Economic Systems Research

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/cesr20

Integrated assessment modelling of degrowth scenarios for Australia

Mengyu Li, Lorenz Keyßer, Jarmo S. Kikstra, Jason Hickel, Paul E. Brockway, Nicolas Dai, Arunima Malik & Manfred Lenzen

To cite this article: Mengyu Li, Lorenz Keyßer, Jarmo S. Kikstra, Jason Hickel, Paul E. Brockway, Nicolas Dai, Arunima Malik & Manfred Lenzen (30 Aug 2023): Integrated assessment modelling of degrowth scenarios for Australia, Economic Systems Research, DOI: 10.1080/09535314.2023.2245544

To link to this article: https://doi.org/10.1080/09535314.2023.2245544

Published online: 30 Aug 2023.

ECONOMIC SYSTEMS RESEARCH
https://doi.org/10.1080/09535314.2023.2245544

Integrated assessment modelling of degrowth scenarios for Australia

Mengyu Li [a,*], Lorenz Keyßer [b,*], Jarmo S. Kikstra [g,h,i], Jason Hickel [c,d,k], Paul E. Brockway [f], Nicolas Dai [a], Arunima Malik [a,e] and Manfred Lenzen [a,j]

[a]ISA, School of Physics, The University of Sydney, Camperdown, Australia; [b]Institute of Geography and Sustainability, Faculty of Geosciences and Environment, University of Lausanne, Lausanne, Switzerland; [c]Institute for Environmental Science and Technology (ICTA-UAB), Autonomous University of Barcelona, Barcelona, Spain; [d]International Inequalities Institute, London School of Economics, London, UK; [e]Discipline of Accounting, Governance & Regulation, Business School, The University of Sydney, Camperdown, Australia; [f]Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds, UK; [g]International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria; [h]Grantham Institute for Climate Change and the Environment, Imperial College London, London, UK; [i]Centre for Environmental Policy, Imperial College London, London, UK; [j]Hanse-Wissenschaftskolleg, Delmenhorst, Germany; [k]Department of Anthropology, Autonomous University of Barcelona, Barcelona, Spain

ABSTRACT
Empirical evidence increasingly indicates that to achieve sufficiently rapid decarbonisation, high-income economies may need to adopt degrowth policies, scaling down less-necessary forms of production and demand, in addition to rapid deployment of renewables. Calls have been made for degrowth climate mitigation scenarios. However, so far these have not been modelled within the established Integrated Assessment Models (IAMs) for future scenario analysis of the energy-economy-emission nexus, partly because the architecture of these IAMs has growth 'baked in'. In this work, we modify one of the common IAMs – MESSAGEix – to make it compatible with degrowth scenarios. We simulate scenarios featuring low and negative growth in a high-income economy (Australia). We achieve this by detaching MESSAGEix from its monotonically growing utility function, and by formulating an alternative utility function based on non-monotonic preferences. The outcomes from such modified scenarios reflect some characteristics of degrowth futures, including reduced aggregate production and declining energy and emissions. However, further work is needed to explore other key degrowth features such as sectoral differentiation, redistribution, and provisioning system transformation.

ARTICLE HISTORY
Received 13 July 2023

KEYWORDS
Integrated Assessment Models; Utility function; Degrowth; energy-economy decoupling; post-growth

1. Introduction

This paper addresses a critical challenge that faces climate mitigation scenario modelling. The established Integrated Assessment Models (IAMs) assume continued economic

CONTACT Manfred Lenzen manfred.lenzen@sydney.edu.au ISA, School of Physics, The University of Sydney, Camperdown, NSW 2006, Australia; Hanse-Wissenschaftskolleg, Lehmkuhlenbusch 4, 27753 Delmenhorst, Germany
*Those authors contribute equally to the manuscript.

growth, but then have difficulty reconciling this with the rapid emissions reductions required to meet the Paris Agreement targets. In Section 1.1, we show that the dominant approaches to dealing with this problem within IAMs, namely, to rely on dramatic rates of technological change, suffer from several key limitations. In Section 1.2, we argue that to solve this problem, climate mitigation modelling needs to incorporate alternative post-growth and degrowth policies alongside feasible technological change. Such policies are designed to focus directly on equity, sufficiency and ecological stability; secure social wellbeing independently from economic growth; and scale down less-necessary forms of production. However, this cannot presently be done within the architecture of the established IAMs, as they are commonly constructed. Degrowth policies were only recently integrated into an established IAM, REMIND-MagPIE, but only for the food sector (Bodirsky et al., 2022). To make it possible for the energy-economy nexus, we modify MESSAGEix by replacing its monotonically growing utility function with an alternative utility function based on non-monotonic preferences (Section 2). We then model results for the Australian economy (Section 3) and discuss the implications (Section 4). Importantly, due to various limitations such as the lack of sectoral detail (see Section 4 and Kikstra et al. (2023) for more information), our modelling only captures some dimensions of degrowth and hence cannot be said to fully implement a degrowth scenario.

1.1. Established IAM scenarios and their limits

Climate mitigation scenario modelling faces a difficult challenge. Most of the mitigation scenarios reviewed by the IPCC – and all of the global scenarios included in the 2018 IPCC Special Report on 1.5 degrees and the IPCC Sixth Assessment Report – assume continued global economic growth for the rest of the century (Byers et al., 2022; IPCC, 2018, 2022c). In most cases, further economic growth also applies to current high-income countries (Byers et al., 2022; Huppmann et al., 2019; Rogelj et al., 2018), where we know that additional growth is not necessary to achieve strong social outcomes (see Section 1.2). The recent literature on climate mitigation scenarios from IAMs is dominated by scenarios that follow one of the Shared Socioeconomic Pathways (SSPs), most of which use an SSP2 'Middle of the Road' pathway (Fricko et al., 2017; IPCC, 2022a). Economic growth is derived from a narrative without integrated climate impacts or adaptation in this set of pathways. The only scenario with low challenges to adaptation and mitigation, SSP1, is interpreted to have high economic growth (Dellink et al., 2017). The pathways with moderately slower rates of economic growth (SSP3 and SSP4 at 1% and 1.7% average global GDP growth p.a. between 2010 and 2100, respectively, compared to between 2 and 2.8% of the other SSPs; see Leimbach et al. (2017)) are assumed to face social, political, and economic instability (O'Neill et al., 2017). This is particularly evident in SSP3, where declining output in high-income nations is linked to negative future outcomes, such as national rivalry and low priorities for environmental concerns, and hence to higher challenges for mitigation, e.g. through less technological innovation (Leimbach et al., 2017; O'Neill et al., 2017). As a result, IAMs could not achieve the 1.5°C target when implementing SSP3 and only barely when following SSP4 (Rogelj et al., 2018).

However, continued economic growth can create difficulties for mitigation, and ambitious mitigation scenarios based on the SSP framework face feasibility concerns across multiple dimensions, including geophysical and technological constraints (Brutschin et al., 2021; Riahi et al., 2022). For instance, the plausibility of strong energy demand reductions from efficiency gains under continued economic growth has been questioned, noting that efficiency-induced rebound effects have been observed in the past, could limit projected energy savings in the future and are not well-represented in established IAMs (Lange & Berner, 2022; Nieto et al., 2020). Increasing economic production and consumption is projected to come paired with a significant increase in energy demand over the coming decades, making sufficiently rapid decarbonisation more challenging (Haberl et al., 2020; Hubacek et al., 2021; Jackson et al., 2022; Lamb et al., 2022; Le Quéré et al., 2019; Wang et al., 2021). Given the pressures that continued growth creates, most mitigation scenarios from established IAMs achieve their mitigation targets mainly by leaning heavily on a combination of three major, technology-focused levers, in descending order (high-to-low) of, from our perspective, associated uncertainty and feasibility concerns: 1) applying carbon capture and storage to coal and gas as well as removing large quantities of CO_2 from the atmosphere via negative emission technologies (NETs), 2) increasing energy efficiency to decouple GDP from energy use and 3) expanding low-emission energy sources such as nuclear and renewable energy (Huppmann et al., 2019; IPCC, 2018; Rogelj et al., 2018). We illustrate a more common modelling approach to climate change mitigation than a scenario with less growth in Figure 1.

All of those levers have substantial limitations and risks (see generally (Hickel et al., 2021; Keyßer & Lenzen, 2021). While many IAM scenarios reduce final energy demand as a means to reduce the share of renewables and energy system investments, only few use it to reduce reliance on NETs (Scott et al., 2022). Yet, there are real concerns about the feasibility and ecological impact of deploying NETs at the large scales assumed in many scenarios (Brutschin et al., 2021; Creutzig et al., 2021; Warszawski et al., 2021). Recognising these concerns, some scenarios explore low-NETs pathways, including the Low Energy Demand scenario by Grubler et al. (2018). Instead, these scenarios commonly rely on unprecedented energy efficiency gains, to an extent that allows high GDP growth alongside dramatically reduced energy consumption (Keyßer & Lenzen, 2021). This may reduce concerns about the feasibility of NETs (Brutschin et al., 2021), but it raises other questions about the feasibility of such dramatic GDP/energy decoupling. The existing low energy demand scenarios do not assess interactions between energy and GDP, and the rate of GDP/energy decoupling assumed in these scenarios is not supported by empirical evidence (Brockway et al., 2021). We now discuss each of the above mentioned mitigation levers in more detail.

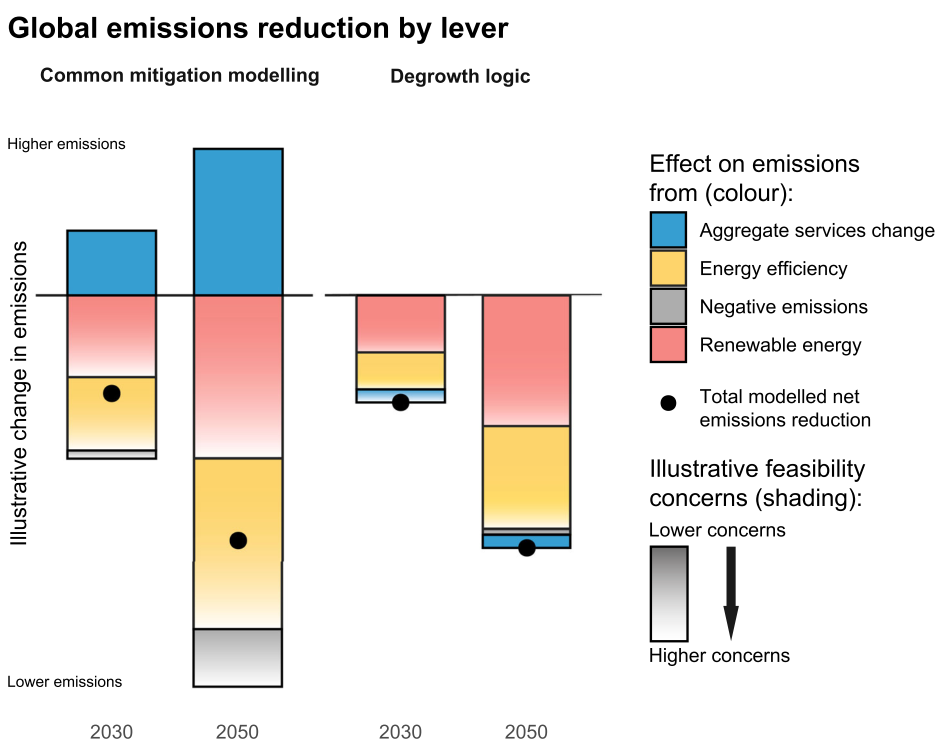
1.1.1. Negative emissions technologies

Often, 1.5°C scenarios rely heavily on negative emissions technologies. In the scenarios modelled on the established IAMs with no or low overshoot, NETs are assumed at large scales, with median values of 6 $GtCO_2$ / yr in 2050 and 13 $GtCO_2$ / yr in 2100 (median cumulative amount of 659 $GtCO_2$ until 2100) (IPCC, 2022c). To put these figures in perspective, the current direct air capture capacity is around 0.1 $MtCO_2$ / yr (IEA, 2022). Although some degree of carbon removal is likely necessary to achieve net-zero CO_2 emissions (Calverley & Anderson, 2022), large-scale deployment faces significant concerns about feasibility, sustainability and justice. This applies to biomass-based NETs such as bioenergy to carbon capture and storage (BECCS) and re – and afforestation, and direct air capture technologies (Calverley & Anderson, 2022; Creutzig et al., 2021; Fuhrman et al., 2020; IPCC, 2018). Hence, the argument against relying on large-scale NETs has received significant support in the scientific literature (Anderson & Peters, 2016; Vaughan & Gough, 2016).

1.1.2. Energy efficiency

All 1.5°C scenarios in the scenario database of the IPCC Special Report on 1.5°C assume rapid, large-scale improvements in energy efficiency, leading to an absolute decoupling between GDP growth and energy use (Brockway et al., 2021; Huppmann et al., 2019; IPCC, 2018). Efficiency improvements are represented as dramatic changes to energy intensity rates (energy/GDP) of −3% to −8% /year. These figures are far above historical trends (−1.0% to −2.0%/year since 1971) and, depending on the scenario, are unprecedented even for single-year observations in the empirical record (Brockway et al., 2021). Such enduring, global absolute decoupling is unprecedented, and there is no empirical evidence that it can be achieved (Haberl et al., 2020). Furthermore, these scenarios do not account for many of the known economy-wide rebound effects that are likely to reduce the impact of

Figure 1. An illustrative representation of a possible global mitigation strategy towards net zero emissions that is more commonly modelled ('Common mitigation modelling'), versus an illustrative scenario that limits activity growth ('Degrowth logic'), with similar levels of emissions reduction ambition. *This is a global aggregate picture, which does not reflect the regional differentiation that is articulated in the degrowth literature, which talks about futures with stronger emissions reductions in the Global North and increases in service provisioning for countries with widespread poverty. Note also that 'Demand: aggregate services' (in blue) refers to the aggregated demand for various services, e.g. amount of kilometres travelled, calories eaten or inhabited flat size. This category is most directly affected by avoid-measures in the avoid-shift-improve framework (see* Creutzig et al. (2018)).



efficiency improvements (Berner et al., 2022; Brockway et al., 2021). Finally, the empirical literature has questioned claims that GDP/energy decoupling can be achieved through digitalisation (Lange & Berner, 2022; Parrique et al., 2019) and by shifting to services (Fix, 2019; Greenford et al., 2020).

