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Ecological macroeconomic assessment of meeting a carbon budget without negative emissions

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Non-technical summary. This paper expands the range of scenarios usually explored in integrated assessment models by exploring unconventional economic scenarios (steady-state and degrowth) and assuming no use of negative emissions. It is shown, using a mathematical model of climate and economy, that keeping cumulative emissions within the 1.5 degree carbon budget is possible under all growth assumptions, assuming a rapid electrification of end use and an immediate upscaling of renewable energy investments. Under business-as-usual investment assumptions no economic trajectory corresponds with emissions reductions consistent with the 1.5 degree carbon budget.
Technical summary. This paper presents a stock-flow consistent input–output integrated assessment model designed to explore the dual dynamics of transitioning to renewable energy while electrifying end use subject a carbon budget constraint. Unlike the majority of conventional integrated assessment model analyses, this paper does not assume the deployment of carbon dioxide removal and examines the role that alternative economic pathways (steady-states and degrowth) may play in achieving 1.5°C consistent emissions pathways. The model is internally calibrated based on a life-cycle energy return on investment scheme and the energy transition dynamics are captured via a dynamic input–output formulation. Renewable energy investment as a fraction of gross domestic product for successful emissions pathways reaches 5%. In terms of new capital requirements and investments, degrowth trajectories impose lower transition requirements than steady-state and growth trajectories.
Social media summary. We explore the role that steady-state and degrowth economic trajectories may play in emissions reductions consistent with a 1.5 degree world..

1. Introduction

Most of the scenarios that have been developed for exploring the possibility of keeping the increase in the average global temperature below 1.5°C assume continued economic growth and a significant contribution from largely unproven negative-emissions technologies. This paper expands the range of scenarios to be considered by allowing for steady-state and degrowth possibilities in the absence of negative-emissions out to 2050. The nature of the problem may be summarized as follows. Keeping global mean temperatures limited to below some given threshold will necessitate that carbon dioxide (CO_2) emissions reach net zero (Rogelj et al., 2018a). Emissions pathways consistent with no or very limited overshoot of the 1.5°C target require declines in emissions (over 2010 levels) by approximately 45% by 2030 and reaching net zero emissions by approximately 2050 (Rogelj et al., 2018a). The majority of modelled pathways assume both continual economic growth and the deployment of some magnitude of carbon dioxide removal (CDR). Recent research however points to the role that degrowth scenarios may play in emissions reductions scenarios with comparatively lower CDR requirements and notes the need for exploring such scenarios in an integrated assessment context (Keyßer & Lenzen, 2021).

Ecological economists and degrowth scholars have long explored the ideas of steady-state and degrowth economic futures (Daly, 1993; Jackson, 2009; Kallis, 2018; Victor, 2008), while macroeconomic modelling of steady-state and degrowth scenarios has shown that these economic pathways may contribute substantially to emissions reductions (Jackson & Victor, 2020; Victor, 2012). The challenges associated with decoupling a growing economy from emissions and other environmental concerns, and the uncertainty of such a phenomena even being possible, makes the consideration of such pathways critical. Concerning decoupling, a recent extensive review concluded that observed rates of intensity decline were insufficient to meet climate goals without being paired with sufficiency measures (Haberl et al., 2020). However, recent work by Zeke Hausfather and the Breakthrough Institute does indicate evidence for absolute decoupling of emissions and growth for 32 countries (see The Breakthrough Institute, 2021). Ultimately, reductions in growth rates imply proportionally less stringent emissions intensity reduction requirements (Sers & Victor, 2020). This is important as decoupling must not only occur absolutely, but at a rate sufficient to meet increasingly stringent emissions reductions requirements.

As explored by Hickel (2019), degrowth especially may be an important strategy to achieve sufficiently rapid emissions reductions without assuming large-scale CDR deployment. The low energy demand scenario of Grubler et al. (2018), which constitutes what might be termed an energy degrowth scenario, was 1.5°C consistent without invoking any negative emissions technologies (NET) but relying on declining final energy demand (40% less than in 2018). However, this scenario is predicated on the shared socio-economic pathway 2 (SSP2) which assumes future economic growth, and therefore is not a degrowth scenario in the economic sense. Furthermore, the macroeconomic component of the integrated assessment model (IAM) used in the study (MESSAGEix-GLOBIOM) is built on neoclassical foundations and lacks strong financial sector representation. In this paper we will examine the role steady-state and degrowth trajectories may play in producing emissions pathways consistent with a 1.5°C budget without the assumption of negative emissions technologies, and including basic financial sector formalism built on the stock-flow consistent approach to macroeconomics. Importantly, we will do so using changes in final demand (the components of gross domestic product (GDP)) as the mechanisms by which to impose steady-states and degrowth futures.

As discussed in Keyßer and Lenzen (2021), degrowth pathways are almost entirely unexplored in the broader IAM community with virtually all scenarios predicated on some assumptions of growth (Rogelj et al., 2018b). This artificial restriction of scenario analysis only to ones understood as conventional or 'politically feasible' arguably represents a significant modelling blind spot as discussed in Hickel et al. (2021). Indeed, as stated in McCollum et al., '…we advocate for modellers to think more freely during the critical and highly imaginative brainstorming phase of the scenario-building process'. Intriguingly, one example given by the authors of such new and unorthodox assumptions is moving away from dominant neoclassical assumptions (McCollum et al., 2020). The recent publication of the OECD's Beyond Growth report (see OECD, 2020), which explicitly calls for policy makers to look 'beyond growth', provides further evidence that degrowth and other alternative growth scenarios are increasingly important to explore. Indeed, the restriction of scenario and pathways analysis to ones assuming growth is also increasingly difficult to defend given increasing empirical evidence suggesting the difficulties of long-term decoupling of economies from their physical basis (see e.g. Haberl et al., 2020; Heun & Brockway, 2019; Ward et al., 2016).[i]

Keyßer and Lenzen (2021) show, using a fuel-energy emissions model, that pathways characterized by relatively low energy–GDP decoupling rates and no carbon capture and storage (CCS) can be consistent with a carbon budget of 580 $GtCO_2$. As noted by the authors, their model does not include a 'monetary sector' and, while detailed in its energy considerations, does not include any macroeconomic modelling. While not large in number, several other models have been constructed to explore similar questions with more detailed macroeconomic modelling. In their recent study using the LOWGROW SFC model Jackson and Victor find, via a combination of policies including increasing renewables in the energy mixture and the electrification of road, rail, and transport, that deep (80%) reductions are obtainable with even faster reductions possible with the model reaching zero emissions by 2040 in the steady-state sustainable prosperity scenario. Another significant ecological macroeconomics study published in 2020 utilizing the EUROGREEN model obtains emissions reductions of up to 80% in their degrowth scenario (D'Alessandro et al., 2020). Importantly, neither LOWGROW SFC or the EUROGREEN model (two large-scale SFC ecological macroeconomics models) assume the deployment of negative emissions technologies while both find (to different extents) the greatest emissions reductions occur in scenarios with the least economic growth (quasi steady-state and degrowth).

To understand more fully the role that degrowth or steady-state trajectories it is necessary to understand also how their macroeconomic dynamics function. As such the key questions of this paper are as follows. First, using the updated 500 $GtCO_2$ carbon budget from the recent AR6 climate change report (see IPCC, 2021), are 1.5 degree pathways still obtainable assuming no negative emissions technologies? Second, can such pathways be obtained with historically observed rates of energy intensity declines? Third, what are the dynamics (magnitudes and pathways) of investment in renewables to generate such pathways? And fourth, how might such investment be financed, and what are the implications of degrowth on such financing?

To explore these questions a novel IAM is constructed to study the energy transition, in a stylized manner, under a carbon budget constraint; the main model components are shown in Figure 1. This links together the stock-flow consistent approach to macroeconomics, with a dynamic three sector input–output model. This stock-flow consistent input–output integrated assessment model (SFCIO-IAM) is designed to capture both the transition of the energy system from predominantly fossil-fuel based to one built on renewables as well as the electrification of end use. The model's energy and production parameters are calibrated according to a life-cycle energy return on investment (EROI) approach capturing both the energetic impacts of depletion of fossil fuels and the electrical storage costs associated with high-penetration variable renewables. The model is coupled with the BEAM carbon cycle model (see Glotter et al., 2013) and a two-layer energy balance model (see Geoffroy et al., 2013) to compute warming trajectories as well as obtain climate damages. Finally, though not a traditional concern in most economic modelling, the equations of the SFCIO-IAM model are dimensionally homogenous; that is, financial and macroeconomic components are integrated with energy and physical climate components in a consistent fashion.

The contributions of this paper are therefore two-fold. First, it serves as an addition to the small but growing literature on merging stock-flow consistent macroeconomic modelling with input–output analysis. This relatively new approach can be found in the works of Berg et al. (2015); Jackson (2018); and King (2020). More broadly, the incorporation of the stock-flow consistent approach, as elaborated most fully in Godley and Lavoie (2007), with ecological macroeconomics is found in a growing body of literature (see e.g. Allen et al., 2019; Barrett, 2018; Bovari et al., 2018; Jackson & Victor, 2015, 2020). Second, it examines the joint dynamics of energy transitions combined with alternative economic pathways (steady-state and degrowth) in order to evaluate the role these may play in emissions reductions and how they may act to reduce the requirement for negative emissions that generally characterize 1.5 and 2°C pathways.

The outline of the remainder of the paper is as follows. In the following subsection, 1.5 degree pathways and electrification are discussed in greater detail. In Section 2 the principal results for

[i]The relationship between growth rates and intensity declines is given in greater detail in Appendix A.

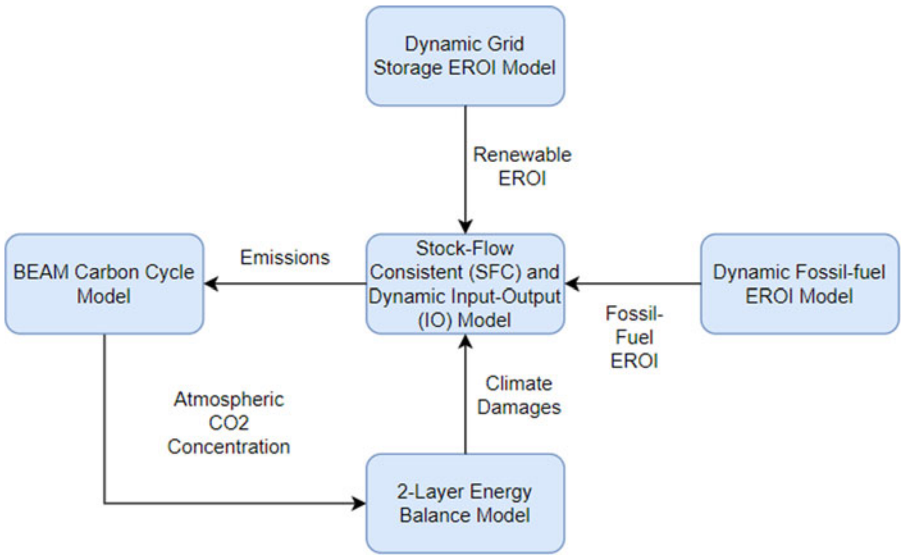

Fig. 1. Overview of key SFCIO-IAM model components.

the base case and 1.5 degree consistent pathways are presented using a combination of scenario and sensitivity analysis. The third section provides discussion of the key results, their relation to both the broader literature, and a brief analysis of the emergent feasibility problems arising from the simulations. Finally, the fourth section provides core mathematical structure of the SFCIO-IAM model.

