Appendix A The Algebra of Decoupling

While the previous section reviewed evidence for and against relative and absolute decoupling it did not indicate the magnitude of the necessary rates of intensity declines for emissions that are now required to meet emissions targets associated with, say, the 1.5 $°C$ 580 $GtCO_2$ Carbon budget from the 2018 IPCC special report. In this section we construct a simple mathematical model linking emissions, economic growth, emissions intensity, and a carbon budget and derive analytical expressions for both the time to budget exhaustion and the rate of intensity decline associated with emissions pathways consistent with a carbon budget of a given magnitude.

Let $Y(t)$ [\$ yr^{-1}], $E(t)$ [$GtCO_2$ yr^{-1}], and $I(t)$ [$GtCO_2$ \$$^{-1}$] denote the GDP, emissions, and emissions intensity at time t respectively and note that $E(t) = Y(t)I(t)$ by definition.[1] Denoting the rate of economic growth as g and the rate of intensity decline as r then we may write the following expressions for the evolution of $Y(t)$ and $I(t)$ as:

$$Y(t) = Y(0)e^{gt} \tag{1}$$

$$I(t) = I(0)e^{-rt} \tag{2}$$

where $Y(0)$ and $I(0)$ are initial year values for GDP and intensity. Emissions per year $E(t)$ is simply the product of $E(t) = Y(t)I(t)$ which after some simplification results:

$$E(t) = E(0) \cdot e^{(g-r)t} \tag{3}$$

Since the $B(t)$ is the remaining carbon budget the emissions $E(t)$ act to reduce the remaining budgets magnitude. The differential equation governing the evolution of the remaining carbon budget can be given as:

$$\frac{dB}{dt} = -E(0) \cdot e^{(g-r)t} \tag{4}$$

Letting $B(0)$ be the initial period remaining carbon budget (4) has the solution:

$$B(t) = -\frac{E(0)}{g-r} \cdot e^{(g-r)t} + B(0) + \frac{E(0)}{g-r} \tag{5}$$

From Equation (5) two useful quantities can be determined; the time of budget exhaustion t_e (the time for the remaining carbon budget to reach 0) and the rate of emissions intensity r_e such that the budget will just be exhausted over an infinite horizon.[2] The year of budget exhaustion is given by (6) and the rate of intensity decline r_e is given as by (7). The year of budget exhaustion t_e is found by setting $B(t) = 0$ in (5) and solving for t which leads to:

$$t_e = \frac{\ln\left[\left(\frac{g-r}{E(0)}\right) \cdot \left(B(0) + \frac{E(0)}{g-r}\right)\right]}{g-r} \tag{6}$$

[1] While it is conventional to write the units of the relevant quantities in square brackets as done above we shall not always do so in this document. Units will be discussed explicitly when necessary and otherwise left unstated when obvious.

[2] An emissions pathway that exhausts a budget over an infinite horizon is one whose cumulative emissions, summed from the initial period to time infinity, equals the budget.

Here (6) states that year from present that the carbon budget B will be exhausted given g, r, $B(0)$, and $E(0)$.

The second quantity of interest is the rate of intensity reductions that, for given values of the other variables, leads to the carbon budget being just exhausted over an infinite horizon. Defining the rate of intensity in this manner may seem somewhat abstract but its connotation is simple. Any value of intensity declines greater than r_e indicates that the carbon budget B will never be exhausted while any value less implies the budget will be exhausted in some finite time. To obtain this value, we make two assumptions; first that as t goes to infinity $B(t)$ goes to 0; and second that $g - r < 0$. The second condition simply states the obvious requirement that the rate of intensity declines is greater than the rate of growth. If this condition were not true, then decoupling would not occur at all. Therefore, we have:

$$\lim_{t\to\infty} B(t) = \lim_{t\to\infty}\left[-\frac{E(0)}{g-r}\cdot e^{(g-r)t}\right] + \lim_{t\to\infty}\left[B(0) + \frac{E(0)}{g-r}\right]$$

By assumption the left-hand side (LHS) is 0 and since $g - r < 0$ the first limit on the right hand side (RHS) also goes to 0. Therefore, we have:

$$0 = B(0) + \frac{E(0)}{g-r}$$

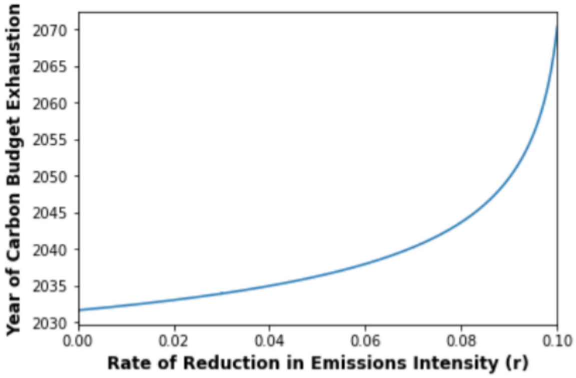
which we may rearrange as follows to obtain the value for r which we denote as r_e:

$$r_e = g + \frac{E(0)}{B(0)} \tag{7}$$

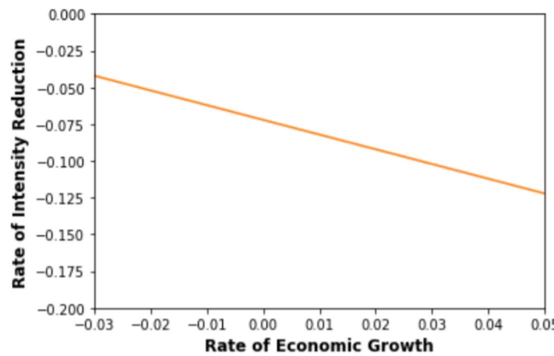
Equation (7) provides a simple relationship between the rate of intensity reductions and the rate of economic growth. For given initial year emissions and remaining carbon budget, the rate of intensity decline increases linearly with the rate of economic growth.

Panel (a) of Figure 1 plots t_e as a function of the rate of reduction in emissions intensity r and panel (b) plots r_e as a function of the rate of economic growth g for a range of values.[3] For example, reading from panel (a) of Figure 1, we see that for an assumed rate of economic growth of 3%, a remaining carbon budget of 520 $GtCO_2$, and yearly rate of intensity decline of 8%, the carbon budget is exhausted by approximately year 2042.

[3]Note well, (6) has no solution if the carbon budget is not exhausted (this occurs for sufficiently high values of r).



(a)



(b)

Figure 1: Panel (a):For an assumed initial budget of of $B(0) = 520$ $\mathrm{GtCO_2}$, a rate of economic growth of $g = 0.02$, and initial year emissions of $E(0) = 37.5$, the plot displays the year of budget exhaustion te (beginning at 2020) for a range of intensity declines r. **Panel (b)**: For an assumed initial budget of 520 $\mathrm{GtCO_2}$ the plot displays rates of intensity reduction (r_e) that correspond to the budget just being exhausted over an infinite time-horizon as a function of rate of economic growth (g).

From (7) we know that $g - r_e$ is simply equal to $-\frac{E(0)}{B(0)}$. Substituting this into the emissions trajectory equation 3, we have:

$$E(t) = E(0) \cdot e^{-\left(\frac{E(0)}{B(0)}\right)t}$$

which defines the emissions trajectory with constant decay rate that will lead to the carbon budget being exhausted over an infinite horizon. The emissions pathway and cumulative emissions pathway are plotted in the following figure.

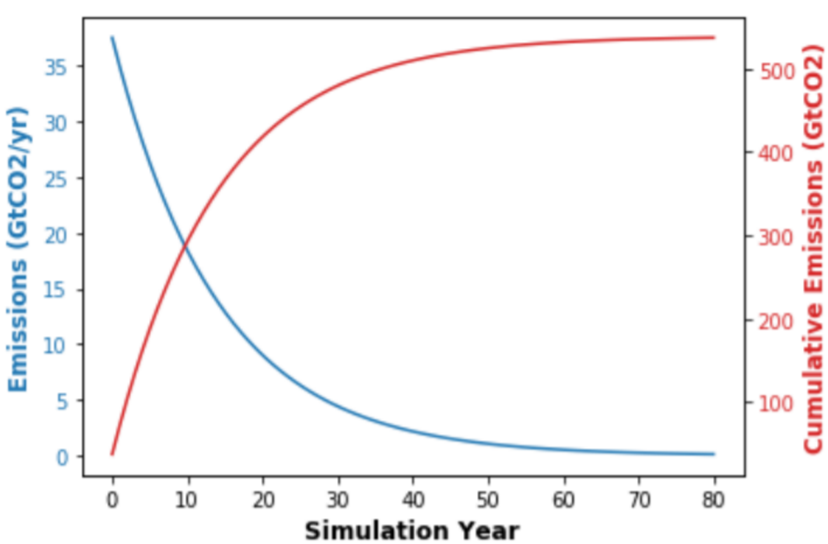


Figure 2: Emissions and cumulative emissions trajectories assuming a remaining carbon budget of $B(0) = 520$ $\mathrm{GtCO_2}$, a rate of economic growth $g = 0.02$, and initial year emissions $E(0) = 37.5$ $\mathrm{GtCO_2}$ yr^{-1}.

