Macroeconomics and Ecological Constraints

An Exercise in Ecological Macroeconomics

Martin Sers[1] Peter Victor[2]

[1]University of Victoria
Department of Civil Engineering

[2]York University
Faculty of Environmental and Urban Change

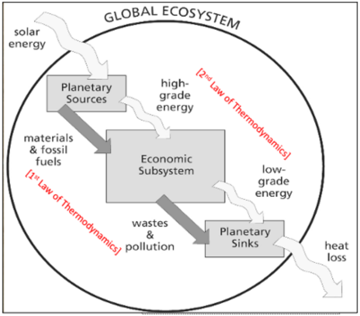
Outline of the Presentation

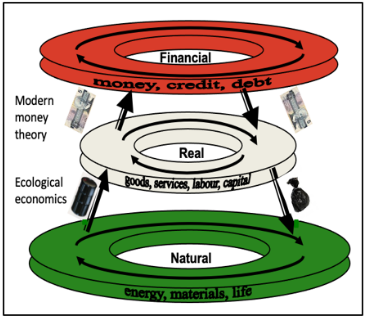
- What is ecological macroeconomics?
- A classification of ecological macroeconomic models
- The IAM view of the future and blind-spot
- Budget consistent pathways and decoupling
- The stock-flow consistent input-output model
- Simulation results

What is Ecological Macroeconomics?

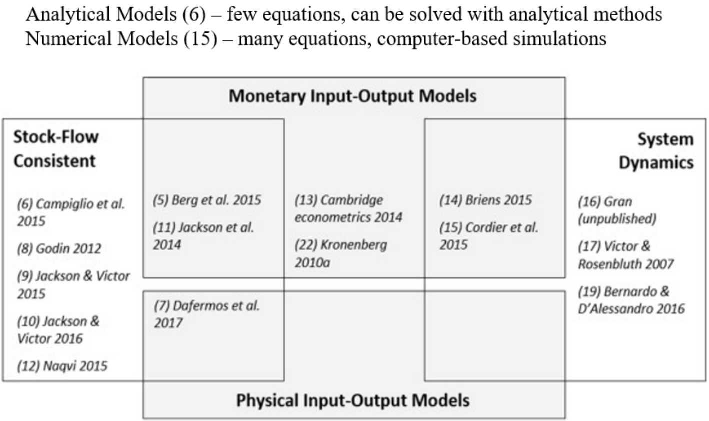
Overarching objective
to investigate and promote transitions to economies that deliver sustainable prosperity

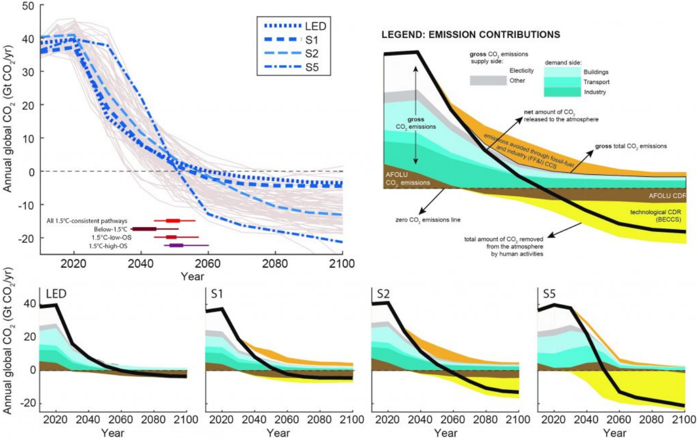
Integration
of ecological economics and modern money theory





Modelling Approaches in Ecological Macroeconomics (Hardt and O'Neill 2017)





Evolution and break down of global anthropogenic CO_2 emissions until 2100 from a suite of Integrated Assessment Models (IAM). 2018 IPCC Special Report (Rogelj et al, 2018).

