

## Analysis

Economic Growth, Income Distribution, and Climate Change<sup>☆</sup>Armon Rezai<sup>a,b,\*</sup>, Lance Taylor<sup>c</sup>, Duncan Foley<sup>c</sup><sup>a</sup> Institute for Ecological Economics, WU - Vienna University of Economics and Business, Welthandelsplatz 1, 1020 Vienna, Austria<sup>b</sup> WIIW - Vienna Institute for International Economic Studies, Austria<sup>c</sup> Department of Economics, New School for Social Research, 6 East 16th Street, New York, NY 10003, United States

## ARTICLE INFO

## JEL Codes:

H21  
Q51  
Q54

## Keywords:

Climate change  
Economic growth  
Integrated assessment  
Demand and distribution  
Energy productivity  
Unemployment

## ABSTRACT

We present a model based on Keynesian aggregate demand and labor productivity growth to study how climate damage affects the long-run evolution of the economy. Climate change induced by greenhouse gas lowers profitability, reducing investment and cutting output in the short and long runs. Short-run employment falls due to deficient demand. In the long run productivity growth is slower, lowering potential income levels. Climate policy can increase incomes and employment in the short and long runs while a continuation of business-as-usual leads to a dystopian income distribution with affluence for few and high levels of unemployment for the rest.

## 1. Introduction

Since before the Industrial Revolution, exponential economic growth has supported rising standards of living around the world. Ever-increasing use of natural resources, notably energy from fossil fuels, has been key to the process. Climate change is a civilization-threatening consequence. Increasing temperature and more frequent natural disasters will impact the economy in many ways, inflicting damage on output and assets. Here we present a model of economic growth based on Keynesian aggregate demand theory to study how climate feedbacks affect the long-run evolution of the economy.

Traditional growth theory attempts to explain sustained exponential increases of labor productivity and income. Early contributions such as Solow's influential model focused on capital accumulation as the engine of growth. Capital deepening (a higher capital/labor ratio) supposedly allows workers to be more productive (Harrod, 1939; Domar, 1946; Solow, 1956). This tradition of growth theory sees technological progress — due to either scientific and technological developments external to the economy or investment in research and development — as the other main driver of growth. Innovations can be technological or organizational such as the division of labor across and within industries. Decreasing costs due to economies of scale also play a role (Smith, 1776). Potential output is determined by the size and skills of

the labor force, the accumulated capital stock, and the available technology. In supply-driven mainstream models it will always be realized through full employment of the available resources.

An important alternative conception of economic growth, based on Keynes' theory of aggregate demand, developed in the work of Nicholas Kaldor, Michal Kalecki, and Joan Robinson, emphasizes demand as the immediate driver of production and income growth in capitalist economies. The model we present here combines such a short-run demand-determined model of output with a model (inspired by Kaldor's thinking on economies of scale) of endogenous long-run technical change depending on the growth of output. We follow the Kaldorian tradition of linking capital accumulation with technological progress: high demand calls forth higher output and income, which over time lead to accumulation and provide a macroeconomic explanation for productivity beyond standard growth theory.

An important strand of thought in ecological economics emphasizes that increasing labor productivity has historically gone hand in hand with rising productive use of energy (Taylor, 2008). Since the 19th century, fossil fuels have been the principal source (Georgescu-Roegen, 1975; Cleveland et al., 1984; Ayres and Warr, 2009). We extend the standard model of economic growth to allow for this productivity-energy link directly. As a virtuous circle of economic growth and technological progress boosts standards of living, the need for natural

<sup>☆</sup> This research was supported by the Institute for New Economic Thinking (INET) (IN01400031). Rezai is grateful for financial support from the Austrian Science Fund (FWF): J 3633. Research assistance from Luiza Pires and Özlem Ömer is gratefully acknowledged.

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resources and energy increases.

So long as energy is derived from carbon-emitting fossil fuels, however, concentration of atmospheric carbon dioxide and other greenhouse gases increases and climate damage worsens. In principle, mitigation efforts can allow energy generation without the emission of carbon dioxide (and other greenhouse gases), severing the negative climate feedback and resolving the dilemma. Mitigation efforts also have an impact on levels of employment and the distribution of income, which our current model can track.

Whether growth is socially sustainable is a further question (Foley, 2012). Mainstream growth theory assumes that labor and capital are fully employed and that the distribution of income between wages and profits is set by their technically determined “marginal” contributions to output. The alternative Keynesian tradition treats output as determined by demand. Income distribution has an immediate impact on output and growth. If there is insufficient demand for labor, unemployment results. For a given level of economic activity, higher labor productivity destroys jobs. High levels of unemployment weaken the bargaining position of workers and lead to lower wages. Faster productivity growth has the potential to increase living standards but also the potential for a less equal distribution of income and lower levels of employment. Climate change worsens the problem.

The economics of economic growth, labor productivity, climate change, and the distribution of distribution are well established but have been seen as mostly separate from each other. Climate change economics mostly uses supply-driven growth models in which the distribution of income is derived from marginal productivity rules and assumptions about the shape of production function isoquants (Nordhaus, 2014). Non-neoclassical growth theory does address the interaction of distribution and output determination, but has only recently begun to study the question of energy use and climate change (Taylor, 2004; Taylor et al., 2013). The emerging field of Ecological Macroeconomics tries to bridge this divide, in particular, the contradiction between stimulation of CO<sub>2</sub> and other greenhouse gas emissions by higher energy use to support output and retardation of production by climate damage (for a review see Rezai and Stagl, 2016). A natural extension is to study endogenous productivity growth and its implications for the distribution of income and aggregate demand.

