equations below.

The first step involves simple linear regressions of the dependent (y) and independent (x) variables, fitting for coefficients a and b, at times 1 and 2. The coefficients a and b are allowed to change over time. e represents the error term.

$$\begin{aligned} \text{Time 1:}\ \ y_{1,i} &= a_1 + b_1 \cdot x_{1,i} + e_{1,i} \\ \text{Time 2:}\ \ y_{2,i} &= a_2 + b_2 \cdot x_{2,i} + e_{2,i}. \end{aligned} \tag{1}$$

We can then express the difference in y between times 2 and 1 by subtracting the upper equation (1) from the lower one:

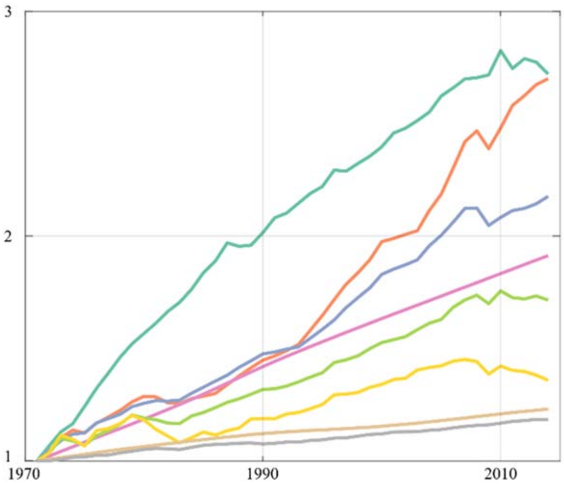
$$\begin{aligned} y_{2,i} - y_{1,i} &= a_2 - a_1 + b_2 \cdot x_{2,i} - b_1 \cdot x_{1,i} + e_{2,i} - e_{1,i} \\ &= a_2 - a_1 + (b_2 - b_1) \cdot \frac{x_{2,i} + x_{1,i}}{2} \\ &+ \frac{(b_2 + b_1)}{2} \cdot (x_{2,i} - x_{1,i}) + e_{2,i} - e_{1,i}\ . \end{aligned} \tag{2}$$

This can be summarised as:

$$\begin{aligned} \Delta y_i &= [\Delta a + \Delta b \cdot \overline{x_i}] + \bar{b} \cdot \Delta x_i + \Delta e_i \\ &= \Delta Function_i + \Delta Driver_i + \Delta e_i, \end{aligned} \tag{3}$$

where the difference between two values in time is denoted as $\Delta a = a_2 - a_1$ (and so on for other variables), and the average between the two points in time is denoted as $\bar{x}_i = (x_{2,i} + x_{1,i})/2$ (and so on for other variables).

Equation (3) is an exact decomposition of the change in each y_i into three terms, each with a straightforward interpretation. The first, in square brackets, corresponds to the *functional change* $\Delta Function$: the change in y_i which can be attributed to the change in the relation between x and y, without any change in x itself. The second term, $\bar{b} \cdot \Delta x_i$, corresponds to the change in y_i which can be attributed to a change in x_i. If x is hypothesized to be a driver of y, we call this term the *driver change*, $\Delta Driver$. The last term, Δe_i, represents the *change in residuals* from the fit procedure, and represents the change in y_i relative to the other



	Indicator	1971	2014	Increase	Growth
—	Residential electricity *(kWh per cap)*	384	1045	661	172%
—	Income (*Purchasing Power Parity $ per cap)*	7,074	19,074	12,010	170%
—	Income (*Market Exchange Rate $ per cap)*	7,661	16,676	9,015	118%
—	Population *(billion persons)*	3.03	5.79	2.76	91%
—	Primary Energy *(GJ per cap)*	57.5	98.6	41.1	72%
—	Carbon emissions *(t CO_2 per cap)*	3.50	4.75	1.25	36%
—	Life expectancy *(years)*	59.90	73.36	13.8	23%
—	Food supply (*kCals per cap per day)*	2,488	2,946	458	18%

Figure 3. International changes in key global indicators.

elements in the sample (moving closer to or further from the sample fit curve).