1.1.3. Renewable energy

Rapid mitigation requires rapid rates of renewable energy deployment. So far, the median of maximum national growth rates for renewable energy has been estimated at 0.8% of the total electricity supply p.a. for onshore wind and 0.6% p.a. for solar (Cherp et al., 2021). However, 1.5°C mitigation scenarios from the IPCC SR15 report have a median global rate of 1.2% p.a. for onshore wind and 1.1% for solar. This disparity is dramatic, even before taking into account equity principles (Anderson et al., 2020; Calverley & Anderson, 2022) and the limitations of negative emissions and energy efficiency, as described above (Diesendorf, 2022; Keyßer & Lenzen, 2021; Sers, 2022). Accounting for equity means that higher-income countries must achieve faster mitigation rates, and hence faster expansion rates for renewables, while the limits of NETs deployment and energy efficiency gains mean needing to rely more heavily on this lever. Further obstacles to a fast and large-scale renewable energy transition abound: the energy return on energy invested in the energy system may decline during a transition from fossil-fueled energy systems to renewable ones (Capellán-Pérez et al., 2019; de Castro & Capellán-Pérez, 2020; Slamersak et al., 2022), while the associated material use (Capellán-Pérez et al., 2019; Deetman et al., 2021; Watari et al., 2021) as well as land use is significant (Luderer et al., 2019; van de Ven et al., 2021) and entails negative social and ecological impacts (Luckeneder et al., 2021; Scheidel et al., 2020; Sonter et al., 2020; Temper et al., 2020). Similar limitations apply to nuclear energy (Muellner et al., 2021).

In sum, it is clear that 1.5°C scenarios from established IAMs lack representation of certain important dynamics and face clearly identifiable feasibility concerns on each of their major mitigation levers: NETs, energy efficiency and low-carbon energy transition.

1.2. Alternative post- and degrowth mitigation scenarios

IAMs thus far have yet to devote much attention to potential synergies between reduced production/consumption and climate mitigation. Still, ecological economics and industrial ecology research has explored this approach in depth. Post-growth and degrowth scholarship questions the normativity of growth, and calls for economic policy to focus instead on human well-being and ecological stability. We use both terms here: post-growth to describe a general shift away from growth as a core economic objective to focus instead on human well-being and ecological stability, and degrowth to describe a planned reduction in less-necessary forms of production to bring the economy back within planetary boundaries in a just and equitable way (for further details see e.g. Schmelzer et al. (2022)). Research in this field demonstrates that high-income economies do not need more aggregate production and consumption; instead, they can support strong social outcomes without growth, by reducing inequality, ensuring living wages, shortening the working week to prevent unemployment, and guaranteeing universal access to public services (Jackson, 2016; Knight et al., 2013; Victor, 2008; Vogel et al., 2021). Degrowth scholarship proposes that ecologically destructive and socially less-necessary forms of production and consumption should be scaled down (Hickel, 2020; Kallis et al., 2012; Kallis et al., 2018). Modelling post-growth and degrowth elements in climate mitigation scenarios would directly reduce projected aggregate energy demand and make it easier to achieve the Paris climate target without relying so heavily on speculative technological change (Keyßer & Lenzen, 2021; Millward-Hopkins et al., 2020).

Post-growth and degrowth scholarship has been represented in several IPCC reports, but corresponding climate mitigation scenarios still need to be formally reviewed by the IPCC (IPCC, 2022b, pp. 3–116). One reason is that post- and degrowth scenarios cannot easily be modelled on established IAMs, as they are commonly constructed (Hardt & O'Neill, 2017; Kuhnhenn, 2018). Nevertheless, some modelling of post- and degrowth scenarios exists. The most extensive and complex modelling to date uses the MEDEAS IAM to model global degrowth pathways (Capellán-Pérez et al., 2020; Nieto et al., 2020), but it is not as widely established in the modelling community compared to other, older IAMs, which e.g. were used for implementing the SSPs (Riahi et al., 2017). MEDEAS can model global degrowth pathways because it is based on post-Keynesian economics and system dynamics as opposed to mainstream economics and optimisation approaches, allowing for economic disequilibrium, demand-led growth, and a feedback-rich integration between economic and biophysical systems. By incorporating biophysical constraints, the model shows that further economic growth in high-income nations may be incompatible with rapid climate mitigation and shows that better outcomes can be achieved in a degrowth scenario with a coordinated decline in production and consumption. Other IAM-based work (Bertram et al., 2018; Van Vuuren et al., 2019) highlights the co-benefits of lifestyle and demand changes for non-climate social and environmental goals, such as improved health outcomes derived from dietary shifts and reduced air pollution resulting from reduced fuel use and changed fuel mix. Pursuing a number of Sustainable Development Goals in parallel has been shown to lead to synergies, for example when climate objectives have a better chance of implementation when equity and poverty concerns are addresses at the same time (Soergel et al., 2021). Other post- and degrowth modelling include scenarios for France using the EUROGREEN model (D'Alessandro et al., 2020), global scenarios using the SFCIO-IAM (Sers, 2022), scenarios for the food sector using REMIND-MagPIE (Bodirsky et al., 2022), scenarios for Canada using LowGrow SFC (Jackson & Victor, 2020) as well as more simplified modelling approaches, e.g. by Keyßer and Lenzen (2021) and Kuhnhenn et al. (2020). However, none of these papers uses an established IAM to model degrowth and post-growth for the energy-economy nexus. In this paper, we seek to address the apparent lack of IAM degrowth modelling by modifying one of the widely used IAMs – MESSAGEix – to make it compatible with post-growth and degrowth scenarios. In what follows, we describe the rationale behind one of these necessary modifications: changing the utility function from a monotonic formulation to a non-monotonic one.

The continuation of economic growth in the established IAMs is largely a result of external green growth scenario assumptions (i.e. GDP up, emissions down driven by policy-makers, as in SSP1). Still, it is also reinforced by the monotonic formulation of the utility function standard in models, where more income and consumption and hence GDP is always preferred over less, as this is assumed to provide higher utility (IPCC, 2022a; Kuhnhenn et al., 2020). But, several arguments rooted in the empirical literature contradict the assumption of monotonic preferences and instead suggest a non-monotonic utility function: after a certain point of income and consumption, utility peaks and subsequently declines.

First, empirical data shows that the correlation of GDP with social indicators exhibits significant diminishing returns (Fanning & O'Neill, 2019; O'Neill et al., 2018, p. 91). This is the case for life expectancy (Fanning & O'Neill, 2019), health (Bishai et al., 2016), education (Gidwitz et al., 2010; UNDP, 2015), sanitation, access to energy, nutrition (O'Neill et al., 2018) and subjective wellbeing (Chen et al., 2019; Fanning & O'Neill, 2019). A sufficient level of productive capacity is clearly necessary in order to meet human needs at a good standard. Nevertheless, the relationship between GDP and social outcomes is not direct and causal; it is mediated by provisioning systems and distributional dynamics (Brand-Correa et al., 2020; Fanning et al., 2020; Vogel et al., 2021). Hence, social performance, e.g. regarding life expectancy and life satisfaction, can differ significantly between countries for the same GDP level and vice versa. For instance, between 2013 and 2015, Costa Rica, among other countries, achieved high life satisfaction (average of 7.1 out of 10) and life expectancy (average of 79 years) with an average of less than 15,000 US$ (PPP 2011) per capita, aligning with the USA's performance at an average of over 51,000 US$ (PPP 2011) per capita (Fanning & O'Neill, 2019). The key drivers of improvements in social outcomes are access to high quality universal public services, e.g. health care, education, transport infrastructure and electricity, an egalitarian distribution of income and high democratic quality (Baltruszewicz et al., 2021a; Baltruszewicz et al., 2021b; Bengtsson et al., 2018; Cereseto & Waitzkin, 1986; Okulicz-Kozaryn et al., 2014; Sen, 1981; Steinberger et al., 2020; Vogel et al., 2021; Wilkinson & Pickett, 2009). Furthermore, evidence also shows that reducing consumption in high-income countries is associated with maintaining or even increasing wellbeing (Hüttel et al., 2020), while advertising, which increases consumption levels (Brulle & Young, 2007), is associated with reduced life satisfaction (Michel et al., 2019). More directly, a recent study by Bain and Bongiorno (2022) shows that only an average of approximately 18-24% (see Box 1 in their paper) of people across 33 countries exhibit unlimited wants in terms of monetary wealth, while an average of approximately 37-42% are satisfied with one million US$ (MER) or less (i.e. 25,000 US$ per year or less over the average remaining lifetime in a Western country).

Second, notwithstanding limited efficiency gains, GDP growth at the global scale remains strongly coupled to negative ecological impacts (Haberl et al., 2020; Otero et al., 2020; Parrique et al., 2019; Wang et al., 2021) and the associated negative impacts on humans (IPBES, 2019; IPCC, 2018; Scheidel et al., 2020; Steinmann et al., 2017). Research on the 'social limits to growth' posits that a point exists beyond which more economic growth becomes 'uneconomic', as the costs exceed the benefits (Daly, 2015; Daly & Farley, 2011). This is corroborated by research on holistic metrics of progress, such as the Genuine Progress Indicator, which modifies GDP to account for non-market goods and the social and ecological impacts of growth. By this definition, globally, progress peaked in the 1970s at a GDP value of around 7,000 US$ (PPP 2005) per capita and has stagnated since then, while in many high-income countries, it has declined, despite rising GDP (Beça & Santos, 2010; Kubiszewski et al., 2013).

Third, survey data indicates strong popular preferences for ecological sustainability and wellbeing over economic growth, or even at the expense of economic growth (Drews et al., 2018; Hövermann et al., 2021; Marlon et al., 2018; Odoxa, 2019; Rice-Oxley & Rankin, 2019). Paulson and Büchs (2022, p. 1) conclude that '*On average among 34 European countries, 60.5% of people are in favour of post-growth*.' Growth-critical attitudes and preferences are especially pronounced within groups of environmental experts (Lehmann et al., 2022). Moreover, polls show substantial approval of degrowth policies, such as reduced working hours (TUC, 2018; YouGov, 2019, 2020). Reducing working hours is associated with higher wellbeing (Barck-Holst et al., 2017; Hayden, 2006; Knight et al., 2013; TUC, 2018; YouGov, 2019, 2020). The additional leisure time may allow for healthy social relations and activities that are crucial for human wellbeing (see studies cited in Bilancini and D'Alessandro (2012)).

This evidence implies that lower-GDP futures are plausible and defensible as part of a modelling exercise. Certainly, if growth does impede climate mitigation and exacerbate climate damages on the scale predicted by recent IPCC reports, we can expect such altered consumer preferences to become much more prevalent in the future.

1.3. Aim and structure of this paper

In this paper, we modify one of the established IAMs – MESSAGEix – to make it compatible with degrowth and post-growth scenarios for the energy-economy nexus. We describe the IAM and the implemented modifications, including the non-monotonic utility function, in Section 2 on Methods and Data below. We then simulate scenarios featuring low and negative growth in a high-income economy (Australia) and detail the impacts on energy consumption and carbon emissions up to 2100 (see Section 3 on Results). We then put these results in perspective through critical discussion in Section 4, and conclude in Section 5.

2. Methods and data

To enhance transparency and applicability, we develop the degrowth modelling capacity based on one of the common IAMs, MESSAGEix, a well-documented and open-source framework for modelling mitigation scenarios (Huppmann et al., 2019). We specifically model the degrowth modelling capacity of MESSAGEix using data on the energy commodities traded and consumed in Australia. Data on the consumption, production and trade of energy commodities in Australia are taken from the Australian Energy Statistics (Department of Industry Science Energy and Resources, 2020). The underlying technologies cost data and performance parameters were sourced from GIS-based energy supply-demand studies (Li et al. 2020) and MESSAGEix-GLOBIOM SSP2 baseline scenario (Krey et al., 2020).

2.1. Modifying the MESSAGE IAM to enable degrowth scenarios

The MESSAGE IAM is composed of an energy model MESSAGEix and an aggregated macro-economic model MACRO, where the former aims to obtain the lowest-cost energy system configurations and the latter incorporates their economic feedback, including optimal savings, investment, and consumption decisions through maximising the intertemporal utility (Messner & Schrattenholzer, 2000). Growth is embedded through assumptions about future growth in GDP, demand, and consumption expenditure. Specifically, GDP and demand are one-time exogenously calibrated inputs converted to growth rates of potential GDP and end-user services in MESSAGE's production function. Once the one-time inputs are specified, the MESSAGE module outputs commodity shadow prices and total system costs to MACRO to compute the optimal mix of production factors in the economy. Iteratively, GDP, consumption, investments, and energy system costs are calculated in MACRO by maximising the utility of consumption. The calculated GDP and demand are calibrated/scaled against the exogenous GDP and demand by a 'growth correction factor' and an 'autonomous energy efficiency improvement factor', respectively, to maintain a high degree of consistency between the calculated and exogenous values (Messner & Schrattenholzer, 2000).

To enable degrowth modelling in MESSAGEix, we introduce user-defined peak final consumption levels for each period, and discard the existing user-defined exogenous GDP trajectory as in the default global MESSAGEix IAM setup (Krey et al., 2020). More specifically, we first delete MESSAGE's scaling-to-exogenous-GDP equality. This means we turn the previously exogenous GDP into an endogenous decision variable subjected to macroeconomic optimisation (Figure 2). We then modify the utility function from a monotonic formulation of maximising consumption as $log(x)$, to a non-monotonic one (as detailed in section 2.2) where utility peaks at a certain consumption level.

In this modified set-up, the location of the peak in the non-monotonic utility function determines consumption (MACRO), which (amongst other factors) determines GDP (MACRO), which in turn affects end-use services demanded by consumers (MESSAGE; Useful Energy in Figure 2), which in turn determines total production (and total energy supply; MESSAGE). *Within* MACRO and MESSAGE, all constraints are solved simultaneously. *Between* MESSAGE and MACRO, the model iterates until the difference between exogenous and endogenous useful energy demand is below 0.01 (Figure 2).