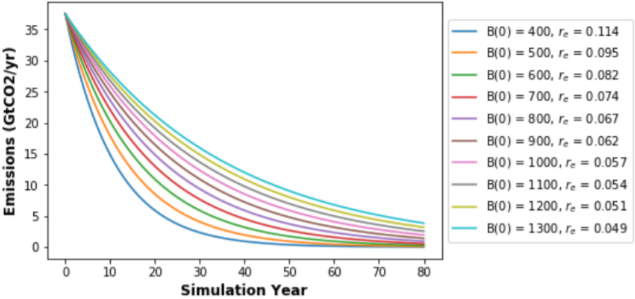
The IAM Triple Blind-Spot

- The visioning blind spot: Only scenarios assuming economic growth examined.
- The technology blind spot: Reliance on unproven negative emissions technologies (NETs) to achieve emissions goals.
- The CGE blind spot: A narrow (or non-existent) accounting of money and financial sector representation. An incoherent story about costs and investment impacts on GDP.

For example ...

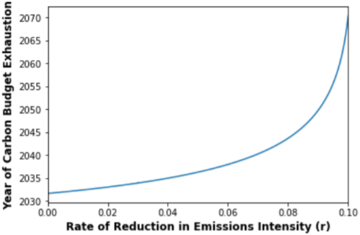
"From where exactly these investment dollars are summoned is outside the scope of our study, and for the most part beyond the capability of the models employed" (McCollum et al, 2018)

Budget Consistent Pathways

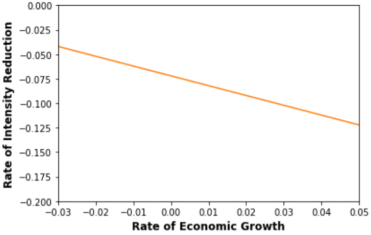


Emissions trajectories assuming a range (400 - 1300 $GtCO_2$) of values for the remaining carbon budget, a rate of economic growth $g = 0.02$, and initial year emissions $E(0) = 37.5$ $GtCO_2$ yr^{-1}. Obtained from $\frac{dB}{dt} = -E(0) \cdot e^{(g-r)t}$

Key aspects of Decoupling



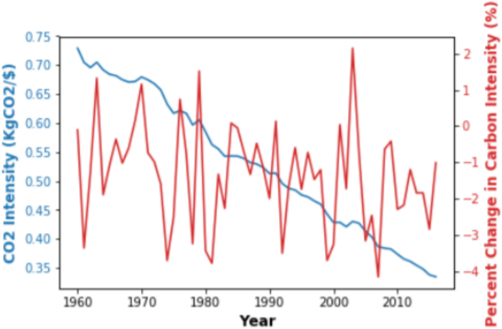
(a)



(b)

Panel (a):For an initial budget of of $B(0) = 520$ $GtCO_2$, a rate of growth of $g = 0.02$, and initial 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 $GtCO_2$ 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).

Global CO_2 Intensities



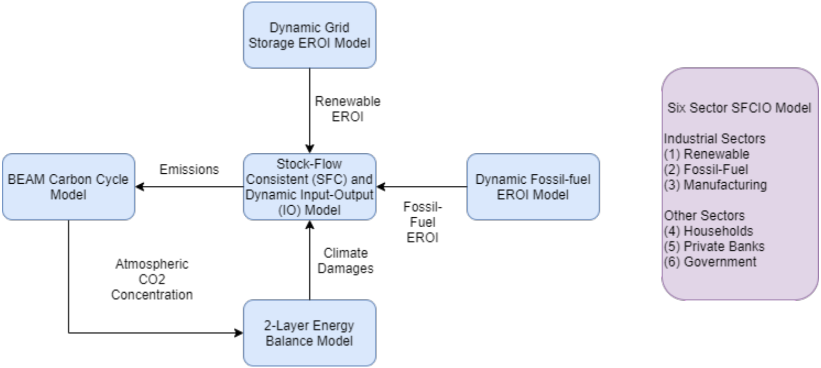
[Global CO2$_2$ intensity] Global CO2$_2$ intensity ($kgCO_2$/2011 ppp $) and annual percentage change in intensity (%).