We then average the terms in equation (3). over i to obtain the international averages of functional change and driver change. Due to the definition of the linear least squares fitting procedure, the residual change Δe_i averages to zero.

FDD thus allows us to statistically decompose the average growth in the dependent variable entirely into two components: one attributable to the growth in the independent variable ('driver change': $\Delta Driver$), the other due to changes in other underlying conditions ('functional change': $\Delta Function$). We interpret a large $\Delta Driver$ contribution as evidence of strong dynamic coupling between the dependent and driver variables, whereas a large $\Delta Function$ contribution is evidence of dynamic decoupling.

An example of dynamic decoupling in the carbon emissions-life expectancy relationship could be widespread improvements in basic health provision, or poverty alleviation efforts which do not require much energy (i.e. improvements in water sanitation or vaccinations [22], technical efficiency or more equitable distribution [25]): these would lead to a change in the functional relation between the two variables over time, and could be measured as the functional change using FDD.

We apply FDD to our variables between two points in time and in a pairwise fashion. We thus estimate how much of the significant improvement in international life expectancy (almost 14 years between 1971 and 2014, see figure 3) can be attributed to contemporaneous growth in primary and final energy, emissions, income or food supply, as well as how much of the growth in international income can be attributed to emissions and energy.

2.3. Data

The data in our analysis is summarised in figure 3 and is sourced as follows: population from the United Nations Population Division [48]; carbon emissions (t CO_2) from the Carbon Dioxide Information Analysis Center [49]; food supply (daily kcal/capita) from FAOSTAT [50] (using 2013 values for 2014); life expectancy (average years at birth) and gross domestic product in market exchange rate (MER) (constant 2005 US$) from the World Bank [51]; gross domestic product in purchasing power parity (PPP) (expenditure-side real GDP at chained PPPs, 2005 US$) from the Penn World table [52]. In 1971 and 2014, there are 70 countries which have all required data, representing 80% of the global population.

2.4. Limitations of the method and variables

It is important to emphasize that our FDD analysis cannot show causality, only association. However, a lack of association is evidence of lack of causation.

In terms of our variables, life expectancy might be considered a rather limited understanding of well-being as physical health, but it reflects many aspects of social function over the life span of a population, and is one of few human development indicators available internationally over decades [16]. Our analysis, like any other statistical or modelling approach, is limited by data availability and choice of indicators.

3. Results

We apply FDD in a pairwise fashion to key indicators representing the four categories in the analytic framework in figure 1 (motivations for the selection of these indicators are presented in the supplementary information is available online at stacks.iop.org/ERL/15/044016/mmedia). (1) Extraction is measured through carbon emissions from fossil fuel combustion, and total primary energy use. (2) Economic activity is given by GDP per capita, both in PPP, which measures domestic purchasing power, and in international MER. (3) Satisfiers of human needs are represented through two types of final energy use: food supply and

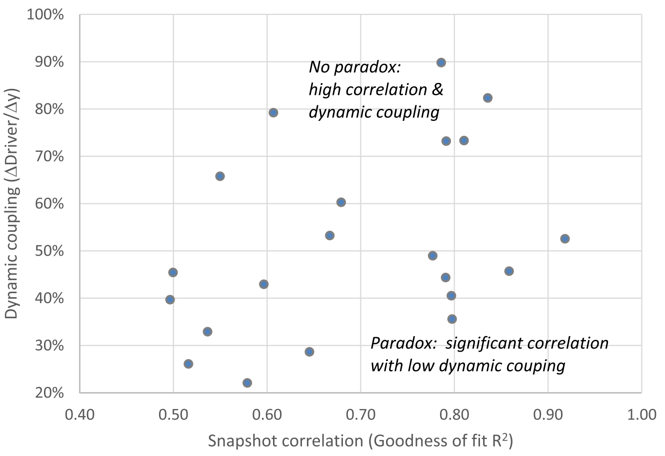


Figure 4. Snapshot correlation versus dynamic coupling (data from table 1).