Modelling consumer utility endogenously rather than GDP exogenously has advantages, because it allows us to observe the behaviour of GDP, investment, energy systems cost, energy use and emissions as a response to user-controlled changes in *consumption*, rather than user-controlled GDP. This is because post-growth thinking starts by imagining altered *consumption* levels, patterns and distributions, whether through changed preferences and/or changed provisioning systems.

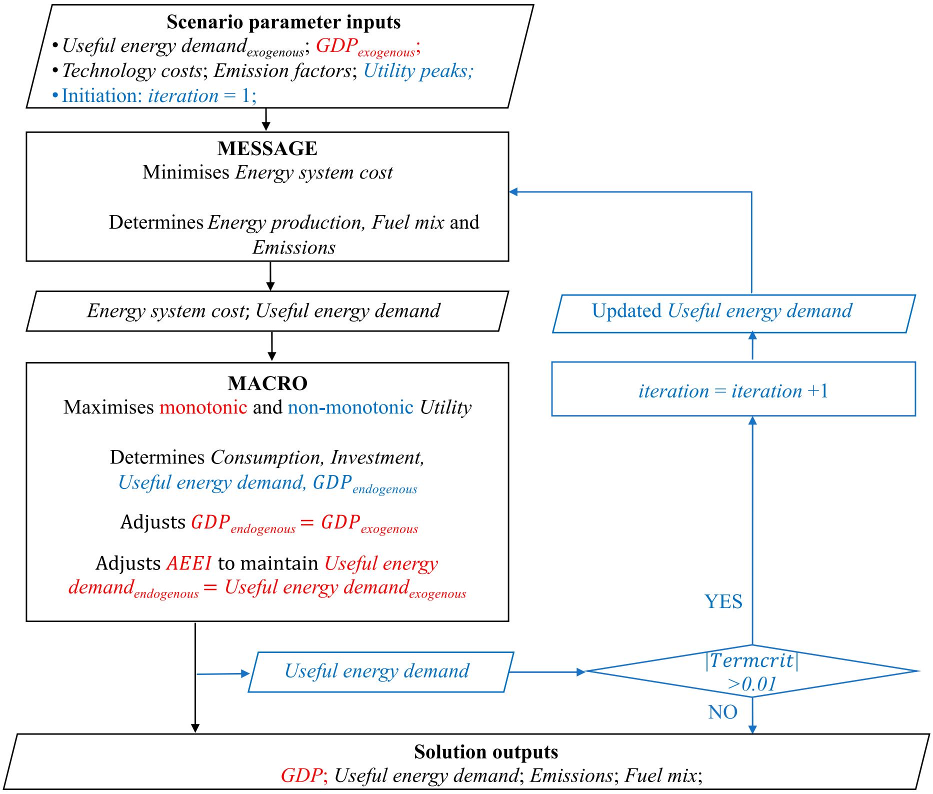
2.2. Non-monotonic preferences and utility

Existing IAMs feature utility descriptions with monotonic preferences, in which more consumption provides higher utility. One way of describing monotonic utility is through the CES function.

$$U(\alpha, x, \sigma) = \left[\sum_i \alpha_i x_i^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}, \tag{1}$$

where x is a vector of consumption of goods, α holds the shares of these goods in the consumption basket (subject to $\sum_i \alpha_i = 1$), and σ is the elasticity of substitution. CES utility for a two-good economy is shown in Figure 3 (top row) for three settings of σ. For $\sigma = 0$, goods 1 and 2 are always exchanged in fixed proportions, represented by the Leontief function, where most utility is derived by consuming either good 1 or good 2, but not a mix

Figure 2. Model interaction flowchart of the MESSAGE-MACRO module tandem.



Black: features common to original and our modified version; red: original version only; blue: modified version only. Slanted boxes contain input and output variables; variables passed on between steps are placed between arrows. Our termination criterion is $Termcrit = \frac{|\text{useful energy demand - exogenous useful energy demand}|}{\text{exogenous useful energy demand}} < 0.01$.

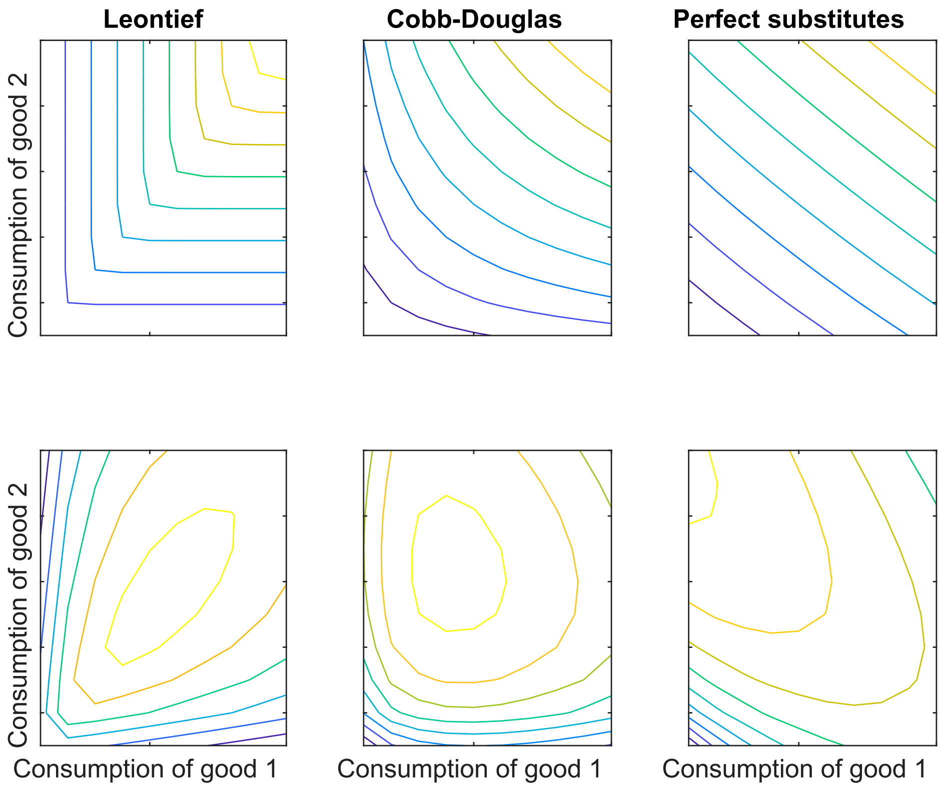
of both. For $\sigma = 1$, we obtain the Cobb–Douglas function. For $\sigma \to \infty$, goods 1 and 2 become perfect substitutes, and utility is independent of the shares α_1 and α_2. In all three cases, $U(\sigma, x_1, x_2)$ is monotonic, that is, more of goods 1 and 2 is always preferred.

A CES utility function with non-monotonic preferences can be formulated using as variable-elasticity form

$$U^*(\alpha, x, \sigma, \eta, \xi) = U(\alpha, x, \sigma)^{\eta(x)} = \left[\sum_i \alpha_i x_i^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}\left(\eta_0 + \xi \sum_i x_i\right)}, \tag{2}$$

where $\eta = \frac{\frac{\partial U}{\partial x}}{U/x}$ is the consumption-elasticity of utility. For $\eta(x) = \eta_0 + \xi \sum_i x_i$ with $\xi < 0$, utility will first increase with increasing consumption, then plateau, and finally decline (bottom row in Figure 3).

Figure 3. CES function for monotonic (U, top) and non-monotonic (U^*, bottom) preferences, in a two-good economy, with $\alpha_1 = 0.55$, $\alpha_2 = 0.45$, and $\sigma = 0.05$ (Leontief), $\sigma = 1$ (Cobb-Douglas) and $\sigma = 10$ (substitutes), and for U^* with $\eta_0 = 0.15$ and $\xi = -1.5 \times 10^{-3}$. *Utility increases from blue to yellow. Contours are asymmetric because of unequal consumption shares.*



2.3. Scenario definitions

We call the default monotonic-preference scenario 'baseline', following the 'middle-of-the-road' storyline of the Shared Socioeconomic Pathways SSP2, where the Australian total GDP increases from 53 US$k in 2020–116 US$k (05 PPP) by 2100 (Dellink et al., 2017; Fricko et al., 2017).

Consumption peaking: To test scenarios that reflect characteristics of limited- or de-growth futures, we investigate seven pathways with individual consumption peaking between 70 and 10 US$k/capita (2005 PPP) (Table 1). To put these consumer preferences into context: Compared to the actual final consumption of around 40 US$k/capita (2005 PPP) in 2020 (The World Bank, 2021), consumption peaking between 50 and 70 US$k/capita (2005 PPP) represent low-to-medium-growth futures. Non-monotonic preferences peaking between 10 and 30 US$k/capita (2005 PPP) bring Australian per-capita consumption back to the 1980–2010 average (Trading Economics, 2023). Interestingly, Australia's Genuine Progress Indicator peaked in the mid-1970s, after which it slightly declined and then stabilised. At the peak, individual consumption was about 10 US$k/capita, providing a rationale for the range chosen here and an indication for higher GDP levels not necessarily resulting in a higher subjective wellbeing (Kubiszewski et al.,

Table 1. Summary of scenario definitions.

Scenarios	Technology cost assumptions	GHG budget	Carbon tax US$/tCO2
Fossil fuel-dominated energy system	Fixing technology costs at historical levels without any future cost variations	N/A	0
Renewable-dominated energy system	Cost reductions of up to 55-90% for wind/solar technologies and 10% for fossil fuels	N/A	0
1.5°C-compliant energy system	Cost reductions of up to 55-90% for wind/solar technologies and 10% for fossil fuels	4 Gt CO2-e from 2020 to 2100	30 (between 2020–2100)

Note that in this study, we focus on trade-offs/interactions between technology-focused levers and degrowth; we, therefore, account for land use, land-use change, and forestry (LULUCF) emissions as a static emission component fixing at 2020 levels (i.e. −39 Mt CO_2-e (Department of Climate Change, 2022)) for all scenarios in all future years:

2013). In order to avoid abrupt trend breaks and model instability, we model the degrowth scenarios by gradually adjusting consumption peaks in a linear way, so that, starting with the current consumption peak at AU$40k/cap, the final utility peaks are reached by 2040.

Technology development: We consider three technology development patterns to examine the potential impact of non-monotonic preferences on emissions (Table 1):

i) A fossil fuel-dominated energy system is modelled by fixing technology costs at historical levels without any future cost variations (Table 1, first row);
ii) A renewable-dominated energy system considering cost reductions of up to 55-90% for wind/solar technologies and 10% for fossil fuels (Table 1, second row); and
iii) A renewable-dominated energy system further complemented by CCS and NETs. On top of the assumptions in ii), the utilisation of CCS and NETs are considered in large-scale power plants or industrial processes such as electricity generation, hydrogen and ethanol production, and as end-of-pipe additions for plants combusting biomass, coal and natural gas. The underlying technologies' cost data and performance parameters were sourced from the MESSAGEix-GLOBIOM SSP2 baseline scenario (Krey et al., 2020). A carbon price of US$ 30 per tonne of CO_2 emissions between 2020 to 2100 is considered to model strong greenhouse gas abatement scenarios. A carbon budget constraint of 4 Gt CO_2-e from 2020 to 2100 for Australia (Nicholls & Meinshausen, 2022) is applied to obtain 1.5°C compatible pathways (Table 1, third row).

3. Results

3.1. Scenario results

We present GDP, energy and emissions trends obtained from the MESSAGE IAM, using the default monotonic and various non-monotonic utility functions (Figure 4). In the unmodified MESSAGE IAM, growth is embedded through an exogenously calibrated GDP and the monotonic utility function, resulting in a more than doubling of individual consumption expenditure between 2020–2100 (Figures 4a and b, red SSP2 baseline curves).

Using the degrowth MESSAGE IAM, we run a wide range of medium-to-low-growth and degrowth scenarios (Figure 4, coloured curves). Specifically, compared to the SSP2 baseline scenario featuring a 58% and 125% increase of per-capita GDP by 2050 and 2100, non-monotonic utility slows down the growth to 8%–55% by 2050, and 14%–62% by 2100, assuming consumption peaks between 50 and 70 US$k/capita (2005 PPP). Further lowering the individual consumption peak toward 10 US$k/capita results in no- or degrowth

Figure 4. GDP, physical energy use and GHG emissions *under three technology development patterns*: ***a***&**b**, *GDP and per-capita GDP for 2020-2100.* **c**&**d**, *total and per-capita physical energy use for 2020-2100. Technology development pattern ranges are indicated by pale-coloured fans.* **e**-**j**, *total and per-capita Australia annual GHG emissions excluding LULUCF for 2020–2100 under three technology development patterns: 1) fossil fuel-dominated energy system (***e**&**f***); 2) renewable energy transformation without (***g**&**h***) and 3) with (***i**&**j***) a large-scale adoption of CCS and NETs. Historical LULUCF emissions are only shown in panels* **g**&**h** *for illustrative purposes; Future LULUCF emissions are assumed to be fixed at 2020 levels (i.e. −39 Mt* CO_2*-e (*Department of Climate Change, 2022*)) for all scenarios. Only scenarios* **i**&**j** *are 1.5°C-compliant: emissions budgets are constrained to 4Gt (see Technology development iii in Section 2.3 for scenario definitions). Red lines indicate the SSP2 baseline scenario simulated by the unmodified 'growth-embedded' MESSAGE IAM. Colored lines represent 'growth-decoupled' scenarios from the modified MESSAGE IAM, assuming consumption utility peaks between 10 - 70 US$k/capita (US$2005). Utility peaks are reached in the year 2100 for SSP2 baseline scenario, and in 2030–2060 for various limited-and de-growth scenarios. UNITS***:** *t US$ = trillion US$; Mt* CO_2*-e = million tonnes* CO_2*-e;*