1.1 1.5 degree pathways

A principal feature of the literature concerning 1.5°C pathways (and emissions pathways in general) is that there is no singular set of assumptions that are necessary to meet the required emissions reductions (Clarke et al., 2014). Of the 90 1.5°C consistent pathways obtained from the set of scenarios examined in the special report, 9 kept warming to below 1.5°C over the 21st century, 44 exhibited low transitory overshoot of the 1.5°C target before return to 1.5 or below (overshoot of less than 0.1°C), and the remaining 37 exhibited higher overshoot (in the range of 0.1–0.4°C) (Rogelj et al., 2018a). A large proportion of scenarios defined by low and high overshoot employs some magnitude of CDR. Five broad classifications for scenarios, covering a variety of assumptions about the future have been introduced called the shared socio-economic pathways (SSPs) (Kriegler et al., 2012; O'Neill et al., 2014, 2017). It was found in a recent study of six global IAMs (see Rogelj et al., 2018b) that 1.5°C consistent pathways could be found for each model assuming SSP1 characteristics and four of the six participating models could generate 1.5°C trajectories for the SSP2 scenario (Rogelj et al., 2018a).[ii] Four 1.5°C pathways are presented in IPCC (2018) representing the low energy demand scenarios (see Grubler et al., 2018), SSP1, SSP2, and SSP5 respectively. With the exception of the low energy demand scenario, increasing quantities of bioenergy with carbon capture and storage (BECCS) are assumed to make the pathways possible. The deployment of CDR on large scale has a number of possible biophysical impacts ranging from possibly very large land surface requirements, water usage, and modifications of albedo. For a more complete discussion of the various impacts of CDR technologies see Smith et al. (2016).

The assumptions of the magnitude of CDR assumed in 1.5°C range from 100 to 1000 $GtCO_2$ depending on the nature of the pathway and the degree of overshoot that occurs (Rogelj et al., 2018a). Major concerns have been raised about the potential for negative emissions technologies to scale sufficiently (Anderson & Peters, 2016; de Coninck & Benson, 2014; Smith et al., 2016). That significant issues may prevent the actual realization of CDR on the scale assumed in IAM analysis has led Anderson and Peters to note 'Negative-emission technologies are not an insurance policy, but rather an unjust and high-stakes gamble'. This use of an unproven suite of technologies as models assumptions making possible the 1.5 and 2°C represents a key weakness in the endeavour. Should BECCS not be possible to scale to required magnitudes than the 'success of many of the modelled pathways' disappears. Betting on the success of negative emissions technology poses a considerable risk and alternatives without large-scale negative emissions technology have been proposed; for example, Grubler et al. (2018) develop a low energy demand scenario devised to meet the 1.5°C target without assuming large-scale negative emissions. This scenario has the novel feature of assuming 40% decline in final global energy demand by 2050, while still assuming continued economic growth (based on SSP2 assumptions).

Estimates of the magnitude of investment necessary for 1.5°C pathways are 'relatively sparse' with the majority of such studies focused on 2°C pathways (Rogelj et al., 2018a). Rough analysis suggests that investments in low carbon energy consistent with 1.5°C pathways must increase by a factor of 4–10 by 2050 over 2015 (Rogelj et al., 2018a). A recent multi-model IAM ensemble study finds:

> As a share of global GDP, the total energy investments projected by the models do not rise significantly from today in any of the scenarios, hovering just over 2% (model range: 1.5–2.6%) in 'CPol' and 'NDC' and growing to 2.5% (1.6–3.4%) and 2.8% (1.8–3.9%) in the '2C' and '1.5C' pathways, respectively (McCollum et al., 2018).

For their 1.5°C consistent scenario this implies total energy sector investments on the order of 3.3 trillion US dollars per annum with a significant fraction corresponding to non-biomass renewables (0.73 trillion), electricity transmission, distribution,

[ii]Similar quantitative modelling was also undertaken in the context of a 2°C target in (Riahi et al., 2017).

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and storage (0.75 trillion), and demand side energy efficiency (0.82 trillion) which substantially outweighs the combined extraction, conversion, and electricity (without CCS) investments in fossil fuels of 0.522 trillion (McCollum et al., 2018). An intriguing statement appears in McCollum et al. (2018) concerning how these investments are financed in the IAMs making up the ensemble. The authors note that, 'From where exactly these investment dollars are summoned is outside the scope of our study, and for the most part beyond the capability of the models employed'. A key feature of the model to be developed in this paper is its use of a macroeconomic modelling approach specifically designed to include financial system considerations.

The large-scale electrification of end use coupled with the decarbonization of electricity production are two critical components of emissions reductions and present both significant real-world engineering challenges as well as considerable modelling challenges.[iii] Past large-scale studies (see e.g. Jacobson et al., 2015) have indicated the feasibility of 100% renewable systems. Furthermore the more recent Princeton Net-Zero America report (see Larson et al., 2020) concludes net-zero emissions could be achieved with an aggressive electrification of end use using 100% renewable energy by 2050. Another major study, undertaken by Bogdanov et al. (2021), indicates both the technical and economic feasibility of a 100% renewable energy pathway that is consistent with the 1.5 degree target (without assuming CDR). In this paper we will take a simpler stylized approach by adapting the EROI and energy stored on invested (ESOI) approach suggested in Barnhart et al. (2013) to relate the magnitude of electrical energy storage with the penetration of variable renewables via a storage fraction term $\phi(t)$ which denotes the fraction of variable renewable energy produced that must be stored over a given period of time, curtailed, or used for some other purpose.[iv] This storage fraction will be used to obtain energy costs associated with storage.

As the proportion of variable renewables in the overall electricity generation mixture increases the storage fraction of renewable energy produced may also increase. In practice it is more complicated than this, sufficiently large geographical spread of solar and wind turbines reduces variability arising from local cloud cover and local wind patterns (NREL, 2013). Furthermore, there is evidence that at 'low' penetrations, renewables do not necessarily need additional storage (Denholm et al., 2010). This is corroborated in Solomon et al. (2017) where the storage capacity whose results indicate that storage capacity becomes a factor only after some minimum threshold variable renewable penetration increasing linearly up until approximately 80% and levelling off afterwards. This linear growth in storage capacity requirements is also found in a National Renewable Energy Laboratory (NREL) study (Kroposki, 2017) though with no decline for variable renewable energy (VRE) penetration above 80% as in the previously mentioned study.

Estimates for the required storage fraction for very high penetrations of VRE range somewhat dramatically. A storage fraction of 10% is calculated for 90% VRE penetration for the continental United States in National Renewable Energy Laboratory (2012). A lower range of storage fraction values is found in Blanco and Faaij (2018) who find values ranging from 1.5 to 6% for VRE penetration ranging from 95 to 100% while an even lower value of less than 0.25% is reported in Blakers et al. (2017) for Australia; alternatively a range from 10 to 20% is reported in Breyer et al. (2017).

There are therefore two sources of uncertainty to consider in the SFCIO-IAM model concerning the modelling of energy storage. The first is how the storage requirements grow with increasing VRE penetration, and the second is how large the storage fraction becomes at very high VRE penetration levels. Concerning the first, we will model the magnitude of the storage fraction as a linearly increasing function of VRE penetration which is in rough approximation with the above discussion; concerning the second, we will deploy sensitivity analysis over a range of possible high-penetration VRE storage values as the 'true' value is not determinable within the bounds of this study.[v]

2. Base case scenario

The core of the SFCIO-IAM model (detailed in Section 4) is a dynamic input–output model formed around three production sectors: renewables, fossil fuels, and 'manufacturing', where the manufacturing sector represents an aggregation of all the non-energy producing sectors. To study the behaviour of the SFCIO-IAM model we will begin by exploring a base case scenario. Roughly this scenario corresponds to an economy that initially derives 10% of its energy needs from renewable sources and where 25% of its manufacturing capital is assumed to be electrified. It is assumed that the rate of replacement of non-electrified capital with electrified capital is simply the depreciation rate for manufacturing capital; that is, non-electrified capital is only replaced at the end of its natural life cycle. It is further assumed that rate of renewable investment as a share of GDP, calibrated to be very roughly in line with those observed globally, ranges from approximately 0.45 to 0.55%. Finally, the energy intensity of the manufacturing sector is assumed to decrease at 2.4% per annum which leads to average yearly declines of 1.5% of the energy intensity of GDP in the growth scenario in line with the EIA reference case (EIA, 2021).[vi]

From these base case assumptions three economic scenarios (degrowth, steady-state, and growth) are explored. These are generated by setting the growth rates of exogenous government expenditures to −2, 0, and 2% respectively.[vii] The speed of renewable capacity construction is governed by the partial adjustment

[iii]While it is beyond the scope of this paper to address, it is worth raising the question of how load profiles might change across different societal assumptions; that is, from growth societies to degrowth ones. How, if at all, might the peaks in daily power demand differ between a growth and degrowth society? Such questions are important as the costs associated with the electric power system are determined in part by the magnitude of peak demands (see Meier, 2006, Chapter 5).

[iv]ESOI is defined by Barnhart et al. as 'the ratio of electrical energy stored over the lifetime of a storage device to the amount of embodied electrical energy required to build the device' (Barnhart et al., 2013).

[v]See Appendix D for the storage fraction sensitivity.

[vi]Note well, the energy intensity of manufacturing is defined as the energy per unit of physical output and therefore declines in this intensity value imply increasing energy efficiency at the technological level. The energy intensity of GDP is defined as energy use per dollar of real GDP and its evolution overtime can reflect both changes in the magnitude of GDP and changes in energy use. Changes in energy use may be further broken down, for example, into those arising from increasing efficiency at the technological level and changes arising from the changing composition of activities making up GDP itself.