Table 1. Pair-wise functional dynamic decomposition between 1971 and 2014. The change in the driver (row) accounts for $\Delta D = \Delta Driver/\Delta y$ percentage of change in the independent variable (column) variable. Average goodness-of-fit R^2 of the regressions in italics.

Dependent variables->:	Primary energy		MER income		PPP income		Food supply		Residential electricity		Life expectancy	
Drivers:	ΔD	R^2	ΔD	R^2	ΔD	R^2	ΔD	R^2	ΔD	R^2	ΔD	R^2
Carbon emissions	73%	*0.81*	73%	*0.79*	41%	*0.80*	33%	*0.54*	36%	*0.80*	22%	*0.58*
Primary energy			90%	*0.79*	49%	*0.78*	40%	*0.50*	44%	*0.79*	26%	*0.52*
MER income					53%	*0.92*	43%	*0.60*	46%	*0.86*	29%	*0.65*
PPP income							79%	*0.61*	82%	*0.84*	53%	*0.67*
Food supply									66%	*0.55*	45%	*0.50*
Residential electricity											60%	*0.68*

Note. Regressions are log–log, except with life expectancy as the independent variable, in which case they are log–linear.

residential electricity. (4) Well-being achievement is assessed by life expectancy. Our results measure how much of the increase in the independent variable (columns in table 1, y in figure 2) can be statistically explained by changes in the driver variable (rows in table 1, x in figure 2), between 1971 and 2014.

Following the Easterlin happiness-income paradox [10], our analysis exposes a carbon-development paradox, whereby a correlation between variables at a single point in time does not imply that they are dynamically coupled over time. We identify a paradoxical situation if there is strong correlation between x and y at each point in time, but $\Delta Driver$ can only account for a small fraction of the change in y, meaning that the evolution in y is decoupled from the evolution in x.

In our results, we can identify cases where no carbon-development paradox exists (upper right hand quadrant of figure 4), for instance between primary energy and MER income: these variables are highly correlated (goodness-of-fit $R^2 = 0.79$) and dynamically coupled (increases in primary energy account for 90% of the growth in MER income). However, there are also striking exceptions, which exhibit paradoxical behaviour. PPP income is highly correlated with primary energy use ($R^2 = 0.78$), but much less dynamically coupled to it, since growth in primary energy can only statistically account for 49% of PPP income growth (lower right hand quadrant of figure 4). A similar difference can be seen between carbon emissions and primary energy (both highly correlated and dynamically coupled), and emissions and residential electricity (highly correlated but weakly dynamically coupled).

We also see evidence of the reverse phenomenon, where a relatively weak correlation corresponds to a rather significant dynamic coupling: this is particularly evident in the relation between food supply and life expectancy (R^2 is only 0.50, one of the lowest in our dataset, although growth in food supply can statistically account for almost half, 45%, of the improvements in life expectancy).

3.1. Dynamically coupled variables

We now focus on highly dynamically coupled variables from table 1. We can identify two clusters, shown as darker blue arrows in figure 5. The first of these consists of emissions, primary energy and MER income. Statistically, increases in carbon emissions can account for almost three quarters of the growth in both primary energy and MER income, while the increase in primary energy use alone can explain 90% of the growth in MER income.