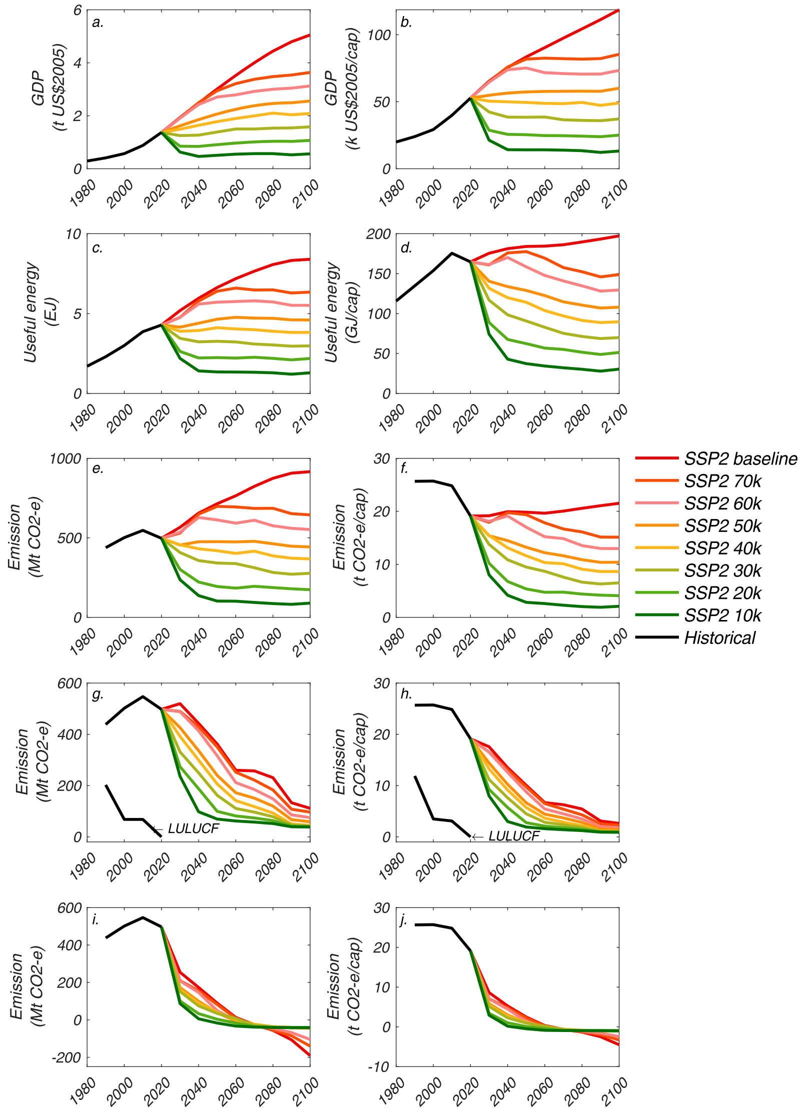
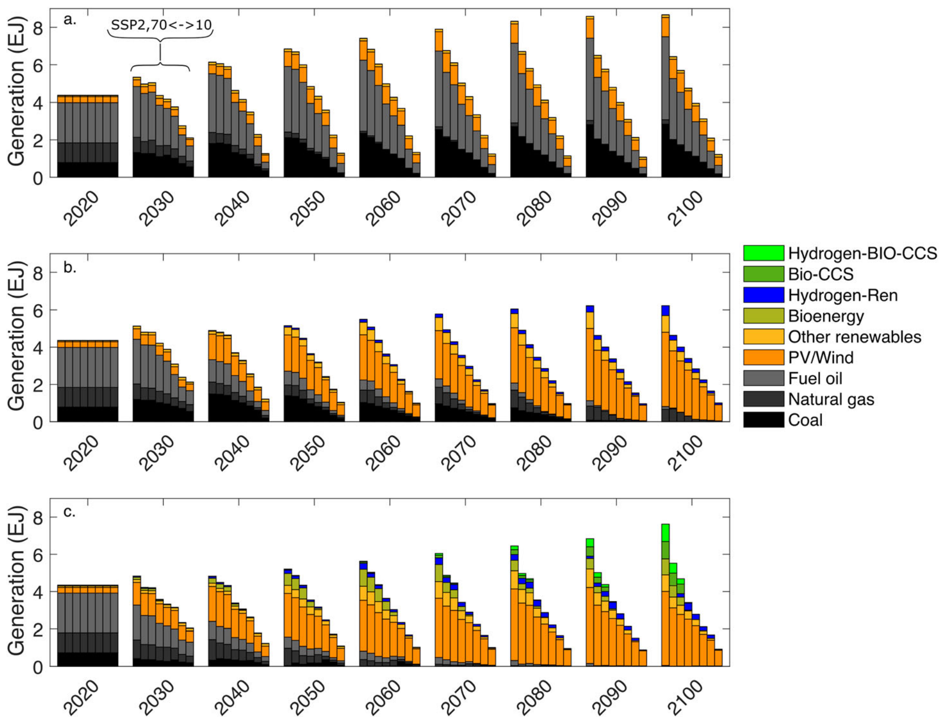


Figure 5. Technology generation mix under three technology development patterns: *fossil fuel-dominated energy system (**a**, corresponding to* Figure 4 *e&f); renewable energy transformation without (**b**, corresponding to* Figure 4 *g&h) and with a large-scale adoption of CCS and NETs (**c**, corresponding to* Figure 4 *i&j; 1.5°-compatible); The eight stacked bars in every year set represent the SSP2 baseline scenario (1st bar; unmodified monotonic MESSAGE) and 'growth-decoupled' scenarios assuming consumption utility peaks between 70 - 10 US $k/capita (the 2nd-to-8th bar), respectively.*



scenarios, leading to a reduction in GDP per capita by up to 75% by 2100 (Figure 4b, green curve).

In line with economic trends, useful energy use shows analogous slow-growing or declining trajectories (Figure 4c-d), reflecting economic feedback on end-use service demands. Degrowth results in a demand reduction by up to 74% by 2100, in comparison to an almost doubling of 2100 energy consumption in the SSP2 baseline scenario (Figure 4c-d).

We further investigated GHG (CO_2, CH4 and N_2O) emission trends, this time without (Figure 4e and f) and with large-scale renewable energy transformation (Figure 4g and h) or further complemented by CCS and NETs (Figure 4i and j). Fixing renewable energy technology costs at the current level limits the scale of renewable deployment in Australia, and energy demand is primarily met by fossil fuels (91% collectively; Figure 5a), resulting in almost doubling GHG emissions by 2100 in the baseline scenario (Figure 4e and f, red curve). In contrast, degrowth without a low-carbon energy transition leads to substantial emissions reductions by up to 79% by 2050 and 83% by 2100 relative to 2020 levels (Figure 4e and f, coloured lines). Notably, the non-monotonic utility with a peak consumption of US$60-70k/capita tends to would stabilise emissions at 2020 levels (Figure 4e, pink-red lines).

Additionally, lowering renewable costs results in MESSAGEix decarbonising Australia's energy systems through increasing penetration of renewables in the electricity generation mix (compare Figure 5a and b), contributing to a further reduction of up to 57% in cumulative emissions relative to the scenario of degrowth without a low-carbon energy transition (Figure 4g and h). More specifically, the non-monotonic utility with a peak consumption of 10–30 US$k/capita reduces national GHG emissions by up to 92% by 2100, leading to cumulative emissions of 9–14 Gt between 2020 and 2100 (Figure 4g and h, green curves). These are almost three times lower than the 25.6 Gt in the baseline Scenario (Figure 4g and h, red curves).

The trajectories in Figure 4e-h are associated with different total carbon budgets, none of which are 1.5°C-compatible. Therefore, we present another set of scenarios (Figure 4i&j) that meet Australia's emissions budget of 4 Gt CO_2-eq (Nicholls & Meinshausen, 2022) associated with a 50% chance of staying below 1.5°C. In the SSP2 baseline scenario (Figure 4i&j, red curves), substantial negative emissions are needed between 2080 and 2100. Degrowth scenarios (green) reduce the reliance on unrealistically high levels of negative emission technologies and rapid rates of renewable energy deployment, thereby increasing the overall chances of staying below 1.5°C. Figure 6 illustrates this and other trade-offs: In degrowth-scenarios (right-hand bar in each group), reductions are demand-driven (red segment), start early in 2030 and reach 600 $MtCO_2$-e in 2100, whereas in the baseline scenario (left-hand bars) reductions are technology-driven (mainly grey, blue, orange and green segments), and more than 1000 $MtCO_2$-eq are needed by 2100. Note, especially the much-reduced reliance on technologies in the degrowth-driven scenarios.

A noteworthy feature of the $20k- and $10k-utility peak scenarios is that the net investment in MACRO's optimisation becomes negative with the economy facing drastically reduced demand, reflecting the obsolescence and stranding of capital infrastructure that had been invested in prior years on the expectation of a growth trajectory. In 2030, stranded assets amount to around US$ 150–200 bn (Figure 7), representing about a quarter of the total 2022 gross fixed capital formation (ABS, 2022).

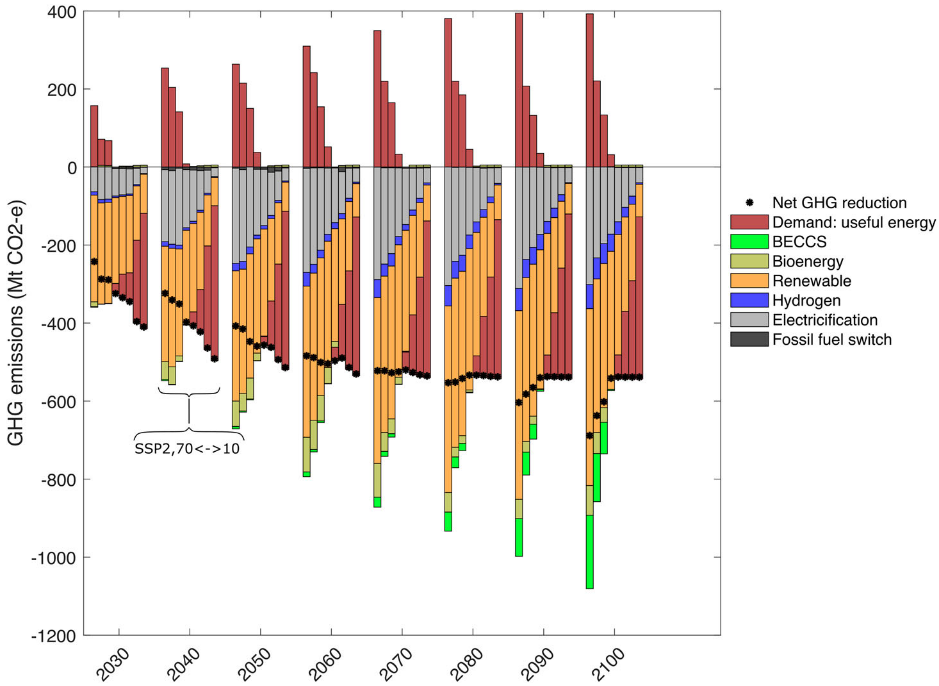
Finally, in a different article in this Special Issue (Kikstra et al., 2023) we report on the carbon prices associated with the various scenarios. These generally increase over time, with decreasing carbon budget (i.e. tighter budgets require higher carbon prices), and with increasing utility peak (i.e. higher consumption levels require higher carbon prices to keep emissions low).

3.2. Contrast with existing IAM mitigation pathways

This article presented new sets of degrowth scenarios for Australia. This set can be used to further research the interplay between a simple set of technology options and a wide range of GDP outcomes due to varying assumptions for the utility function. Figure 8 juxtaposes these scenarios with the scenarios available in the AR6 Scenario Database (Byers et al., 2022) for future emissions, energy use, and GDP (PPP) characteristics for the region, which combines Australia, Japan, and New Zealand (IPCC, 2022b, p. 1824).

The degrowth scenarios with rapid renewable deployment but no negative emissions see GHG reductions from 8% (SSP2-baseline (renewables)-ren) to about 58% (SSP2-10k (-renewables)) in 2030 and 47-90% in 2050. This puts near-term action roughly in line with the regional emissions reductions in C1-C3 IPCC pathways that limit warming to 2C with

Figure 6. GHG emission reduction levers in the 1.5°-compatible pathways (corresponding to Figure 4 i&j). *The eight stacked bars from left to right represent the SSP2 baseline scenario (1st bar; unmodified monotonic MESSAGE) and 'growth-decoupled' scenarios with consumption utility peaks between 70 - 10 US $k/capita, respectively. Net GHG reductions: changes in GHG emissions (*Figure 5c*) w.r.t. the baseline scenario; Demand: GHG emissions level attributable to changes in useful energy; BECCS: Reductions attributable to bioenergy with carbon capture and storage; Bioenergy: Reductions attributable to bioenergy without carbon capture and storage (e.g. biofuels for vehicles).*

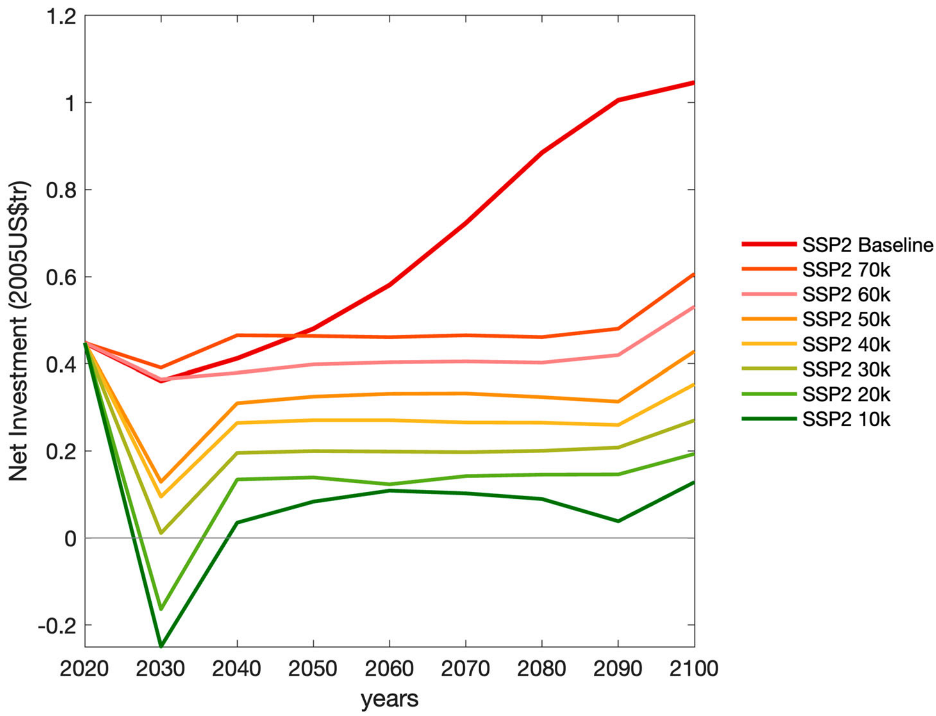


at least a 66% likelihood, with the exception of the highest-growth pathways. However, these renewables expansion pathways for Australia are not enough to be in line with a longer-term global temperature stabilisation because of long-lived residual emissions that are not abated. The energy use (final energy demand) in these pathways covers a range much wider than the 231 global scenarios investigated in the AR6 Scenario Database in C1-C3 with the Australia, Japan, and New Zealand regions. The main novelty here is the increased range of GDP per capita, especially on the lower end. While the scenarios in the IPCC all increase steadily with a 31-99% growth range in 2050, our scenarios range much wider from a 74% decline to a 58% increase.