[vii]Using government expenditures in this manner is an example of closing the model with so-called non-capacity creating autonomous expenditures. In Appendix D, the same experiments are conducted again with the additional assumption that energy demands by households and government also grow at the rates of −2, 0, and 2%. Note well, imposing 'degrowth' on the model in this manner is an act of making necessary simplifications. Degrowth is obviously a far richer and more complex notion than the simple mechanics used here. Indeed, Kallis states that 'The goal of sustainable degrowth is not to degrow GDP. GDP will inevitably decline as an outcome of sustainable degrowth, but the question is whether this can happen in a socially and environmentally sustainable way' (Kallis, 2011). To be clear, we are examining the impacts of what might be considered a planned

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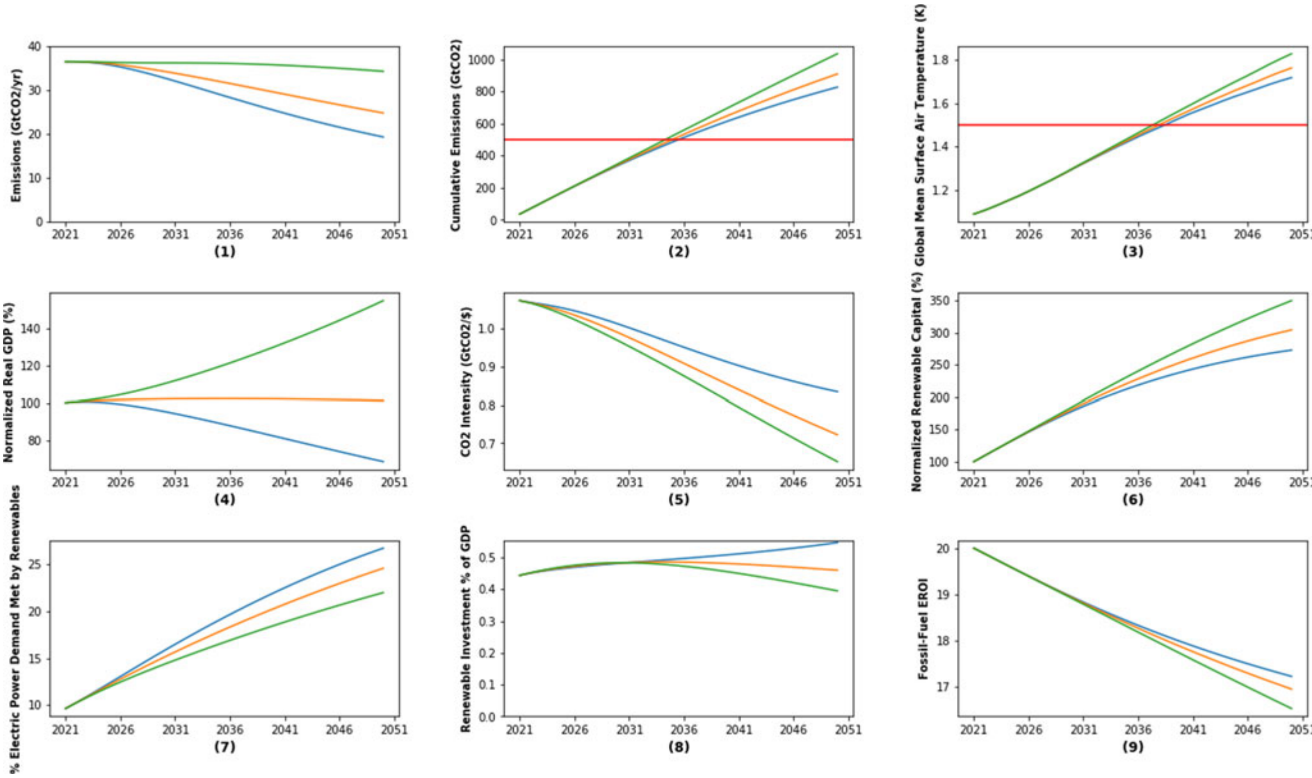

Fig. 2. Trajectories for select SFCIO-IAM model variables assuming $\Delta_1 = 0.01$ and $\sigma_{ne}^M = 0.03$. Growth scenario trajectories (green plots), steady-state trajectories (orange plots), degrowth scenario trajectories (blue plots). The solid red lines in panels (2) and (3) correspond to the 500 $GtCO_2$ carbon budget and 1.5°C warming threshold, respectively.

parameter (Δ_1) which determines the rate at which the new renewable capacity is constructed.[viii] The speed of electrification of end use is modelled as the rate that non-electrified manufacturing capital is depreciated and decommissioned, governed by the parameter σ_{ne}^M. Finally, and importantly, it is assumed that all new capital constructed by the manufacturing sector to replace the depreciated non-electrified capital is electrified in order to avoid the production of new fossil-fuel-dependent assets during the transition.

The impact of different assumptions about future economic growth on emissions is clearly visible from panel (1) of Figure 2. Emissions decline over time in both the degrowth and steady-state scenarios and remain largely stable in the growth scenario.[ix] However, as detailed in panel (2), cumulative emissions for all three scenarios exceed the 500 $GtCO_2$ budget before 2040 with global mean surface air temperatures, panel (3), exceeding the 1.5 degree warming threshold before 2040 in all three scenarios. That the budget is transgressed despite the relatively rapidly declining emissions in the degrowth scenario is indicative of the severity of the budget constraint. While the cumulative emissions and warming outcomes are broadly similar for each scenario, growth outcomes vary substantially (panel (4)). By design, the real-GDP (normalized to 100 to display percentage differences) grows, remains approximately constant, or declines in line with the exogenous scenario drivers. Panel (5) shows that CO_2 intensities, regardless of growth assumptions, decline over the model run with the highest reductions observed in the growth scenario. Panel (6) shows the growth of the renewable energy capital stock with the largest increase occurring in the growth scenario. Panel (7) shows that the percentage of electric power demand met by renewable generation increases over time for each growth assumption with the largest increase in the degrowth scenario. In panel (8) we see that the total fraction of real GDP dedicated to renewable investment is relatively stable over the model run across all three scenarios. Finally, panel (9) indicates a steady, approximately linear, decline in the EROI of fossil fuels for each growth assumption with the smallest decline occurring in the degrowth scenario. As fossil-fuel EROI is modelled as a function of the depletion of a stock of remaining fossil fuels (see Appendix C.4) the lower fossil-fuel usage in the degrowth scenario consequently implies the least depletion and lower EROI declines.

The key message of the above scenario is that no scenario (degrowth, steady-state, or growth) is capable of producing emissions reductions consistent with 1.5 degree warming for what might be termed business as usual renewable investment rates. While imposing degrowth or steady-state assumptions on the model does lead to declining emissions, as compared with the growth scenario, these declines are insufficient given the severity of the constraint posed by the relatively small remaining carbon budget (500 $GtCO_2$).

As noted in the Introduction the rate of which new renewable capacity is constructed, and the rate of electrification of end use is important for reducing emissions. In order to determine what assumptions for these parameters may lead to scenarios producing budget consistent emissions pathways a sensitivity analysis

degrowth or contraction of economic activity and acknowledge that this definition captures only one possible way of examining degrowth.

[viii]See Section 4 for a more thorough discussion of this parameter.

[ix]This stability out to 2050 is in rough agreement with the EIA (2021) reference case (EIA, 2021).

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is performed, the results of which are displayed in Figure 3. The model sensitiveness are obtained by running the model over ranges of single parameters (e.g. panel (4) displaying impact of manufacturing energy intensity declines) or over the joint space of two interacting parameters (e.g. the contour plot in panel (1)) and obtaining year 2050 cumulative emissions. All sensitivities, unless explicitly concerned with the growth rate of government expenditures, are performed assuming no economic growth (steady-state assumptions).[x]

Several salient features emerge from the sensitivity. First, from panel (1) of Figure 3 it is clear that the size of the renewable investment parameter must be substantially larger than assumed in the base case scenario. Notably, for an assumed 2% degrowth, the value of the renewable investment parameter must be 0.11, or an order of magnitude larger than that in the base case. Second, panel (2) indicates that for large values of the renewable investment rate parameter, substantial emissions reductions in line with the remaining carbon budget require larger rates of the depreciation and decommissioning rate of non-electrified manufacturing capital. Interestingly, panel (2) also indicates the phenomena of perverse electrification whereby rapid electrification without commensurate increases in renewable generating capacity may actually lead to larger cumulative emissions. Though not a large effect, panel (3) indicates that across a large variety of growth assumptions, for the base case magnitude of the renewable investment rate, cumulative emissions increase for an increasing rate of turnover of the non-electrified capital stock, again indicating perverse electrification. Finally, panel (4) indicates the critical role that energy efficiency plays in emissions reductions and its relationship with growth assumptions. All else equal, increasing energy efficiency in the model leads to lower cumulative emissions for all growth assumptions; however, the difference in year 2050 cumulative emissions between the three scenarios is smaller for larger assumed rates of manufacturing energy intensity decline.

It is useful to explore how the model results change via sensitivity analysis over key physical parameters. In the model we assume a 25-year life-cycle EROI of 40 for the abstract renewable capital which may be seen as both an over and underestimate of 'renewable EROI' depending on the specifics of the renewable technology investigated. While modelling renewables as a single-composite technology is certainly more tractable, it has the downside that the value of its EROI is ultimately somewhat ambiguous. As such it is necessary to perform a sensitivity over a large range of EROI assumptions. Figure 4 displays the sensitivity results for the steady-state scenario.

Panel (1) shows the cumulative emissions at year 2050 for various magnitudes of renewable EROI values, ranging from 7 to 100. All else equal, a higher assumed renewable EROI does lead to

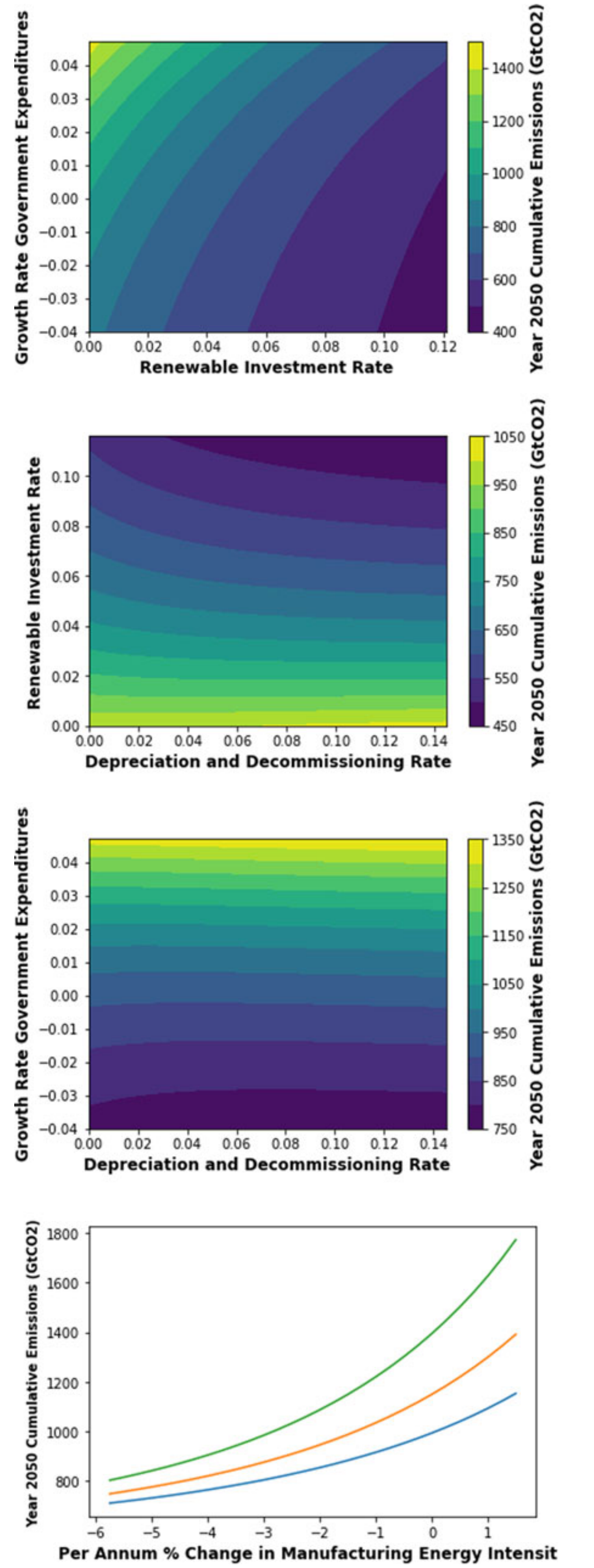

Fig. 3. Panels (1), (2) and (3) display contour plots of year 2050 cumulative emissions for various combinations of underlying model variables. Panel (4) displays a sensitivity analysis of year 2050 cumulative emissions over a range of per annum energy intensity declines. Growth scenario trajectories (green plots), steady-state trajectories (orange plots), degrowth scenario trajectories (blue plots).