The salient feature of Figure 2 is that emissions must decline initially very rapidly. As this trajectory is constructed from approximate global level data it indicates an example of a global emissions pathway that assumes no overshoot and no carbon dioxide removal (CDR).[4] The shape of the trajectory is dependent on the magnitude of the remaining carbon budget assumed. Trajectories for several different carbon budgets are shown in the following figure.

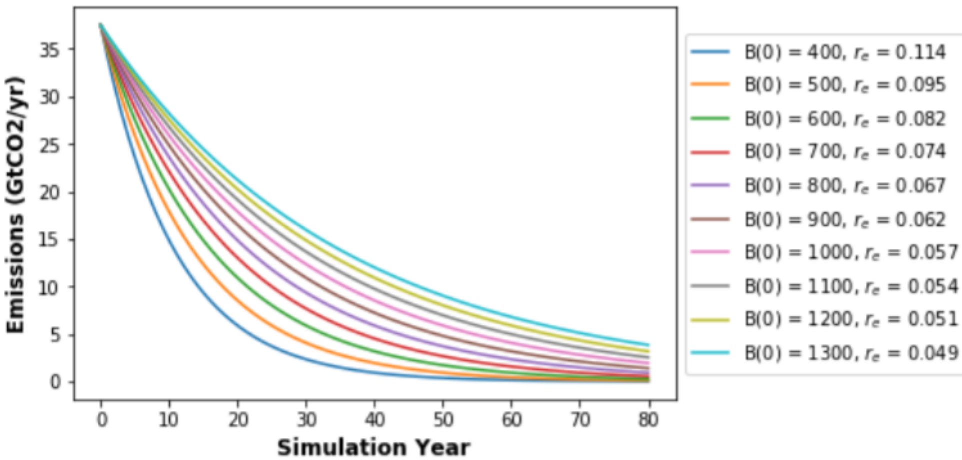


Figure 3: Emissions trajectories assuming a range (400 - 1300 $GtCO_2$) of values for the remaining carbon budget, a rate of economic growth $g = 0.02$, and initial year emissions $E(0) = 37.5$ $GtCO_2$ yr^{-1}. Legend values display the value of the assumed budget and the magnitude of the intensity declines r_e assumed for each pathway.

All else being equal, Figure 3 indicates (the obvious) that emissions pathways associated with larger remaining carbon budgets are characterized by slower reductions and longer times to reach zero emissions. Notably, even for relatively larger budgets the intensity reductions are still on the order of 5% per annum.[5,6] The rates of intensity decline necessary to just exhaust carbon budgets over this range varies from approximately 11% to 8%; that is, every year emissions intensity must decline by these amounts.

Appendix B Balance Sheet, Transactions Flow, and Input-Output Matrices

Figure 4 presents the balance sheet (stock) matrix which contains the main model variables and presents the accounting structure of the model. The entries of Figure 4 display the value in current prices of the assets and liabilities of each sector. The model economy is divided into six sectors: households, three production sectors (renewable sector, fossil-fuel sector, and the manufacturing sector), private banks, and the government. Each

[4]Similar pathways could just as easily be constructed at the individual country level by using country level emissions and an appropriate share of the remaining budget as the target.

[5]In 2018 the carbon budget for a 50% chance of staying within a 1.5 °C temperature rise was 580 GtCO2 and 1500 GtCO2 for a 50% chance of staying within a 2 °C temperature rise.

[6]Naturally these budgets have since declined given the emissions produced since the publication of the report.

of the production sectors operates capital equipment to produce its output and finances the construction and replacement of depreciated capital via loans obtained from the banking sector. The banking sector also holds and pays interest on household deposits.

$$
\begin{array}{l}
\\ \text{Money} \\ \text{Deposits} \\ \text{Fixed Capital} \\ \text{Loans} \\ \text{Advances} \\ \text{Net Worth}
\end{array}
\begin{array}{c}
\begin{array}{ccccccc}
\text{Households} & \text{Renewable Firms} & \text{Fossil-Fuel Firms} & \text{Manufacturing} & \text{Banks} & \text{Government} & \Sigma
\end{array} \\
\begin{pmatrix}
H^h(t) & 0 & 0 & 0 & 0 & -H(t) & 0 \\
M(t) & 0 & 0 & 0 & -M(t) & 0 & 0 \\
0 & K_e^R(t) + K_f^R(t) & K^F(t) & K_e^m(t) + K_{ne}^M(t) & 0 & 0 & K(t) \\
0 & -L^R(t) & -L_t^F & -L^M(t) & L(t) & 0 & 0 \\
0 & 0 & 0 & 0 & A(t) & -A(t) & 0 \\
-V(t)* & -V^R(t) & -V^{FF}(t) & -V^M(t) & 0 & -V^g(t) & K(t)
\end{pmatrix}
\end{array}
\tag{8}
$$

Figure 4: Balance Sheet Matrix

Figure 5 displays the transactions (flow) matrix where the rows record the transactions between each sector and the columns and the columns display the budget constraint of each sector.[7] For example, the first row of Figure 5 states that consumption expenditure by households at time t, denoted $C(t)$, is matched by the sales recorded in the first row for the renewable, fossil fuel, and manufacturing sectors, denoted $C^R(t)$, $C^F(t)$, and $C^M(t)$ respectively. The negative sign on the consumption term in for households indicates that this is an outflow of funds; correspondingly, the positive sign of the sales terms for each industrial sector indicates inflows of funds. The first column states that the change in the stocks of money and deposits held by households is equal to the difference between income (wages and interest on deposits) and consumption and taxation expenditures. Considering interindustry transactions Figure 5 shows by symmetry that the sum of payments made by, and received from, each industry to each other industry is zero and therefore the inclusion of multiple industries into the SFC framework is consistent with the requirement of zero row sums.

The interdependencies between the production sectors are shown in the following input-output table in Figure 6. The manufacturing sector is assumed to purchase inputs in the form of electricity and fuels from both the renewable and fossil fuel sectors as well as use some of its output as an input in its production process. The fossil fuel sector is assumed to purchase as inputs only its own output (energy in the form of fuel) to power its operations (extraction, refinement, transportation, etc.). Finally, the renewable sector does not purchase inputs from any of the sectors; rather, the renewable sector purchases capital equipment from the manufacturing sector which is recorded as investment and hence appears in final demand. The purchase of capital equipment for the other two sectors is also considered investment and hence counted in final demand.[8]

[7] Note well; the entries of the transaction (flow) table are flows variables and therefore have units of dollars per unit time. The entries in the balance sheet matrix are measured in dollars.

[8] Figures 5 and 6 present two different economic accounting schemes and in order to successfully merge stock-flow consistent modelling with input-output analysis it must be the case that both systems of accounting are coherent. For example, the sum of the first four entries of row one of Figure 6 equals $X^R(t)$ which must also equal the column sum. This implies that, after rearrangement, $WB^R(t) = z_{13} + C^r(t) + G^R(t) - (r + Z_R)L(t)$; for the model to work this must be consistent with the