The degrowth scenarios that also model negative emissions technologies have approximately the same energy and GDP pathways. However, as described above, they see lower emissions as they are restricted to a GHG-based emissions budget (4GtCO2eq) until net-zero GHGs. The emissions reductions in these pathways are faster than the AR6 Scenario Database category C1 pathways.

This paper has described the development of degrowth scenarios for Australia. Here, we discuss some key characteristics to show where the scenarios explore different assumptions beyond what is available in the AR6 Scenarios Database. It is beyond the scope of this paper to explore the details and implications of the specific scenario combinations and

Figure 7. Trajectories of net investment for the eight scenarios in Figures 4–6. *We calculate net investment as investment minus stranding of assets. The $10k-utility peak scenario experiences asset stranding worth more than US$ 200bn.*

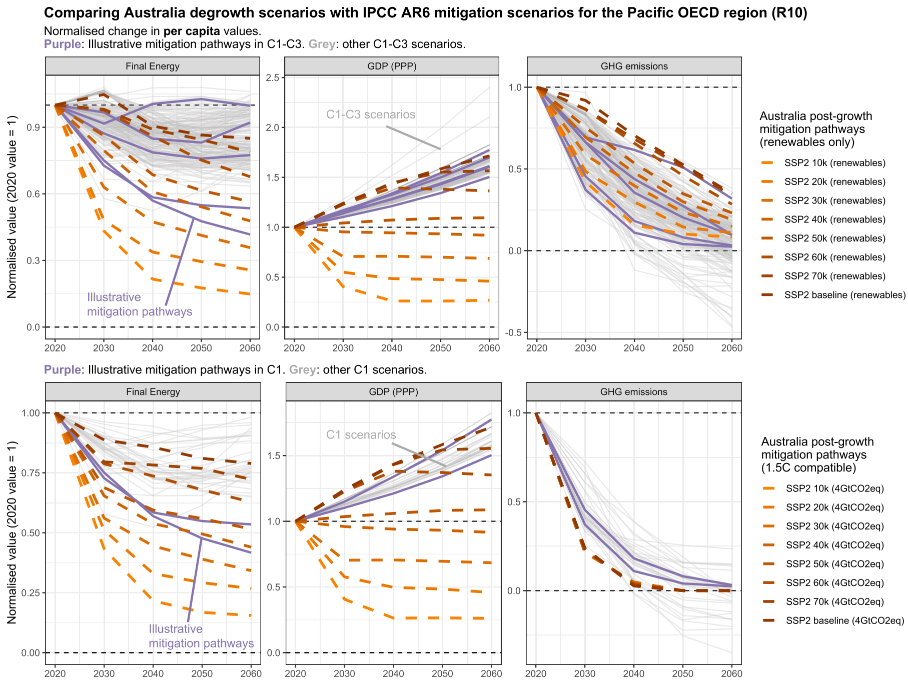


interpret the modelling in more detail, which we leave for future work (including in Kikstra et al. (2023)). This includes comparing decoupling rates, understanding the relationship between GDP, final energy, and changes in aggregate service, sectoral characteristics, and feasibility, and comparing renewables to GDP change rates.

4. Discussion

Our modelling finds significant declines to GDP/capita and associated energy use and CO_2 emissions from amending the core utility function to non-monotonic preferences with tightening consumer utility levels (see Figure 4). The CO_2 emission reductions are especially pronounced at the lower peak consumption levels ($10-$30k/capita) and in the short-term until 2030. In these scenarios, renewable energy deployment only leads to small additional CO_2 reductions in the short-term (see Figures 4 and 5). In contrast, the need for negative emission technologies and energy efficiency gains is significantly reduced in the short-, medium- and long-term (see Figure 6). Hence, the challenges to feasibility in these dimensions are lower, while the scenarios arguably are more in line with equity concerns (Anderson et al., 2020) when compared to established scenarios in several dimensions. More specifically, the advantages in terms of equity here are rooted in a faster short-term reduction of carbon emissions in rich countries such as Australia, in line with common but differentiated responsibilities as emphasised in the Paris Agreement, as

Figure 8. Australian degrowth scenarios compared to the IPCC AR6 mitigation scenarios. *Upper row features IPCC climate category C1, C2, and C3 (total: 232 scenarios of 7 model families) in comparison with the renewables only scenarios, and the bottom row features only category C1 (35 scenarios of 6 model families) in comparison with 1.5C compatible scenarios. The AR6 database scenarios are for the IPCC region Pacific OECD (Australia, Japan, and New Zealand - and also South Korea for a minority of scenarios), excluding REMIND scenarios which do not include Australia in this region, and excluding scenarios that did not report population. All values are per capita, normalised in 2020. Values below zero indicate negative values, being negative GHG emissions. GHG emissions here include only CO_2, CH_4, and N_2O for the Australia degrowth scenarios, while it includes a wider set of GHGs in the IPCC scenarios.*



well as significantly lower demands on resource and land use and negative emission technologies, which strongly impact the global South (see Anderson & Peters, 2016; Keyßer & Lenzen, 2021; Scheidel et al., 2020). International dimensions of redistribution and climate finance, while certainly crucial (Soergel et al., 2021), are beyond the scope of this paper.

This paper faces several limitations, which need to be kept in mind when interpreting our results and which give rise to further research opportunities. First, implementing a degrowth scenario into MESSAGEix, as put forward in this paper, with a low consumption utility peak leading to low demand for end-use services and low GDP and energy consumption, is a an oversimplication of degrowth as theorised in the literature. Since MACRO includes a mono-sectoral utility function, our degrowth scenarios do not assume any distribution of consumption among various segments of the population. Distributional issues can be addressed in future studies by coupling IAMs with sectorally and regionally detailed Social Accounting Matrices (SAMs) and Input–Output Tables (IOTs), where the income distributions are handled by the SAM and IOT features. Furthermore, degrowth is usually conceptualised as an equitable and democratic social transformation, leading to stringent reductions in energy and material consumption and carbon emissions, with GDP declining only as a consequence (Kallis et al., 2018). How our modelling relates to this literature and what differentiates our degrowth scenario from a recession is discussed in more detail in subsequent paragraphs. Still, to complement our simplified implementation of degrowth in an established IAM, additional modelling with modified and new models which can integrate insights from research in, e.g. social metabolism, industrial ecology and ecological economics is necessary (see D'Alessandro et al. (2020), Hardt and O'Neill (2017), and Nieto et al. (2020)). Secondly, our modelling of degrowth is only a first exploration for one country, with one established IAM and without an assessment of sectoral detail, as such detail is lacking in MESSAGEix. This lack of sectoral detail is a significant limitation, since the degrowth literature emphasises a sectorally differentiated downscaling depending on the social and ecological impacts of different sectors in order to ensure wellbeing and sustainability (see Kikstra et al. (2023) for a more detailed discussion). Additionally, differentiated downscaling could further reduce the energy intensity of the economy, which is not captured here. In order to make our results more robust and valuable, additional modelling at a global, yet regionally differentiated scale, with sectoral detail and with other established IAMs to allow for comparisons, is needed. Such modelling is also crucial for assessing differential dynamics between the global North and global South, as theorised in the degrowth literature, including convergence pathways and their implications for global poverty, redistribution, climate finance, technological transfers and climate mitigation (see Hickel (2021) and Hickel and Slamersak (2022)). Lastly, as argued in the introduction, while non-monotonic preferences certainly are plausible and defensible as part of a modelling exercise, more research is necessary to substantiate their empirical basis.

After considering the GDP reductions in Figure 4, one might reasonably ask whether this represents what is typically understood as a recession or depression, which we know to be disastrous regarding social consequences (see Tokic (2012)). While we have argued for the plausibility of individual non-monotonic preferences, the current capitalist economy, with its particular arrangements of provisioning, distribution and power, is dependent on economic growth for macroeconomic 'stability' and social well-being (i.e. employment, funding for public services, etc.) (see Blauwhof (2012), Kallis et al. (2018) and Richters and Siemoneit (2019)). Within this context, declines in GDP are associated with social problems. It follows that individuals, as well as other agents, such as firms and states, are currently likely to pursue consumption and economic growth notwithstanding their probable non-monotonic preferences in order to avoid negative social consequences, such as unemployment, bankruptcies and economic instability (Kallis et al., 2018; Richters & Siemoneit, 2019; Wiedmann et al., 2020).

Despite many questions still being open, actively researched and debated (see, e.g. Richters and Siemoneit (2019)), several growth dependencies have been identified to exist on various levels of society and can include:

1. **Consumers**: structural barriers to sufficiency (Alexander, 2012, 2013; Alexander & Ussher, 2012), e.g. car-focused infrastructure (Mattioli et al., 2020), and people's need to maintain their social status via positional consumption (Exner, 2014; Wiedmann et al., 2020);

2. **Employees**: workers need to increase their time and cost efficiency via efficiency consumption, e.g. via kitchen appliances and smartphones, in the face of competition for jobs with other workers (Siemoneit, 2019);
3. **Firms**: the need for firms to reinvest profits into minimising costs, innovation and an increase in the sales effort in order to defend or increase their market shares against competition and insure themselves against economic uncertainty (Exner, 2014; Lange, 2018; Nelson, 2022; Stützle, 2015); and
4. **States**: the need for states to maintain social legitimacy, a stable currency, high tax revenues and low unemployment in the face of competition with other states (Blauwhof, 2012; Carter, 2013; Richters & Siemoneit, 2019; Stützle, 2021).

Taken together, these dynamics result in a systemic growth imperative, which effectively couples social wellbeing to continued economic growth (Blauwhof, 2012; Kallis et al., 2018) and explains why the economic growth paradigm is currently hegemonic (see Schmelzer (2015)), despite the possibility of non-monotonic preferences.

However, post-growth and degrowth scholarship details policy packages, as well as transformational pathways driven by social movements to achieve them, that would make wellbeing independent from economic growth (see generally Cosme et al. (2017), Fitzpatrick et al. (2022), Parrique (2019), and Schmelzer et al. (2022)). Again, this is a sizable field of active research and academic debate, so our treatment here needs to be completed. However, following Kuhnhenn et al. (2020, p. 66), such a transformation clearly '*is not primarily about producing and consuming less; it is about organising society differently. [...] Instead of focusing on material welfare – fostering economic growth, competition and profit-making – we focus on fulfilling concrete human needs and serving common welfare – fostering cooperation, care, solidarity and sustainability in order to achieve a good life for all.*' In other words, degrowth and post-growth transformations enable the practical realisation of non-monotonic preferences.

Such changes are wide-ranging, affect all levels of society and combine sufficiency, efficiency and consistency strategies (O'Neill et al., 2018; Wiedmann et al., 2020). They can include:

1. On a household and community level, the adoption of values and practices of sufficiency (Sandberg, 2021), the collective creation and expansion of alternative institutions for direct human needs satisfaction, e.g. commons (Alexander & Gleeson, 2020), as well as the widespread creation, cooperation and strengthening of progressive social movements, such as the union, tenant, feminist and anti-racism movements (Schmelzer et al., 2022);
2. On the firm level, the strengthening of worker self-management, not-for-profit and needs-focused models, localisation as well as cooperation over competition (Lange, 2018; Nesterova, 2021) and finally;
3. On the state level, the introduction of reforms such as working time reductions, ecological investment programmes, universal basic incomes, services and vouchers, income, wealth and ecological caps, limits on advertising, alternative indicators of progress and reparations (Fitzpatrick et al., 2022).

Taken together, these changes aim at decoupling wellbeing from economic growth, by focusing on meeting human needs directly, sufficiently and equitably via collective provisioning, and hence substantially reduce the social importance of monetary market values (Büchs & Koch, 2017; Hickel, 2020). Ultimately, the goal is to secure a good life for all via more equitable, collective and democratic provisioning systems, which evidence shows to be more efficient in meeting human needs at lower resource use (Baltruszewicz et al., 2021a; Baltruszewicz et al., 2021b; Vogel et al., 2021). In further support, modelling studies, as well as empirical evidence, substantiate the possibility of satisfying human needs for all at substantially reduced energy use if sufficiency, equity, and reduced inequalities are taken seriously (Hickel, 2018; Kikstra et al., 2021; Millward-Hopkins, 2022; Millward-Hopkins et al., 2020; Rao et al., 2019). Other degrowth and post-growth scenario storylines, such as the one tentatively described here, can also be found in the publications by D'Alessandro et al. (2020), Hickel (2021), Kuhnhenn et al. (2020) and Otero et al. (2020). The question of how a degrowth transition would impact technological innovation and efficiency gains is still open and in need of further research, but we can point to 1) empirical data showing that slower rates of economic growth between 1972–2002 in high-income countries have been associated with higher reductions in CO2 intensity and energy intensity of GDP (Victor, 2008) and 2) modelling studies such as ours which lend support for investment in technological innovation within a degrowth transition being a question of societal prioritisation (D'Alessandro et al., 2020; Nieto et al., 2020).