The Stock-Flow Consistent Input-Output Model (I)

In this dissertation I examine models constructed on fundamentally different principles than those underpinning conventional IAMs.

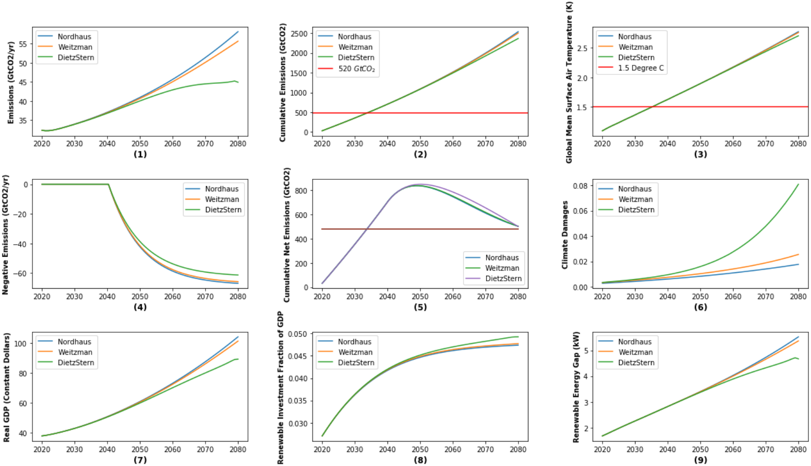
- Integration of stock-flow consistent and dynamic input-output models in continuous time capturing electrification and energy generation transitions.
- A simple financial system.
- Production and energy parameters calibrated via a normalized life-cycle energy return on investment (EROI) approach.
- Integration of BEAM and Energy Balance physical climate Models

Growth



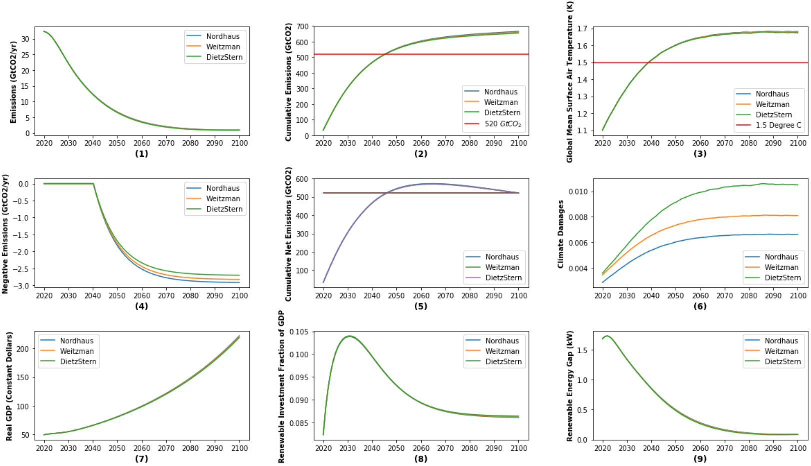
Overview of key SFCIO-IAM Model Components

Growth



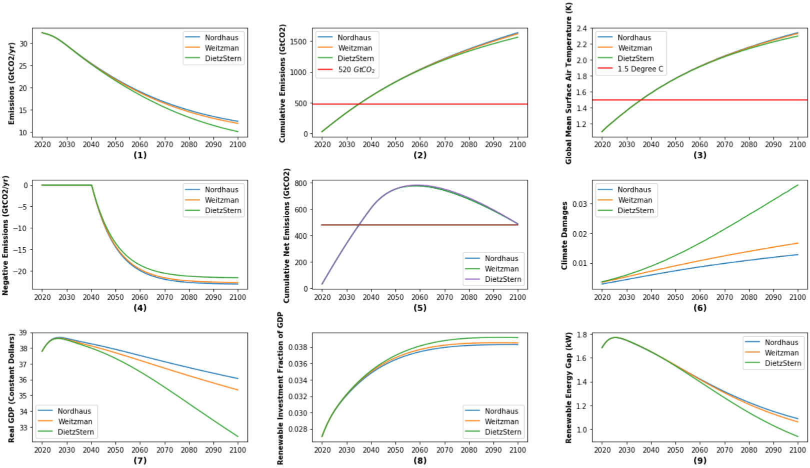
Trajectories for the main model variables for Nordhaus damages (blue line), Weitzman damages (orange line), and Dietz and Stern damages for $\Delta_1 = 0.3$, and 2% growth in government expenditures and energy consumption per annum.