	Households	Renewable Current	Renewable Capital	Fossil Current	Fossil Capital	Manufacturing Current	Manufacturing Capital	Bank Current	Bank Capital	Government	Σ
Consumption	$-C(t)$	$C^R(t)$	0	$C^{FF}(t)$	0	$C^M(t)$	0	0	0	0	0
Government	0	$G^R(t)$	0	$G^{FF}(t)$	0	$G^M(t)$	0	0	0	$-G(t)$	0
Wages	$WB(t)$	$-WB^R(t)$	0	$-WB^{FF}(t)$	0	$-WB^M(t)$	0	0	0	0	0
Taxes	$-T(t)$	0	0	0	0	0	0	0	0	$T(t)$	0
Investment	0	0	$-I^R(t)$	0	$-I^{FF}(t)$	$I(t)$	$-I^M(t)$	0	0	0	0
Inter-Industry	0	$z_{13}(t)$	0	$z_{23}(t)$	0	$-z_{13}(t) - z_{23}(t)$	0	0	0	0	0
Interest Deposits	$rM(t)$	0	0	0	0	0	0	$-rM(t)$	0	0	0
Interest Loans	0	$-rL^R(t)$	0	$-rL^{FF}(t)$	0	$-rL^M(t)$	0	$rL(t)$	0	0	0
Interest Advances	0	0	0	0	0	0	0	$-rA(t)$	0	$rA(t)$	0
Loan Repayment	0	$-Z_R L^R(t)$	$Z_R L^R(t)$	$-Z_{FF} L^{FF}(t)$	$Z_{FF} L^{FF}(t)$	$-Z_M L^M(t)$	$Z_M L^M(t)$	0	0	0	0
dMoney	$-\frac{dH^h}{dt}$	0	0	0	0	0	0	0	$\frac{dH}{dt}$	$\frac{dH}{dt}$	0
dDeposits	$-\frac{M}{dt}$	0	0	0	0	0	0	0	$\frac{dM}{dt}$	0	0
dLoans	0	0	$\frac{dL^R}{dt}$	0	$\frac{dL^{FF}}{dt}$	0	$\frac{dL^M}{dt}$	0	$-\frac{dL}{dt}$	0	0
dAdvances	0	0	0	0	0	0	0	0	$\frac{dA}{dt}$	$-\frac{dA}{dt}$	0
Σ	0	0	0	0	0	0	0	0	0	0	0

(9)

Figure 5: Transactions Flow Matrix

$$
\begin{array}{l}
\\
\text{Renewable} \\
\text{Fossil Fuel} \\
\text{Manufacturing} \\
\text{Wages} \\
\text{Loans} \\
\hline
\text{Total Outlays}
\end{array}
\begin{pmatrix}
\text{Renewable} & \text{Fossil Fuel} & \text{Manufacturing} & \text{Final Demand} & \text{Total Output} \\
0 & 0 & z_{13}(t) & C^R(t) + G^R(t) & X^R(t) \\
0 & z_{22}(t) & z_{23}(t) & C^{FF}(t) + G^{FF}(t) & X^{FF}(t) \\
0 & 0 & z_{13}(t) & C^m(t) + G^M(t) + I(t) & X^M(t) \\
WB^R(t) & WB^F(t) & WB^M(t) & 0 & WB(t) \\
(r+Z_r)L^R(t) & (r+Z_r)L^R(t) & (r+Z_r)L^R(t) & 0 & \sum_i (r+Z_i)L^i(t) \\
\hline
X^R(t) & X^F(t) & X^M(t) & C(t)+I(t)+G(t) & X(t)
\end{pmatrix} \tag{10}
$$

Figure 6: Extended Input-Output Matrix

accounting in the transactions matrix. Indeed, substituting the expressions for $WB^R(t)$ just found into the second column of the transactions flow matrix returns an identity as it must.

Appendix C Energy Return on Investment, Model Calibration, and Fossil-Fuel Depletion

Up until this point we have been relatively cavalier in the discussion of the role of energy in the model and have left aside, until now, any discussion of how to properly assign magnitudes to the rate parameters ϕ_e and ϕ_m or how, necessarily, they must relate to each other. Recall that these two parameters denote the power output per unit machine and machine output per unit machine per unit time respectively. This section will explore a method to calibrate SFCIO-IAM models using a life-cycle energy approach such that they are energetically "internally consistent".[9]

In the following sections we introduce two new power output parameters that are use to model simplified and idealized energy generation via renewable energy capacity and fossil-fuel capacity and show how these parameters can be related back to life-cycle energy measurements as determined in the physical analysis of these technologies.

C.1 Power Requirements

Consider the parameter ϕ_M from the model presented in the main body of the paper. This parameter denotes the output per unit time per unit capital and hence when multiplied by some physical quantity of capital equipment, gives the output of manufacturing goods per unit time. Due to the highly aggregated nature of the model attempting to estimate some empirical value for this parameter is not especially useful; and fortunately, not required. Rather, ϕ_M will take the form of an arbitrarily chosen parameter from which the other model parameters will be obtained.

For simplicity let us set $\phi_M = 1[\frac{m/yr}{m}]$ which states that new manufacturing sector output (which, we recall, can take the form of either capital goods or consumption goods) is produced at a rate of one unit per year. Now, using the concept of energy return on investment, the overall logic for proceeding is to calibrate the remaining production parameters. Since one unit of capital is produced per year then it is simplest to assume that the process consumes power at the rate of one unit per year as well. Therefore, let us set the power consumption parameters as follows $\tau_E = 1[\frac{kW}{m}]$ and $\tau_{FF} = 1[\frac{kW}{m}]$; that is both electrified and non-electrified manufacturing capital consumes power at a rate of one kilowatt.[10]. To be clear the previous assumptions imply that one unit of manufacturing capital operating over one year will produce one unit of output and consume one kilowatt-Year of energy. To see this formally consider the following. A single unit of manufacturing capital will, over some very small time interval of operation dt, produce $\phi_M \cdot 1 \cdot dt$ units of output [11] and likewise would consume $\tau_E \cdot 1 \cdot dt$ energy. Now if we "sum" up the output and energy consumption over an entire year we have:

$$\int_0^1 \phi_M \cdot 1 \cdot dt = 1[m]$$

[9]What is meant by internally consistent here will become clear in the following sections.

[10]To be clear this number is ultimately arbitrary; obviously different types of real world capital consumer power at different rates but it must be recalled that the number chosen here acts only as the anchor to determine the other parameters. One kilowatt of continuous power consumption over a year is equivalent to 31,447,600 kJ of energy

[11]The 1 in the equation is the unit of capital and therefore has units of machines [m].

and

$$\int_0^1 \tau_E \cdot 1 \cdot dt = 1[kWy]$$

These expressions simply formalize what was noted above. The output produced and the energy consumed by one unit of a given type of manufacturing capital operating continuously over one year are both normalized to one. A complexity arises however due to the model included both electrified and non-electrified manufacturing capital. Since the manufacturing sector output is modelled as a single universal good in the SFCIO-IAM model it follows that said good's production can be attributed to the operation of both types of capital over the production cycle. A further complexity arises in that the electrified manufactured capital is powered both directly by the electrical output of renewables and via electricity produced by the conversion of primary fossil-fuels into electricity which implies energy conversion losses.

Let $\beta = \frac{k_e^M}{k_e^M + K_{ne}^M}$ denote the ratio of electrified manufacturing capital to total manufacturing capital for initial year values of each capital type. Furthermore, let ϵ be the fraction of electric power used by the electrified manufacturing sector that comes from renewables. Finally, let CF denote the conversion factor from fossil fuels to electricity (generously assumed to be 2 in the model implying a conversion efficiency of 50%). The energy input per production of one unit of manufacturing sector output is therefore given as:

$$ID_e = (\epsilon \cdot CF \cdot \tau_E \cdot \beta + (1-\epsilon)\tau_E \beta + \tau_{FF}(1-\beta)) \int_0^1 1dt \tag{11}$$

Note well, we are able to pull the term out in front as we construct the β ratio from initial year values. Obviously as this ratio evolves, the calculation changes.

C.2 Power Output of Fossil-Fuel Capacity

In this section we present a method to obtain a magnitude for the power output per unit of fossil fuel capital σ_{FF} from estimated values of energy payback ratios. Following the definition in (White and Kulcinski, 2000), an energy payback ratio is the ratio of the total power output over the operational life of the generating technology divided by the energy costs associated with construction, gathering and processing fuels, operation and maintenance, and decommissioning. Notably, this fraction does not include the energy content of the fuels used to generate the electricity. Now, from the previous section, we know that the energy associated with construction is given as ID_e. We can, with some algebra, include the energy costs associated with gathering the fuel.

The direct energy requirements for fossil-fuel capacity is simply the energy we will define the direct or extraction energy costs. As noted in the previous main paper the technical coefficient a_{22} represents the ratio of the purchases of fossil-sector input by the fossil-fuel sector to its total output, or in physical terms, the physical quantity of fossil-fuel sector output used by the fossil-fuel sector to gather fuels and run its operations. This ratio is the energy cost to produce fossil-fuel derived energy. To obtain an energy return of one unit requires an energy cost of a_{22}, to obtain an energy return of arbitrary magnitude ER_F require an investment of $a_{22} \cdot ER_F$.