[x]The ranges for the parameters were selected as follows. The range in the renewable investment parameter [0, 0.12] covers the entire range of stable model outcomes and corresponds to renewable investment rate shares of GDP ranging from those observed presently to 6% which is far larger than observed. The range of government expenditures which drive growth at approximately the same rates cover the spectrum from very rapid degrowth (−4%) to growth rates up to 5% which are larger than the highest observed global growth rate since 1975 (see World Bank, 2021). The range for depreciation and decommissioning (from 0 to 15%) is chosen to cover a wide range of possible rates. As the manufacturing capital stock is a model aggregate without good correspondence to real capital stocks the range is not based on historical data. This issue is mitigated by choosing a rather large range of possible values. Finally, the range of annual manufacturing sector energy intensity declines was chosen to approximately centre the −1.5% used in the IEA reference scenario and include both very high rates of decline and also include (unlikely) positive values to show the impact of increasing energy intensities.

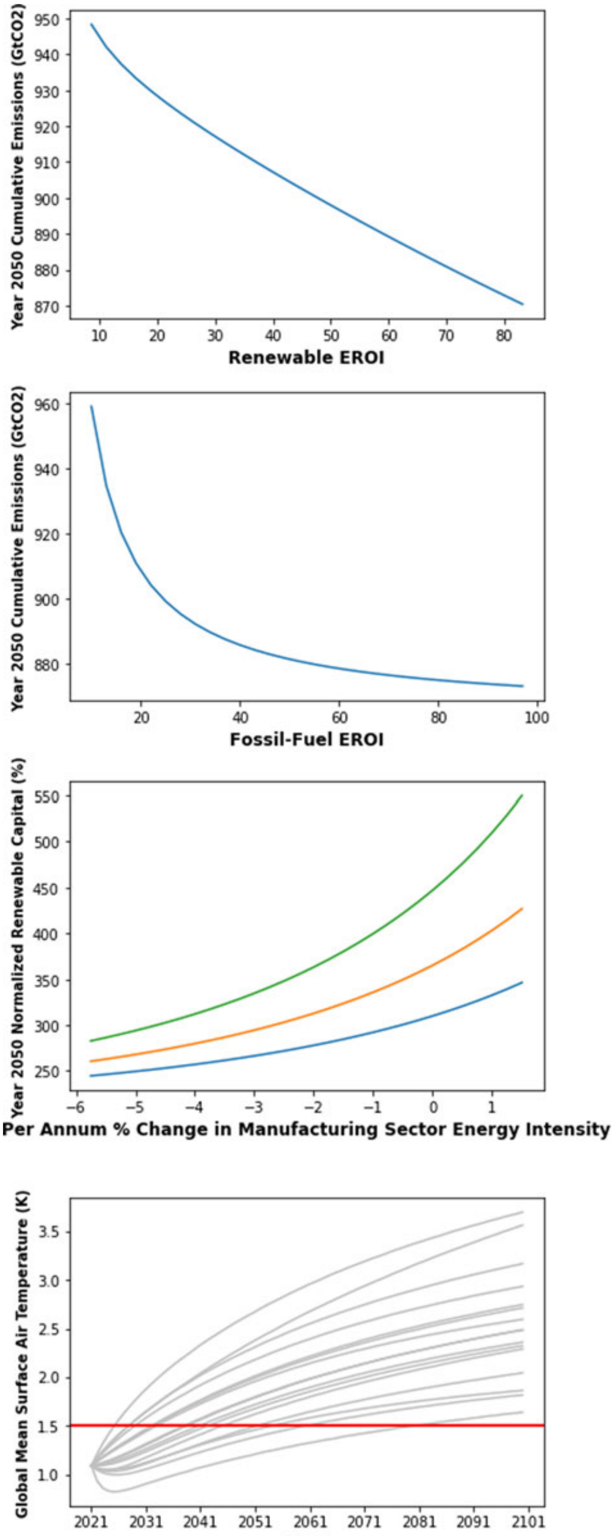

Fig. 4. Panels (1) and (2) display a sensitivity of year 2050 cumulative emissions over a range of assumed values for the renewable and fossil-fuel EROIs. Panel (3) displays the year 2050 renewable capital stock for each of the growth assumptions across a range of energy intensity assumptions. Panel (4) (grey plots) displays the global average surface temperature trajectories for each of model representative parametrizations of the underlying CMIP5 climate models. Growth scenario trajectories (green plots), steady-state trajectories (orange plots), degrowth scenario trajectories (blue plots).

lower cumulative emissions with a roughly negative linear relationship for EROI.[xi] Panel (2) displays the impact on year 2050 emissions for a range of values of fossil-fuel EROI; notably, year 2050 emissions begin to increase rapidly for EROI values lower than approximately 10.[xii] Panel (3) displays the percentage difference between the 2021 renewable capital stock and that in 2050 for the three growth assumptions. Notably, even assuming modest renewable investments, the magnitude of the renewable energy capital stock is significantly larger in the growth scenario as compared to the degrowth scenario across all assumptions of energy intensity declines. Finally, in panel (4) the impact of various assumptions concerning the values of the underlying climate parameters is shown on global temperature increases. Using data representing the CMIP5 climate models (see Geoffroy et al, 2013), it is clear that substantial variation exists across a variety of climate system assumptions. However, critically, even for models with the lowest assumed climate sensitivities, global average surface temperatures exceed the 1.5 degree threshold and continue to rise. Put differently, even assuming the most generous response from the climate system to anthropogenic emissions, warming cannot be kept under 1.5 degrees under base case assumptions about renewable investment magnitudes.

2.1 1.5 degree consistent degrowth pathway

In this section we explore a transition scenario designed so that the emissions trajectory in the degrowth scenario is ultimately 1.5°C consistent. The parameters necessary to just obtain a 1.5 degree consistent emissions pathway in the degrowth scenario can be determined, approximately, from the sensitivity analysis in Figure 3. The following scenarios assume that the renewable investment rate parameter $\Delta_1 = 0.105$ and $\sigma^M_{ne} = 0.05$. Results for key variables are displayed in Figure 5.

In this fast transition scenario, emissions decline rapidly in all three scenarios (panel (1)), with cumulative emissions (panel (2)) remaining below the 500 $GtCO_2$ budget for the degrowth scenario while transgressing the budget in approximately year 2045 in the growth scenario and year 2050 for the steady-state scenario. Consequently, global mean surface temperatures do not exceed 1.5 degrees in the degrowth scenario by 2050 (panel (3)). Unlike the base case scenario, there is a period of transient economic growth (panel (4)) in both the steady-state and degrowth scenarios associated with the very rapid energy transition being imposed on the model. Panel (6) shows that renewable capital is significantly larger in year 2050 for all three scenarios, and panel (7) indicates that in the degrowth and steady state scenarios, the percentage of electric power demand met by renewable sources is approaching unity.

The key assumption driving these results is the immense upfront investment in renewables assumed in all three scenarios. As shown in panel (8), the renewable investment fraction of real

[xi]Note well, as renewable EROI is calculated as the ratio of life-cycle energy output to a one time energy cost of construction, changes to the EROI reflect differing assumptions about the power output per unit of renewable capacity. A higher EROI renewable therefore has a greater assumed power output which acts to speed the transition leading to lower year 2050 emissions. See Appendix C for further details.

[xii]Note well, while the term EROI is used for both renewables and fossil fuels in Figure 4, they are not inherently comparable. The renewable EROI denotes the ratio of energy produced over 25 years of operation divided by the energy cost of construction of the unit of renewable capacity. The fossil-fuel EROI is the instantaneous ratio of power output to power invested which captures the direct energy costs of fossil-fuel energy production. See Appendix C for a more complete discussion.

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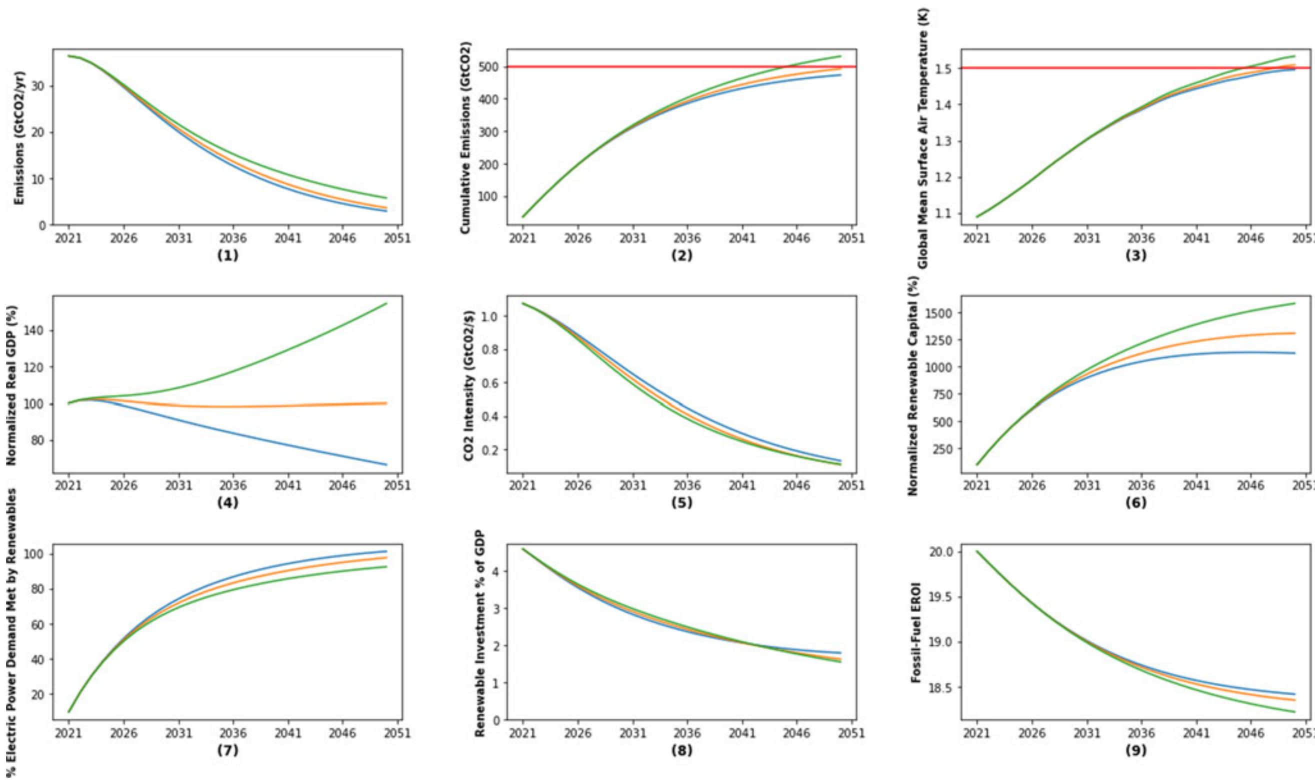

Fig. 5. Trajectories for select SFCIO-IAM model variables assuming $\Delta_1 = 0.105$ and $\sigma_{ne}^{M} = 0.05$. Growth scenario trajectories (green plots), steady-state trajectories (orange plots), degrowth scenario trajectories (blue plots). The solid red lines in panels (2) and (3) correspond to the 500 $GtCO_2$ carbon budget and 1.5°C warming threshold, respectively.

