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Downscaling down under: towards degrowth in integrated assessment models

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ABSTRACT

IPCC reports, to date, have not featured ambitious mitigation scenarios with degrowth in high-income regions. Here, using MESSAGEix-Australia, we create 51 emissions scenarios for Australia with near-term GDP growth going from +3%/year to rapid reductions (−5%/year) to explore how a traditional integrated assessment model (IAM) represents degrowth from an economic starting point, not just energy demand reduction. We find that stagnating GDP per capita reduces the mid-century need for upscaling solar and wind energy by about 40% compared to the SSP2 growth baseline, and limits future material needs for renewables. Still, solar and wind energy in 2030 is more than quadruple that of 2020. Faster reductions in energy demand may entail higher socio-cultural feasibility concerns, depending on the policies involved. Strong reductions in inequality reduce the risk of lowered access to decent living services. We discuss research needs and possible IAM extensions to improve post-growth and degrowth scenario modelling.

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KEYWORDS

Integrated assessment models; degrowth; post-growth

1. Introduction

Scholars disagree about the desirability and feasibility of further economic growth in high-income countries, due to concerns related to social justice, environmental damages, and the feasibility of sufficiently rapid climate mitigation, with implicit or explicit disagreement on the benefits of certain types of consumption (Jakob et al., 2020). Moreover, it is unclear to

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what extent current modeling tools are fit-for-purpose to provide insights for such questions. Keyßer and Lenzen (2021) illustrated that pathways with limited gross domestic product (GDP) and energy consumption growth have the potential to minimize several climate mitigation feasibility concerns, compared to other existing scenarios generated with integrated assessment models (IAMs) which generally follow the Shared Socioeconomic Pathway (SSP) framework (Riahi et al., 2017) where GDP grows in all pathways for virtually all regions and points in time during the twenty-first century (Dellink et al., 2017). However, feasibility is multidimensional (Brutschin et al., 2021), and scholarly understanding of it is currently limited. For example, sociocultural and institutional feasibility concerns of lower-growth transitions have not yet been quantified. While virtually all IAM scenarios follow economic pathways defined by the SSPs, this is not necessary, as van Vuuren et al. (2014) already noted early in the SSP development process: 'It is clear, however, that specific, tailor-made, scenarios are also needed to answer particular research questions' (p. 384). Hickel et al. (2021) have recently called upon the scientific community to develop degrowth or post-growth mitigation scenarios, using analyses that go beyond the simplicity of a fuel-energy-emissions model as in Keyßer and Lenzen (2021) to enable further investigation of the sectoral dynamics, feasibility, and desirability of such pathways. Arguments for exploring this part of the future possibility space in climate mitigation pathways include: (1) enabling faster emissions reductions in rich countries, for instance in line with justice arguments; (2) reducing reliance on absolute energy-GDP decoupling in scenarios; and (3) reducing the necessary upscaling speed of renewables and carbon dioxide removal. Although some degrowth IAM modeling exists, such as with MEDEAS (Capellán-Pérez et al., 2020; Nieto et al., 2020), EUROGREEN (D'Alessandro et al., 2020), and International Futures (Moyer, 2023) (for further examples see Li et al., 2023), comprehensive quantification of the potential benefits of lower growth for reaching alternative climate mitigation targets is still lacking. For instance, Nieto et al. (2020) model emissions as an (unconstrained) outcome of changes in the economy through modifying input–output tables, changing energy intensities, limiting energy availability, and varying economic growth. They afterwards ask whether emissions reduction targets have been met. Here, we take a different approach, asking what transition is required – under different economic growth assumptions – to meet a certain emissions reduction target. Moreover, for lower or negative growth pathways limited or no literature exists on quantifying the necessary conditions to avoid unintentional negative effects such as increased risk of poverty, reduced innovation, or sociocultural and institutional barriers.

A degrowth transition would break with past trends in many ways. Modeling such a transition is highly complex and limited modeling tools are available to accurately represent such transition dynamics. Li et al. (2023) propose a simple method to create a scenario ensemble for exploring high-level, aggregate characteristics of energy and emissions in lower-growth futures. Their exploratory scenario ensemble is quantified using the energy-economy core of integrated assessment model (IAM) MESSAGEix-GLOBIOM (Fricko et al., 2017; Huppmann et al., 2019; Kishimoto et al., 2023; Krey et al., 2020) to create a one-region model version for one high-income, high-resource use country; Australia. MESSAGEix-Australia currently includes the detailed energy supply model MESSAGEix coupled with the one-sector economy model MACRO. The key innovation in Li et al. (2023) is the substitution of MACRO's in-built monotonic utility function with a non-monotonic equivalent, peaking at per-capita consumption levels between 10 and 70

US$k/cap, resulting in lower-GDP futures compared to pathways in the SSP framework. This scenario setup allows for explicitly exploring alternative GDP pathways, driven by assumptions about the optimal level of consumption for utility. One possible way such futures could come about is from ‘change within’ (for a more expansive introduction and motivation, see Li et al., 2023). That is, a shift towards an economy in which most utility, or highest human well-being, is provided at some specific level of aggregate industrial production and individual consumption. This approach, where peak utility is encoded in the economic pathways, is set up to ask the question ‘what if peak utility would occur at X consumption per capita?’.

Here, we expand upon the study of Li et al. (2023) in two ways. Firstly, we limit GHG budgets to not be net-negative and explore a wider range of GHG budgets. Secondly, we provide a more detailed analysis and interpretation of 51 emissions scenarios to inform the development of future degrowth and post-growth scenarios. We first explain the methods used to derive the scenarios, followed by an extensive analysis. Then, we explore how these new scenarios relate to the existing scenario literature in terms of progress towards the Paris Agreement. Covering key progress indicators, we compare lower-growth scenarios to the most ambitious global long-term mitigation scenarios that were used in the IPCC Sixth Assessment Report (AR6) on mitigation (IPCC, 2022a), as available in the AR6 Scenario database (Byers et al., 2022). Here, we focus on (a) how aggregate energy demand reductions have been modeled, (b) how reduced energy demand in lower-growth pathways reduces pressure on upscaling renewable energy and could enable more ambitious emissions reductions, (c) how lower-growth affects energy and emissions decoupling rates from GDP, and (d) how energy demand and inequality in lower-growth pathways relate to energy requirements for providing decent living standards.

The last part of this paper deals with setting out several requirements for comprehensively modeling the characteristics and dynamics of a degrowth transition as described in the wider degrowth and post-growth literature. We discuss to what extent the scenario ensemble developed by Li et al. (2023) represents these elements. In this work, we use both terms, degrowth and post-growth. Post-growth describes a general shift away from economic growth as a core societal objective towards a well-being – and sustainability-based economy. Degrowth in turn describes a reduction in less-necessary forms of production and consumption with the goal of reducing environmental pressures, in a way that is democratically planned, and improves equity and human well-being (Parrique, 2022; Schmelzer et al., 2022). Importantly, degrowth does not aim to reduce GDP, and does not rely on GDP reduction as a primary climate mitigation lever, however, some have made the argument that lower GDP is a possible outcome of the necessary changes to achieve well-being and sustainability (Vogel & Hickel, 2023). To distinguish our exploratory scenarios (which reduce aggregate production and consumption without differentiating by sector or industry) from degrowth scenarios, we use the term ‘lower-growth’ for the scenarios that reduce GDP growth compared to the SSP2-baseline.

Altogether, the aim of this manuscript is to discuss to what extent a cost-minimization energy supply model framework can represent a degrowth transition with minimal alterations, and what developments are required towards reflecting characteristic degrowth policy goals and instruments in integrated assessment modeling.

2. Methods

We chose Australia for this case study due to good availability of data and because it is a high-income country, making it a suitable case for degrowth and post-growth analyses. MESSAGEix is a well-known, flexible, open-source IAM that has been used for many existing scenario studies. Therefore, we deem it a suitable choice to learn about how far amending an existing IAM framework could go in describing the high-level dynamics of lower-growth scenarios. Still, we acknowledge that no currently available model is perfectly geared to answer the complex questions that come with quantifying degrowth transitions in full. The setup in this paper is not an exception. For instance, it is clear that investigating only one (affluent) country cannot provide a full answer to questions of climate justice and equity. Secondly, modeling lower-growth pathways based on a one-sector economic growth model does not reflect economic dynamics of a degrowth transition. However, this article helps in (i) further clarifying and unpicking currently poorly understood high-level characteristics of degrowth in the context of climate mitigation in line with the Paris Agreement that have previously been left unquantified, and (ii) describe some actionable research avenues for a more comprehensive modeling of degrowth pathways.

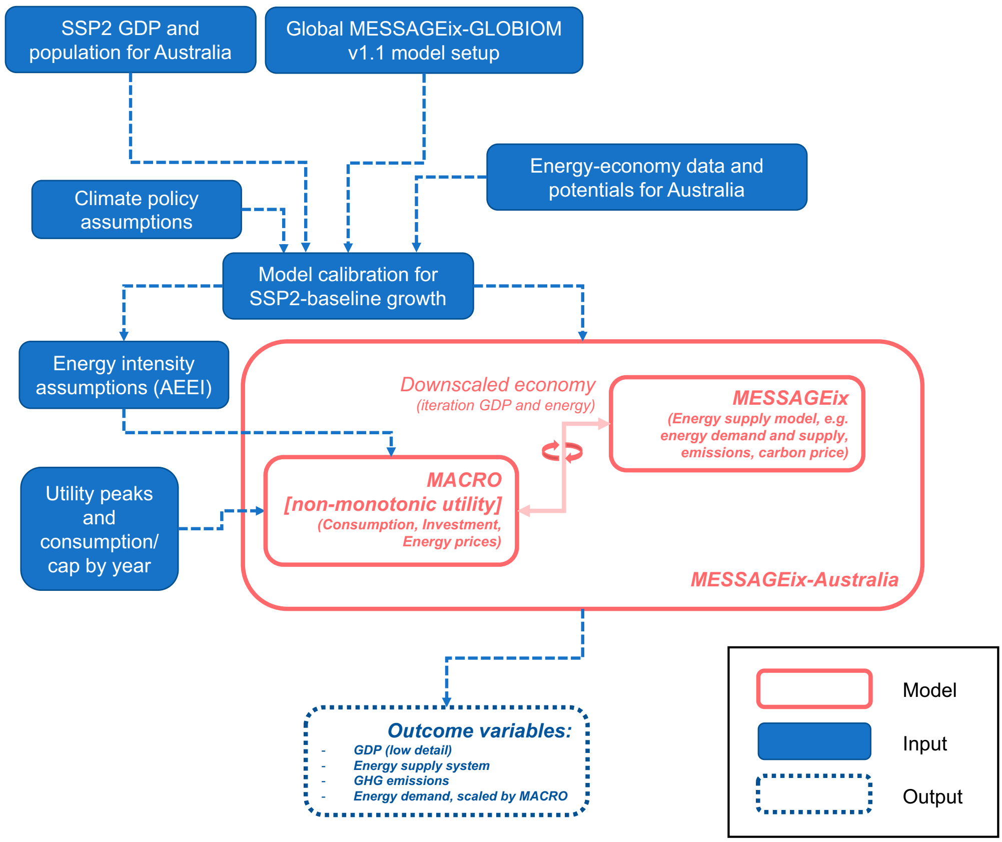
2.1. MESSAGEix-Australia energy-economy model

MESSAGEix-Australia as presented here is based on the MESSAGEix-GLOBIOM R11 version used in (Riahi et al., 2021) as made available by Fricko et al. (2023) (Figure 1). Apart from updating the parameters to national Australian statistics, the model is intentionally kept as similar to the global model as possible. We choose to limit the number of changes to be able to isolate the effect of the core model change, while having a body of literature for the MESSAGEix-GLOBIOM model and its energy-economy core MESSAGEix-MACRO to draw upon to understand key model behavior with a standard monotonic utility function.