Finally, it needs to be acknowledged that the changes implied by degrowth, as described above, face substantial socio-political barriers, specifically in the lower peak consumption cases such as the $10k/capita scenario (Blauwhof, 2012; Kallis et al., 2018). A degrowth transformation challenges widely held values, habits and power structures (Schmelzer et al., 2022; Wiedmann et al., 2020). Thus, its socio-political feasibility under current circumstances can be regarded as relatively low. In an accompanying paper in this special issue, Kikstra et al. (2023) analyse the feasibility of the energy demand reductions in our pathways, while acknowledging such quantitative methods are still uncertain. This however can change with strengthened social movements, improved knowledge about degrowth as well as awareness of possible transition pathways (see Keyßer and Lenzen (2021); Schmelzer et al. (2022)). Despite these points and the above discussion, the desirability especially of the $10k/capita scenario can certainly be questioned as being potentially problematic from a wellbeing perspective. For this scenario, Kikstra et al. (2023) show that meeting decent living standards for all strongly depends on a high degree of equality as well as on the widespread availability of current state-of-the art technology to enable a high degree of energy efficiency.

5. Conclusions

Existing Integrated Assessment Models of climate change mitigation assume renewables expansion, energy efficiency, and negative emissions technologies provide three large enough emissions reduction levers to keep global warming well below 2°C. However, there are clear feasibility concerns associated with these levers, increasing with the scale of reliance on them, from multiple perspectives, including technological and geophysical concerns. To compound this problem, IAMs assume continued economic growth, leading to a central issue in the modelling process: the assumed absolute energy-GDP global decoupling has never before occurred.

Therefore in this article, we examine a fourth, underexplored lever that could reduce these feasibility concerns: namely, degrowth - via a reduction in general total aggregate services, mainly in rich countries, leading to reduced or negative global GDP growth. Degrowth is focussed on an equitable, coordinated and democratic reduction in socially unnecessary production and consumption. Successful degrowth would limit energy use, and reduce the weight of lifting that renewables, energy efficiency and NETs would need to do.

However, to date, the exploration of degrowth scenarios, combining all four levers, has been rarely attempted. In principle, degrowth futures can be modelled in two ways: 1) exogenise the energy-GDP relationship so that it follows historical trends, based on this set exogenous GDP levels, and then model resultant energy use and CO_2 emissions; and 2) explore degrowth scenarios via endogenous means, ie. internally amend the IAM's utility function. In this work, we have focused on the second option. We modify the central utility function via lower variants of non-monotonic preferences in the MESSAGEix model for the case of Australia. We model several degrowth futures, based on individual consumption peaking between 10–70 US$k/capita (2005 PPP) in 2100, resulting in a decline in future GDP growth.

Based on our results, we reach several key conclusions:

1. The modification of the central utility function towards a non-monotonic formulation provides an effective method for endogenous implementation of degrowth scenarios, with significant energy (and associated emissions) reductions following.
2. Therefore, we recommend that other IAMs start including degrowth scenarios as part of a future suite of 1.5°C-2°C scenarios as well as for the IPCC to prominently feature them, not least as a backup in case any/all of the current 'big three' levers (renewables, efficiency, NETs) lack effectiveness at the necessary speed and scale. We have no time to gamble that all of these levers will work as assumed in speculative scenarios.
3. Not only do degrowth scenarios broaden the landscape of options for IAMs to meet climate targets, but they also provide signposts for policy-makers as well as social movements and society at large for moving to degrowth futures, which focus on improving equity, human wellbeing and ecological sustainability.

Acknowledgements

Arunima Malik acknowledges support from the University of Sydney SOAR Prize. Jason Hickel acknowledges support from the María de Maeztu Unit of Excellence (CEX2019-374 000940-M) grant from the Spanish Ministry of Science and Innovation. The authors thank Narasimha Rao for valuable comments on earlier manuscript drafts, and Volker Krey for providing data for model development and analysis.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was financially supported by the Australian Research Council under its Discovery project ARC DP200102585, and by the Hanse-Wissenschaftskolleg Delmenhorst through a HWK Fellowship for Manfred Lenzen. Sebastian Juraszek managed the HPC fleet used for calculations. Jarmo S. Kikstra has been supported by the Natural Environment Research Council under grant agreement NE/S007415/1 and by funding from the SHAPE project, which is part of AXIS, an ERA-NET initiated by JPI Climate, and funded by FORMAS (SE), FFG/BMWFW (AT, grant number 871994), DLR/BMBF (DE, grant number 01LS1907A-B-C), NWO (NL) and RCN (NO) with co-funding by the European Union (grant number 776608). Paul Brockway's time was funded by the UK Research and Innovation (UKRI) Council, supported under Engineering and Physical Sciences Research Council Fellowship award EP/R024254/1.

ORCID

Mengyu Li http://orcid.org/0000-0002-6791-1170
Lorenz Keyßer http://orcid.org/0000-0002-0823-9150
Jarmo S. Kikstra http://orcid.org/0000-0001-9405-1228
Jason Hickel http://orcid.org/0000-0002-7490-9757
Paul E. Brockway http://orcid.org/0000-0001-6925-8040
Nicolas Dai http://orcid.org/0000-0002-5924-6326
Arunima Malik http://orcid.org/0000-0002-4630-9869
Manfred Lenzen http://orcid.org/0000-0002-0828-5288

References

ABS. (2022). *Australian national accounts: Input–output tables*. Australian Bureau of Statistics. Retrieved 12 December from.

Alexander, S. (2012). Planned economic contraction: the emerging case for degrowth. *Environmental Politics*, *21*(3), 349–368. https://doi.org/10.1080/09644016.2012.671569

Alexander, S. (2013). Voluntary simplicity and the social reconstruction of Law: Degrowth from the grassroots Up. *Environmental Values*, *22*(2), 287–308. https://doi.org/10.3197/096327113X13581561725356

Alexander, S., & Gleeson, B. (2020). Urban social movements and the degrowth transition: Towards a grassroots theory of change [Other Journal Article]. *The Journal of Australian Political Economy*, *86*, 355–378. https://search.informit.org/doi/10.3316informit.664843066090286 https://search.informit.org/doi/full/10.3316/informit.664843066090286 https://search.informit.org/doi/pdf/10.3316/informit.664843066090286

Alexander, S., & Ussher, S. (2012). The Voluntary Simplicity Movement: A multi-national survey analysis in theoretical context. *Journal of Consumer Culture*, *12*(1), 66–86. https://doi.org/10.1177/1469540512444019

Anderson, K., Broderick, J. F., & Stoddard, I. (2020). A factor of two: how the mitigation plans of 'climate progressive' nations fall far short of Paris-compliant pathways. *Climate Policy*, *20*(10), 1290–1304. https://doi.org/10.1080/14693062.2020.1728209

Anderson, K., & Peters, G. (2016). The trouble with negative emissions. *Science (American Association for the Advancement of Science)*, *354*(6309), 182–183. https://doi.org/10.1126/science.aah4567

Bain, P. G., & Bongiorno, R. (2022). Evidence from 33 countries challenges the assumption of unlimited wants. *Nature Sustainability*, *5*(8), 669–673. https://doi.org/10.1038/s41893-022-00902-y

Baltruszewicz, M., Steinberger, J. K., Ivanova, D., Brand-Correa, L. I., Paavola, J., & Owen, A. (2021a). Household final energy footprints in Nepal, Vietnam and Zambia: composition, inequality and links to well-being. *Environmental Research Letters*, *16*(2), https://doi.org/10.1088/1748-9326/abd588

Baltruszewicz, M., Steinberger, J. K., Owen, A., Brand-Correa, L. I., & Paavola, J. (2021b). Final energy footprints in Zambia: Investigating links between household consumption, collective provision, and well-being. *Energy Research & Social Science*, *73*, https://doi.org/10.1016/j.erss.2021.101960

Barck-Holst, P., Nilsonne, Å, Åkerstedt, T., & Hellgren, C. (2017, July). *Reduced working hours and stress in the Swedish social services: A longitudinal study*. *SAGE Publications*. 769-1068.

Beça, P., & Santos, R. (2010). Measuring sustainable welfare: A new approach to the ISEW. *Ecological Economics*, *69*(4), 810–819. https://doi.org/10.1016/j.ecolecon.2009.11.031

Bengtsson, S. E. L., Barakat, B., Kebede, E. B., & Muttarak, R. (2018). *The role of education in enabling the sustainable development agenda (First edition. ed.)*. Taylor and Francis. https://doi.org/10.4324/9781315142708.

Berner, A., Bruns, S., Moneta, A., & Stern, D. I. (2022). Do energy efficiency improvements reduce energy use? Empirical evidence on the economy-wide rebound effect in Europe and the United States. *Energy Economics*, *110*, https://doi.org/10.1016/j.eneco.2022.105939

Bertram, C., Luderer, G., Popp, A., Minx, J. C., Lamb, W. F., Stevanović, M., Humpenöder, F., Giannousakis, A., & Kriegler, E. (2018). Targeted policies can compensate most of the increased sustainability risks in 1.5 °C mitigation scenarios. *Environmental Research Letters*, *13*(6), 0064038. https://doi.org/10.1088/1748-9326/aac3ec

Bilancini, E., & D'Alessandro, S. (2012). Long-run welfare under externalities in consumption, leisure, and production: A case for happy degrowth vs. unhappy growth. *Ecological Economics*, *84*, 194–205. https://doi.org/10.1016/j.ecolecon.2011.10.023

Bishai, D. M., Cohen, R., Alfonso, Y. N., Adam, T., Kuruvilla, S., & Schweitzer, J. (2016). Factors contributing to maternal and child mortality reductions in 146 Low- and middle-income countries between 1990 and 2010. *PloS one*, *11*(1), e0144908. https://doi.org/10.1371/journal.pone.0144908

Blauwhof, F. B. (2012). Overcoming accumulation: Is a capitalist steady-state economy possible? *Ecological Economics*, *84*, 254–261. https://doi.org/10.1016/j.ecolecon.2012.03.012

Bodirsky, B. L., Chen, D. M.-C., Weindl, I., Soergel, B., Beier, F., Molina Bacca, E. J., Gaupp, F., Popp, A., & Lotze-Campen, H. (2022). Integrating degrowth and efficiency perspectives enables an emission-neutral food system by 2100. *Nature Food*, *3*(5), 341–348. https://doi.org/10.1038/s43016-022-00500-3

Brand-Correa, L. I., Mattioli, G., Lamb, W. F., & Steinberger, J. K. (2020). Understanding (and tackling) need satisfier escalation. *Sustainability: Science, Practice and Policy*, *16*(1), 309–325. https://doi.org/10.1080/15487733.2020.1816026

Brockway, P. E., Sorrell, S., Semieniuk, G., Heun, M. K., & Court, V. (2021). Energy efficiency and economy-wide rebound effects: A review of the evidence and its implications. *Renewable and Sustainable Energy Reviews*, *141*, 110781. https://doi.org/10.1016/j.rser.2021.110781

Brulle, R. J., & Young, L. E. (2007). Advertising, individual consumption levels, and the natural environment, 1900–2000. *Sociological Inquiry*, *77*(4), 522–542. https://doi.org/10.1111/j.1475-682X.2007.00208.x

Brutschin, E., Pianta, S., Tavoni, M., Riahi, K., Bosetti, V., Marangoni, G., & van Ruijven, B. J. (2021). A multidimensional feasibility evaluation of low-carbon scenarios. *Environmental Research Letters*, *16*(6), https://doi.org/10.1088/1748-9326/abf0ce

Büchs, M., & Koch, M. (2017). *Postgrowth and wellbeing: Challenges to sustainable welfare*. Springer International Publishing AG. https://doi.org/10.1007/978-3-319-59903-8.

Byers, E., Krey, V., Kriegler, E., Riahi, K., Schaeffer, R., Kikstra, J., Lamboll, R., Nicholls, Z., Sandstad, M., Smith, C., & van der Wijst, K. (2022, November). *AR6 Scenarios Database hosted by IIASA*. Zenodo. https://doi.org/10.5281/zenodo.7197970.

Calverley, D., & Anderson, K. (2022). *Phaseout pathways for fossil fuel production within Paris-compliant carbon budgets* [report]. T. C. A. T. U. O. Manchester.

Capellán-Pérez, I., de Blas, I., Nieto, J., de Castro, C., Miguel, L. J., Carpintero, Ó, Mediavilla, M., Lobejón, L. F., Ferreras-Alonso, N., Rodrigo, P., Frechoso, F., & Álvarez-Antelo, D. (2020). MEDEAS: a new modeling framework integrating global biophysical and socioeconomic constraints. *Energy & Environmental Science*, *13*(3), 986–1017. https://doi.org/10.1039/C9EE02627D