GDP begins at approximately 5% (an order of magnitude larger than that in the base case) and declines slowly over the model run to just over 2%, which is four times that witnessed in the base case scenario. While the renewable fraction of GDP dedicated to renewable investment is similar across all three scenarios, the real magnitude of investments are substantially different given the differences in real-GDP pathways shown in panel (4). That broadly similar climate objectives are realized (emissions and cumulative emissions) across all three scenarios is due to this real difference in investment flows. By year 2051, cumulative renewable investment (in real terms) is approximately 34% larger in the growth scenario as compared with the degrowth scenario which implies that the trajectory of real investments necessary to meet the 1.5 degree target in the degrowth scenario is unambiguously smaller than that in the growth scenario. As discussed further in the modelling section, the SFCIO-IAM model attempts to build new renewable capital rapidly and immediately without assuming a period of slowly ramping up investments which accounts for the high and declining trajectories in panel (8).[xiii]

As noted in the base case, assumptions concerning changes in energy efficiencies and the underlying climate model have large impacts on the model outcomes. Repeating the sensitivity experiments from the base case indicates similar results for the 1.5 degree consistent scenario. Panel (1) of Figure 6 indicates that for higher rates of manufacturing energy intensity decline the cumulative emissions across all three scenarios become comparable. Importantly, the model shows that for rates of intensity decline higher than approximately 3.5%, all scenarios are capable of reducing emissions in line with the 1.5 degree carbon budget. However, should progress in energy efficiency slow, and consequently energy intensity declines decrease, this result disappears. Indeed, for energy intensity declines less than 1% per annum, both the steady-state and growth scenarios are no longer budget consistent. This result is shown, across a wider range of renewable investment rates in the contour plot in panel (4). Finally, panel (3) indicates a key difference arising from the growth assumptions in that the size of the renewable energy system must be significantly larger in the growth scenario as compared to the degrowth scenario; especially so for intensity decline rates lower than 2%. While not modelled explicitly in this paper, this difference might imply substantial differences in the materials requirements of the energy transition.

Given the steady-state scenario is almost consistent with the 1.5 degree carbon budget which gives a 50% chance of remaining within 1.5 degrees of warming, the results of panel (3) in Figure 6 are not surprising. Running the model for parametrizations underlying each of the CMIP5 climate models shows that about half of the pathways remain below 1.5 degrees warming while half exceed the value by year 2100.

Given the emissions reductions results of the above scenario are dependent on both an unprecedented rate of renewable build-out and electrification of end use, it is necessary to explore in greater detail the impacts on the production sectors as well as on households and governments. Figure 7 displays the trajectories for the net worth, loans, and capital stocks for each of the three

[xiii]This is both a feature of partial adjustment accelerator nature of the investment equations and a requirement given the severe constraint posed by the remaining carbon budget.

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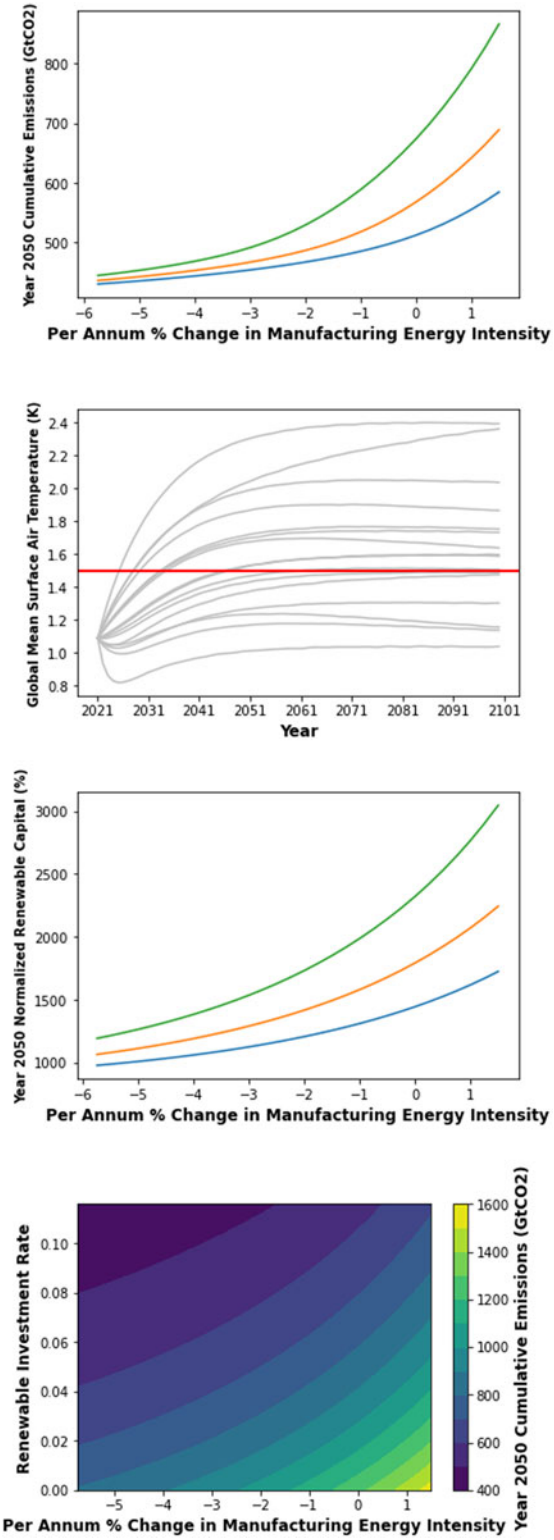

Fig. 6. Panels (1) and (3) display a sensitivity analysis of year 2050 cumulative emissions and year 2050 renewable capital stock sizes over a range of per annum energy intensity declines. Panel (2) (grey plots) displays the global average surface temperature trajectories for each of model representative parametrizations of the underlying CMIP5 climate models. Panel (4) displays the contour plot for year 2050 cumulative emissions over a range of energy intensity declines and renewable investment rates. Growth scenario trajectories (green plots), steady-state trajectories (orange plots), degrowth scenario trajectories (blue plots). The solid red lines in panels (2) and (3) correspond to the 500 $GtCO_2$ carbon budget and 1.5°C warming threshold, respectively.

productive sectors across degrowth, steady-state, and growth assumptions. Across all three growth assumptions the large increase in renewable sector capital (panel (7)) is financed by a transient surge in loans provided by private banks (panel (4)). Ultimately (panel(1)), the net worth of the renewable sector increases significantly over the model run. In contrast to this, the net worth (panel(2)) and capital stock (panel (8)) of the fossil fuel sectors decline steadily. Panel (5) indicates that the fossil-fuel sector eventually begins selling off its capital stock (this selling off is represented as negative loans) given the lack of demand for its output.[xiv]

In the SFCIO-IAM model wages paid to households are assumed to simply be the difference between revenues and costs from the three production sectors. As such, the simultaneous increase in loans (and hence loan interest and principal payments) by the renewable and manufacturing sectors accompanied by the decline in fossil-fuel sector revenue act to suppress wages; this is shown in panels (1) and (2) of Figure 8. While wages eventually recover in the growth scenario, they stay permanently lower in the steady-state scenario and decrease continuously in the degrowth scenario.

The role of private banks in the SFCIO-IAM model is simple with banks acting as passive lenders to the production sectors. It is assumed banks have zero-net worth for simplicity. By the mechanics of the scenarios, the demand for loans by the renewable and manufacturing sectors increases substantially, requiring private banks to borrow from the government in order to keep the required reserves on hand which is shown in panel (3). While this pattern holds initially, it reverses in the steady-state and degrowth scenarios whereby banks, eventually end up as purchasers of interest-earning government treasuries after the initial spike in the demand for loans levels off.

3. Discussion

In their 2020 paper, Keyßer and Lenzen discuss three principle transition risks that degrowth scenarios may act to mitigate; these are the reliance on high energy–GDP decoupling, the speed of renewable transitions, and the deployment of negative emissions (Keyßer & Lenzen, 2021). As displayed in the model sensitivities undertaken in this paper, lower rates of economic growth unequivocally reduce the requirement for energy intensity declines. Concerning the author's second point on the speed of transition risk, degrowth scenarios in the SFCIO-IAM model lead to the smallest requirement (in physical capacity terms) of new renewable capacity.[xv] However, given the plausible value of the storage fraction for high-penetration renewables used in this paper, substantial declines in renewable EROI at the grid level are not observed in the model outputs. Furthermore, the impact of higher energy storage requirements on cumulative emissions is not large relative to the impact of other model variables (see Appendix D, Figure 14). Perhaps most critically, the model is still able to produce

[xiv]That the fossil-fuel sector is able to sell off is excess capital stock as the demand for its output declines means the model does not allow for asset stranding. The case where the fossil-fuel sector witnesses negative net-worth as its assets become increasingly valueless is interesting but beyond the scope or purpose of this model. Asset stranding in the context of SFCIO models is explored in the doctoral dissertation of Andrew Jackson (see Jackson, 2018).

[xv]When additionally allowing for energy demands to follow the growth assumptions (shown in Appendix D), the degrowth scenario is also characterized by the lowest proportion of GDP dedicated to renewable investment.

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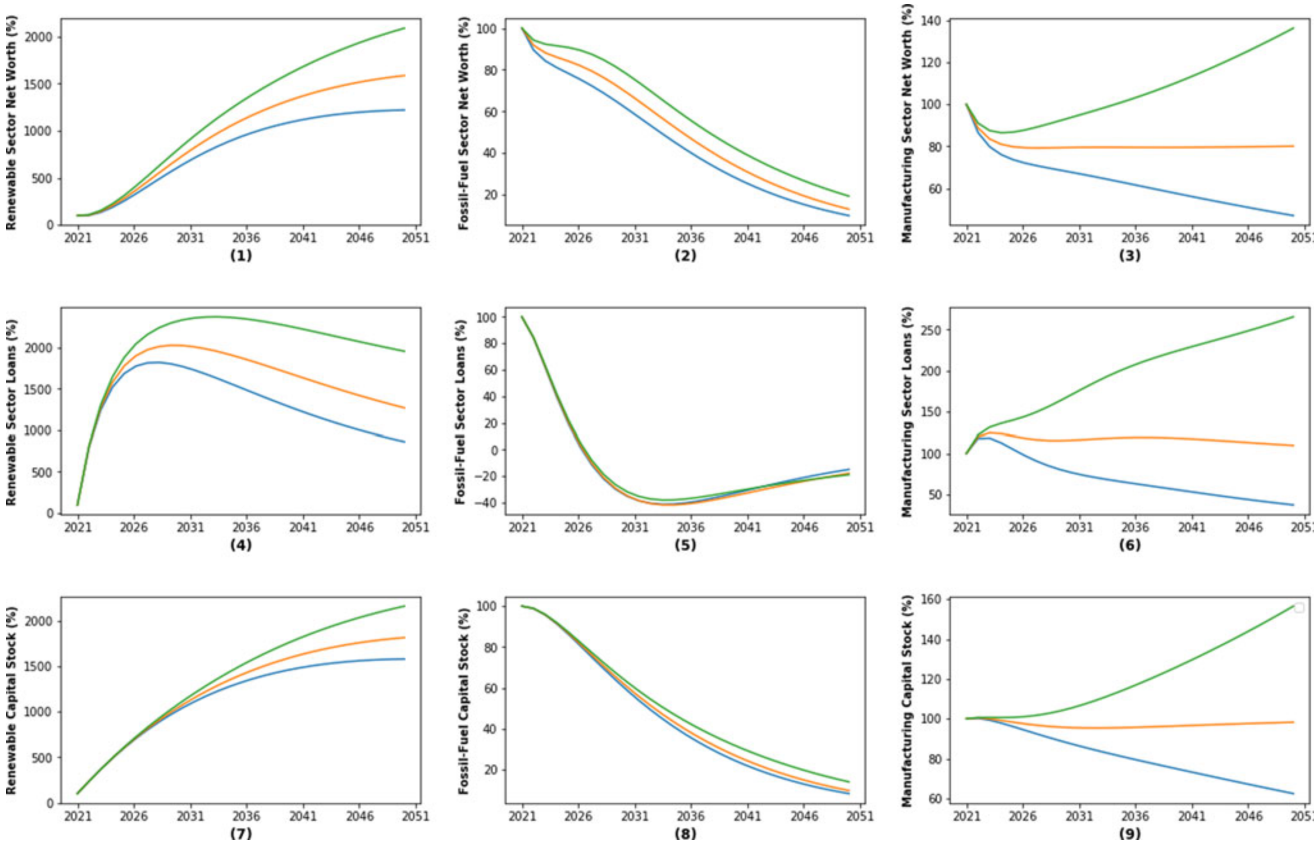

Fig. 7. Trajectories for SFCIO-IAM sectoral model variables assuming $\Delta_1 = 0.105$ and $\sigma_{ne}^{M} = 0.05$. Growth scenario trajectories (green plots), steady-state trajectories (orange plots), degrowth scenario trajectories (blue plots).