In the conventional version, which we use for the SSP2-baseline growth pathways, economic consumption and demand are auto-calibrated by scaling with exogenously specified GDP and energy demand trajectories. This process is rooted in the historical observation that energy intensity (energy consumption per unit of $ output) has decreased steadily over time. In essence, the calibration process results in combined GDP, useful energy demand, and 'autonomous energy efficiency improvement' (AEEI) pathways, with the latter describing the change in energy intensity relating useful energy to GDP (van der Zwaan et al., 2002). If this calibration would be kept, projected energy efficiency could slow down or reverse with lower-growth pathways. However, it is not obvious that such energy efficiency improvements should indeed slow down or even reverse under lower-growth pathways, because introducing limits and seeing societal change towards lower energy use may also spur innovation. Therefore, this auto-calibration is disabled for all of the non-baseline scenarios. All scenarios use the SSP2-baseline calibrated AEEI parameters (Supplementary Figure 1), in line with historical trends.

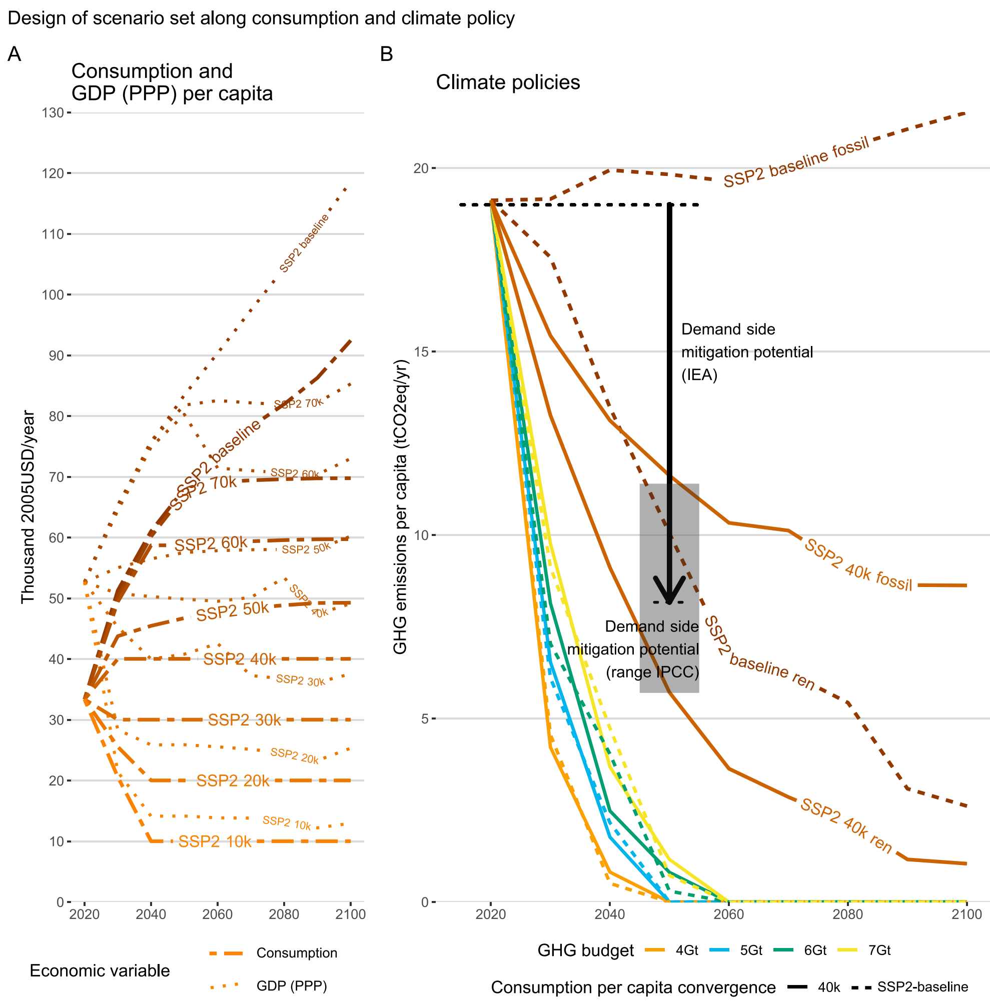
We reiterate that degrowth research understands GDP as an outcome rather than a policy (or mitigation) lever. Referring also to Figure 1, stepping through the MESSAGEix-MACRO (Messner & Schrattenholzer, 2000) iterative loop helps explain how lower-growth pathways are modeled in our case: via an exogenous non-monotonic utility function. MACRO sets the relationship between the economy and the energy system. In MACRO, there are two equations for GDP (Manne et al.,

Figure 1. Methods flowchart. AEEI is an abbreviation of 'autonomous energy efficiency improvement', GDP of gross domestic product, and GHG of greenhouse gas.



1995; Messner & Schrattenholzer, 2000). One is an expenditure-based identity, where GDP = 'consumption' + 'investment' + 'energy system cost', whilst the other employs a constant elasticity of substitution (CES) based aggregate production function for capital, labor and energy, in a conventional capital-labor-(energy) KL(E) formulation. Both need to be equal in the final solution after iteration (equations and a longer description are in the Supplementary Information). This means that, in our setup, constraining expenditure-based GDP by reducing consumption (via the exogenous non-monotonic utility function) also constrains GDP in the CES-based GDP equation, and consequently capital, labor and energy inputs, versus a baseline scenario. The AEEI ratios translate MACRO's energy in economic terms to energy in physical terms (which is input to MESSAGEix). MESSAGEix then produces an energy supply system to meet that demand, with a minimized overall energy system cost that is input back into the expenditure-based GDP identity in MACRO. Strictly speaking, therefore, energy demand and GDP are determined endogenously in the MESSAGEix-MACRO iteration (Figure 1), through the maximisation of consumer utility. Since we use different non-monotonic utility functions to cover a range of different consumption-utility combinations, MACRO settles at different GDP per capita levels (Figure 2(a)). We note that in practice, in the current version the outcome is dominated by the prescribed form of the utility function, as the constituents of GDP beyond consumption (investment and energy) are smaller shares of GDP.

Figure 2. Scenario ensemble setup. Panel A shows (for the 'Keep fossil fuels' climate policy) the range of economic growth outcomes in the scenario ensemble. Panel B compares a few highlighted growth levels (SSP2 and 40k) for different climate policies (ren = 'Expand renewables', fossil = 'Keep fossil fuels'), compared to empirical global demand-side GHG reduction potential estimates 57% reduction following IEA microdata (IEA, 2021, Annex A) and a 40-70% range from the IPCC (IPCC, 2022b).

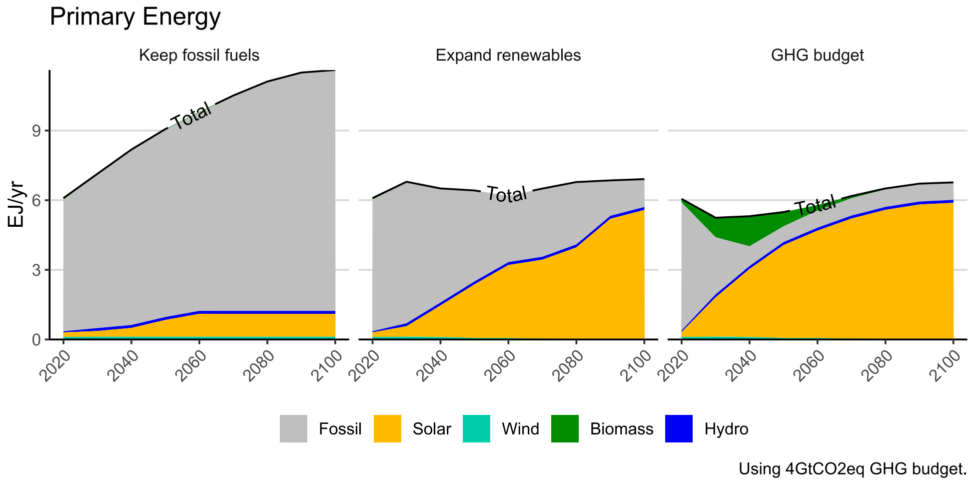


For further information on the general characteristics of MESSAGEix-MACRO, we refer to the Supplementary Information and the Data Availability statement.

2.2. *Scenario ensemble*

For this study, we explore a structured scenario ensemble ($n = 51$). The starting point is a 'middle-of-the-road' SSP2 scenario. Then, the monotonic utility function is replaced by a non-monotonic function that is parameterized to peak at different consumption levels, with peaks at 10, 20, 30, 40, 50, 60, and 70 thousand USD (2005) per capita per year (hereafter '10k', '20k', etc.), all of which have lower consumption and GDP than the SSP2-baseline reference scenario, over time (Figure 2(a)).

Figure 3. Primary energy supply characteristics of the SSP2 baseline consumption scenarios resulting from the stylized climate policy assumptions discussed in this study.



In the first two decades these scenarios range from continued GDP growth trends (+3.0%/year, for SSP2-baseline growth) to significant GDP reduction (−5.3%/year, for the 10k scenario). The useful energy demand derived for the starting point of each of these scenarios serves as input to MESSAGEix (Figure 1), which calculates cost-effective energy supply given these energy demands. For each of these energy demand scenario sets, we simulate three climate policies: 'Keep fossil fuels', 'Expand renewables', and 'GHG budget'. Whilst the 'GHG budget' scenarios explore the space around one interpretation of a 1.5°C-aligned mitigation target for Australia (Nicholls & Meinshausen, 2022), 'Keep fossil fuels' and 'Expand renewables' neither respect a particular GHG budget nor any specific mitigation target (Figure 2(b)). The energy supply characteristics capture different ambition levels for low-carbon upscaling, differing predominantly in the extent and speed of fossil fuel replacement by solar energy (Figure 3).

We explore multiple 'GHG budget' versions with different remaining GHG budgets until net-zero (Figure 2(b)). We run MESSAGEix-Australia with GHG budgets from 2020 ranging from 2GtCO2eq to 7GtCO2eq, in steps of 1 Gt. The model did not find any solutions for an energy system that stays within 2GtCO2eq emissions until net-zero GHG emissions, and only in a few cases for 3 GtCO2eq. This scenario set aims to provide crucial model evidence on how assumptions on GDP and aggregate energy demand influence the achievement of scenarios with ambitious climate mitigation. Details for the assumptions across scenarios are set out in Table 1, with a larger set of characteristics visualized over time across all scenarios in Supplementary Figures 1–6.

2.3. Compatibility with decent living energy

Recent work (Kikstra, Mastrucci, et al., 2021; Millward-Hopkins et al., 2020; Rao et al., 2019) has quantified the minimum energy requirements (known as Decent Living Energy, abbreviated to DLE) for providing decent living standards, and compared this to current and projected energy levels, including inequality considerations (Kikstra, Mastrucci, et al.,

Table 1. Modeling assumptions.