High Investment Rate



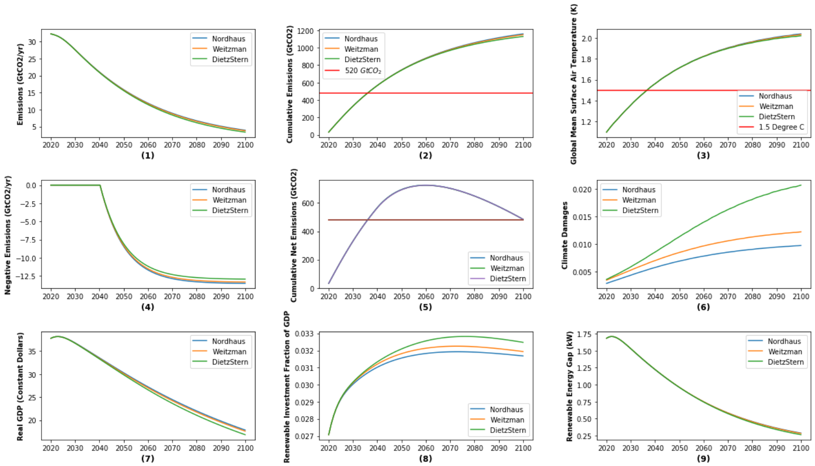
Trajectories for the main model variables for Nordhaus damages (blue line), Weitzman damages (orange line), and Dietz and Stern damages for $\Delta_1 = 0.9$, and 2% growth in government expenditures and energy consumption per annum.

Quasi Steady-State



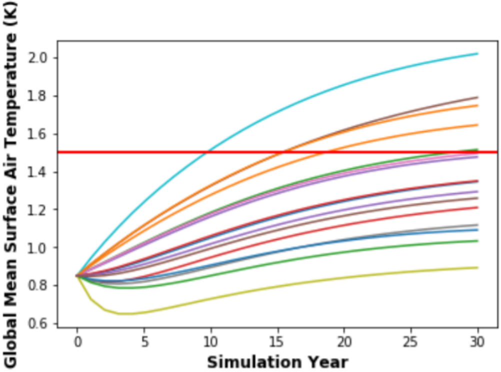
Trajectories for the main model variables for Nordhaus damages (blue line), Weitzman damages (orange line), and Dietz and Stern damages for $\Delta_1 = 0.3$, and 0% growth in government expenditures and energy consumption per annum.

Degrowth



Trajectories for the main model variables for Nordhaus damages (blue line), Weitzman damages (orange line), and Dietz and Stern damages for $\Delta_1 = 0.5$, and -1% growth in government expenditures and energy consumption per annum.

Climate System Uncertainty



Global Mean Surface Air Temperature pathways for the SFCIO-IAM model parametrised to correspond to each of the 16 underlying CMIP5 AOGCM models.

The Unorthodox Behavioural Assumptions Underlying Intentional Degrowth

Ultimately, the degrowth scenario requires certain behavioural assumptions that are somewhat unorthodox.

- Final demands reduced via declining household and government expenditures.
- Firms construct a large amount of new capital despite knowing future of declining demands.
- Banks provide all the loans that are demanded despite being aware that recipient sectors face long term degrowth.

Main Findings

- 1.5 Degree Pathways are possible to obtain across a variety of growth assumptions assuming some negative emissions.
- All such pathways imply investment in renewables (as a fraction of GDP) and the electrification of end use at rates many times higher than observed.
- Degrowth requires relatively less stringent transition policies but requires substantial long term reductions in consumption and government expenditures.