Now. we know that the parameter ϕ_{FF} has units of power produced per unit capital (or machine). The fossil-fuel capital in the model can be interpreted as a composite capital stock that extracts and refines fuels for energy usage. Like all other capital discussed so far in the model, a unit of fossil-fuel capital can only provide its service at some rate and therefore, over its life-cycle, will produce some energy return ER_F. Now, what must the magnitude of ϕ_{FF} be such that over the life cycle of one unit of capital, ER_F energy is produced accounting for depreciation at rate σ_{FF}? This calculation is simply:

$$\int_0^\infty \phi_F \cdot e^{-\sigma_F \cdot t} \cdot dt = ER_F$$

which leads to:

$$\phi_{FF} = ER_F \cdot \sigma_F \tag{12}$$

Examining the literature on life-cycle energy costs, the dominant proportion of energy inputs for fossil-fuel power generation is the fuel cycle (See Meier and Kulcinski, 2000 and (White and Kulcinski, 2000)). For example, from Meier and Kulcinski (Figure 7), the energy costs of construction and materials, operation, and decommissioning account for slightly over 5% of the life-cycle energy costs for electricity production via a gas turbine. The approximate 95% of the remaining input energy costs are associated with the fuel cycle.

We assume, for simplicity, that ID_e embodies the construction, operation, and maintenance costs. Using the 5% figure, we have that the fuel cycle portion of the energy inputs $a_{22} \cdot ER_F$ must be:

$$a_{22} ER_F = 19 \cdot ID_e$$

Now, using the sum of energy costs associated with construction and the provisioning of the life-cycle energy return ER_F we have that the energy payback ratio is:

$$EPR = \frac{ER_F}{ID_e + a_{22} ER_F} = \frac{ER_F}{20 * ID_e} \tag{13}$$

which is the ratio of life-cycle energy output divided by the SFCIO-IAM model's simplified construction and operation costs. Finally, if we "know" the value of EPR, we can solve for ϕ_{FF} as follows by rearranging and substituting and equation 12 into equation 13.

$$\phi_{FF} = 20 \cdot EPR \cdot ID_e \cdot \sigma_{FF} \tag{14}$$

Finally, if we assume a value of 5 for the EPR then the power output per unit of fossil-fuel capital is, for $ID_e = 1.025$ and $\sigma_{FF} = 0.03$:

$$\phi_{FF} = 3.075 \text{ [kW/m]}$$

Note well, the units of power are here (kilowatts) are important only in that they are the same as those used to measure the power requirements of manufacturing capital. Ultimately, the unit chosen for this purpose is not important, only the relative magnitude of power required to the power produced by the energy generation capital matters. As such we might have just as simply measured power in megawatts or gigawatts.

C.3 Power Output of Renewable Capacity

Calculating a value of ϕ_R using the above methodology is complicated by the problem of selecting a single life-cycle EROI to represent a heterogeneous suite of generation technologies (e.g., wind turbines, geothermal, large hydro, solar PV, etc.) possessing different life-cycles and EROIs. Furthermore, such a method might lead to price estimates per kilowatt hour delivered that are substantially different than observed, given the assumption that manufacturing sector output, which takes the form of several different capital types, is valued at price P_m. As such, we instead obtain a value of ϕ_R via relating the weighted average of capital costs per kilowatt hour of a suite of renewable generation technologies to the same capital costs for fossil-fuel capital. This method is necessarily imprecise and its outcome is heavily dependent on the underlying assumptions which is part of the justification for for the model sensitivities undertaken in the paper.

To facilitate the comparison of capital costs per kilowatt hour we use EIA data concerning the overnight costs of various generation technologies. We assume that the renewable technology in the model is a composite of off-shore wind, onshore wind, photovoltaic panels, hydro, and geothermal and that the proportion of each of these technologies in the overall mixture is roughly that found for year 2050 in the 100% renewable E+ RE+ scenario in the Net Zero America report (Larson et al, 2020). Finally, using these proportions, we form a weighted average of the total overnight costs for each of these technologies using data from the Energy Information Administration EIA 2021.

Generation Technology	**Total Overnight Cost ($/kW)**	**Proportion**
Onshore wind	1846	0.52
Offshore wind	5,453	0.115
Rooftop PV_2[a]		
Utility Scale PV (Storage)	1,612	0.35
Hydro[b]	2,769	0.018
Geothermal[b]	2,772	0.0016
Combined Cycle	1,082	
Industrial Combustion Engine	957	
Combustion turbine — aeroderivative	1,813	
Combustion turbine—industrial frame	1,169	

The weighted average of renewables using the given proportions is $\approx$ 1579 [$/kW]. Assuming no new coal construction, we take a simple average of the four electric power generation types obtaining $\approx$ 1255 [$/kW]; the ratio of the two is $\chi = \frac{1255}{1579} \approx 0.776$. Therefore, the amount of actual capacity per dollar spent on renewables is 0.776 that of fossil-fuel capacity. Now quite obviously, this ratio (and the method to obtain it) is relatively crude and subject to a number of assumptions, hence the necessity for the sensitivities of renewable EROI undertaken in the main paper.

Since the cost of one unit of manufacturing output in the model is P_m, and both fossil-fuel and renewable capital is valued at this price, the power generation of renewable capacity necessary to make this consistent must be $\chi \cdot \phi_{FF}$. From this, we can work backwards to obtain the models renewable EROI.

Now, a note of caution is necessary here concerning the life-span of the technology. Since we assume a fixed energy construction cost and no explicit decomissioning time or operation costs for renewables, the life-cycle energy return and hence its life-cycle EROI is a function of the assumed life-span. For example,over the approximately 30 years the model runs over, the life-cycle EROI of the renewable technology is:

$$\frac{1}{ID_e}\int_0^{30} \chi \cdot \phi_{FF} \cdot e^{-\sigma_R \cdot t} \cdot dt = EROI = \frac{1}{1.025}\int_0^{30} (0.776 \cdot 3.025) e^{-0.03t} dt \approx 45$$

where σ_R is the depreciation rate of a unit of renewable capacity. For 25 and 20 year life-spans the values are 40 and 34 respectively. Two things must be noted here. First, this value may seem both too high or too low depending on the technology considered (e.g. solar PV or hydro). Ultimately the renewable technology in the model represents a composite of real technologies so the magnitude of the EROI is necessarily somewhat different from any single given actual generation technology.

Second, it is important to note the dependence of the EROI on the assumed life-span of the technology. The model has no explicit decommissioning mechanism and capital simply depreciates at some fixed rate per unit time. As such, the life-span of a unit of renewable capacity is technically infinite and will produce energy over the entire model simulation horizon. However, given the exponential depreciation this value is bounded. For an infinite horizon the above integration may be solved to obtain:

$$EROI = \frac{\chi \cdot \phi_{FF}}{ID_e \cdot \sigma_R} \tag{15}$$

Using the example numbers from above we would calculate an EROI of the renewable capacity of:

$$\frac{0.776 \cdot 3.025}{1.025 \cdot 0.03} \approx 76$$

Since the EROI of renewables in the model is dependent on the assumed life-cycle there is no single value conclusive value to report. In the paper we report the EROI values assuming 25 years of continuous operation. As explored in (Kubiszewski et al, 2010) the life-cycles for wind turbines used in EROI calculations range significantly (from 15 to 30 years). This 25 year horizon also captures, approximately, the lifespan of solar PV.

C.4 Fossil-Fuel EROI and Depletion

This subsection will introduce a net energy based formulation to tie the EROI of fossil-fuels to the magnitude of the remaining stock of fossil-fuels.

In order to capture the dynamic of fossil-fuel EROI declining with extraction we denote a stock of extractable fossil-fuels as $S(t)$. A simple formulation of EROI declining with extraction is given as follows:

$$EROI(t) = \frac{EROI(0) \cdot S(t)}{S(0)} \tag{16}$$

where $EROI(0)$ and $S(0)$ are initial conditions for EROI and the stock of fossil-fuels respectively. By equation (16) the EROI of fossil-fuels is modelled to decline linearly with the decline in the stock of fossil-fuels which, as will be shown, implies a non-linear depletion trajectory for the stock itself. Now, to relate this back to the input-output structure of the model we note that the EROI (of extraction) is simply the reciprocal of the fossil-fuel sector technical coefficient $a_{22}(t)$:[12]

$$a_{22}(t) = \frac{1}{EROI(t)} \tag{17}$$

[12] That is, the ratio of energy production to the direct energy requirements to meet that production.

Substituting (16) into (17) we obtain the following expression which relates the technical coefficient $a_{22}(t)$ to the decline in EROI as modelled by the depletion of the underlying stock $S(t)$:

$$a_{22}(t) = \frac{S(0)}{EROI(0) \cdot S(t)} \tag{18}$$

Finally, since EROI is by construction a dimensionless ratio, and the stock of fossil-fuels appears in both the numerator and denominator, the resulting expression for $a_{22}(t)$ is dimensionless as required.