Scenario design element	Model assumptions
Consumption	Prescribed, based on scenario design. Consumption levels are close to utility peaks of each scenario in 2030–2050 depending on degrowth or growth levels (Figure 2(a)).
GDP	GDP is a decision variable in the optimization process. GDP is composed of consumption, investment, and energy costs (export and import are outside of the modeling scope in our study). Since utility peaks are prescribed exogenously corresponding to predetermined consumption levels, the endogenous determination of GDP depends more strongly on investment and energy prices for the pathways with steady or declining consumption, whereas consumption is still constrained by total GDP in pathways that continue to grow. Thus, of the GDP components, energy costs and investment are endogenous, while consumption is determined exogenously through the utility function, conditional on GDP constraints.
Climate policy: 'Keep fossil fuels'	*Energy generation potentials:* The annual renewable energy potential upper bound for Australia is assumed to be limited to 9.7e4 PJ for wind (based on Li et al. (2020)), 1.58e6 PJ for solar PV (based on Li et al. (2020)), 882 PJ for rooftop PV (based on Roberts et al. (2019)). Hydro (0.014 PJ, based on Li et al. (2020)), and bioenergy (2600 - 3982 PJ, based on Enea and Deloitte for ARENA (2021)) potentials are smaller. All potentials are applied for the entire modeling period (2020–2100). *Technology change constraints:* To reflect limitations on the speed of change in energy system infrastructure, we implement the following growth/stranding rate constraints: *Upper bound:*• 25% per year, for renewable power plants for the entire modeling period (2020-2100), in line with recent fast growth (IEA, 2022) in new solar PV installations.*Lower bound:*• −20% for fossil power plants and −10% for all other technologies, in line with the range of coal retirements scenarios forecasted by Australian Energy Market Operator (AEMO, 2022).*Technology costs* To determine the most cost-effective energy supply solution, the relative technology cost is important. For this scenario, we assume the technology costs over time to remain constant, meaning for each of the fossil and renewable technologies represented in MESSAGEix-Australia, we keep the 2020 levels throughout the century.
Climate policy: 'Expand renewables'	*Energy generation constraints:* Same as 'Keep fossil fuels'. *Technology change constraints:* Same as 'Keep fossil fuels'. *Technology costs:* For this scenario, we assume costs will go down by 2100 by up to 55% for wind and 90% solar technologies, while it is reduced by 10% for fossil fuels, following Australian Energy Market Operator (AEMO, 2022).
Climate policy: 'GHG budget'	*Energy generation constraints:* Same as 'Keep fossil fuels'. *Technology change constraints:* Same as 'Keep fossil fuels'. *Technology costs:* Same as 'Expand renewables'. *GHG budget constraint:* On top of a baseline of renewables expansion as resulting from the cost assumptions in 'Expand renewables', these scenarios are not allowed to exceed a certain GHG budget until net-zero. After net-zero GHGs, the model is constrained to remain at net-zero GHG emissions. The model looks for a cost-effective solution to stay within the GHG budget, by applying a carbon price. The budgets explored are 2-7GtCO2eq. The 2Gt run was infeasible, while net-zero is constrained to be reached by or before 2060.
Innovation (autonomous energy efficiency improvements)	Following the default version of MESSAGEix-GLOBIOM, we apply autonomous energy efficiency improvement (AEEI) factors as calibrated to the SSP2 baselines by climate policy, for 'Keep fossil fuels', 'Expand renewables', and 'GHG budget' (using the 5GtCO2eq version). This AEEI is then applied across all lower-growth scenarios (see supplementary information). This should be interpreted as the continuation of innovation and energy efficiency improvements regardless of the GDP per capita trends.
Investment	If consumption decreases steeply, it is possible that the levels of capital are too high for current and future consumption (i.e. when the constant costs are higher than the depreciation cost). Thus we enable the premature stranding of assets (theoretically: negative investment), while changing the way GDP is calculated in MESSAGE such that premature decommissioning of installed capacity.
Discount rate	5% following the default MESSAGEix setting in Riahi et al. (2021).
Final-to-Useful energy efficiency improvements	In line with historical trends, with slight differences across scenarios depending on the energy system characteristics. The highest end-use technology efficiency improvements are seen under the 'GHG budget' pathways (rapid switch to electrification which include much higher efficiencies e.g. for EVs), the lowest under 'Keep fossil fuels' (which retain fossil fuel-based systems with limited efficiency improvements; Supplementary Figure 2).

2021; Millward-Hopkins, 2022; Millward-Hopkins & Oswald, 2023). Here, we compare average final energy consumption in our MESSAGEix-Australia pathways to such minimum levels. To provide an estimate of the share of population consuming less energy than this hypothetical minimum energy requirement, one needs to understand within-country inequality of energy consumption per capita. We estimate the Gini of direct and indirect energy consumption in Australia (using Lenzen, 1998; Lenzen et al., 2004, 2006; *UNU-WIDER*, *2020*). Two scenarios are explored: constant Gini and strong inequality reduction (at 2% reduction per year). The share of population below an energy consumption level is calculated as the integral from zero to the DLE level of the lognormal distribution determined by the Gini and the mean of energy consumption. To align the final energy requirement for DLE with the energy efficiency improvements in the MESSAGEix-Australia scenarios, we adjust the DLE threshold by final-to-useful energy ratios over time (Supplementary Figure 2).

3. Modeling results

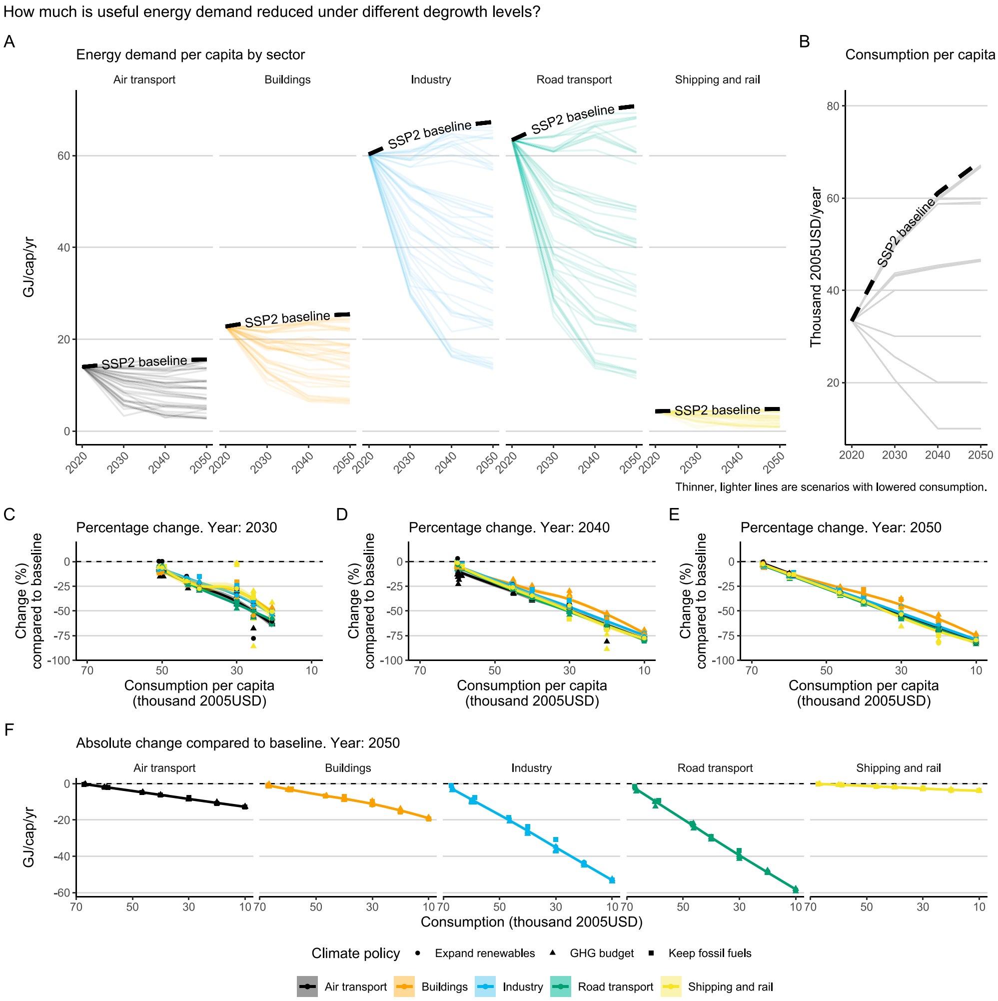
3.1. Feasibility of modeled energy demand reduction pathways

Under the strongest GDP reduction of the lower-growth scenario set (10k), consumption (Figure 2) and energy demand drop abruptly (Figure 4) and cause reductions far in excess of those observed during the COVID-19 pandemic (Kikstra, Vinca, et al., 2021). This scenario with the lowest utility peak (10k) sees a reduction of close to 65% and 80% in average useful energy demand per capita by 2030 and 2050, respectively. These demand reductions in useful energy are mirrored by final energy demand reductions, at 60% (2030) and over 80% (2050). Within our energy model, we separate demand for buildings (heat and electricity), industry (heat, electricity, and feedstocks), and transport (air, road, and rail and shipping). Because of the non-differentiated implementation of energy demand reductions, the useful energy demand pattern is the same for all sectors (Figure 4(a)) across consumption levels (Figure 4(b)), with sectoral useful energy demand reductions that scale linearly with reductions in consumption (Figure 4(c–f)). Minor scatter in percentage reductions across scenarios appears only for small sectors, and is restricted to earlier years (Figure 4(c)).

The thought behind our MESSAGEix-Australia lower-growth scenarios is that utility can peak at different levels, which leads to consumption and energy demand decreasing fast. While such a transition scenario is very different from other existing estimates, it is still useful for context to just compare how fast such reductions are in comparison to other energy and emissions reductions potentials related to demand-side changes. For instance, the demand-side greenhouse gas (GHG) mitigation potentials for 2050 reported by the IEA (57%) and IPCC (40-70%) are in the same neighborhood as the 40k ‘Keep fossil fuels’ and ‘Expand renewables’ scenarios (Figure 2(b)). The energy per capita consumption levels that the Low Energy Demand (LED) scenario (Grubler et al., 2018) moves to for the OECD region (Figure 5(b)) is comparable to that in the 30k scenario (‘Expand renewables’), with the caveat that energy consumption per capita in Australia is higher in the base year.