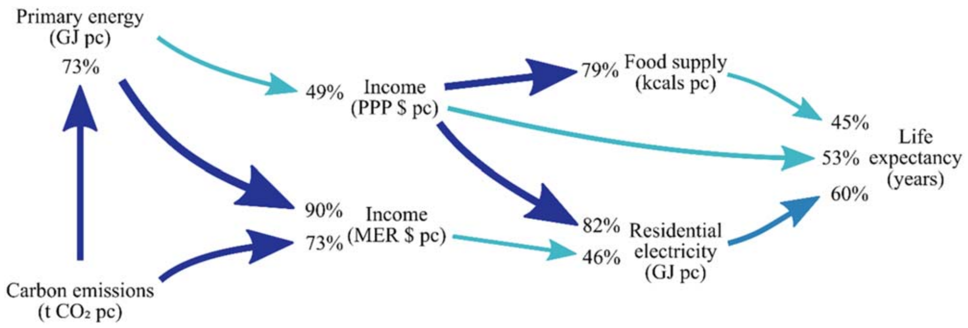


Figure 5. Strong dynamic coupling of key variables. Each arrow indicates what percentage of the change in the destination variable can be statistically accounted for by the change in the origin variable.[4]

The second cluster of strongly dynamically coupled variables consists of PPP income, food supply, residential electricity and life expectancy. Growth in PPP income can statistically account for roughly 80% of the increases in both food supply and residential electricity use, as well as half of the improvement in life expectancy. The indicator in our dataset that is the most dynamically coupled to life expectancy is not economic, however: residential electricity use increases can explain 60% of international improvements in life expectancy.

Perhaps the most surprising aspect of these results is the stark difference between MER and PPP incomes. PPP income is much less dynamically coupled to primary energy and carbon emissions than MER (less than half its growth can be accounted for by each). MER income growth, in turn, is much more weakly coupled than PPP to food supply, electricity and life expectancy. Since PPP income reflects the affordability of domestic goods and services, a stronger link to increases in human need satisfiers (food and electricity) and life expectancy can be intuitively expected when compared to MER. Nevertheless, the magnitude of the difference is striking.

The presence of strong dynamic coupling, as measured by FDD, cannot demonstrate a causal connection, but a weak coupling can disprove one. In particular, the weak dynamic couplings between CO_2 emissions and primary energy use on the one hand, and life expectancy on the other, demonstrate that fossil fuels are not, as often imagined or stated [53, 54], significant contributors to improvements in human development.

3.2. Testing satisfiers of human well-being over time

The results in table 1 enable us to explore different hypothesized satisfiers of human needs, corresponding to different assumptions on the most important prerequisites for human well-being, and thus the appropriate foci of policy efforts. These are: (A) an economic framing, where priority is given to increasing aggregate incomes; (B) a physiological framing, where priority is given to material subsistence levels; and (C) an energy service framing, where modern and clean household energy services are emphasised. In figure 6, we present possible pathways towards human well-being through these three types of satisfiers.

The economic narrative of increasing income (utility) driving progress in human development is empirically mixed, with large PPP and MER gains accounting for 53% and 29%, respectively, of direct life expectancy improvements (figure 6(A)). Economic growth is thus not enough on its own: the question is what type of economic growth. Physiological subsistence, represented through food supply, performs better than MER income, at 45% (figure 6(B)), but worse than PPP income. Modern energy carriers and energy services have recently achieved political recognition as the 'golden thread' of modern human development [55] and through Sustainable Development Goal 7 'Affordable and clean energy' [56]. Our results bear out this perspective, with increases residential electricity use statistically accounting for 60% of the improvements in life expectancy (figure 6(C)).

Residential electricity itself, however, is still a very aggregated form of energy, masking many uses (or energy 'services' [57]), including heating, cooling, cooking, food storage, communication, lighting and many more. Understanding which of these are the most essential to healthy and longer lives should be essential to guiding energy access policies [33, 35].

Regarding economic activity, which is an indirect driver of human need satisfaction according to our pre-analytic understanding (figure 1), in figures 6(B) and (C) we observe that PPP income growth is highly dynamically coupled to increases in both food supply and residential electricity, whereas MER income remains relatively weakly coupled.