Capellán-Pérez, I., de Castro, C., & Miguel González, L. J. (2019). Dynamic Energy Return on Energy Investment (EROI) and material requirements in scenarios of global transition to renewable energies. *Energy Strategy Reviews*, *26*, https://doi.org/10.1016/j.esr.2019.100399
Carter, A. (2013). *A radical green political theory*. Routledge. https://doi.org/10.4324/9781315008707.
Cereseto, S., & Waitzkin, H. (1986). Economic development, political-economic system, and the physical quality of life. *American Journal of Public Health*, *76*(6), 661–666. https://doi.org/10.2105/AJPH.76.6.661
Chen, L.-Y., Oparina, E., Powdthavee, N., & Srisuma, S. (2019). Have Econometric Analyses of Happiness Data Been Futile? A Simple Truth About Happiness Scales. *Social Science Research Network (SSRN)*. https://doi.org/10.2139/ssrn.3349935.
Cherp, A., Vinichenko, V., Tosun, J., Gordon, J. A., & Jewell, J. (2021). National growth dynamics of wind and solar power compared to the growth required for global climate targets. *Nature Energy*, *6*(7), 742–754. https://doi.org/10.1038/s41560-021-00863-0
Cosme, I., Santos, R., & O'Neill, D. W. (2017). Assessing the degrowth discourse: A review and analysis of academic degrowth policy proposals. *Journal of Cleaner Production*, *149*, 321–334. https://doi.org/10.1016/j.jclepro.2017.02.016
Creutzig, F., Erb, K.-H., Haberl, H., Hof, C., Hunsberger, C., & Roe, S. (2021). Considering sustainability thresholds for BECCS in IPCC and biodiversity assessments. *Global Change Biology Bioenergy*, *13*(4), 510–515. https://doi.org/https://doi.org/10.1111gcbb.12798
Creutzig, F., Roy, J., Lamb, W. F., Azevedo, I. M. L., Bruine de Bruin, W., Dalkmann, H., Edelenbosch, O. Y., Geels, F. W., Grubler, A., Hepburn, C., Hertwich, E. G., Khosla, R., Mattauch, L., Minx, J. C., Ramakrishnan, A., Rao, N. D., Steinberger, J. K., Tavoni, M., Ürge-Vorsatz, D., & Weber, E. U. (2018). Towards demand-side solutions for mitigating climate change. *Nature Climate Change*, *8*(4), 260–263. https://doi.org/10.1038/s41558-018-0121-1
D'Alessandro, S., Cieplinski, A., Distefano, T., & Dittmer, K. (2020). Feasible alternatives to green growth. *Nature Sustainability*, 1–7. https://doi.org/10.1038/s41893-020-0484-y
Daly, H. E. (2015). *From uneconomic growth to a steady-state economy*. Edward Elgar Publishing.
Daly, H. E., & Farley, J. C. (2011). *Ecological economics: principles and applications* (2nd ed.). Island Press.
de Castro, C., & Capellán-Pérez, I. (2020). Standard, point of Use, and extended energy return on energy invested (EROI) from comprehensive material requirements of present global wind, solar, and hydro power technologies. *Energies*, *13*(12), https://doi.org/10.3390/en13123036
Deetman, S., de Boer, H. S., Van Engelenburg, M., van der Voet, E., & van Vuuren, D. P. (2021). Projected material requirements for the global electricity infrastructure – generation, transmission and storage. *Resources, Conservation and Recycling*, *164*, https://doi.org/10.1016/j.resconrec.2020.105200
Dellink, R., Chateau, J., Lanzi, E., & Magné, B. (2017). Long-term economic growth projections in the Shared Socioeconomic Pathways. *Global Environmental Change*, *42*, 200–214. https://doi.org/10.1016/j.gloenvcha.2015.06.004
Department of Industry, Science, Energy and Resources (2020). Australian Energy Update 2020, Australian Energy Statistics, September, Canberra.
Department of Climate Change, E., the Environment and Water,. (2022). *Australia's national greenhouse accounts*. Australian Government. Retrieved 12 December from https://ageis.climatechange.gov.au/.
Diesendorf, M. (2022). Scenarios for mitigating CO2 emissions from energy supply in the absence of CO2 removal. *Climate Policy*, *22*(7), 882–896. https://doi.org/10.1080/14693062.2022.2061407
Drews, S., Antal, M., & van den Bergh, J. C. J. M. (2018). Challenges in assessing public opinion on economic growth versus environment: Considering European and US data. *Ecological Economics*, *146*, 265–272. https://doi.org/10.1016/j.ecolecon.2017.11.006
Exner, A. (2014). Degrowth and demonetization: On the limits of a Non-capitalist market economy. *Capitalism Nature Socialism*, *25*(3), 9–27. https://doi.org/10.1080/10455752.2014.882963

Fanning, A. L., & O'Neill, D. W. (2019). The Wellbeing–Consumption paradox: Happiness, health, income, and carbon emissions in growing versus non-growing economies. *Journal of Cleaner Production*, *212*, 810–821. https://doi.org/10.1016/j.jclepro.2018.11.223

Fanning, A. L., O'Neill, D. W., & Büchs, M. (2020). Provisioning systems for a good life within planetary boundaries. *Global Environmental Change*, *64*, https://doi.org/10.1016/j.gloenvcha.2020.102135

Fitzpatrick, N., Parrique, T., & Cosme, I. (2022). Exploring degrowth policy proposals: A systematic mapping with thematic synthesis. *Journal of Cleaner Production*, *365*, https://doi.org/10.1016/j.jclepro.2022.132764

Fix, B. (2019). Dematerialization through services: Evaluating the evidence. *BioPhysical Economics and Resource Quality*, *4*(2), https://doi.org/10.1007/s41247-019-0054-y

Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., Kolp, P., Strubegger, M., Valin, H., & Amann, M. (2017). The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Global Environmental Change*, *42*, 251–267. https://doi.org/10.1016/j.gloenvcha.2016.06.004

Fuhrman, J., McJeon, H., Patel, P., Doney, S. C., Shobe, W. M., & Clarens, A. F. (2020). Food–energy–water implications of negative emissions technologies in a +1.5 °C future. *Nature Climate Change*, *10*(10), 920–927. https://doi.org/10.1038/s41558-020-0876-z

Gidwitz, Z., Heger, M. P., Pineda, J., & Rodríguez, F. (2010). *Understanding Performance in Human Development: A Cross-National Study*. https://EconPapers.repec.org/RePEc:hdr:papers:hdrp-2010-42.

Greenford, D. H., Crownshaw, T., Lesk, C., Stadler, K., & Matthews, H. D. (2020). Shifting economic activity to services has limited potential to reduce global environmental impacts due to the household consumption of labour. *Environmental Research Letters*, *15*(6), https://doi.org/10.1088/1748-9326/ab7f63

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D. L., Rao, N. D., Riahi, K., Rogelj, J., De Stercke, S., Cullen, J., Frank, S., Fricko, O., Guo, F., Gidden, M., Havlík, P., Huppmann, D., Kiesewetter, G., Rafaj, P., … Valin, H. (2018). A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nature Energy*, *3*(6), 515–527. https://doi.org/10.1038/s41560-018-0172-6

Haberl, H., Wiedenhofer, D., Virág, D., Kalt, G., Plank, B., Brockway, P., Fishman, T., Hausknost, D., Krausmann, F., Leon-Gruchalski, B., Mayer, A., Pichler, M., Schaffartzik, A., Sousa, T., Streeck, J., & Creutzig, F. (2020). A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights. *Environmental Research Letters*, *15*, https://doi.org/10.1088/1748-9326/ab842a

Hardt, L., & O'Neill, D. W. (2017). Ecological macroeconomic models: Assessing current developments. *Ecological Economics*, *134*, 198–211. https://doi.org/10.1016/j.ecolecon.2016.12.027

Hayden, A. (2006). France's 35-hour week: Attack on business? Win-Win reform? Or betrayal of disadvantaged workers? *Politics & Society*, *34*(4), 503–542. https://doi.org/10.1177/0032329206293645

Hickel, J. (2018). Is it possible to achieve a good life for all within planetary boundaries? *Third World Quarterly*, *40*(1), 18–35. https://doi.org/10.1080/01436597.2018.1535895

Hickel, J. (2020). *Less is more: How degrowth will save the world*. William Heinemann.

Hickel, J. (2021). The anti-colonial politics of degrowth. *Political Geography*, *88*, https://doi.org/10.1016/j.polgeo.2021.102404

Hickel, J., Brockway, P., Kallis, G., Keyßer, L., Lenzen, M., Slameršak, A., Steinberger, J., & Ürge-Vorsatz, D. (2021). Urgent need for post-growth climate mitigation scenarios. *Nature Energy*, *6*(8), 766–768. https://doi.org/10.1038/s41560-021-00884-9

Hickel, J., & Slamersak, A. (2022). Existing climate mitigation scenarios perpetuate colonial inequalities. *The Lancet Planetary Health*, *6*(7), e628–e631. https://doi.org/10.1016/S2542-5196(22)00092-4

Hövermann, A., Kohlrausch, B., & Voss, D. (2021). *Anti-Demokratische Einstellungen Der Einfluss von Arbeit, Digitalisierung und Klimawandel* (Forschungsförderung Policy Brief Issue).

Hubacek, K., Chen, X., Feng, K., Wiedmann, T., & Shan, Y. (2021). Evidence of decoupling consumption-based CO2 emissions from economic growth. *Advances in Applied Energy*, *4*, 100074. https://doi.org/10.1016/j.adapen.2021.100074

Huppmann, D., Gidden, M., Fricko, O., Kolp, P., Orthofer, C., Pimmer, M., Kushin, N., Vinca, A., Mastrucci, A., Riahi, K., & Krey, V. (2019). The MESSAGE Integrated Assessment Model and the ix modeling platform (ixmp): An open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development. *Environmental Modelling & Software*, *112*, 143–156. https://doi.org/10.1016/j.envsoft.2018.11.012

Hüttel, A., Balderjahn, I., & Hoffmann, S. (2020). Welfare beyond consumption: The benefits of having less. *Ecological Economics*, *176*, https://doi.org/10.1016/j.ecolecon.2020.106719

IEA. (2022). *Direct Air Capture* [Tracking report](CC BY 4.0). https://www.iea.org/reports/direct-air-capture.

IPBES. (2019). *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*.

IPCC. (2018). *Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*.

IPCC. (2022a). *Annex III: Scenarios and modelling methods* (climate change 2022: Mitigation of climate change. *Contribution of Working Group III to the Sixth Assessment Report*.

IPCC. (2022b). *Climate change 2022: Mitigation of climate change. Contribution of working group III to the sixth assessment report of the intergovernmental panel on climate change*. C. U. Press.

IPCC. (2022c). *Mitigation of climate change summary for policymakers* (working group III contribution to the sixth assessment report of the intergovernmental panel on climate change, Issue. U. N. F. C. O. C. Change.

Jackson, R. B., Friedlingstein, P., Le Quéré, C., Abernethy, S., Andrew, R. M., Canadell, J. G., Ciais, P., Davis, S. J., Deng, Z., Liu, Z., Korsbakken, J. I., & Peters, G. P. (2022). Global fossil carbon emissions rebound near pre-COVID-19 levels. *Environmental Research Letters*, *17*(3), 0031001. https://doi.org/10.1088/1748-9326/ac55b6

Jackson, T. (2016). *Prosperity without growth. Foundations for the economy of tomorrow*. Routledge.

Jackson, T., & Victor, P. A. (2020). The transition to a sustainable prosperity-A stock-flow-consistent ecological macroeconomic model for Canada. *Ecological Economics*, *177*, https://doi.org/10.1016/j.ecolecon.2020.106787

Kallis, G., Kerschner, C., & Martinez-Alier, J. (2012). The economics of degrowth. *Ecological Economics*, *84*, 172–180. https://doi.org/10.1016/j.ecolecon.2012.08.017

Kallis, G., Kostakis, V., Lange, S., Muraca, B., Paulson, S., & Schmelzer, M. (2018). Research On degrowth. *Annual Review of Environment and Resources*, *43*(1), 291–316. https://doi.org/10.1146/annurev-environ-102017-025941

Keyßer, L. T., & Lenzen, M. (2021). 1.5 °C degrowth scenarios suggest the need for new mitigation pathways. *Nature Communications*, *12*(1), 2676. https://doi.org/10.1038/s41467-021-22884-9

Kikstra, J., Li, M., Lenzen, M., Brockway, P., Malik, A., Keysser, L., Hickel, J., Ruijven, B. V., & Rogelj, J. (2023). Towards degrowth in integrated assessment models. *Economic Systems Research (Under review)*.

Kikstra, J. S., Mastrucci, A., Min, J., Riahi, K., & Rao, N. D. (2021). Decent living gaps and energy needs around the world. *Environmental Research Letters*, *16*(9), https://doi.org/10.1088/1748-9326/ac1c27

Knight, K. W., Rosa, E. A., & Schor, J. B. (2013). Could working less reduce pressures on the environment? A cross-national panel analysis of OECD countries, 1970–2007. *Global Environmental Change*, *23*(4), 691–700. https://doi.org/10.1016/j.gloenvcha.2013.02.017

Krey, V., Havlik, P., Kishimoto, P., Fricko, O., Zilliacus, J., Gidden, M., Strubegger, M., & Kartasasmita, G. (2020). *MESSAGEix-GLOBIOM Documentation - 2020 release* https://pure.iiasa.ac.at/id/eprint/17115/.

Kubiszewski, I., Costanza, R., Franco, C., Lawn, P., Talberth, J., Jackson, T., & Aylmer, C. (2013). Beyond GDP: Measuring and achieving global genuine progress. *Ecological Economics*, *93*, 57–68. https://doi.org/10.1016/j.ecolecon.2013.04.019

Kuhnhenn, K. (2018). *Economic Growth in mitigation scenarios: A blind spot in climate science* (Publication Series on Ecology 25, Issue.

Kuhnhenn, K., da Costa, L., Fílípe, C., Mahnke, E., Schneider, L., & Lange, S. (2020). *A societal transformation scenario for staying below 1.5°C* (Publication Series Economic & Social Issues., Issue.

Lamb, W. F., Grubb, M., Diluiso, F., & Minx, J. C. (2022). Countries with sustained greenhouse gas emissions reductions: an analysis of trends and progress by sector. *Climate Policy*, *22*(1), 1–17. https://doi.org/10.1080/14693062.2021.1990831

Lange, S. (2018). *Macroeconomics without growth - sustainable economies in neoclassical, keynesian and marxian theories*. M. Verlag.

Lange, S., & Berner, A. (2022). The growth rebound effect: A theoretical–empirical investigation into the relation between rebound effects and economic growth. *Journal of Cleaner Production*, *371*, 133158. https://doi.org/10.1016/j.jclepro.2022.133158

Le Quéré, C., Korsbakken, J. I., Wilson, C., Tosun, J., Andrew, R., Andres, R. J., Canadell, J. G., Jordan, A., Peters, G. P., & van Vuuren, D. P. (2019). Drivers of declining CO2 emissions in 18 developed economies. *Nature Climate Change*, *9*(3), 213–217. https://doi.org/10.1038/s41558-019-0419-7

Lehmann, C., Delbard, O., & Lange, S. (2022). Green growth, a-growth or degrowth? Investigating the attitudes of environmental protection specialists at the German Environment Agency. *Journal of Cleaner Production*, *336*, https://doi.org/10.1016/j.jclepro.2021.130306

Leimbach, M., Kriegler, E., Roming, N., & Schwanitz, J. (2017). Future growth patterns of world regions – A GDP scenario approach. *Global Environmental Change*, *42*, 215–225. https://doi.org/10.1016/j.gloenvcha.2015.02.005

Li, M., Lenzen, M., Yousefzadeh, M., & Ximenes, F. A. (2020). The roles of biomass and CSP in a 100 % renewable electricity supply in Australia. *Biomass and Bioenergy*, *143*, 105802. ISSN 0961-9534. https://doi.org/10.1016/j.biombioe.2020.105802

Luckeneder, S., Giljum, S., Schaffartzik, A., Maus, V., & Tost, M. (2021). Surge in global metal mining threatens vulnerable ecosystems. *Global Environmental Change*, *69*, https://doi.org/10.1016/j.gloenvcha.2021.102303

Luderer, G., Pehl, M., Arvesen, A., Gibon, T., Bodirsky, B. L., de Boer, H. S., Fricko, O., Hejazi, M., Humpenoder, F., Iyer, G., Mima, S., Mouratiadou, I., Pietzcker, R. C., Popp, A., van den Berg, M., van Vuuren, D., & Hertwich, E. G. (2019). Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies. *Nature Communications*, *10*(1), 5229. https://doi.org/10.1038/s41467-019-13067-8

Marlon, J., Howe, P., Mildenberger, M., Leiserowitz, A., & Wang, X. (2018). *Yale Climate Opinion Maps* 2018. Retrieved 30 March from.