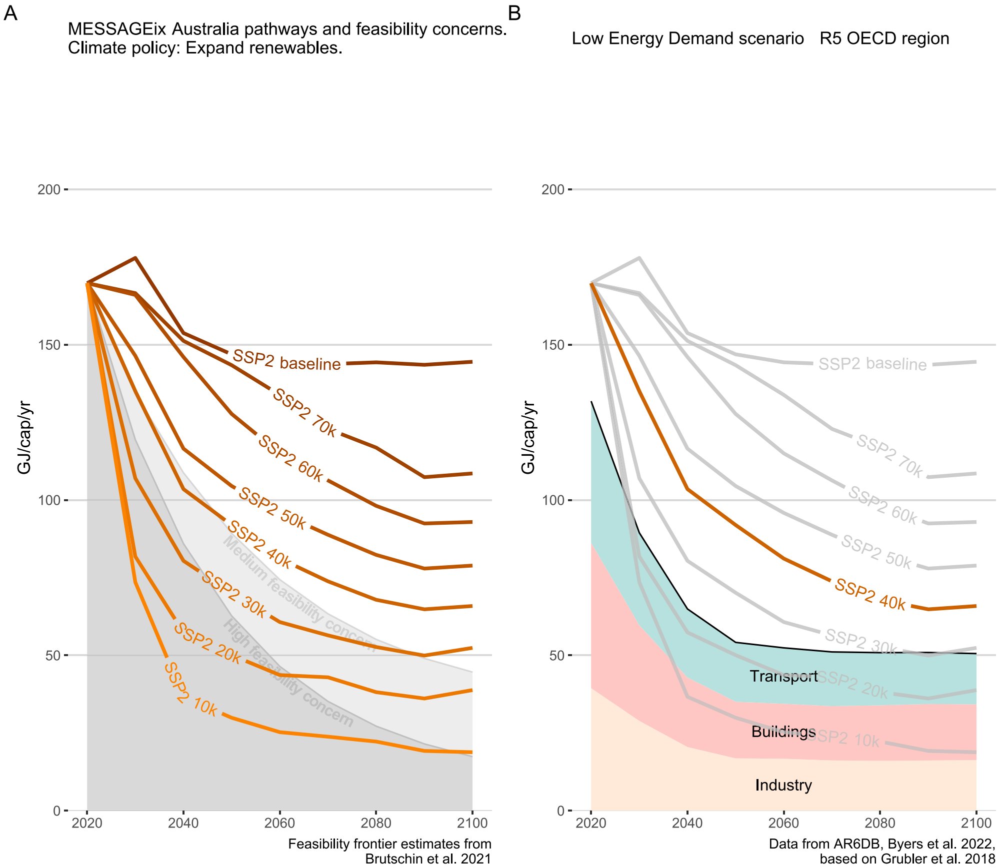
In an attempt to better assess feasibility concerns in different IAM pathways, the literature has suggested a multidimensional feasibility framework (Brutschin et al., 2021). This

Figure 4. Useful energy demand reduction by sector, at different consumption levels, compared to the SSP2 baseline. Panel A: range of useful energy demand pathways levels across sectors over time, with corresponding consumption per capita levels (panel B). Panel C-E: percentage reduction compared to SSP2-baseline useful energy demand per capita, for 2030, 2040, and 2050. Panel F: absolute difference in useful energy demand per capita in 2050 at each consumption level, compared to SSP2-baseline useful energy demand.



framework assesses feasibility concerns around five main dimensions: geophysical, economic, technological, socio-cultural, and institutional. The framework compares future changes to threshold values derived from the literature. The socio-cultural dimension includes thresholds for behavioral changes around energy demand and dietary change. More specifically, if final energy demand reductions outpace the Low Energy Demand scenario (Grubler et al., 2018), this would raise feasibility concerns. Following the Brutschin et al. (2021) analysis, we find high feasibility concerns regarding the speed of energy consumption reduction in the 10-30k scenarios, while the 40k scenario falls in the medium concern range – for the 'Expand renewables' scenario set (Figure 5(a)). While methodologies to assess the feasibility of demand reductions are still uncertain, especially so

Figure 5. Final energy demand projections for the 'Expand renewables' climate policy scenario ensemble. Panel A compares the final energy per capita projections versus feasibility concern thresholds, and Panel B compares them to final energy per capita consumption in the OECD region of a global Low Energy Demand pathway.

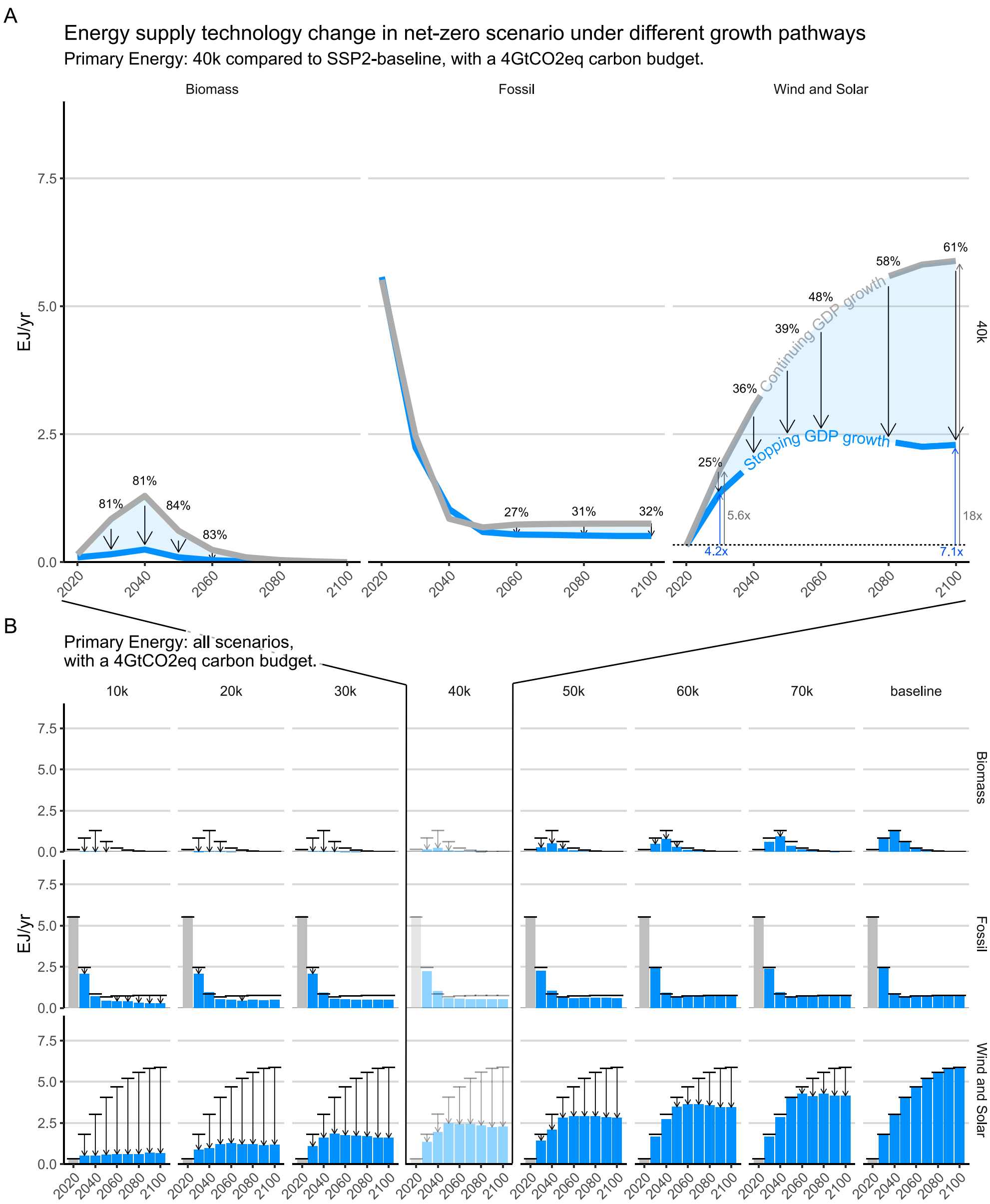


for socio-cultural and political aspects, this indicates potential feasibility concerns in the socio-cultural dimension especially for the 10k-30k scenarios. We should note here that the social feasibility of degrowth pathways depends strongly on the policies involved and on broader factors beyond the pace of final energy demand reduction (which is a combination of both energy service reductions and structural changes). Degrowth scholarship calls for strong social policy (universal public services, a job guarantee, reduced inequality) to secure and improve well-being. Output reductions are achieved by targeting destructive and less-necessary forms of production, while improving access to necessary goods and services. While policies like these may encounter political resistance, it has also been argued that they could dramatically improve social feasibility (Li et al., 2023). Unfortunately, the modeling approach we use here does not capture these dynamics.

3.2. Speed of upscaling renewable energy technologies across GDP scenarios

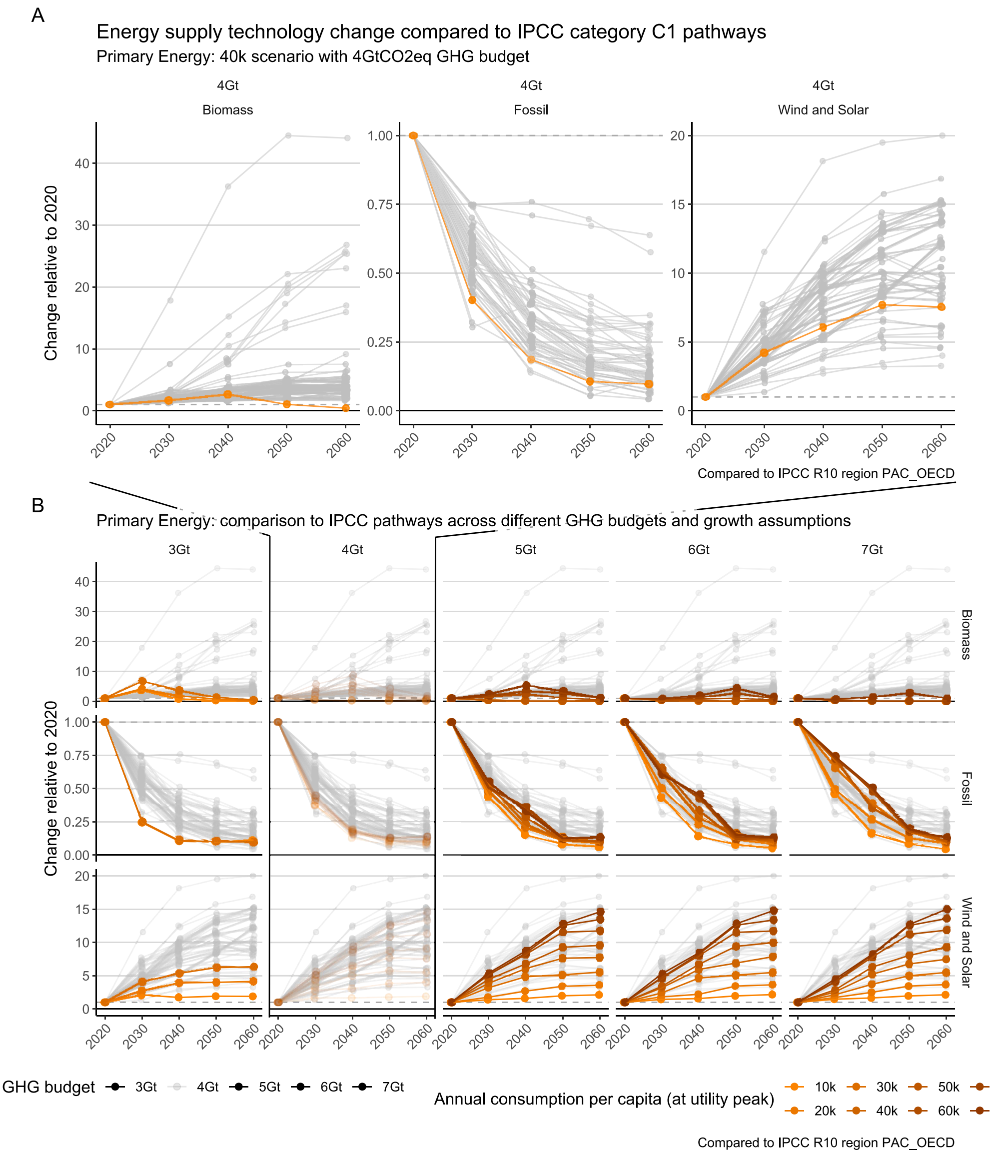
Next, we compare how renewable energy technologies need to be upscaled in a scenario that stays within a 4 GtCO2eq national GHG budget.