References

Barnhart, C. J., Dale, M., Brandt, A. R., & Benson, S. M. (2013). The energetic implications of curtailing versus storing solar- and wind-generated electricity. Energy & Environmental Science, 6(10), 2804–2810. https://doi.org/10.1039/C3EE41973H

Glotter, M., Pierrehumbert, R., Elliott, J., & Moyer, E. (2013). A simple carbon cycle representation for economic and policy analyses. 13.

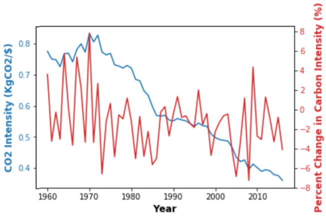
Geoffroy, O., Saint-Martin, D., Olivié, D. J. L., Voldoire, A., Bellon, G., & Tytéca, S. (2012). Transient Climate Response in a Two-Layer Energy-Balance Model. Part I: Analytical Solution and Parameter Calibration Using CMIP5 AOGCM Experiments. Journal of Climate, 26(6), 1841–1857. https://doi.org/10.1175/JCLI-D-12-00195.1

van Vuuren, D. P., Stehfest, E., Gernaat, D. E. H. J., van den Berg, M., Bijl, D. L., de Boer, H. S., Daioglou, V., Doelman, J. C., Edelenbosch, O. Y., Harmsen, M., Hof, A. F., & van Sluisveld, M. A. E. (2018). Alternative pathways to the 1.5 $^\circ$C target reduce the need for negative emission technologies. Nature Climate Change, 8(5), 391–397. https://doi.org/10.1038/s41558-018-0119-8

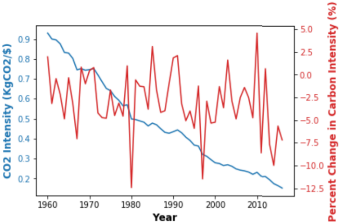
McCollum, D. L., Zhou, W., Bertram, C., de Boer, H.-S., Bosetti, V., Busch, S., Després, J., Drouet, L., Emmerling, J., Fay, M., Fricko, O., Fujimori, S., Gidden, M., Harmsen, M., Huppmann, D., Iyer, G., Krey, V., Kriegler, E., Nicolas, C., . . . Riahi, K. (2018). Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. Nature Energy, 3(7), 589–599. https://doi.org/10.1038/s41560-018-0179-z

Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., Handa, C., Kobayashi, S., Kriegler, E., Mundaca, L., Séférian, R., Vilariño, M. V., Calvin, K., Emmerling, J., Fuss, S., Gillett, N., He, C., Hertwich, E., Höglund-Isaksson, L., Schaeffer, R. (2018). Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. 82.

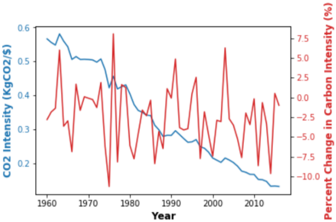
Select Country Level Intensities



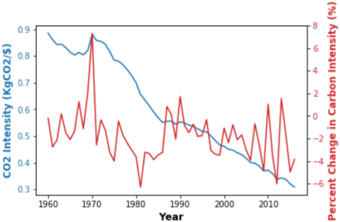
(a) Canada



(b) United Kingdom



(c) France



(d) United States

The Balance Sheet Matrix

$$
\begin{array}{l}
\\
\text{Money} \\
\text{Deposits} \\
\text{Fixed Capital} \\
\text{Loans} \\
\text{Advances} \\
\text{Net Worth}
\end{array}
\begin{array}{ccccccc}
\text{Households} & \text{Renewable Firms} & \text{Fossil-Fuel Firms} & \text{Manufacturing} & \text{Banks} & \text{Government} & \Sigma \\
\end{array}
$$