Mattioli, G., Roberts, C., Steinberger, J. K., & Brown, A. (2020). The political economy of car dependence: A systems of provision approach. *Energy Research & Social Science*, *66*, https://doi.org/10.1016/j.erss.2020.101486

Messner, S., & Schrattenholzer, L. (2000). MESSAGE–MACRO: linking an energy supply model with a macroeconomic module and solving it iteratively. *Energy (Oxford)*, *25*(3), 267–282. https://doi.org/10.1016/S0360-5442(99)00063-8

Michel, C., Sovinsky, M., Proto, E., & Oswald, A. J. (2019). Advertising as a major source of human dissatisfaction: Cross-national evidence on One million europeans. In (pp. 217-239). Springer International Publishing. https://doi.org/10.1007/978-3-030-15835-4_10.

Millward-Hopkins, J. (2022). Inequality can double the energy required to secure universal decent living. *Nature Communications*, *13*(1), 5028. https://doi.org/10.1038/s41467-022-32729-8

Millward-Hopkins, J., Steinberger, J. K., Rao, N. D., & Oswald, Y. (2020). Providing decent living with minimum energy: A global scenario. *Global Environmental Change*, *65*, https://doi.org/10.1016/j.gloenvcha.2020.102168

Muellner, N., Arnold, N., Gufler, K., Kromp, W., Renneberg, W., & Liebert, W. (2021). Nuclear energy - The solution to climate change? *Energy Policy*, *155*, https://doi.org/10.1016/j.enpol.2021.112363

Nelson, A. (2022). *Beyond money - A postcapitalist strategy*. Pluto Press.
Nesterova, I. (2021). Small firms as agents of sustainable change. *Futures*, *127*, https://doi.org/10.1016/j.futures.2021.102705
Nicholls, Z., & Meinshausen, M. (2022). *Comparison between Australia's 2030 and 2050 emission reduction targets and 1.5°C pathways*. C. Resource.
Nieto, J., Carpintero, Ó, Miguel, L. J., & de Blas, I. (2020). Macroeconomic modelling under energy constraints: Global low carbon transition scenarios. *Energy Policy*, *137*, 111090. https://doi.org/10.1016/j.enpol.2019.111090
Odoxa. (2019). *Les Français*. Retrieved 2022 from http://www.odoxa.fr/sondage/barometre-economique-doctobre-francais-plus-ecolos-jamai.
Okulicz-Kozaryn, A., Holmes, O., & Avery, D. R. (2014). The subjective well-being political paradox: Happy welfare states and unhappy liberals. *Journal of Applied Psychology*, *99*(6), 1300–1308. https://doi.org/10.1037/a0037654
O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M., & Solecki, W. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, *42*, 169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004
O'Neill, D. W., Fanning, A. L., Lamb, W. F., & Steinberger, J. K. (2018). A good life for all within planetary boundaries. *Nature Sustainability*, *1*(2), 88–95. https://doi.org/10.1038/s41893-018-0021-4
Otero, I., Farrell, K. N., Pueyo, S., Kallis, G., Kehoe, L., Haberl, H., Plutzar, C., Hobson, P., Garcia-Marquez, J., Rodriguez-Labajos, B., Martin, J. L., Erb, K. H., Schindler, S., Nielsen, J., Skorin, T., Settele, J., Essl, F., Gomez-Baggethun, E., Brotons, L., … Pe'er, G. (2020). Biodiversity policy beyond economic growth. *Conservation Letters*, *13*(4), e12713. https://doi.org/10.1111/conl.12713
Parrique, T. (2019). *The political economy of degrowth*.
Parrique, T., Barth, J., Briens, F., Kerschner, C., Kraus-Polk, A., Kuokkanen, A., & Spangenberg, J. H. (2019). *Decoupling debunked: Evidence and arguments against green growth as a sole strategy for sustainability*.
Paulson, L., & Büchs, M. (2022). Public acceptance of post-growth: Factors and implications for post-growth strategy. *Futures*, *143*, https://doi.org/10.1016/j.futures.2022.103020
Rao, N. D., Min, J., & Mastrucci, A. (2019). Energy requirements for decent living in India, Brazil and South Africa. *Nature Energy*, *4*(12), 1025–1032. https://doi.org/10.1038/s41560-019-0497-9
Riahi, K., Schaeffer, R., Arango, J., Calvin, K., Guivarch, C., Hasegawa, T., Jiang, K., Kriegler, E., Matthews, R., Peters, G. P., Rao, A., Robertson, S., Sebbit, A. M., Steinberger, J., Tavoni, M., & van Vuuren, D. P. (2022). *Mitigation Pathways Compatible with Long-term Goals* (IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Issue.
Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., Kc, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., … Tavoni, M. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, *42*, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009
Rice-Oxley, M., & Rankin, J. (2019, 1 April). *Europe's south and east worry more about emigration than immigration – poll*. The Guardian. Retrieved 12 December from https://www.theguardian.com/world/2019/apr/01/europe-south-and-east-worry-more-about-emigration-than-immigration-poll.
Richters, O., & Siemoneit, A. (2019). Growth imperatives: Substantiating a contested concept. *Structural Change and Economic Dynamics*, *51*, 126–137. https://doi.org/10.1016/j.strueco.2019.07.012
Rogelj, J., Popp, A., Calvin, K. V., Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T., Marangoni, G., Krey, V., Kriegler, E., Riahi, K., van Vuuren, D. P., Doelman, J., Drouet, L., Edmonds, J., Fricko, O., Harmsen, M., … Tavoni, M. (2018). Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change*, *8*(4), 325–332. https://doi.org/10.1038/s41558-018-0091-3

Sandberg, M. (2021). Sufficiency transitions: A review of consumption changes for environmental sustainability. *Journal of Cleaner Production*, *293*, https://doi.org/10.1016/j.jclepro.2021.126097

Scheidel, A., Del Bene, D., Liu, J., Navas, G., Mingorria, S., Demaria, F., Avila, S., Roy, B., Ertor, I., Temper, L., & Martinez-Alier, J. (2020). Environmental conflicts and defenders: A global overview. *Global Environmental Change*, *63*, 102104. https://doi.org/10.1016/j.gloenvcha.2020.102104

Schmelzer, M. (2015). The growth paradigm: History, hegemony, and the contested making of economic growthmanship. *Ecological Economics*, *118*, 262–271. https://doi.org/10.1016/j.ecolecon.2015.07.029

Schmelzer, M., Vansintjan, A., & Vetter, A. (2022). *The future Is degrowth. A guide to a world beyond capitalism*. Verso.

Scott, K., Smith, C. J., Lowe, J. A., & Garcia-Carreras, L. (2022). Demand vs supply-side approaches to mitigation: What final energy demand assumptions are made to meet 1.5 and 2 °C targets? *Global Environmental Change*, *72*, 102448. https://doi.org/10.1016/j.gloenvcha.2021.102448

Sen, A. (1981). Public action and the quality of life in developing countries. *Oxford Bulletin of Economics and Statistics*, *43*(4), 287–319. https://doi.org/10.1111/j.1468-0084.1981.mp43004001.x. (Oxford Bulletin of Economics and Statistics).

Sers, M. R. (2022). Ecological macroeconomic assessment of meeting a carbon budget without negative emissions. *Global Sustainability*, *5*, https://doi.org/10.1017/sus.2022.2

Siemoneit, A. (2019). An offer you can't refuse: Enhancing personal productivity through 'efficiency consumption'. *Technology in Society*, *59*, https://doi.org/10.1016/j.techsoc.2019.101181

Slamersak, A., Kallis, G., & O'Neill, D. W. (2022). Energy requirements and carbon emissions for a low-carbon energy transition. *Nature Communications*, *13*(1), 6932. https://doi.org/10.1038/s41467-022-33976-5

Soergel, B., Kriegler, E., Weindl, I., Rauner, S., Dirnaichner, A., Ruhe, C., Hofmann, M., Bauer, N., Bertram, C., & Bodirsky, B. L. (2021). A sustainable development pathway for climate action within the UN 2030 Agenda. *Nature Climate Change*, *11*(8), 656–664. https://doi.org/10.1038/s41558-021-01098-3

Sonter, L. J., Dade, M. C., Watson, J. E. M., & Valenta, R. K. (2020). Renewable energy production will exacerbate mining threats to biodiversity. *Nature Communications*, *11*(1), 4174. https://doi.org/10.1038/s41467-020-17928-5

Steinberger, J. K., Lamb, W. F., & Sakai, M. (2020). Your money or your life? The carbon-development paradox. *Environmental Research Letters*, *15*(4), https://doi.org/10.1088/1748-9326/ab7461

Steinmann, Z. J. N., Schipper, A. M., Hauck, M., Giljum, S., Wernet, G., & Huijbregts, M. A. J. (2017). Resource footprints are good proxies of environmental damage. *Environmental Science & Technology*, *51*(11), 6360–6366. https://doi.org/10.1021/acs.est.7b00698

Stützle, I. (2015). Der Gott der Waren: Die ökonomische Theorie und ihr Geld. *PROKLA. Zeitschrift für Kritische Sozialwissenschaft*, *45*(179), 177–198. https://doi.org/10.32387/prokla.v45i179.216

Stützle, I. (2021). Money makes the world go green? Eine Kritik der Modern Monetary Theory als geldtheoretisches Konzept. *PROKLA. Zeitschrift für Kritische Sozialwissenschaft*, *51*(202), 71–94. https://doi.org/10.32387/prokla.v51i202.1930

Temper, L., Avila, S., Bene, D. D., Gobby, J., Kosoy, N., Billon, P. L., Martinez-Alier, J., Perkins, P., Roy, B., Scheidel, A., & Walter, M. (2020). Movements shaping climate futures: A systematic mapping of protests against fossil fuel and low-carbon energy projects. *Environmental Research Letters*, *15*(12), https://doi.org/10.1088/1748-9326/abc197

Tokic, D. (2012). The economic and financial dimensions of degrowth. *Ecological Economics*, *84*, 49–56. https://doi.org/10.1016/j.ecolecon.2012.09.011

Trading Economics. (2023). *Australia - GDP Per Capita, PPP (constant 2005 International $)*. Retrieved 12 December from https://tradingeconomics.com/australia/gdp-per-capita-ppp-constant-2005-international-dollar-wb-data.html.

TUC. (2018). *A future that works for working people*.

UNDP. (2015). *Training Material for Producing National Human Development Reports* [Occasional Paper].

van de Ven, D. J., Capellan-Perez, I., Arto, I., Cazcarro, I., de Castro, C., Patel, P., & Gonzalez-Eguino, M. (2021). The potential land requirements and related land use change emissions of solar energy. *Scientific Reports*, *11*(1), 2907. https://doi.org/10.1038/s41598-021-82042-5

Van Vuuren, D. P., Bijl, D. L., Bogaart, P., Stehfest, E., Biemans, H., Dekker, S. C., Doelman, J. C., Gernaat, D. E., & Harmsen, M. (2019). Integrated scenarios to support analysis of the food–energy–water nexus. *Nature Sustainability*, *2*(12), 1132–1141. https://doi.org/10.1038/s41893-019-0418-8

Vaughan, N. E., & Gough, C. (2016). Expert assessment concludes negative emissions scenarios may not deliver. *Environmental Research Letters*, *11*(9), https://doi.org/10.1088/1748-9326/11/9/095003

Victor, P. A. (2008). *Managing without growth: slower by design, not disaster*. Edward Elgar Publishing.

Vogel, J., Steinberger, J. K., O'Neill, D. W., Lamb, W. F., & Krishnakumar, J. (2021). Socio-economic conditions for satisfying human needs at low energy use: An international analysis of social provisioning. *Global Environmental Change*, *69*, https://doi.org/10.1016/j.gloenvcha.2021.102287

Wang, R., Assenova, V. A., & Hertwich, E. G. (2021). Energy system decarbonization and productivity gains reduced the coupling of CO2 emissions and economic growth in 73 countries between 1970 and 2016. *One Earth*, *4*(11), 1614–1624. https://doi.org/10.1016/j.oneear.2021.10.010

Warszawski, L., Kriegler, E., Lenton, T. M., Gaffney, O., Jacob, D., Klingenfeld, D., Koide, R., Costa, M. M., Messner, D., Nakicenovic, N., Schellnhuber, H. J., Schlosser, P., Takeuchi, K., Van Der Leeuw, S., Whiteman, G., & Rockström, J. (2021). All options, not silver bullets, needed to limit global warming to 1.5 °C: a scenario appraisal. *Environmental Research Letters*, *16*, https://doi.org/10.1088/1748-9326/abfeec

Watari, T., Nansai, K., Nakajima, K., & Giurco, D. (2021). Sustainable energy transitions require enhanced resource governance. *Journal of Cleaner Production*, *312*, https://doi.org/10.1016/j.jclepro.2021.127698

Wiedmann, T., Lenzen, M., Keyßer, L. T., & Steinberger, J. K. (2020). Scientists' warning on affluence. *Nature Communications*, *11*(1), 1–10. https://doi.org/10.1038/s41467-020-16941-y

Wilkinson, R. G., & Pickett, K. E. (2009). Income inequality and social dysfunction. *Annual Review of Sociology*, *35*(1), 493–511. https://doi.org/10.1146/annurev-soc-070308-115926

The World Bank. (2021). *Final consumption expenditure (% of GDP) - Australia*. Retrieved 12 December from https://data.worldbank.org/indicator/NE.CON.TOTL.ZS?locations=AU.

YouGov. (2019). *YouGov / Eurotrack Survey Results*.

YouGov. (2020). *YouGov / NEON Survey Results*.