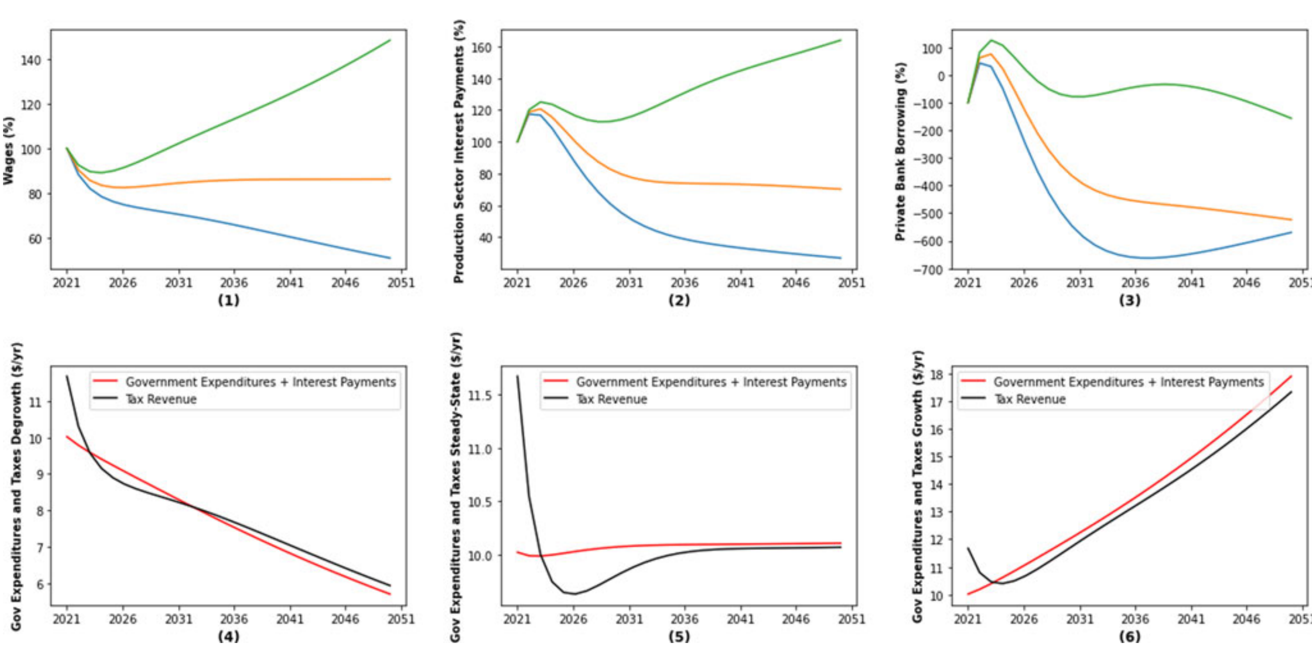

Fig. 8. Trajectories for SFCIO-IAM sectoral macroeconomic variables assuming $\Delta_1 = 0.105$ and $\sigma_{ne}^{M} = 0.05$. Growth scenario trajectories (green plots), steady-state trajectories (orange plots), degrowth scenario trajectories (blue plots).

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budget consistent pathways that are not reliant on negative emissions technologies even for the smaller budget of 500 $GtCO_2$ as compared to the 580 $GtCO_2$ budget used by Keyßer and Lenzen.

Several emergent results from the modelling are worth noting here. First, when assuming base case energy intensity declines, the cumulative emissions outcomes for degrowth and steady-state scenarios are very close in magnitude when also assuming very fast rates of renewable energy construction. As such, the additional difficulties imposed in the degrowth scenario do not seem warranted compared to the steady-state scenario when renewable investment rates are very high.[xvi] However, as shown in panel (1) of Figure 6, the degrowth scenario can generate budget consistent emissions pathways for even relatively modest energy intensity declines. Furthermore, panel (3) of the same figure shows that the size of the renewable build out is also significantly smaller in the degrowth scenario for slower energy intensity declines. Finally, as shown in panel (4) of Figure 4, both degrowth and steady-state scenarios initially experience a period of very modest economic growth arising from the increased energy transition activities. This challenges the construction of any simple degrowth narrative based on gross domestic product as the pathway of GDP might necessarily reflect the surge in energy transition activities.

The nature of the degrowth scenarios above indicate a set of non-trivial 'feasibility' risks that must be addressed here. While recent work has indicated that needs might in principle be met with lower energy and materials consumptions (see e.g. Millward-Hopkins et al., 2020; O'Neill et al., 2018; Vogel et al., 2021) the risks associated with the degrowth scenarios above are significant and not obvious from a policy perspective. First, the modelling shows that the degrowth scenario, like the steady-state and growth scenarios, is reliant on a huge quantity of upfront financing to be available to the renewable sector which ultimately faces a long term, degrowth induced, decline in the demand for its output. This raises the simple question of why such investments would ever be made available? While investment magnitudes (in the absolute sense) are lower in the degrowth scenarios above, the model relies on private banks to extend all loans demanded. While it is beyond the scope of this paper to answer, it is worth questioning where investment funds might come from in degrowth scenarios, what policies ensure their steady and long-term availability, and what mechanisms might ensure the smooth operation of financial systems. In this paper the possibility of financial system instability or collapse is not modelled and smooth operation is assumed regardless of the scenario. Further research concerning both financial system stability and alternate forms of financing the transition (e.g. direct government funding) is necessary.

The second major class of risks might be understood as socio-political ones arising from the steady decline in consumption and government expenditures, and resulting impacts on key metrics such as unemployment. Should such declines imply real and substantial declines in material well-being (this is not a foregone conclusion) then the task of generating intentional long-term degrowth seems politically extremely challenging. Furthermore, without changes to the nature and expectations of work, the degrowth scenarios above imply increasing unemployment. Should labour productivities (output per worker) and the magnitude of the labour force itself be growing (or even remain constant), the degrowth assumption would necessitate fewer workers to produce the declining output. While again beyond the scope of the relatively simple model in this paper, policies such as work time reductions and wealth redistribution might play a significant role (explored in Jackson and Victor, 2020). Ultimately, degrowth pathways imply a radical and profound transformation of society (Büchs & Koch, 2019; Keyßer & Lenzen, 2021), which make judging their feasibility by current standards potentially moot given the possibility that norms and aspirations of societies may change significantly.

While the speculative nature of degrowth modelling and its attendant assumptions may raise criticisms, it is necessary to note that many common assumptions (continual decoupling of energy from GDP or mass deployment of NETs) are in any sense similarly speculative or unproven. Ultimately, political feasibility may be rather more fluid as climate change impacts worsen. As put succinctly by Jewell and Cherp (p. 6), '…if a certain solution or its analogues have not occurred in the past this does not necessarily mean that it is not politically feasible in the future' (Jewell & Cherp, 2020). While degrowth and steady-state scenarios do not follow current conventional wisdom, recent evidence suggests that sustainability goals cannot be met without far-reaching lifestyle changes (Wiedmann et al., 2020) which calls into question the physical feasibility of scenarios currently deemed most politically feasible. As such, the significant socio-political transition risks associated with degrowth examined in the literature and, for example, the specific financial system risks emerging from the modelling in this paper, must be viewed as challenges requiring further study rather than insurmountable barriers.

Ultimately, the results obtained in this paper must be understood in the context of deep uncertainty. As shown in sensitivities, the EROI of renewables, the magnitude of energy intensity declines, and the underlying climate system characteristics play significant roles in the possibility of generating 1.5 degree consistent pathways. Should the climate sensitivity be larger than the average assumed, or should increases in energy efficiency slow sufficiently, then the transition becomes exceedingly difficult under all assumptions of future economic growth. While cumulative emissions are smallest in degrowth scenarios across all assumptions, the degrowth scenario is particularly important when energy intensities decline more slowly or not at all over the model run. Conversely, higher than baseline energy intensity declines reduces the impact of degrowth on emissions reductions as compared to steady-state and growth scenarios.

The key result of this paper may be stated as follows. Under the assumption of mean climate conditions and assuming no deployment of negative emissions technologies, renewable energy investment as a share of GDP must peak at approximately 5% per annum in order to generate a 1.5°C consistent emissions pathway under assumptions of sustained economic degrowth assuming no deployment of negative emissions technologies and continual improvements in energy efficiency. This is unequivocally higher than the upper bound estimates of 3.9% as obtained in McCollum et al. (2018) indicating the significant challenge associated in reducing emissions with no assumption of negative emissions technologies.

That the transition is physically possible within the model is essentially the minimum criteria to meet as evidence that 1.5°C pathways are still attainable. The SFCIO-IAM model does not in any manner indicate the larger social issues that may arise, for example, in the context of long-term degrowth with a substantial redirection of economic activity towards renewable capacity

[xvi]This point requires some caution in its interpretation. As the SFCIO-IAM model only examines emissions, it has nothing to say whatsoever about other physical problems (materials usage, biodiversity decline, etc.) that may be ameliorated by degrowth.

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construction and electrification activities. While it was shown that degrowth and steady-state trajectories may play an important role in keeping emissions within the 1.5 degree carbon budget (especially for when energy intensity declines are slower than baseline) without invoking speculative negative emissions technologies, the scenarios themselves rely on speculative large-scale societal transformations. While this study points to the utility of steady-state and degrowth scenarios, further work is necessary in understanding the nature of societal transformations that underpin these scenarios and how they might come about.