$$
\begin{pmatrix}
H^h(t) & 0 & 0 & 0 & 0 & -H(t) & 0 \\
M(t) & 0 & 0 & 0 & -M(t) & 0 & 0 \\
0 & K_e^R(t) + K_f^R(t) & K^F(t) & K_e^m(t) + K_{ne}^M(t) & 0 & 0 & K(t) \\
0 & -L^R(t) & -L_t^F & -L^M(t) & L(t) & 0 & 0 \\
0 & 0 & 0 & 0 & -A(t) & A(t) & 0 \\
-V(t)* & -V^R(t) & -V^{FF}(t) & -V^M(t) & 0 & -V^g(t) & K(t)
\end{pmatrix}
\tag{1}
$$

	Households	Renewable Firms	Fossil-Fuel Firms	Manufacturing	Banks	Government	Σ
Money	$H^h(t)$	0	0	0	0	$-H(t)$	0
Deposits	$M(t)$	0	0	0	$-M(t)$	0	0
Fixed Capital	0	$K_e^R(t) + K_f^R(t)$	$K^F(t)$	$K_e^m(t) + K_{ne}^M(t)$	0	0	$K(t)$
Loans	0	$-L^R(t)$	$-L_t^F$	$-L^M(t)$	$L(t)$	0	0
Advances	0	0	0	0	$-A(t)$	$A(t)$	0
Net Worth	$-V(t)*$	$-V^R(t)$	$-V^{FF}(t)$	$-V^M(t)$	0	$-V^g(t)$	$K(t)$

(1)

Figure: Balance Sheet Matrix

The Transactions Flow Matrix

	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

(2)

Figure: Transactions Flow Matrix

Key Model Non-Linearities (I): Grid Level EROI

- The EROI of renewables at a storage balanced "grid" level is given by Barnhart and friends as:

$$EROI_g(t) = \frac{1 - \phi(t) + \eta\phi(t)}{\frac{1}{EROI} + \frac{\eta\phi(t)}{ESOI}} \tag{3}$$

- The key parameter here is $\phi(t)$ which is the fraction of renewable energy generated that must be stored.
- The model makes $\phi(t)$ endogenous as an increasing function of the ratio of renewable electricity produced to total electricity consumed.

Key Model Non-Linearities (II): Fossil-Fuel EROI and Extraction

- The model includes endogenous FF EROI according to the following simple rule:

$$EROI(t) = EROI(0)\left(\frac{S(t)}{S(0)}\right) \quad (4)$$

- Here $S(t)$ denotes the stock of fossil-fuels at time t. Clearly EROI declines with extraction.

$$a_{22}(t) = \frac{1}{EROI(t)} = \frac{S(0)}{EROI(0)S(t)} \quad (5)$$

$$\frac{dS}{dt} = \frac{1}{\tau}\frac{X^{FF}(t)}{P_f} \quad (6)$$

Key Model Non-Linearities (III): Climate Feed-Backs

$$D(t) = 1 - \frac{1}{(1 + \pi_1 T(t) + \pi_2 T(t)^2) + \pi_3 T(t)^{0.6754}} \tag{7}$$

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).

$$\sigma_i(t) = \sigma_i + \beta D(t) \tag{8}$$

while the climate damage modified productivity terms are given as:

$$\phi_i(T) = \phi_i \left(\cdot \frac{1 - \alpha}{1 - \beta\alpha} \right) \tag{9}$$

An Example Investment Equation

Investment in the model is treated rather simply in that each sector builds additional capacity so as to equalize physical supply and demand at a given normal price.

$$i_e^R(t) = \Delta_1 \left(\mu_1 \phi_g^{-1} \tau_E k_e^m(t) - k_e^R(t) \right) \tag{10}$$

The Dynamic Input-Output Matrix

Transitioning off of fossil-fuels in the models requires both a shift in final demands away from fossil-fuels and a change in sectoral technical coefficients.