Figure 6. Change in primary energy supply, for the 4GtCO2eq GHG budget until net-zero. Panel A highlights the 40k lower-growth scenario compared to the SSP2-baseline growth scenario, whereas panel B shows outcomes for all growth variants.



All future projections with strong climate mitigation, no matter the size of the economy, see energy from fossil fuels decline dramatically, by about 81-88% in 2040 compared to 2020 (Figures 6 and 7), to reduce emissions in line with the remaining GHG budget. Most of this energy is replaced by energy from Australia's large potential for solar and wind (for detail, see Supplementary Figure 4). In this 4GtCO2eq budget scenario, the growth rate constraint on solar PV (the cheapest renewable energy technology in our model) is binding

Figure 7. Relative change (versus 2020 value, where 2020 = 1) of primary energy sources for different GHG budgets in our MESSAGEix-MACRO analysis, compared to scenarios for R10 PAC OECD countries (Australia, Japan, and New Zealand), in global scenarios used in the IPCC WG3 report that end up below 1.5C in 2100, with no or low overshoot this century (category C1). IPCC scenarios are taken from the IIASA AR6 Scenario Database v1.1 (Byers et al., 2022).



in the near-term at 25%/yr (Table 1), such that also wind and biomass need to increase to meet energy demand. This behavior is most prevalent in the 60k, 70k, and SSP2 baseline which see per-capita GDP growing in the near-term (2020–2040). Figure 6(a) shows that an immediate stabilization of GDP per capita (40k) shows a strong reduction in the need for biomass compared to the SSP2 baseline (−81% in 2040), and also sees a lower need for energy from solar and wind (−36% in 2040, −39% in 2050, −48% in 2060, and −61% in 2100; for other GHG budgets, see Supplementary Figure 6), reducing technological feasibility concerns. Importantly, such a lower-growth pathway with stabilized consumption and production limits future material needs for renewables compared to the SSP2-baseline which features energy supply growth throughout the century. Still, the amount of wind and solar energy supply needs to increase 4.2x the 2020 supply by 2030, versus 5.6x in the SSP2 baseline. An upscaling of solar and wind is seen in all scenarios, also 10-30k but at a slower rate and to a smaller extent than in the 40k case.

3.3. Mitigation ambition compared to IPCC AR6 C1 scenarios

Next, we compare the relative mitigation ambition and decoupling to the most ambitious scenarios in the IPCC Sixth Assessment Report – category C1 with no or low temperature overshoot and median projected 2100 global-mean temperature less than 1.5°C above pre-industrial levels (1850-1900). Since the IAM results in the AR6 Scenario Database (Byers et al., 2022) are available on a regional rather than a country level, we compare against the R10 Pacific OECD region, which contains Australia, Japan, and New Zealand (for exact model mapping, see Supplementary Table 1).

We find that the relative near-term (2030) reduction in fossil fuels (primary energy) in our SSP2-baseline growth scenario range roughly covers the range of IPCC C1 scenarios, with GHG budgets reducing from 7GtCO2eq to 4 GtCO2eq (Figure 7). Subsequently, it also covers the range of GHG emissions outcomes in the C1 scenarios (Figure 8). The 2030 level of fossil fuel use is lower across all GHG budgets in the 10k, 20k, and 30k scenarios (Figure 7), which are also the only scenarios that can stay below a 3 GtCO2eq budget. The 40k scenario, with a flatlining of GDP per capita from 2020, also allows for emissions reductions in the current decade (2020–2030) that are more ambitious than $>95\%$ of the C1 scenarios (Figure 8). Where MESSAGEix-Australia finds a solution for the 3GtCO2eq budget (10k-30k), net-zero is reached by 2040, and emissions reduction rates are substantially more ambitious than C1 scenarios for the Pacific OECD region (Figure 8).

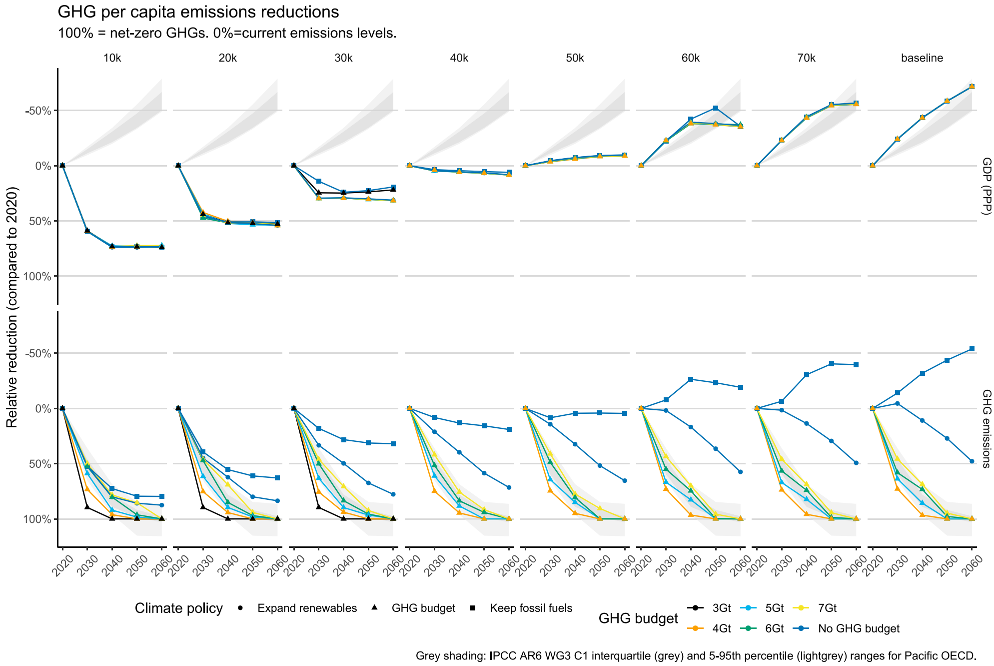
While meeting the same mitigation ambition as in these most ambitious scenarios, the need for relative increases in biomass and solar and wind is clearly lower under reduced economic growth. For comparison, our SSP2-baseline already falls roughly in the middle of the upscaling speed in the IPCC scenario range for solar and wind, and is on the lower end of the range for energy from biomass (Figure 7).

In our GHG budget scenarios, the carbon price is the factor that can be interpreted as the main proxy for mitigation effort when comparing different scenarios. Increased carbon prices lead to a faster scaling up of low-emissions technologies, and a faster phasing out of fossil fuels. Our results show a clear relationship between both the carbon budget and the size of the economy with the ramping up of the carbon price over time (Figure 9).

3.4. Energy and emissions decoupling from GDP compared to IPCC AR6 C1 scenarios

To reach net-zero emissions, and to stabilize global mean temperatures, CO_2 emissions need to be absolutely decoupled from GDP. While some countries have started decoupling emissions from GDP growth, the current global rates of relative decoupling as well

Figure 8. Annual GHG emissions reductions and GDP growth per capita compared to scenarios for R10 PAC OECD countries (Australia, Japan, and New Zealand), in global scenarios used in the IPCC WG3 report that end up below 1.5C in 2100, with no or low overshoot this century (category C1). IPCC scenarios are taken from the IIASA AR6 Scenario Database v1.1 (Byers et al., 2022).

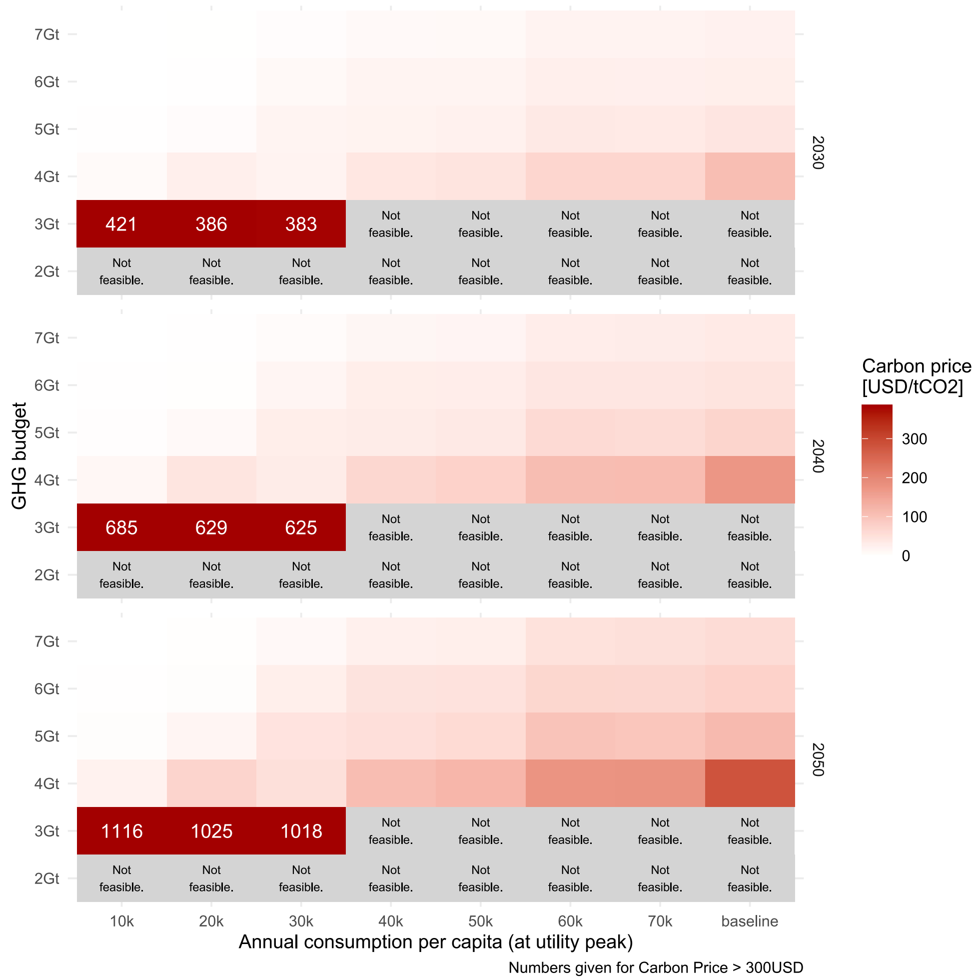


as national rates of absolute decoupling are still far from being at the level of total emissions reductions needed for meeting ambitious climate targets (Lamb et al., 2022; Vogel & Hickel, 2023).

All scenarios from the AR6 Scenarios Database (category C1) show absolute decoupling of both final energy and GHGs from GDP during the period 2020–2030 for the R10 Pacific OECD region. Recent literature has questioned this rapid departure from historical trends (Haberl et al., 2020), which for Australia have seen growth in GDP, final energy, and GHGs for the 1990–2019 period (Gütschow et al., 2021; IEA, 2023; World Bank, 2023).