4. The model

In this section we lay out the principal model equations. The balance sheet, transactions flow, and input–output matrices that make up the core accounting structure of the SFCIO-IAM model are found in Appendix B while all initial values and parameters values are found in Appendix E. First, total household consumption $C(t)$ is given by the following consumption function:

$$C(t) = \alpha_1 YD(t) + \alpha_2 V(t) \tag{1}$$

where $YD(t)$ is the disposable income and $V(t)$ is the wealth where $V(t) = M(t) + H^h(t)$; the sum of interest-earning deposits $M(t)$, and cash $H^h(t)$ held by households with $\alpha_1, \alpha_2 \in (0, 1)$. Households' consumption is divided between expenditures on energy sector goods and manufacturing sector goods. Denoting these as $C^E(t)$ and $C^M(t)$ respectively, we have:

$$C(t) = C^E(t) + C^M(t) \tag{2}$$

Energy consumption expenditures by the household sector are left exogenous so as to be a freely adjustable model component in scenario and sensitivity analysis. As such, the expression for $C^E(t)$ is simply:

$$C^E(t) = f_E(t) \tag{3}$$

where $f_E(t)$ is some time-dependent function.[xvii] Households purchase energy from both the fossil-fuel sector $C^{FF}(t)$ and the renewable sector $C^R(t)$ with total energy expenditures given by the following sum:

$$C^E(t) = C^R(t) + C^{FF}(t) \tag{4}$$

Government expenditures follow a similar logic with total government expenditure comprised of energy and manufacturing expenditures:

$$G(t) = G^E(t) + G^M(t) \tag{5}$$

Like consumption, government expenditure on energy can be separated into energy purchases from the renewable and fossil-fuel sectors:

$$G^E(t) = G^R(t) + G^{FF}(t) \tag{6}$$

Household disposable income is made up of the difference between wages $WB(t)$ received from the industrial sectors, interest on deposits held at banks $r_d \cdot M(t)$ where r_d is the interest rate on deposits and $M(t)$ is the magnitude of the deposits, and taxes paid to the government $T(t)$:

$$YD(t) = WB(t) + r \cdot M(t) - T(t) \tag{7}$$

The total wages received by households is simply the sum of the wages paid to households from each sector so that $WB(t) = WB^R(t) + WB^{FF}(t) + WB^M(t)$. For simplicity it is assumed that firms simply distribute all profits to households via wages and therefore do not have retained earnings. This sum can be found directly from the transactions flow matrix by summing the second, fourth, and sixth columns of the transactions flow matrix in Appendix B and solving for $WB(t)$; this results in:

$$\begin{aligned} WB(t) = C(t) + G(t) + I(t) - (r + Zr)L^R(t) \\ - (r + Zf)L^{FF}(t) - (r + Zm)L^M(t) \end{aligned} \tag{8}$$

Here, the Z_i represents the fraction of total outstanding loans $L^i(t)$ held by each sector that must be paid back at time t.[xviii] From the transactions flow table each of the individual sectors also engage in interindustry transactions which net to zero across all three sectors by necessity. As such, the wages earned by households are simply the difference between the sales of each sector and their costs. Profits are assumed to be distributed wholly back to the household sector and are therefore not represented explicitly.

Households in the model can hold two types of assets: cash $H(t)$ and interest-earning deposits at banks $M(t)$. It is assumed that households desire to hold a certain proportion (λ_0) of their wealth $V(t)$ as deposits and the remainder as cash (following the logic of Godley & Lavoie, 2007, Chapter 4). This proportion is however modulated by interest rates and disposable income. Households will desire to hold relatively more of their wealth as interest-earning deposits at banks given a higher rate of return r_d, and conversely, hold relatively less of their wealth as deposits at banks as disposable income increases leading to a greater demand for a cash to undertake transactions. As such $M(t)$ can be determined as:

$$\frac{M(t)}{V(t)} = \lambda_0 + \lambda_1 \cdot r - \lambda_2 \cdot \left(\frac{YD(t)}{V(t)}\right) \tag{9}$$

Finally, the taxes levied by the government on households are simply a proportion θ of wages:

$$T(t) = \theta WB(t) \tag{10}$$

4.1 Input–output model

The interrelationships between the three sectors are captured in the following matrix of input–output technical coefficients where the order of sectors on the rows of columns is renewable, fossil fuels, and manufacturing respectively. We assume, for tractability, that the renewable sector does not utilize any inputs from the other sectors to produce its output while the fossil-fuel sector (which we model as vertically integrated) uses some of its own output to power its operation.[xix] Finally, the manufacturing sector

[xvii]For example, we may assume household energy expenditures increase linearly or at some constant percentage indicating increasing energy consumption over time.

[xviii]Note well that $i = R, FF, M$.

[xix]Note well, while the renewable sector is assumed to produce its output (electric power) without requiring intermediate goods, it most certainly does require goods from the manufacturing sector in the form of capital equipment. These requirements are captured in the investment portion of final demand.

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sources both electric power and fuels from the renewable and fossil-fuel sectors (third column):

$$A(t) = \begin{pmatrix} 0 & 0 & \dfrac{P_R\phi_g(t)k_e^R(t)}{X^M(t)} \\ 0 & \dfrac{S(0)}{EROI(0)\cdot S(t)} & \dfrac{P_{FF}[CF[\tau_E k_e^M(t) - \phi_g(t)k_e^R(t)] + \tau_{FF}k_{ne}^M(t)]}{X^M(t)} \\ 0 & 0 & a_{33} \end{pmatrix}$$

Here, the P_i terms denote the prices for each sectors output, while the $X^i(t)$ denotes the total sectoral outputs where $(i = R, FF, M)$.[xx] $S(t)$ denotes the magnitude of the stock of fossil fuels at time t, while $EROI(0)$ denotes the initial period value for the EROI of fossil-fuel production. Here $a_{22} = \frac{S(0)}{EROI(0)\cdot S(t)}$ is designed to capture the effects of declining fossil-fuel EROI with extraction induced declines in $S(t)$. Chiefly, this formulation implies that as EROI declines, more fossil-fuel sector-derived energy is required to produce any given quantity of fossil-fuel sector output. The differential-equation governing the evolution of the stock of fossil-fuels is given as:

$$\frac{dS}{dt} = \frac{-X^{FF}(t)}{P_{FF}} \tag{12}$$

which states that the stock of fossil-fuels declines with extraction necessary to meet total demand per unit time.

Physical capital in the model is separated into five classifications. Renewable capital is separated, for accounting reasons, into that capital $k_e^R(t)$ necessary to meet intermediate demand arising from the manufacturing sector, and final demand from households and government $k_f^R(t)$. The manufacturing sector operates electrified and non-electrified manufacturing capital $k_e^M(t)$ and $k_{ne}^M(t)$ respectively. Finally, $k^{FF}(t)$ denotes the quantity of fossil-fuel sector capital. All capital types are assumed to be measured in a common physical unit of machines [m]. The terms τ_E and τ_{FF} denote the power requirements per unit of electrified and non-electrified manufacturing capital, respectively. The term ϕ_g is a 'grid-corrected' term denoting the power output per unit of renewable capacity. Finally, CF is the conversion factor between fossil-fuel energy and the electricity produced via combustion.

The matrix $A(t)$ captures two key physical dynamics. First, examining the a_{23} element, we see that the demand for fossil-fuel sector output in the form of fuels to power non-electrified capital is given as $P_{FF}\tau_{FF}k_{ne}^M(t)$. As non-electrified capital is replaced by electrified capital, $k_{ne}^M(t)$ will decline towards zero indicating a decline in the demand for fuels from the fossil-fuel sector. Second, as the magnitude of renewable sector capital $k_e^R(t)$ increases, the term $\tau_E k_e^M(t) - \phi_g(t)k_e^R(t)$ decreases indicating a decrease in fossil-fuel sector-derived electricity to power electrified manufacturing capital. The a_{23} term therefore captures both of the necessary energy transition components; the electrification of the manufacturing sector and the displacement of fossil-fuel sector-derived electricity by that produced by the renewable sector. When both of these phenomena occur in the model the a_{23} technical coefficient will be equivalent to zero.

From the matrix $I - A(t)$ we may calculate the Leontief coefficients necessary to obtain expressions for total sectoral outputs. First the determinant $D(t)$ is given as:

$$D(t) = \frac{1}{(1 - (S(0)/(EROI(0)\cdot S(t))))(1 - a_{33})} \tag{13}$$

which can be used to obtain the following nine Leontief coefficients:

$$L_{11}(t) = 1, \quad L_{12}(t) = 0, \quad L_{13}(t) = \frac{P_r\phi_g(t)k_e^R(t)}{(1 - a_{33})\cdot X^M(t)} \tag{14}$$

$$\begin{aligned} L_{21}(t) &= 0, \quad L_{22}(t) = \frac{1}{1 - S(0)/(EROI(0)\cdot S(t))}, \\ L_{23}(t) &= \frac{P_{FF}(t)[CF[T_E k_e^M(t) - \phi_g(t)k_e^R(t)] + \tau_{FF}k_{ne}^m(t)]}{(1 - S(0)/(EROI(0)\cdot S(t)))(1 - a_{33})X^m(t)} \end{aligned} \tag{15}$$

$$L_{31} = 0, \quad L_{32}(t) = 0, \quad L_{33} = \frac{1}{1 - a_{33}} \tag{16}$$

Assuming, that renewable generation displaces fossil-fuel generation when new renewable capacity comes online (therefore making fossil fuel the provider of the residual power requirements) we may write the following expressions for each sector's final demand:

$$C^R(t) + G^R(t) = P_R\phi_g(t)k_f^R(t) \tag{17}$$

The final demand for fossil fuels is therefore given below as the difference between the energy demands $C^e(t) + G^e(t)$ and that provided by the renewable sector:

$$C^{FF}(t) + G^{FF}(t) = C^e(t) + G^e(t) - P_r\phi_g(t)k_f^R(t) \tag{18}$$

The final demand faced by the manufacturing sector is given the sum of consumption, government, and investment expenditures:

$$I(t) + C^M(t) + G^M(t) = Y(t) - C^E(t) - G^E(t) \tag{19}$$

Finally, combining the Leontief coefficients with these expressions for sectoral final demands we can write the following expressions for the total sectoral outputs:

$$X^R(t) = L_{13}(t)Pr\phi_g(t)k_f^R(t) + L_{23}[Y(t) - C^E(t) - G^E(t)] \tag{20}$$

$$\begin{aligned} X^{FF}(t) = {} & L_{22}(t)[C^E(t) + G^E(t) - Pr\phi_g(t)k_f^R(t)] \\ & + L_{23}(t)\cdot[Y(t) - C^E(t) - G^E(t)] \end{aligned} \tag{21}$$

$$X^M(t) = L_{33}[Y(t) - C^E(t) - G^E(t)] \tag{22}$$

Each sector (renewable, fossil fuel, and manufacturing) operates a stock of capital whose output, in physical terms, is

[xx] Here R denotes the renewable sector, FF the fossil-fuel sector, and M the manufacturing sector.

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proportional to the magnitude of the capital stock. Therefore, the physical output (supply) of each sector per unit time is give as:

$$s_R(t) = \phi_g(t)(k_e^R(t) + k_{ne}^R(t)) \tag{23}$$

$$s_{FF}(t) = \phi_{FF}(k^{FF}(t)) \tag{24}$$

$$s_M(t) = \phi_M(k_e^M(t) + k_{ne}^M(t)) \tag{25}$$

The ϕ terms appearing in the above three supply equations have a simple and natural interpretation as parameters denoting the output per unit of capital. For example, $\phi_{g(t)}$ is the power output per unit of renewable capital.