The EROI of fossil-fuels and depletion of the stock $S(t)$ form a positive feedback loop. To supply a given magnitude of energy return ER requires extraction of fossil-fuels which depletes the stock and lowers the EROI. This declining EROI implies that to continue supplying just some constant ER requires progressively greater energy investment EI (the energy return portion of EROI is unchanged so the denominator must be increasing).[13] This greater energy investment must itself be met by the consumption of additional fossil-fuels and hence greater extraction and so on.

The EROI-depletion dynamics can be explored using the concepts of net and total energy where net energy is defined as the energy return ER minus the energy invested EI and total energy is defined as $ER + EI$. Now, for a given ER what is the EI? From equation (16) we have that:

$$\frac{EROI(0) \cdot S(t)}{S(0)} = \frac{ER}{EI(t)} \tag{19}$$

solving for EI we have:

$$EI(t) = \frac{ER * S(0)}{EROI(0) \cdot S(t)} \tag{20}$$

Total energy is therefore

$$TE = ER + \frac{ER * S(0)}{EROI(0) \cdot S(t)} \tag{21}$$

or in more compact form

$$TE = ER \left(1 + \frac{S(0)}{EROI(0) \cdot S(t)}\right) \tag{22}$$

This last expression will be used in specifying the differential equation for $S(t)$ but it should be noted that, by substituting in equation (16), the equation becomes:

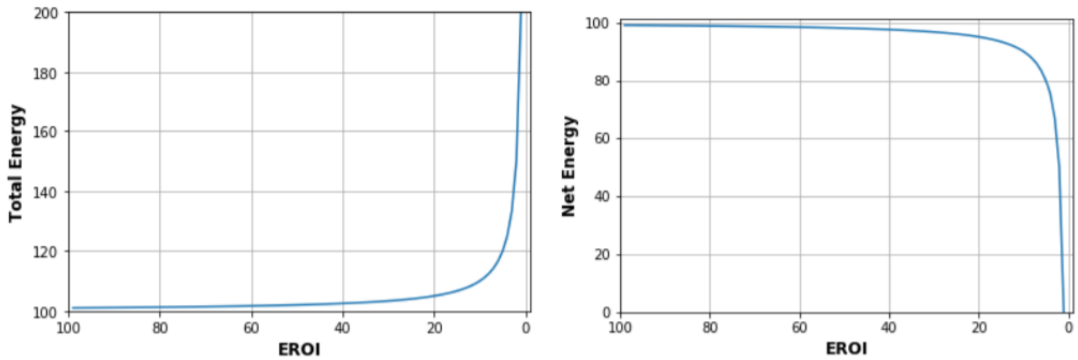
$$TE = ER \left(1 + \frac{1}{EROI(t)}\right) \tag{23}$$

Which displays the non-linear behaviour of the total energy requirements. Similarly we may write the expression for net energy as:

$$NE = ER \left(1 - \frac{1}{EROI(t)}\right) \tag{24}$$

Equations (23) and (24) indicate fundamentally important behaviour. To supply some constant energy return ER it is clear that the quantity of total energy will increase non-linearly as $EROI(t)$ declines and that the net energy available will decline non-linearly; the latter decline has been termed the EROI cliff by Euan Mearns. The following figures plot TE and NE for a constant $ER = 100$ for a range of EROI values.

[13] Why do we model EROI as declining with extraction? As presented in (Hall et al, 2014) the EROI of various types of fossil fuels has been declining linearly over the last several decades. The simple logic as to why is that as the easiest to extract sources of fossil fuel are depleted it becomes necessary to exploit more energetically expensive productions processes. Fracking, deep sea extraction, tar sands are all good examples of low EROI oil extraction technologies that have come into play.



(a) (b)

Figure 7: (a) Total and Net energy as a function of declining EROI.

Panel (a) of Figure 7 shows that as EROI declines from 100, the total energy necessary to deliver an energy return of 100 increases only very slowly and then increases dramatically for EROI values lower than 10. Similarly, panel (b) shows that the net energy available decreases in a symmetric fashion

Now, to deliver some given energy ER requires some total energy TE of overall energy use (energy invested plus energy returned). As such the depletion of the stock of fossil-fuels $S(t)$ is proportional to the total energy TE. Let us, for the sake of this derivation, assume that the stock of fossil-fuels is measured in tonnes of coal. Then, given some conversion factor τ which measures the joules per tonne of coal, producing TE energy requires $\frac{1}{\tau}TE$ tonnes of coal.

The above logic states simply that to provision some quantity of energy (Joules) will require the usage of some quantity of a primary energy source (in our example coal); the above states nothing about the rate at which this occurs. Ultimately, we require a differential equation governing the depletion of the fossil-fuel stock and to obtain that we must also specify the rate at which total energy is consumed.

Suppose the energy return ER is consumed every second, then, by the above, TE energy per second is the total energy that must be used per second to obtain and deliver this energy return. More simply, this implies a rate of energy consumption of TE per second or TE Watts which gives total power which we denote TP. Now, in some infinitesimal time interval dt we have that $TE \cdot dt$ [Ws] energy is consumed, and therefore (recalling the conversion factor τ) the differential change in the stock of fossil-fuels dS is:

$$dS = -\frac{1}{\tau}TP \cdot dt \tag{25}$$

which is negative to reflect that the stock of fossil-fuels is being depleted. Finally, we obtain the differential equation for the depletion of the stock of fossil-fuels by dividing both sides of the above expression by dt:

$$\frac{dS}{dt} = -\frac{1}{\tau}TP \tag{26}$$

which relates the depletion per unit time of the stock of fossil-fuels with the total power requirement. We may take this one step further by substituting in equation (24) which leads to:

$$\frac{dS}{dt} = -\tau PR\left(1 + \frac{S(0)}{EROI(0) \cdot S(t)}\right) \tag{27}$$

where PR is the power return which is simply the energy return ER per unit time. As noted at the outset of these calculations the differential equation governing the depletion of the stock of fossil-fuels is non-linear. Figure 8 displays the trajectory of the stock of fossil-fuels for assumed values of initial EROI, $S(0)$, and a constant energy return of 10. Note well that a small value of EROI is chosen to more clearly indicate the non-linearity. Panel (a) shows, as expected, that to supply a constant energy return under declining EROI implies increasingly rapid depletion. Panel (b) indicates that as the stock is depleted the EROI declines commensurately.

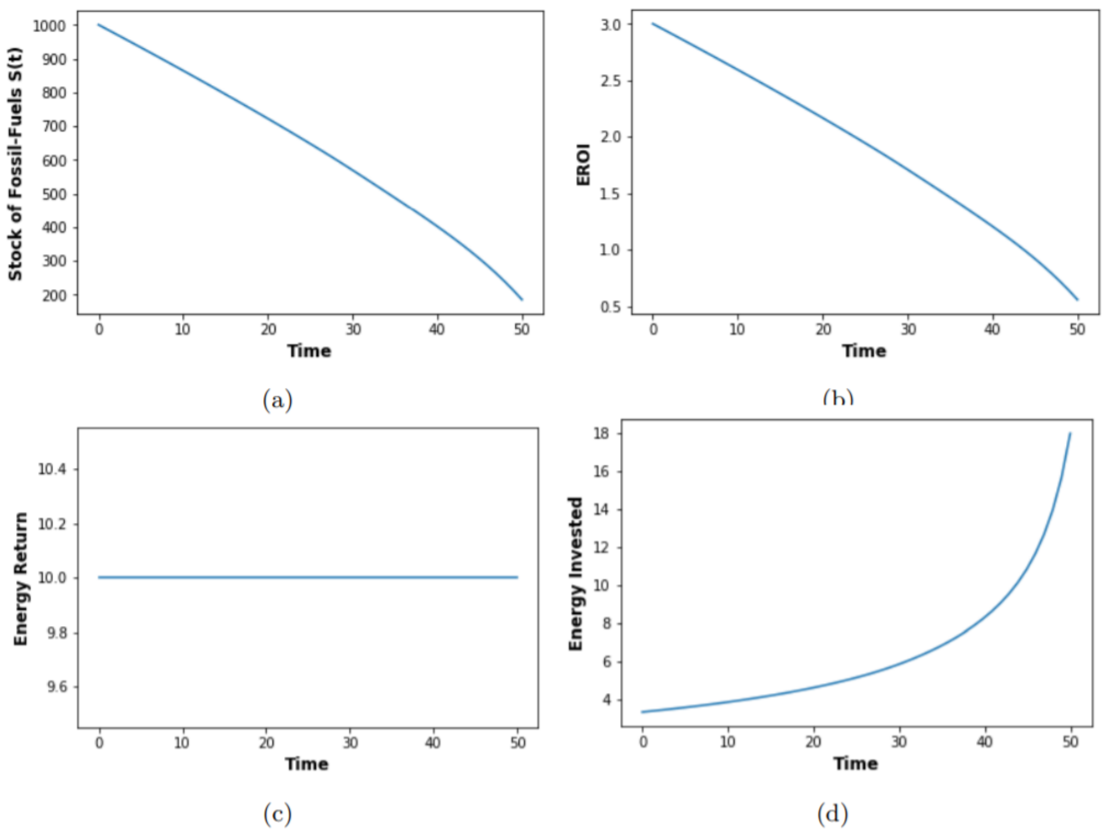


Figure 8: Assuming $S(0) = 1000$, $EROI(0) = 3$, and, $ER = 10$. **(a)** Depletion path for the stock of fossil-fuels $S(t)$ **(b)** EROI trajectory due to depletion of the stock of fossil-fuels $S(t)$. **(c)**Constant Energy Return. **(d)** Trajectory of energy invested necessary to the constant energy return.