In Figure 10, we observe values in three quadrants of the final energy – GDP plot for 2020–2030. First, we see relative decoupling in the top right-hand quadrants for the higher (60k, 70k, SSP2-baseline) scenarios, as significant GDP growth is coupled to lower but still positive energy growth rates, owing to energy efficiency improvements. Next, we see absolute decoupling in the bottom right-hand quadrants for our 40-50k scenarios, owing to low (positive) GDP growth occurring at the same time as low (negative) final energy growth, caused by the assumed energy efficiency improvements. Absolute decoupling is a common feature of the scenarios from the IPCC AR6 scenario database, shown as gray dots in Figure 10. Last, we see re-coupling in the bottom left-hand quadrants for 10k-20k scenarios, as these scenarios feature highly negative growth rates for both GDP and energy. After 2030, many scenarios have flat consumption and GDP per capita, while energy efficiency improvements continue (Supplementary Figures 1–3). For 2030–2050,

Figure 9. The effect of more or less stringent GHG budgets until net-zero GHGs on the carbon price, across different Consumption scenarios.



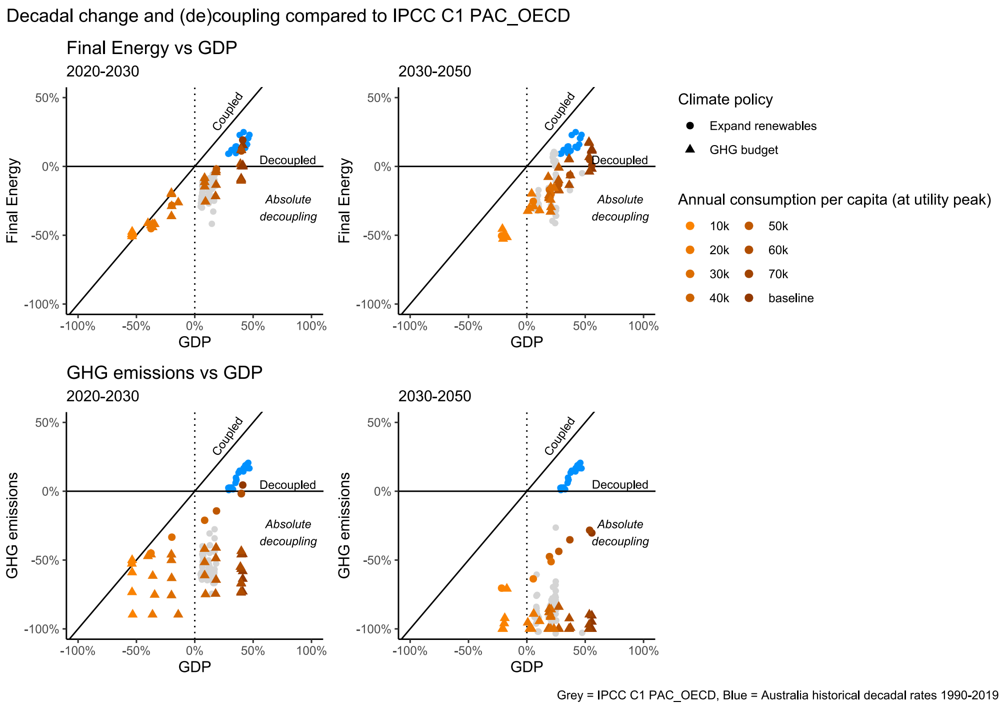
final energy decoupling rates span across the range of the scenarios from the IPCC AR6 scenario database (Figure 10).

For GHGs, a wide range is covered in 2020–2030, with absolute decoupling for all scenarios with a GHG budget due to the speed of renewables uptake, but ranging from near-full coupling to decoupling rates slightly above the range in the IPCC database. The latter is narrow because the large majority of scenarios use the same SSP2 baseline narrative. All GHG budget scenarios go to zero GHG emissions, meaning strong decoupling for GHGs during the period 2030–2050 is necessary and observed in the scenarios (Figure 10).

3.5. Energy availability for meeting decent living standards

Evaluating the desirability of alternative IAM scenarios is not a straightforward task, especially when assuming alternative utility functions like in our exercise. However, if people

Figure 10. decadal change and decoupling rates from GDP of final energy (a) and GHG emissions (b). The percentages on both axes refer to the total percentage change over the indicated period. Historical data, as collected in Marshall et al. (2024), are from IEA (2023) for final energy, the World Bank (2023) for GDP, and PRIMAP-HISTCR v2.3.1 (Gütschow et al., 2021) for GHGs. IPCC scenarios are taken from the IIASA AR6 Scenario Database v1.1 (Byers et al., 2022).

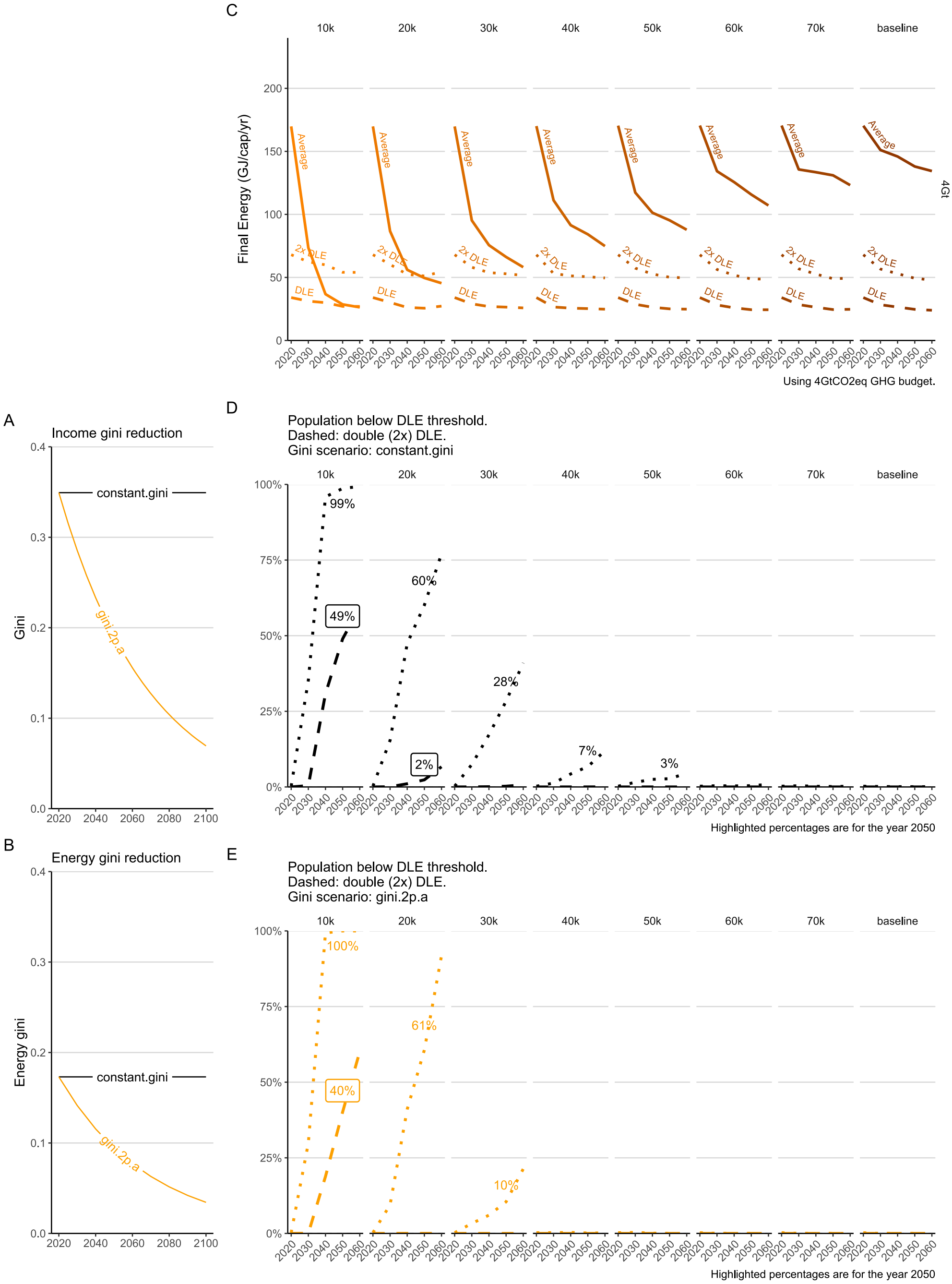


consider lower consumption levels as 'optimal' from a utility perspective, this should be coherent with (or mirrored in) well-being indicators, e.g. people should not fall below decent living standards (Rao & Min, 2018). We therefore calculate the number of people whose energy consumption falls below the 'Decent Living Energy (DLE)' threshold, assuming a lognormal distribution of energy consumption per capita. As it may be desirable to have higher-than-minimum standards of living, we also estimate how many people would consume less energy than double the DLE thresholds (2x DLE). Note that these minimum requirements for a decent life are based on a selected basket of goods and services and do not relate to immaterial needs. We explore the extent to which reduced inequality impacts the results.

We look at two different inequality reduction scenarios in this scenario post-processing analysis. In the first scenario, we keep the Gini index of income and energy consumption constant. A constant Gini index over time is near-identical to the income Gini for Australia for SSP in the projections of Rao et al. (2019). The second scenario assumes strong inequality reduction within Australia, at 2% reduction per year; for both energy and income (Figure 11(a) and (b)).

To account for energy efficiency improvements in the modeled scenarios, we adjust the DLE final energy threshold downwards by the improvements seen in the final-to-useful energy ratio (Supplementary Figure 2, Figure 11(c)). We use the estimates from Kikstra, Mastrucci, et al. (2021) for DLE, arriving at 24–28 GJ/capita (depending on the scenario)

Figure 11. Projected DLE deprivations. 'gini.2p.a' represents a scenario which reduces the Gini with 2% (not percentage points) per year (a and b). DLE is adjusted for changes in the ratio between Final and Useful energy over time (c). (d and e) showing the share of population below the 1x and 2x DLE thresholds for constant inequality (e) and inequality reduction (e).



for Australia in 2050. These numbers are dependent on the normative choices of what to include in the basket of decent living standards, as well as on the technological efficiency assumptions (see e.g. Millward-Hopkins et al. [2020] and Millward-Hopkins and Oswald [2023]). In this respect, our DLE threshold estimates can be considered conservative as they do not use the currently available technological state-of-the-art, but rather start from widely used technological efficiencies with future improvements scaled modestly. For instance, Millward-Hopkins (2022) estimates of about 20 GJ/cap with current best-practice technologies for Australia, or at about 14 GJ/cap with high energy efficiency, by 2050 (see Supplementary Figure 7 for an analysis using these numbers).

We find that with a constant level of energy inequality (constant energy Gini) the percentage of the Australian population consuming less than the DLE threshold remains below 1% in the 30k and higher scenarios by mid-century. For 20k and lower, deprivations start to grow seriously, with 2% in the 20k scenario in 2050 and about half the population falling below DLE in the 10k scenario (Figure 11(d)). Strong inequality reduction strongly reduces this number for all scenarios except the 10k scenario (Figure 11(e)). Still, in the 10k scenario, inequality reduction brings the average annual deprivation among the deprived population at 2.9 GJ/cap down from 5.5 GJ/cap, in 2050. For the 20k scenario, these numbers are 1.0 and 2.7 GJ/cap, respectively. The level of deprivation can be expected to be even bigger if one were to look into different sectors, without directed policies which are not considered in this study. In other words, even with strong reductions in inequality, a consumption level of 10k in such an aggregate demand reduction scenario looks incompatible with desirable social outcomes following our DLE threshold values. To avoid this shortfall given the current basket of decent living standards, one would need to see for instance further increases in energy efficiency, as per the other DLE estimates above utilizing more efficient technologies or collectively moving towards low-energy service provisioning systems. Similarly, the level of deprivation at low aggregate energy use can be mitigated by strong social policies and decommodified provisioning systems, but these are not considered in this study.