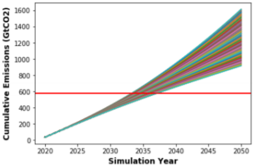
$$\mathbf{A(t)} = \begin{pmatrix} 0 & 0 & \frac{P_R \phi_g(t) k_e^R(t)}{X^M(t)} \\ 0 & \frac{S(0)}{EROI(0) \cdot S(t)} & \frac{P_F \left[CF[\tau_E k_e^M(t) - \phi_g(t) k_e^R(t)] + \tau_F k_{ne}^m(t) \right]}{X^M(t)} \\ 0 & 0 & a_{33} \end{pmatrix} \tag{11}$$

The Differential-Equations Model Representation

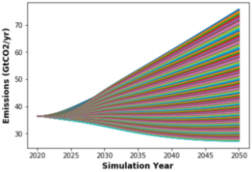
Variable Name	Symbol	Differential Equation
Renewable Intermediate Capital	$k_e^R(t)$	$\dot{k_e^R} = i_e^R(t) - \sigma_R(t)k_d^R(t)$
Renewable Final Capital	$k_f^R(t)$	$\dot{k_f^R} = i_f^R(t) - \sigma_R(t)k_f^R(t)$
Fossil-Fuel Capital	$k^F(t)$	$\dot{k^F} = i^F(t) - \sigma_F(t)k^F(t)$
Electrified Manufacturing 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	$L^F(t)$	$\dot{L^F} = Pm(t)i_e^F(t) - Z_F L^F(t)$
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	$S(t)$	$\dot{S} = -X^F(t) \cdot P_F^{-1}$
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	$T_0(t)$	$\mathcal{C}_0\dot{T_0} = \gamma(T - T_0)$

Table 1: State Variables and their Associated Differential Equations

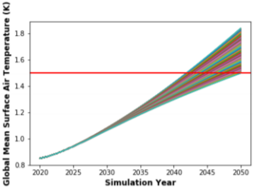
Sensitivities (I): Rate of Renewable Construction and Electrification



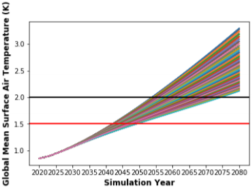
(a)



(b)



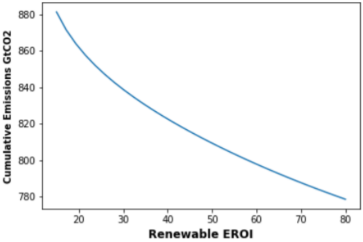
(c)



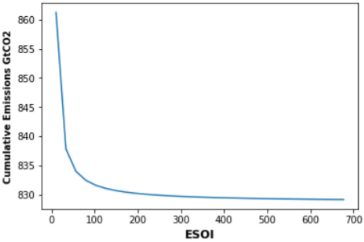
(d)

Trajectories of cumulative emissions, emissions per year, and global mean surface temperature for a sensitivity analysis over the joint parameter space $\Delta_1 \in \{0.006, 0.075\}$ and $\sigma_M^{NE} \in \{0.03, 0.12\}$, where Δ_1 is the rate of renewable capacity build out and σ_M^{NE} is the rate of depreciation and decommissioning of the non-electrified capital stock.

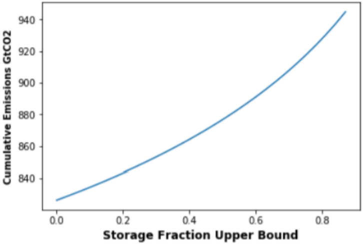
Sensitivities (II): Renewable Parameters



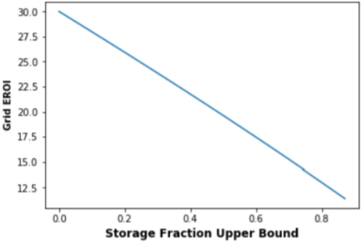
(a)



(b)



(c)



(d)

Next Steps and Questions

- Build a more realistic electric power sector model possibly including a stylized circuit model and add transmission energy losses.
- Introduce more sophisticated financial sector behaviours and additional financial entities.
- Questions?