Panel (c) displays the energy return ER which is assumed constant over time. Finally, panel (d) shows that the energy invested necessary to provide the constant energy return grows in an exponential manner as EROI declines.

Now, if we assume simply that emissions are proportional to total fossil-fuel usage than the emissions overtime, arising from the provisioning of a constant energy return, are plotted in the following figure.

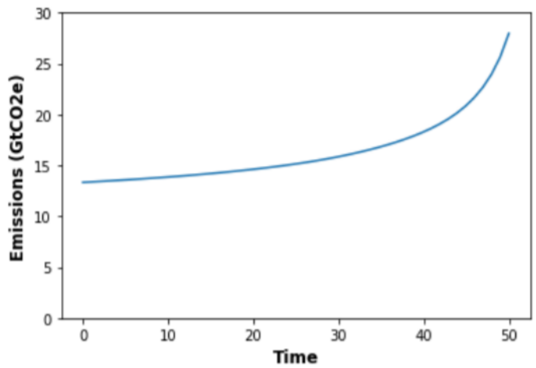


Figure 9: Trajectory of emissions $E(t)$ for $E(t) = \zeta TP(t)$ where $\zeta = 1$ is a constant of proportionality set to one for simplicity and assumed values of initial $EROI = 3$, $S(0) = 1000$, and $ER(t) = 10$.

Figure 9 displays a critically important result; as the EROI of fossil fuels decline, the emissions associated with providing some given energy return increase non-linearly. Now, the above figures all use a relatively low EROI value of 3 in order to better display the non-linear behaviour. For more realistically large values of EROI the same dynamics exist and can be clearly seen by compressing the y-axis. The trajectory of emissions for the same process described above except with an EROI of 20 is shown below.

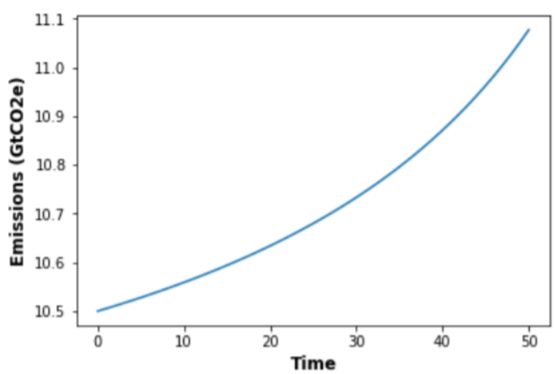


Figure 10: Trajectory of emissions $E(t)$ for $E(t) = \zeta TE(t)$ where $\zeta = 1$ is a constant of proportionality set to one for simplicity and assumed values of initial $EROI = 20$, $S(0) = 1000$, and $ER(t) = 10$.

Finally, we may link the above work back to the SFCIO energy transition framework by replacing the total power TP term with the total fossil-fuel power requirements given by $X^{FF}(t)P_f^{-1}$. By construction this quantity is measured in Watts so we may write the fundamental equation relating the depletion in some stock of fossil fuels to a key SFCIO model component as:

$$\frac{dS}{dt} = \frac{1}{\tau}\frac{X^{FF}(t)}{P_f} \tag{28}$$

C.5 Renewable EROI Dynamics

The transition to large-scale renewable based electricity generation is potentially complicated by the storage requirements arising from the inherent variability underlying solar and wind as energy sources. This variability requires energy storage to smooth the flow of energy produced, however, as this storage is itself energetically costly to produce. To incorporate aspects of this issue we turn to the grid storage EROI model of (Barnhart et al, 2013). This section provides a surface overview of the model of which the full details can be found in the publication and the supplementary material. First, the author's use the concept of energy storage on investment (ESOI) from a previous study (Barnhart and Benson, 2013). This ESOI is defined as:[14]

$$ESOI_e = \frac{\lambda \eta D}{\varepsilon_e} \tag{29}$$

where λ is the number of charge-discharge cycles of the battery (cycle-life); η is the round-trip AC–AC efficiency, D is the depth of discharge of the battery, and ε_e is the embodied electrical energy per unit of electrical storage capacity.

Some fraction ϕ of the energy produced by a variable renewable must be either stored for later usage or curtailed.[15] Therefore, for each unit of energy produced ϕ enters storage and $\eta\phi$ is taken from storage. Of the one unit of energy produced, $1 - \phi + \eta\phi$ units of energy are available to society after accounting for storage losses. The authors show that the energy costs to produce this unit of energy return is given as $\frac{1}{EROI_R} + \frac{\eta\phi}{ESOI_e}$. They define the EROI at the "grid" level as:

$$EROI_g = \frac{1 - \phi + \eta\phi}{\frac{1}{EROI_R} + \frac{\eta\phi}{ESOI_e}} \tag{30}$$

The following figure, using the authors data, plots $EROI_g$ as a function of increasing storage ϕ for solar and wind under three different storage technologies. Figure 11 shows that the EROI at the grid level declines as a function of increasing electrical energy storage. That the transition of economies to renewable energy may imply dramatically larger storage requirements implies that over the course of such a transition the storage fraction ϕ would increase and consequently, that the grid level EROI would decline. This is arguably a dynamic of key importance in modelling the energy transition and will therefore be added to the basic SFCIO-ETM framework.

To ensure our energy accounting is correct, we need to obtain a "grid corrected" power output parameter ϕ_g that, when applied to the renewable capacity constructed from one unit of energy invested, matches the life-cycle grid-level energy return EROI$_g$. Assuming for simplicity the same depreciation rate σ_R, we may obtain ϕ_g is the same manner as we did ϕ_R by solving the following for the ϕ_g term:

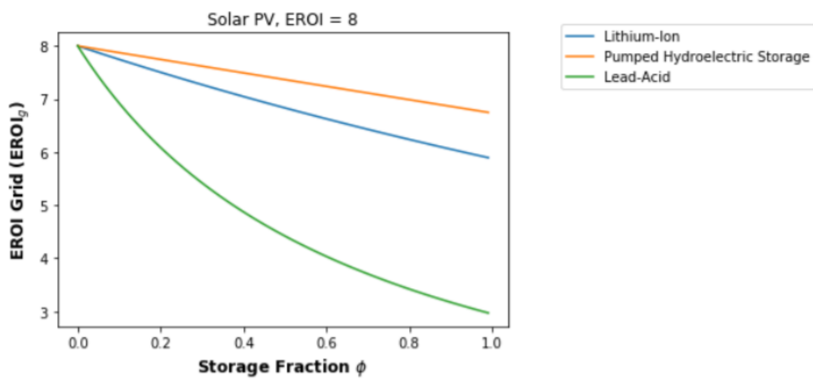
$$\int_0^\infty \phi_g \cdot e^{-\sigma_R \cdot t} \cdot dt = EROI_g \tag{31}$$

which leads to

$$\phi_g = \left(\frac{1 - \phi + \eta\phi}{\frac{1}{EROI_R} + \frac{\eta\phi}{ESOI_e}} \right) \sigma_R \tag{32}$$

[14]The range of ESOI values for different types of storage is quite large. In (Barnhart and Benson, 2013) a value of 5 is reported for lead acid batteries while a value of 797 is reported for compressed air energy storage.

[15]Note well, this is a simplification as this does not take into account Power-to-X technologies. See (Bogdanov et al, 2021) for a discussion of the role of Power-to-X in energy transitions.