At lower-growth levels, sizable shares of the population fall between the 1x and 2x DLE range. 3% (50k) to 99% (10k) are below the higher 2x DLE threshold in 2050 without inequality reduction, with 60k and higher seeing nearly no share of the population below 2x DLE. With strong inequality reductions, nearly the entire population stays above the 2x DLE threshold for the 40k scenario and higher growth scenarios.

We note that these estimates remain dependent not only on the assumptions relating to the distribution and scenario assumptions, but also on the estimate of minimum energy requirements. Supplementary Figure 7 shows that a lower DLE threshold would come with much lower deprivations.

4. Discussion

Here, we discuss to what extent our model and our scenarios can represent a degrowth transition as it is described in the relevant literature, highlight key insights derived from the current implementation, and indicate points for future research.

4.1. Model features necessary for degrowth modeling

Table 2 below provides an overview of common degrowth goals and policies as well as their representation in our IAM scenarios. These policy goals are summarized as five key themes

Table 2. A selection of characteristic degrowth policy goals and instruments, the latter being broadly defined as actions implemented by specific social actors in the course of a degrowth transformation, and their representation in the IAM modeling of this paper.

Degrowth policy goal	Examples of instruments	Modeling representation
(1) Achieve feasible efficiency improvements and technological change (*efficiency*)	• Regulations mandating strict energy efficiency standards, e.g. for housing, industry equipment and electric appliances. • Retrofitting programs for the housing sector (insulation, efficient appliances, heat pumps, etc.). • Investment to expand community-controlled renewable energy projects. • Mandatory warranties and rights to repair lengthening product life spans. • Ecological tax reform shifting taxes from labor to resources.	Represented by scenario assumptions on energy efficiency increase, costs of renewable energy expansion, carbon prices and negative emission technologies as well as lower peaks of non-monotonic utility function leading to a decline in consumption expenditure, energy use and GDP. While in principle this could represent e.g. reduced consumption from retrofitting, rights to repair and warranties, it is modeled as an aggregate (possibly uncontrolled) reduction. The multidimensional feasibility of the modeled changes is not explored in detail, but aggregate indicators such as decoupling rates are derived.
(2) Scale down less-necessary and resource-intensive forms of production (*sufficiency and consistency*)	• Declining caps on fossil fuel consumption, production and import. • Regulations limiting SUVs aside from special uses, and substantially reducing car use, e.g. congestion zones and parking space reductions. • Expansion or improvement of public transport, cycling and walking infrastructure. • Frequent flier levies to reduce commercial flights • Regulations substantially reducing industrial meat production, especially beef. • Limits on house sizes. • Limits on advertisement. • Ending planned obsolescence and extending product lifespans. • Reducing arms production, e.g. demilitarization efforts and defunding police.	Partly represented by lower peaks of non-monotonic utility function leading to a decline in consumption expenditure, energy use in specific sectors such as aviation and road transport, and GDP, however, this requires additional modeling of policies in those sectors to differentiate percentage reductions between sectors.
(3) Reduce the purchasing power of the rich (*meeting human needs, equity, and democracy*)	• A relatively low maximum income cap or ratio, e.g. in line with popularly supported fairness considerations. • Relatively high wealth taxes, in line with ethical limitarianism. • Reduce monopoly power and increase democratic control over industries and land.	Implicitly represented in the model; only total energy is explicitly modeled from which averages can be derived, but no explicit distribution. Using an estimate of current inequality and implied future inequality changes in income, one can however derive an implied possible distribution of energy consumption in the future (Figure 8). Inequality reductions are implied by the baseline SSP2 narrative, though in the degrowth scenarios levels of inequality may change, but this is not modeled.
(4) Ensure decent living for all (*meeting human needs, equity, and democracy*)	• Guarantee universal access to fully or partially decommodified public services, including housing, healthcare, education, public transit, clean energy, water, nutritious food (EAT-Lancet), recreational facilities, childcare and internet. • Working time reductions and more even allocation of necessary work helping to prevent unemployment and increase leisure time. • Public job guarantees enabling anyone to train and participate in socially useful and ecologically necessary forms of production, ensuring a just transition, reducing inequality and ending unemployment.	Implicitly represented; 'welfare purchasing power' of income can change drastically depending on social institutions and provisioning systems. Inequality reductions are implied by the baseline SSP2 narrative, though in the degrowth scenarios levels of inequality may change, but this is not modeled.
(5) Achieve international convergence in material and energy use between global North and South to safe and sufficient levels (*meeting human needs, equity, and democracy*)	• Global North countries pursuing faster climate mitigation in line with climate justice considerations and reducing resource use. • Global North ending net appropriation of labor and resources from the global South (unequal exchange). • Reparations from global North to South for ecological and neo-colonialist damages. • Technology transfers and patent waiving from actors in the global North. • Democratization of international organizations, e.g. World Trade Organisation and World Bank, and renegotiation of trade agreements • Material support for refugees and emancipatory social movements in the global South. • Land back to indigenous communities.	While the model is national, and thus cannot show international convergence, it represents a rich country exhibiting faster emissions reduction and scaling down of production and consumption. No representation of technology transfers, reparations, democratization, refugees, or indigenous communities.

Notes: The implementing social actors comprise international state organizations, national, regional and local governments, intersectional social movements, including labor, feminist, anti-racist, global justice and ecological movements, as well as local communities. There are debates within the degrowth literature on exactly how this transformation is to take place (see e.g. Schmelzer et al. [2022] and Wiedmann et al. [2020]). This list is necessarily incomplete and is based on Bodirsky et al. (2022), Creutzig et al. (2021), Fitzpatrick et al. (2022), Hickel (2021), and Schmelzer et al. (2022). The column 'Modeling representation' of the policies is our own assessment.

essential for modeling degrowth: (1) projecting feasible efficiency and technology improvements, (2) scaling down non-necessary forms of production and consumption leading to sufficiency, (3) reducing the purchasing power of the wealthiest households, (4) meeting decent living standards for all, and (5) international convergence; all in relation to staying within planetary boundaries, or returning within the safe operating space as soon as possible. Policy goals one and two link to reducing resource use to sustainable levels through a combination of sufficiency, consistency and efficiency measures (see e.g. Creutzig et al. (2018)), including reducing the purchasing power of the rich and downscaling ecologically destructive and socially less-necessary forms of production and consumption (Hickel, 2021; Kallis et al., 2018; Parrique, 2019). Policy goals three to five relate to degrowth as the idea of an equitable and democratic transformation of high-income economies that ensures wellbeing for all, independently of economic growth, including through reducing inequality, securing access to livelihoods, and establishing universal public services.

Based on these themes, we identify five key areas of improvements to move from our modeling using MESSAGEix-Australia towards a better representation of degrowth in IAMs.

First, there is a lack of detailed demand-side, sector and product-specific modeling. In this study, the percentage reduction in useful energy demand between economic sectors is not differentiated on the basis of their relative social necessity and ecological impact (see Figure 4). This conflicts with the degrowth call for a differentiated downscaling of production and consumption (Fitzpatrick et al., 2022; Hickel, 2021; Oswald et al., 2020). It is crucial to capture the interdependencies between sectors (e.g. downstream industrial demand reduction from lower transport demand), including industrial policy considerations, in future modeling of demand-side changes.

Second, there is no representation of radical changes in provisioning systems, such as a private-to-public transformation, which could allow improved satisfaction of needs with lower resource use (Baltruszewicz et al., 2021; Vogel et al., 2021). We also do not explore the effects of decommodification and price controls on decoupling access to essential goods and services from income. Sectoral differentiation and changes in the provisioning system are necessary conditions to be able to adequately analyze changes in ‘welfare purchasing power’ of income (Hickel & Hallegatte, 2022) and assess sector-specific DLE shortfalls (Kikstra, Mastrucci, et al., 2021).

Third, in this study income and energy use inequality is implicitly represented in the DLE analysis, by exploring assumptions around how the income and energy Gini coefficient might change in the future, alongside changes in the energy system (see Figure 11). This procedure of representing inequality only allows for a limited exploration of the interaction between lower growth and poverty because the distribution is not explicitly modeled, e.g. only approximating phenomena such as the most wealthy individuals (Millward-Hopkins, 2022). Moreover, no demographic distinctions are explicitly modeled, and thus differences across age groups, gender, education, or other characteristics are not represented. For degrowth, reductions in inequality are vital to ensure DLE for all (Millward-Hopkins & Oswald, 2023), allow for democratic participation (Nielsen et al., 2021) as well as reduce environmental impacts (Millward-Hopkins, 2022).

Fourth, in our study we chose to keep the same autonomous energy efficiency improvements for higher- and lower-growth pathways. More research is needed to understand how broader economic change and investment relate to innovation and energy efficiency. This needs to go beyond demand-side modeling and service provisioning changes, towards an understanding of for instance the interaction between government and private investment, education, and energy efficiency gains.

Finally, MESSAGEix-Australia only covers one country. Hence, it cannot represent international dynamics of convergence between the global North and South, along with implications for international trade, which are emphasized in the degrowth literature (Hickel et al., 2022; Schmelzer et al., 2022), nor can it reflect whether global environmental policy targets such as the Paris Agreement are met under alternative scenarios. For understanding and modeling transitions away from current financial systems, models with a different structure and design are necessary, representing the economic system in more detail.