4. Discussion and conclusions

Economic growth as usual may be threatened by full decarbonization, given the extremely rapid rates that are necessary to avert dangerous climate change [5, 28, 42]. But the same may not hold true for

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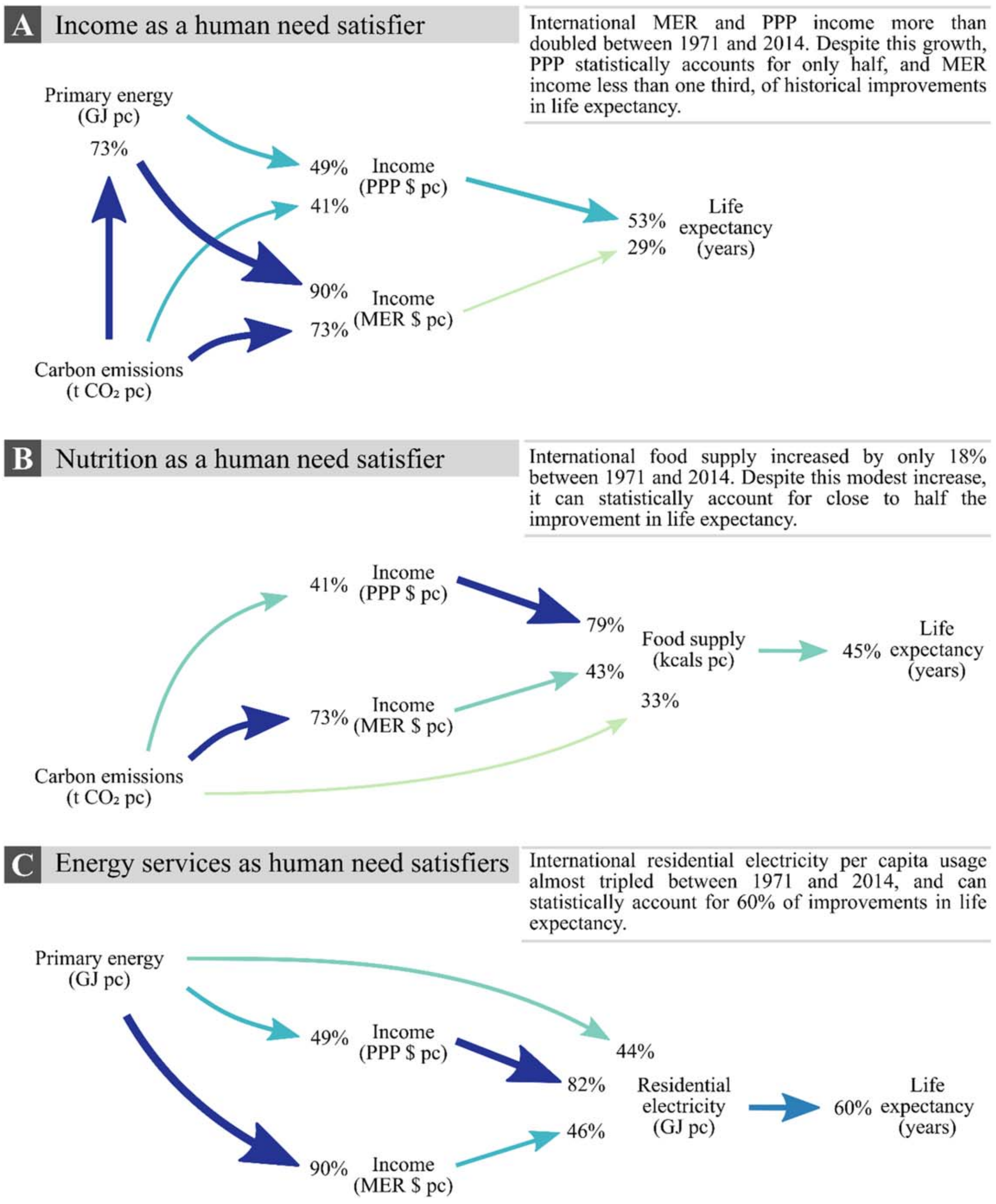
[4] Please note the representation in figure 5 and 6 should not be confused with structural equation modelling, which, unlike our approach, implies causality.