(a)

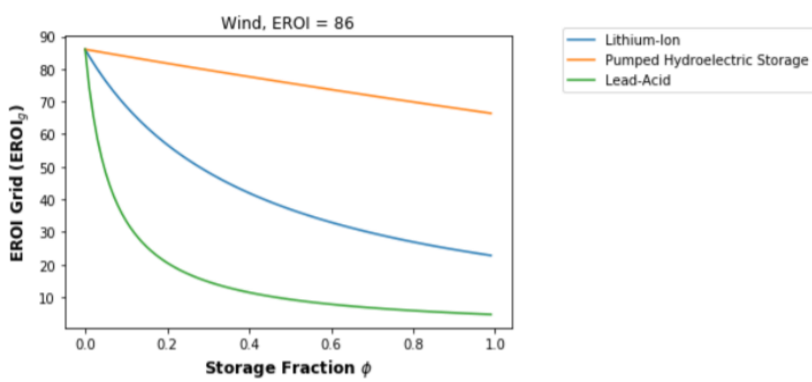


Figure 11: EROI grid values for solar PV and wind for three different energy storage technologies. EROI values chosen to match those found in (Barnhart et al, 2013).

Recalling from equation (15) that $\sigma_R = \frac{\phi_R}{EROI_R}$ we have:

$$\phi_g = \left(\frac{1 - \phi + \eta\phi}{\frac{1}{EROI_R} + \frac{\eta\phi}{ESOI_e}} \right) \frac{\phi_R}{EROI_R} \tag{33}$$

Of course, the bracketed term is simply the definition of $EROI_g$ so the entire expression may be simplified in a more intuitive (though less physically informative) form as:

$$\phi_g = \phi_R \left(\frac{EROI_g}{EROI_R} \right) \tag{34}$$

This last formulation is particularly appealing as it states that the power output when corrected for grid losses is simply the power output of renewables ϕ_R scaled by the ratio of the grid scale EROI to the EROI of renewable not accounting for storage costs. It follows from this that for any storage fraction ϕ greater than zero that the grid level EROI will be lower than the EROI of the renewable considered directly; therefore, the power output per unit renewable capacity (at the grid level) will decline continuously as the storage fraction increases.

Finally, making this process dynamic requires that the storage fraction parameter ϕ be endogenous in the model. The idea, roughly stated, is that storage fraction is an increasing function of the fraction of total electricity used in the model that is generated by renewables (renewable market penetration). This is informally shown as follows:

$$\phi(t) = f(\text{Renewable Market Penetration}) \tag{35}$$

Appendix D Additional Model Runs and Sensitivities

The model runs (degrowth, steady-state, and growth) in the main body of the paper are generated by assuming different growth rates of autonomously determined government expenditures. In this section we explore the same experiments but allow for degrowth and growth in the energy demands by the household and government sector as well. The following figure presents the base case scenario modified to include the additional impacts of the changing energy demands.

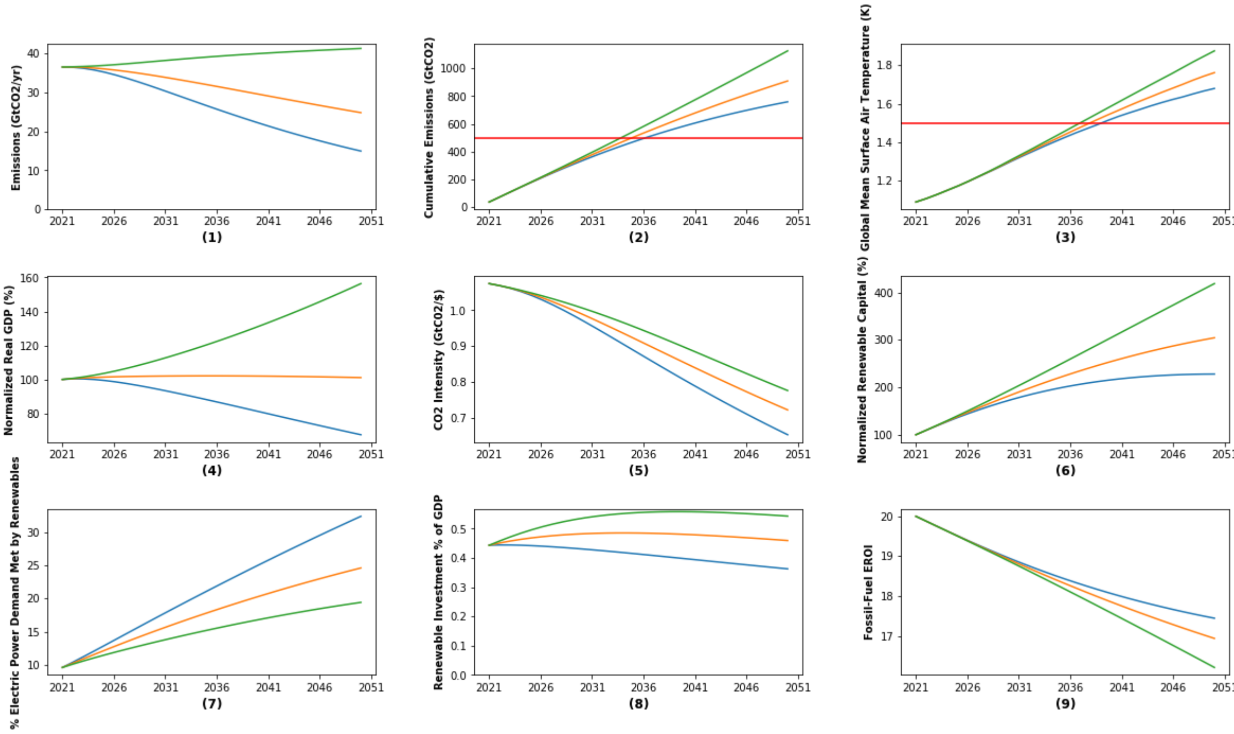


Figure 12: Trajectories for select SFCIO-IAM model variables assuming $\Delta_1 = 0.01$ and $\sigma_M^{NE} = 0.03$. **Growth** scenario trajectories (green plots –) **Steady-State** trajectories (orange plots –) **Degrowth** scenario trajectories (blue plots –). The solid red lines in panels (2) and (3) correspond to the 500 $GtCO_2$ carbon budget and 1.5 °C warming threshold respectively.

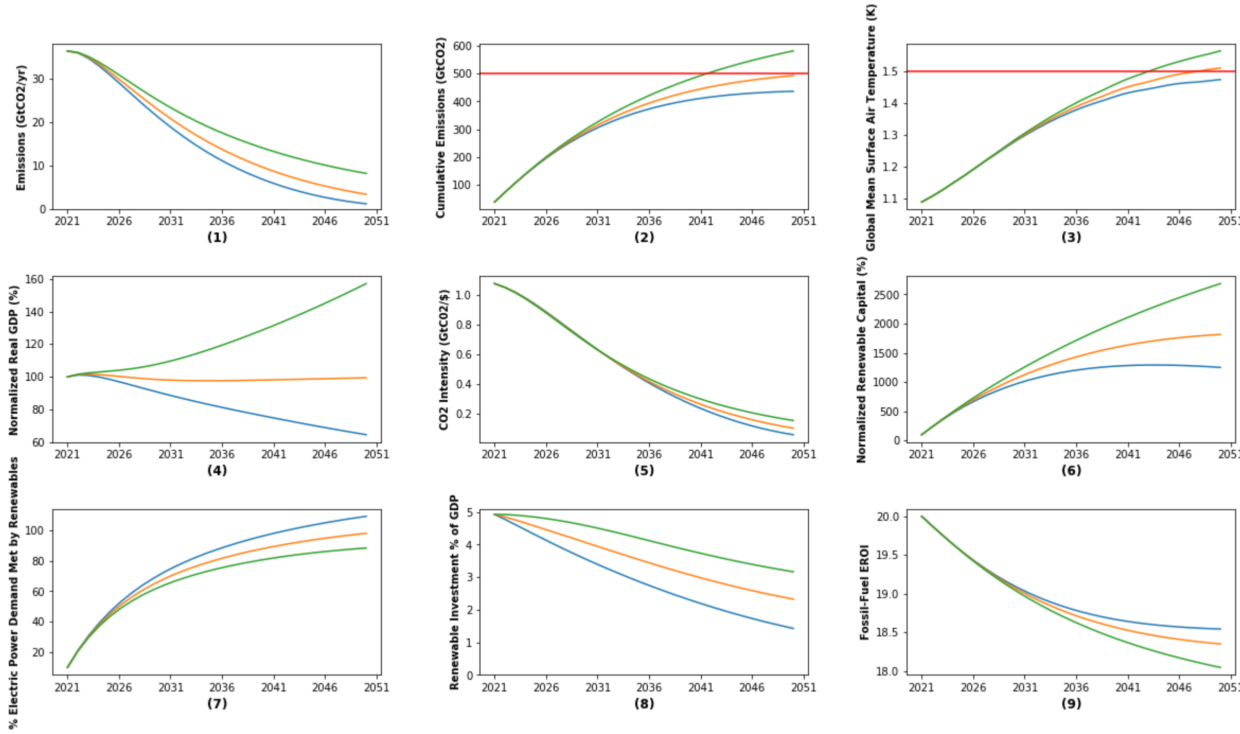


Figure 13: Trajectories for select SFCIO-IAM model variables assuming $\Delta_1 = 0.11$ and $\sigma_M^{NE} = 0.06$. **Growth** scenario trajectories (green plots –) **Steady-State** trajectories (orange plots –) **Degrowth** scenario trajectories (blue plots –). The solid red lines in panels (2) and (3) correspond to the 500 $GtCO_2$ carbon budget and 1.5 °C warming threshold respectively.