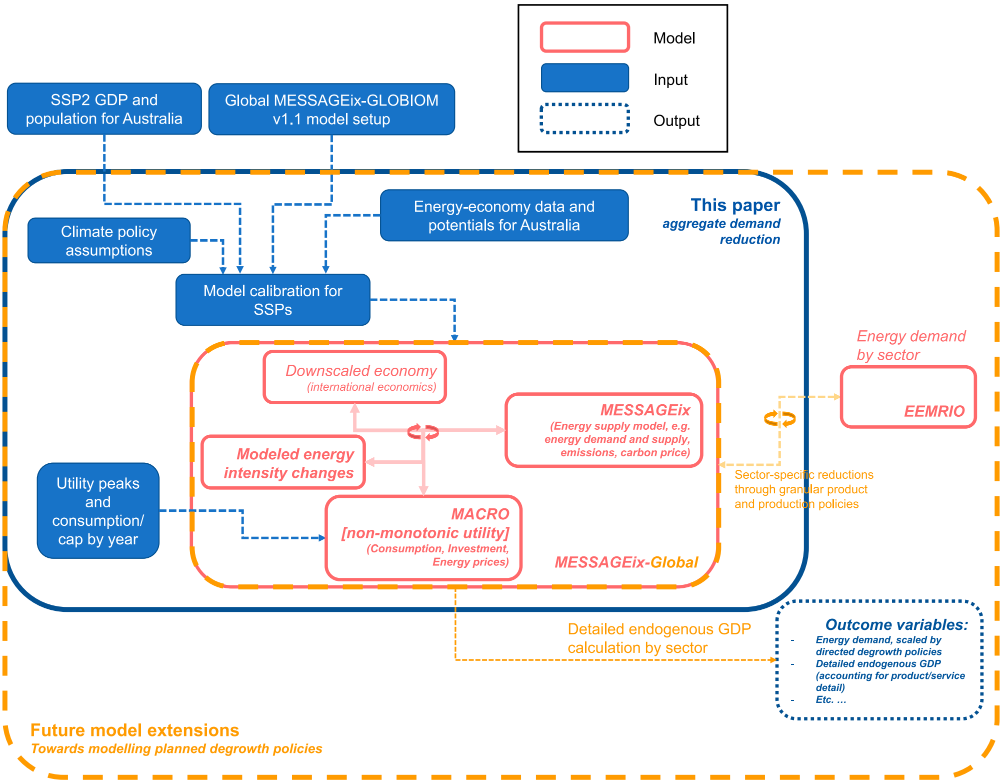
4.2. Insights from the current implementation

In light of the previous section, the scenarios in this paper cannot be said to fully represent a local or global degrowth scenario within an IAM. Nevertheless, they provide important information, specifically regarding policy goals (1) and (2) in Table 2. The 'lower-growth' scenarios show that a social transformation towards lower consumption while maintaining decent living standards results in a strong decline in energy consumption and carbon emissions, broadly representing gains that can be achieved through sufficiency and efficiency measures. These results demonstrate the specific advantages delivered by reduced production and consumption in terms of lower energy infrastructure requirements and reduced required renewable energy scale up speeds while maintaining the same rates of decarbonization (see Figures 6 and 8). For instance, we highlight that under a near-term GDP per capita stabilization scenario with small consumption per capita improvements, the need for solar and wind energy remains high in the first decade, but is reduced by close to 40% compared to the SSP2 growth baseline, in 2050 (Figure 6). Such insights on the differential energy system size requirements may be useful in future studies that analyze the environmental impacts, space, and resource requirements of such alternative energy systems. A strength of the scenario set presented here is its coverage of a very wide range of potential GDP pathways, enabling the exploration of radically different futures. This wide range of pathways also illustrates that to reach net-zero, absolute GHG decoupling from GDP is required for most of the period until 2050 (Figure 10). In almost all cases, the relationship of GDP trends with GHG and final energy trends strongly deviates from past tendencies in the Australian economy. Limited recoupling is observed in the scenarios with GDP reductions in the near-term.

Furthermore, our exercises demonstrate that in cases where utility peaks at lower levels of consumption, dramatic reductions in inequality may be necessary alongside energy efficiency improvements in order to maintain DLE for all (see Figure 11), although those results are dependent on the assumed DLE threshold (see Supplementary Figure 7).

This work represents a first step in bringing an economics entry-point to integrated assessment modeling of scenarios that meet differentiated climate targets, and provides example avenues for evaluating mitigation benefits, feasibility in energy supply and energy demand changes, decoupling, and energy availability for meeting decent living standards.

Figure 12. suggested methods flowchart for future work.



4.3. Points for a research agenda

The methodology applied in this paper is extendable (Figure 12). Aside from reducing GDP growth, our modeling exercise assumes macro societal developments that are largely reflective of historical dynamics. This assumption can and should be questioned, in particular where dynamics might be intricately linked to the dominant economic growth system.

Examples of embedded modeling assumptions that might not be valid in a degrowth future are the assumed pace of energy efficiency improvements, technological innovation and technological diffusion rates (a degrowth scenario may use public finance and planning to target necessary innovation and faster diffusion). These assumptions are key determinants of the attainability of technological transition pathways and stringent climate change mitigation outcomes. However, how they can change under a different economic paradigm remains a fundamental research gap.

Future work could be directed at better understanding the economic dynamics of a planned degrowth transition. In our study, the economic dynamics of this transition are not modeled beyond endogenously determined investment and energy and carbon prices. There is no research consensus yet on national and global economic dynamics, stability, and resilience with reduced or negative economic growth. Concepts and assumptions like competitiveness, innovation, productivity, and capital accumulation need to be revisioned in model frameworks, and a multitude of model frameworks such as agent-based models (e.g. Lamperti et al., 2019) and stock-flow models (e.g. D'Alessandro et al., 2020; Jackson &

Victor, 2020; Leoni et al., 2023; Sers, 2022) as well as more conventional detailed economic models could play a role. The MACRO sub-model features a Constant Elasticity of Substitution (CES) GDP equation, of KL(E) nesting structure. Whilst this is a very common and indeed mainstream approach, it only allows a small 'cost-share' role for energy in economic growth. Using IAMs for degrowth analysis where energy demand is the limiting variable, may therefore mean a change to MACRO's CES equation may be required, to better replicate the impact of those demand-side changes in economic growth (e.g. Santos et al., 2021). In general, our current modeling also reflects the large uncertainty in how to deal with the relationship between consumption and utility, which remains a topic for further empirical and modeling analysis. Modeling of the finance system is missing, too, with the current study not representing the financial sector.

On the energy demand side, we only describe futures with a constant percentage change across sectors per economic contraction, as evident from Figure 4. This limitation can be overcome by adding more detailed modeling (e.g. Mastrucci et al., 2021), enabling the discussion of energy sufficiency, with detailed future final consumption scenarios where for example certain goods and services are classified as non-essential and are phased out. The paper by (Liu et al., this issue) moves in this direction, starting from the standard supply-side representative agent model MESSAGEix-Australia towards a model representing such dynamics, by coupling an input–output-model (IO) to an IAM. This strategy can significantly increase sectoral detail in the model (see also e.g. Lefèvre, 2023; Budzinski et al., 2023; Pauliuk et al., 2017), which is necessary for modeling sectoral-level options and measures proposed for degrowth transitions (such as mode shifts in passenger transport, smaller cars, or moves towards sufficiency in building utilization). One could also assume transport infrastructure and other service provisioning systems are made to increase the resource efficiency of satisfying human needs. Similarly, technical efficiencies could be modeled in a much more commodity-specific way rather than more aggregate AEEI ratios used here. Moreover, the comparison with DLE levels would alter as an enhanced model setup becomes sensitive to distinguish between elastic and inelastic energy commodities, and enable sectoral DLE comparisons. Ideally, intersectoral distinctions would be made between luxury and non-luxury technology and progress, but such a setup requires going beyond what is conventionally possible in IAMs and IO models. The sectorally explicit IO descriptions can be aided by a set of constraints that ensure for example that public transport replaces private transport, and that household energy does not decrease. Such a setup would be capable of linking post-growth consumption with inequality reduction (Sampedro et al., 2022).

Moving beyond a one-country setup allows the exploration of further policy options. Little is yet known about first-mover or cooperation vs non-cooperation dynamics (i.e. some one country or bloc moving to degrowth, while other regions stay growth-oriented), international monetary and technological transfers and investments, geographical differentiation respecting local characteristics and differentiated needs (e.g. energy needs for thermal comfort), responsibilities (e.g. remaining carbon budget shares), and regional mitigation potentials and feasibility (e.g. following a potentially adapted framework such as in Brutschin et al., 2021). All these will interact with power dynamics, international economics, and also resource trade with embodied emissions and energy, which could affect the insights in total global environmental degrowth policies as international effects of changes in wealthy countries may either multiply or offset domestic effects.

This study has focused on Australia as a case study for a high-income country where economic downscaling could take place. A degrowth transition is likely to come with different challenges, depending, inter alia, on the national setting. A key feature of the current Australian economy is its high fossil fuel exports. Barriers to reducing the Australian fossil fuel sector may be both national and international. National barriers could include opposition against the reduction of domestic profits of energy sectors, the change of jobs, the increased risk of stranded assets in the strongest economic reduction scenarios, and the relationship these have to political and social tensions. International barriers could include pressure to continue exports. As seen during the invasion of Ukraine by Russia, international pressure may grow stronger in times of trade disruptions and reduced energy security. While many challenges in a degrowth scenario may overlap with common climate mitigation policy challenges, a unilateral degrowth transition is expected to face other challenges, too, but analysis quantifying such scenarios is lacking.

Finally, future work could include a more detailed study of capabilities, gaps, and potentials of the current landscape of IAMs and other models to represent degrowth transitions. Analyzing multiple models would be crucial to understand the robustness of insights across alternative representations of degrowth transitions.

5. Conclusions

In this study, we used MESSAGEix-Australia to explore an ensemble of 51 scenarios that spans growth in line with historical trends, flatlining of consumption, and even strong reduction in consumption in the near term. We combined this with various supply-side climate policy ambitions by using a traditional IAM carbon budget scenario setup with no net-negative GHG emissions and a non-monotonic utility function.

Focussing on the 40k USD per capita per year consumption scenarios with a 4GtCO2eq GHG budget until net-zero GHGs, which sees a flatlining of GDP per capita and a slight increase in consumption compared to 2020, we weigh the potential benefits and potential disadvantages of lower-growth pathways.

Compared to a continued growth SSP2 baseline, we find that a lower-growth (40k) pathway can reduce the need for solar and wind technologies by close to 40% by mid-century, while the 2030 upscaling still needs to be 4.2x higher than in 2020, reducing the challenge in the first decade only slightly (down from 5.6x). The pressure on an otherwise challenging long-term scale-up is reduced. Moreover, biomass is held to a minimum and future material demand for solar and wind is reduced as generation stabilizes in the second half of the century, as opposed to ever-growing generation.

We also find the potential to increase mitigation ambition. In the 4GtCO2eq scenario, emissions fall faster than emissions in the Pacific OECD region in virtually all of the most ambitious mitigation scenarios from the IPCC AR6 Scenario Database. Under such a scenario, decoupling of final energy and GHG emissions from GDP is still strong, similar to other continued growth scenarios.

Risks for a too limited energy availability to deliver decent living standards for all start growing at stronger demand and production reduction scenarios below 40 thousand dollar per capita consumption. At 40k, with strong inequality reduction, virtually the entire population remains above a ‘2x DLE’ energy consumption threshold.

The sociocultural and economic feasibility of lower-growth pathways is contested. While acknowledging that quantitative methods for analysing such transitions are yet to be developed, we find medium feasibility concerns regarding the speed of final energy reduction in the near term.

We conclude with a note of care in interpreting these lower-growth scenarios. The way that we have modeled aggregate demand reductions may provide some first indications of high-level, supply-side characteristics of the relationship between lower-growth and climate mitigation, but it does not yet represent the comprehensive and complex dynamics to be expected in an actual real-world degrowth transition. In order to represent such dynamics, models need to include more detailed sectoral demand-side modeling, a better representation of possible changes in provisioning systems, higher social heterogeneity and more information about inequality. Future work would further need to investigate international dynamics, financial modeling, and the role of innovation in the transition to a lower-growth society.

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Data availability statement

Documentation is available in Krey et al. (2020) [2020 release], and at https://docs.messageix.org/projects/global/en/latest/ [latest documentation for MESSAGEix global model, see also Fricko et al. (2023)], https://docs.messageix.org/en/latest/index.html [latest documentation for the MESSAGEix modeling platform, see also Kishimoto et al. (2023)], and https://docs.messageix.org/en/latest/model/MACRO/macro_core.html [latest documentation for the MACRO economic model, see also

Manne et al. (1995) and Messner and Schrattenholzer (2000)]. All data and code to reproduce the figures in this manuscript are available at https://github.com/iiasa/message-australia-degrowth.

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