A Income as a human need satisfier

International MER and PPP income more than doubled between 1971 and 2014. Despite this growth, PPP statistically accounts for only half, and MER income less than one third, of historical improvements in life expectancy.

B Nutrition as a human need satisfier

International food supply increased by only 18% between 1971 and 2014. Despite this modest increase, it can statistically account for close to half the improvement in life expectancy.

C Energy services as human need satisfiers

International residential electricity per capita usage almost tripled between 1971 and 2014, and can statistically account for 60% of improvements in life expectancy.

Figure 6. Testing satisfiers of human needs using functional dynamic decomposition. Each arrow indicates what percentage of the change in the destination variable can be statistically accounted for by the change in the origin variable.

maintaining and enhancing human well-being. Past advances in life expectancy are very weakly coupled to increases in primary energy use and carbon emissions. The implications of this are profound: rapidly decreasing emissions, even through reductions in primary energy demand, need not be catastrophic in terms of our well-being, so long as instrumental need satisfiers (such as food and household electricity) are prioritized [22, 26, 27, 38, 58, 59].

Our analysis shows that increases in residential electricity use, PPP income and food are strongly dynamically coupled to improvements in life expectancy. This result bolsters the validity of the analytic framework in figure 1: if human well-being (SDG 3) is the ultimate goal, we need to understand the links between diverse satisfiers of human needs (other SDGs, or Universal Basic Services) and their social and physical preconditions, rather than assuming that blanket economic growth or increases in primary energy supply will automatically result in enhanced well-being. Effectively, achieving the SDGs relies on an explicit understanding of their interdependencies, and separating satisfiers (means) from well-being (ends).

A focus on satisfiers highlights the importance of moving beyond technical solutions in achieving sustainability. Eudaimonic research suggests that dimensions of well-being are satiable: that material need satisfaction (e.g. nutrition, shelter, energy services) improves lives only up to a threshold of consumption [60]. Overconsumption, by contrast, strains individuals and societies, as revealed by research across the fields of philosophy, psychology and the medical sciences [61]. Yet overconsumption often sits alongside appalling material deprivations. Distributive policies are therefore key to enabling flourishing societies at a minimum of biophysical cost [37, 38, 62].

Despite criticism at the highest levels [34, 63], GDP remains a focal point for much research that aims to reconcile social progress with environmental sustainability, including climate change. In agreement with our prevailing expectations based on cross-country correlations, growth in income valued at international exchange rates is strongly coupled to increases in primary energy use and carbon emissions. PPP income, on the other hand, is markedly more weakly coupled to emissions and primary energy. These results provide evidence that domestic consumption (measured through PPP) may be easier to decouple from fossil fuels than international trade (the exchange basis for MER).

A detailed analysis of consumption and need satisfaction should encompass social, institutional and political factors. In other words, climate research is no longer just a matter of identifying cost-effective mitigation measures; it must expand the solution space to social policy, action and activism as well [38, 64–66]. In this regard, embracing a well-being orientation directs us towards understanding how human needs can be provisioned equitably and sustainably within biophysical limits [6, 32, 67]. This involves exploring lightly trodden research paths: which are the most important satisfiers of human needs? What social, economic and technical conditions are necessary to put them in place? And what possibilities exist for the low-carbon satisfaction of human needs [38]?

In terms of research, we need scenarios and models which prioritize human well-being and equitable provision of vital satisfiers over economic growth and raw resource extraction. Moreover, in terms of policies and politics, we need to face the reality that feeding fossil fuels to the economy is far less beneficial to human development outcomes than directly satisfying our own needs.

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Data availability statement

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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