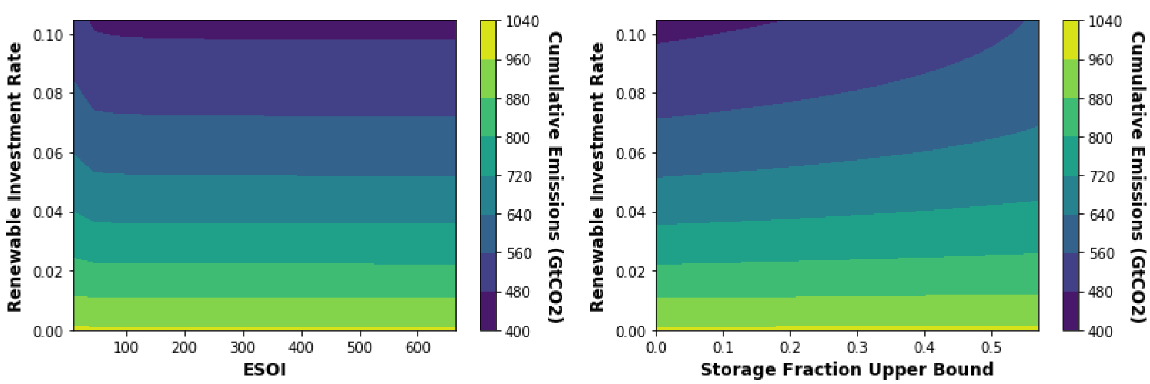


Figure 14: Contour plots for ESOI and storage fraction upper bounds across a range of renewable investment rates. The storage fraction upper bound denotes the maximum required storage that occurs at 100% renewable penetration.

Appendix E Parameter and Initial Value Tables

Note well, units with dimensions given as 1 in Figure 1 are dimensionless.

Parameter Name	Symbol	Units	Value
Inverse exchange timescales between atmosphere-ocean[a]	k_a	yr^{-1}	0.2
Inverse exchange timescales between upper-lower ocean[a]	k_d	yr^{-1}	0.05
Equilibrium ratio of atmospheric to upper ocean inorganic carbon	A·B	1	Derived Quantity
Ratio of volume of lower to upper ocean[a]	δ	1	50
Ratio of the molar concentrations of CO2 in atmosphere and ocean[a]	k_h	1	1910
Disassociation Coefficient[a]	k_1	mol kg^{-1}	0.000006
Disassociation Coefficient[a]	k_2	mol kg^{-1}	0.000000000753
Number of Moles in Atmosphere[a]	AM	mol	1.77×10^{20}
Number of Moles in Ocean[a]	AM	mol	7.8×10^{20}
Net radiative forcing for a doubling of CO_2[b]	$\mathcal{F}_{2xCO_2}$	Wm^{-2}	5.35
Effective heat capacity per unit area upper ocean[b]	C	JK^{-1}m^{-2}	7.3
Effective heat capacity per unit area deep ocean[b]	C_0	JK^{-1}m^{-2}	106
Radiative Feedback Parameter[b]	δ	Wm^{-2}K^{-1}	1.13
Heat Exchange Coefficient[b]	γ	Wm^{-2}K^{-1}	0.7
Initial Fossil-Fuel Sector EROI	EROI(0)	1	20
Renewable Sector 25-year life-cycle EROI	$EROI_R$	1	40
Round-trip AC–AC efficiency[c]	η	1	0.8
Energy Stored on Invested[c]	$ESOI_e$	1	30
Upper Bound Storage Fraction	b	1	0.05
Normal price of fossil-fuel sector output (dollars per Joule)	P_{F0}	$\$J^{-1}$	1
Price of manufacturing sector output (dollars per unit of capital)	P_{M0}	$\$k^{-1}$	10
Propensity to consume from disposable income	α_1	1	0.7
Propensity to consume from savings	α_2	1	0.3
Tax Rate	θ	1	0.3
Fraction of wealth held as deposits	λ_0	1	0.5
Interest rate modulation factor	λ_1	1	0.1
Disposable income modulation factor	λ_2	1	0.1
Power output per unit renewable capital	ϕ_R	$kW \cdot k^{-1}$	≈ 2.36
Power output per unit of fossil-fuel capital	ϕ_F	$kW \cdot k^{-1}$	3.08
Manufacturing output per unit time per unit of manufacturing capital	ϕ_M	yr^{-1}	1
Conversion factor of fossil-fuels to electricity	CF	1	2
Power requirement per unit of electrified manufacturing capital	τ_E	$kW \cdot k^{-1}$	1
Power requirement per unit of non-electrified manufacturing capital	τ_F	$kW \cdot k^{-1}$	1
Renewable capital depreciation rate	σ_R	yr^{-1}	0.03
Fossil-Fuel capital depreciation rate	σ_F	yr^{-1}	0.03
Electrified manufacturing capital depreciation rate	σ_M	yr^{-1}	0.03
Non-electrified manufacturing depreciation and decommissioning rate	σ_{ne}	yr^{-1}	0.03
Interest rate	r	yr^{-1}	0.03
Loan fraction repaid by renewable sector in given time period	Z_R	yr^{-1}	0.3
Loan fraction repaid by fossil-fuel sector in given time period	Z_F	yr^{-1}	0.3
Loan fraction repaid by manufacturing sector in given time period	Z_M	yr^{-1}	0.3
Technical coefficients matrix exogenous manufacturing sector parameter	a_{33}	1	0.05
Renewable capital stock adjustment factor	Δ_1	yr^{-1}	0.1
Fossil-Fuel capital stock adjustment factor	Δ_2	yr^{-1}	0.1
Manufacturing capital stock adjustment factor	Δ_3	yr^{-1}	0.1
Emissions Calibration Factor	ξ	EF^{-1}	5.95

Table 1: Table of model parameter values. Parameters noted with [a] are from (Glotter et al, 2013), [b] from (Geoffroy et al, 2013), and [c] from (Barnhart et al, 2013).

Variable Name	Symbol	Units	Initial Condition
Mass of Atmospheric CO_2[a]	$M_{at}(t)$	GtC	879
Mass of Atmospheric CO_2[a] Reference	$M_{at}(1750)$	GtC	596
Mass of Upper-Ocean CO_2[a]	$M_{up}(t)$	GtC	611
Mass of Lower-Ocean CO_2[a]	$M_{lo}(t)$	GtC	29604
Global-Average Surface Temperature[b]	$T(t)$	K	1.09
Deep Ocean Temperature[b]	$T_0(t)$	K	0.0368
Renewable Loans	$L^R(t)$	\$	0.24
Fossil-Fuel Loans	$L^R(t)$	\$	3.96
Manufacturing Loans	$L^R(t)$	\$	4.4
Household Wealth	$V(t)$	\$	24
Renewable Intermediate Capital	$K_e^R(t)$	physical capital [m]	0.035
Renewable Final Capital	$K_f^R(t)$	physical capital [m]	0.085
Fossil-Fuel Capital	$K^F(t)$	physical capital [m]	1.99
Electrified Manufacturing Capital	$K_e^M(t)$	physical capital [m]	0.84
Non-Electrified Manufacturing Capital	$K_{ne}^M(t)$	physical capital [m]	2.52
Initial Government Expenditure	$G(t)$	$\$yr^{-1}$	10

Table 2: Table of initial conditions. Initial values noted with [a] are from (Glotter et al, 2013) and [b] from (Geoffroy et al, 2013).

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