The above equations state the physical supply of each sector's output per unit time. To be physically sensible, this supply in physical terms must match the demand in physical terms. Using the sectoral final demands as measures of the total physical demand for each sector's production, we define prices as the mechanisms that equate physical supply and demand at any given moment:

$$P_R(t) = \frac{X^R(t)}{\phi_R k^R(t)} \tag{26}$$

$$P_{FF}(t) = \frac{X^{FF}(t)}{\phi_{FF} k^{FF}(t)} \tag{27}$$

$$P_M(t) = \frac{X^M(t)}{\phi_M(t) k^M(t)} \tag{28}$$

Having defined the physical supply and demands, and the price mechanism in the model, we may turn to investment. Assuming capital is valued at replacement cost and since capital is the output of the manufacturing sector in this model, the replacement cost is simply the price of manufacturing sector output $P_M(t)$ multiplied by the magnitude of capacity being replaced. The non-renewable sectors invest in new capital in order to close the gap between the demand for its output at some target normal price and its current capacity. The renewable sector invests in new capital until it meets all power requirements in the model:

$$i_e^R(t) = \Delta_1(\mu_1 \phi_g^{-1} \tau_E k_e^M(t) - k_e^R(t)) \tag{29}$$

The bracketed term in Eq. (29) is the difference between the capacity of renewable generation necessary to power electrified manufacturing capital $\tau_E k_e^M$ and the currently built capacity k_e^R. The parameter Δ_1 is the rate at which the gap closes while μ_1 denotes the percentage of excess capacity that the renewable sector aims to construct. The remaining investment equations follow the same logic:

$$i_f^R(t) = \delta_1 \mu_1 \phi_g^{-1} P_R^{-1}[C^E(t) + G^E(t)] - \Delta_1 k^R(f) \tag{30}$$

$$i^F(t) = \Delta_2 \mu_2 \phi_{FF}^{-1}(t) P_{F0}^{-1} X^{FF}(t) - \Delta_2 k^{FF}(t) \tag{31}$$

$$i_e^M(t) = \Delta_3 \mu_3 \phi_M^{-1}(t) P_{M0}^{-1} X^M(t) - \Delta_3 k_e^M(t) + \Delta_3 k_{ne}^M(t)) \tag{32}$$

Finally, aggregate investment in monetary terms is determined by valuing the above investment terms at the price of manufacturing sector output. Therefore, we have that:

$$\begin{aligned} I(t) &= I^R(t) + I^{FF}(t) + I^M(t) \\ &= P_M(t)[i_e^R(t) + i_f^R(t)] + P_M(t) i^{FF}(t) + P_M(t) i_e^M(t) \end{aligned} \tag{33}$$

Each sector finances their investment via loans received from private banks upon which they must make both interest payments and pay back the principal. The capital stocks of each sector grow with investment and decline with depreciation. Finally, each sector finances the purchase of new capital via loans taken from private banks. For example, the stock of physical capital held by the fossil fuel sector is determined by the differential equation:

$$\frac{dk^{FF}}{dt} = i^{FF}(t) - \sigma_{FF}(t) k^{FF}(t) \tag{34}$$

where $\sigma_{FF}(t)$ is an endogenous depreciation rate. The magnitude of the loans extended to the same sector is governed by:

$$\frac{dL^{FF}}{dt} = Pm(t) i_e^{FF}(t) - Z_{FF} L^{FF}(t) \tag{35}$$

where Z_{FF} denotes the fraction of the total outstanding loan repaid per unit time. The dynamics for all of the capital stocks and loans are shown in Table 1. Finally, we assume that the banking sector acts as passive lenders, extending loans to the three sectors as required to finance their capital investment.

4.2 Renewable power dynamics

Following the discussion in the Introduction, we denote the storage fraction $\phi(t)$ as a linearly increasing function of the ratio of total renewable electric power produced to that of total electric power consumed in the model where an increase in this ratio indicates that variable renewable generation provides a greater fraction of total electric power in the model. This ratio, $\psi(t)$ is denoted as follows:

$$\psi(t) = \frac{\phi_R(k_e^R(t) + k_f^R(t))}{\tau_E k_e^M(t) + (C^E(t) + G^E(t)) P_r^{-1}} \tag{36}$$

where ϕ_R is the power output per unit of renewable capacity before taking into account possible energy losses due to storage. Therefore, the numerator is the total electric power produced by the models stocks of renewable energy capital $k_e^R(t) + k_f^R(t)$ divided by the quantity of electric power consumed by the electrified manufacturing capital $\tau_E k_e^M(t)$ and the electric power demanded as part of household and government final demand $(C^E(t) + G^E(t)) P_r^{-1}$.

Now letting a and b determine the minimum and maximum values that $\phi(t)$ can obtain, the storage fraction is given as the following function of $\psi(t)$:

$$\phi(t) = a + b\psi(t) \tag{37}$$

Here a is the base level storage fraction that occurs at zero VRE penetration (we assume $a = 0$ in all modelling) and b is given as

Table 1. State variables and their associated differential equations

Variable name	Symbol	Differential equation
Renewable Intermediate Capital	$k_e^R(t)$	$\dot{k_e^R} = i_e^R(t) - \sigma_R(t)k_d^R(t)$
Renewable Final Capital	$k_f^R(t)$	$\dot{k_f^R} = i_f^R(t) - \sigma_R(t)k_f^R(t)$
Fossil-Fuel Capital	$k^{FF}(t)$	$\dot{k^{FF}} = i^{FF}(t) - \sigma_{FF}(t)k^{FF}(t)$
Electrified Manufacturing Capital	$k_e^M(t)$	$\dot{k_e^M} = i_e^M(t) - \sigma_M(t)k_e^M(t)$
Non-Electrified Manufacturing Capital	$k_{ne}^M(t)$	$\dot{k_{ne}^M} = -\sigma_M(t)k_{ne}^M(t)$
Renewable Loans	$L^R(t)$	$\dot{L^R} = Pm(t)[i_e^R(t) + i_f^R(t)] - Z_r L^R(t)$
Fossil-Fuel Loans	$L^{FF}(t)$	$\dot{L^{FF}} = Pm(t)i_e^{FF}(t) - Z_{FF}L^{FF}(t)$
Manufacturing Loans	$L^M(t)$	$\dot{L^M} = Pm(t)i^M(t) - Z_M L^M(t)$
Household Wealth	$V(t)$	$\dot{V} = WB(t) + rM(t) - C(t) - T(t)$
Stock of Fossil-Fuels	$S(t)$	$\dot{S} = -X^{FF}(t) \cdot P_{FF}^{-1}$
Mass of Atmospheric CO_2	$M_{at}(t)$	$\dot{M_{at}} = E(t) - k_a(M_{at}(t) - A(t) \cdot B(t)M_{up}(t))$
Mass of Upper-Ocean CO_2	$M_{up}(t)$	$\dot{M_{up}} = k_a(M_{at}(t) - A(t) \cdot B(t)M_{up}(t)) - k_d\left(M_{up}(t) - \frac{M_{lo}(t)}{\delta}\right)$
Mass of Lower-Ocean CO_2	$M_{lo}(t)$	$\dot{M_{lo}} = k_d\left(M_{up}(t) - \frac{M_{lo}(t)}{\delta}\right)$
Global-Average Surface Temperature	$T(t)$	$\mathcal{C}\dot{T} = \mathcal{F}(t) - \lambda T - \gamma(T(t) - T_0(t))$
Deep Ocean Temperature	$T_0(t)$	$\mathcal{C}_0\dot{T_0} = \gamma(T - T_0)$

the upper bound storage fraction minus a so that when VRE penetration is at 100%, $\psi(t) = 1$ and therefore $\phi(t)$ will be equivalent to its upper bound value.

The grid-corrected power output $\phi_g(t)$ is therefore given as a function of the EROI of the renewable technology, the storage fraction, and the ESOI of electrical energy storage. See Appendix C for a full derivation.

$$\phi_g(t) = \left(\frac{1 - \phi(t) + \eta\phi(t)}{1/EROI_R + \eta\phi(t)/ESOI_e}\right)\frac{\phi_R}{EROI_R} \tag{38}$$

4.3 Climate

In this section we introduce the (BEAM) carbon cycle model of Glotter et al. (2013) in order to link the emissions produced by economic activities to atmospheric concentrations while also capturing some key carbon-cycle processes. BEAM models a three-reservoir carbon-cycle system where M_{at}, M_{up}, and M_{lo} are the masses of inorganic carbon in the atmosphere, upper ocean, and lower ocean respectively. A set of three coupled non-linear differential equations governs the evolution of each the stocks of carbon which are presented as follows:

$$\frac{dM_{at}}{dt} = E(t) - k_a(M_{at} - A \cdot BM_{up}) \tag{39}$$

$$\frac{dM_{up}}{dt} = k_a(M_{at} - A \cdot BM_{up}) - k_d\left(M_{up} - \frac{M_{lo}}{\delta}\right) \tag{40}$$

$$\frac{dM_{lo}}{dt} = k_d\left(M_{up} - \frac{M_{lo}}{\delta}\right) \tag{41}$$

where $E(t)$ is an emissions term. Global average surface temperatures in the SFCIO-IAM model are obtained using the two-component energy balance model (2-EBM) described in Geoffroy et al. (2013). The equations that govern the evolution of the global mean surface air temperature T and the temperature of the deep ocean T_0 are given as:

$$\mathcal{C}\frac{dT}{dt} = \mathcal{F}(t) - \lambda T - \gamma(T - T_0) \tag{42}$$

$$\mathcal{C}_0\frac{dT_0}{dt} = \gamma(T - T_0) \tag{43}$$

where $\mathcal{F}(t)$ is a radiative forcing term given by:

$$\mathcal{F}(t) = \frac{\mathcal{F}_{2xCO_2}}{\ln(2)}\ln\left(\frac{M_{at}(t)}{[M_{at}^0}\right) \tag{44}$$

where M_{at}^0 is the reference period (pre-industrial) mass of atmospheric carbon. Finally, emissions $E(t)$ are given as:

$$E(t) = \frac{\zeta X^{FF}(t)}{P_{FF}(t)} \tag{45}$$

which states that emissions per unit time $E(t)$ are proportional to the total physical output of the fossil-fuels sector by a factor ζ.

Finally, we turn to the climate feedback which is included in the form of a damage function whose output losses are shared between declines in the productivity parameters of each sectors capital, and to enhanced depreciation of the capital stocks. We use the form, calibrated so that $D(t) = 0.5$ at $T = 6°C$, proposed by economist Martin Weitzman as follows (Weitzman, 2012):

$$D(t) = 1 - \frac{1}{(1 + \pi_1 T(t) + \pi_2 T(t)^2) + \pi_3 T(t)^{0.6754}} \tag{46}$$

The climate damage $D(t)$ is shared out between impacts on the ϕ_i productivity terms and the depreciation terms the σ_i ($i = R, F, M$) using an approach similar to that in Moyer et al. (2014).

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A fraction β of the $D(t)$ damages occurs as additional depreciation to the capital stock $k^i(t)$ leading to the following climate damage modified depreciation term:

$$\sigma_i(t) = \sigma_i + \beta D(t) \tag{47}$$

while the climate damage modified productivity terms are given as:

$$\phi_i(T) = \phi_i \cdot \left(\frac{1-\alpha}{1-\beta\alpha}\right) \tag{48}$$

The full model boils down to the following set of 15 coupled non-linear differential equations which are expressed in Table 1.

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