In the short run in our model, economic output is determined by aggregate demand that depends on the distribution of income, labor productivity, the amount of accumulated capital, and climate change. If the economy is operating at a high level of aggregate demand, employment grows and the distribution of income shifts toward labor. Greenhouse gas accumulation accelerates. Both factors induce a squeeze on profits, which ultimately limits demand. Over a period of decades, ongoing climate change lowers profitability and investment sufficiently to reduce output to sustainable levels where emissions and climate change stabilize. This process will entail overshooting of emissions and atmospheric carbon concentrations and cyclical adjustment due to the long lags in the climate system. The impacts on the distribution of income and employment levels will depend on society's institutions. Mitigation has the potential to take off the brakes: decarbonizing energy generation avoids carbon emissions and reduces the negative impact of growth-induced climate change. In the absence of other resource limitations, the economy resumes a stable path of continued economic and labor productivity growth. In Section 3 we present illustrative numerical simulations of the model, with details of the specification in the Appendix.

## 2. A Post-Keynesian Model of Economic Growth and Climate Change

Keynesian models basically say that spending determines income which includes profits  $P$  and wages  $W$ . In practice, a portion of profits is retained within business (with an implicit saving rate of 100%) and the rest distributed to households via interest, dividends, and capital gains.

Rich households receive the bulk of distributed profits; the remainder with low or negative saving rates mostly receive wages (and government transfers). These observations suggest that the saving rate from profits ( $s_c$ ) exceeds the rate from wages ( $s_w$ ). The profit rate is equal to profits over capital stock,  $r = P/K$ , the wage share equals wages over total income,  $\psi = W/X$ , and the profit share is  $\pi = P/X = 1 - \psi$ .

Aggregate private sector saving is

$$S = s_c P + s_w W = s_c r K + s_w \psi X = s_c r K + s_w (1 - \pi) X = (s_c - s_w) r K + s_w X \tag{1}$$

with  $rK = \pi X$ .

Firms hire labor at the total wage bill  $W$ . They also undertake investment into new capital stock. We assume a linear independent investment function in which capital formation responds to profits and economic activity. Autonomous investment is scaled to capital via the coefficient  $g_0$ .

$$I = \alpha P + \beta X + g_0 K. \tag{2}$$

Output creates emissions which lead to climate change. The government spends a fraction of GDP on mitigation to reduce these emissions. Throughout this section we assume that it does so without balancing its books and ignore business cycle complications.<sup>1</sup> Total mitigation expenditure  $M$  is thus proportional to output,

$$M = m X. \tag{3}$$

Under “business-as-usual” (BAU) the government does not undertake any mitigation,  $m = 0$ .

In the model at hand, the *level* of the capital stock,  $K$ , scales the system. Its use is not subject to decreasing returns so that marginal productivity rules to determine  $r$  and  $\pi$  do not apply. As described in Eq. (7) below, *growth* of capital stimulates rising labor productivity.

### 2.1. Short Run Equilibrium

In accordance with the principle of effective demand, output adjusts in the short run so that saving equals the sum of conventional and mitigation investment. At any time the capital stock is given and the output-capital ratio,  $u = X/K$ , equals<sup>2</sup>

$$u = \frac{g_0 + m + [\alpha - (s_c - s_w)]r}{s_w - \beta}. \tag{4}$$

The Keynesian stability condition requires that investment responds less strongly than savings to output so  $s_w > \beta$ .<sup>3</sup> Output responds positively to profits in the short run if  $\alpha > (s_c - s_w)$ . Higher government expenditure to fight global warming, which in this section is financed by public debt, increases output unambiguously. Given a level of labor productivity,  $\xi$ , output determines employment:  $L = X/\xi$ . Higher output increases employment, while higher productivity at a given level of output leads to loss of jobs. Output is constrained by aggregate demand, not aggregate supply, in our model. This implies that output remains below capacity, despite aggregate demand and supply equalizing much quicker than the geological time scales considered in our model (see Taylor (2004) and Lavoie (2014) for introductions to demand-constrained traditions).

<sup>1</sup> Our assumption of the government taxing the private sector and using these funds to finance mitigation efforts is a simplification which allows by-passing the intricate dynamics of the energy system. In a more decentralized framework, the government would use several policy instruments (e.g. carbon taxes, renewable subsidies) in addition to direct investments to guide private investment behavior.

<sup>2</sup> Eq. (4) follows from solving Eqs. (1)–(3) for  $X$  and dividing by  $K$ . The ratio  $u$  is basically a scale-free gauge of economic activity. As discussed below, its level feeds back into the profit rate.

<sup>3</sup> The stability condition ensures that a small demand injection (e.g. consumption or investment) is met by larger demand leakage (e.g. saving) such that overall demand moves back toward its previous level. In this case the equilibrium level of output is dynamically stable.

The distribution of income is determined in the labor market (Goodwin, 1967): if demand is strong and employment high, workers can bid for higher wages and the wage share rises. If the economy is going through a slump, unemployment increases and the labor share falls. We capture this relation in a linear equation for the profit rate.<sup>4</sup> The distribution of income is also impacted by damages from climate change. We assume that damages are borne by business owners and hence lower the profit rate.<sup>5</sup> Let  $\lambda = \frac{L}{N} = \zeta u$  with  $\lambda$  as the employment rate,  $L$ , relative to population,  $N$ , and  $\zeta = \kappa/\xi$  as the ratio of capital intensity ( $\kappa = K/N$ ) to labor productivity discussed further below. Let the atmospheric stock of carbon be denoted by  $G$ . Then distributional conflict is captured by the relationship

$$r = \mu_0 - \mu_1 \lambda - \mu_2 G = \mu_0 - \mu_1 \zeta u - \mu_2 G. \tag{5}$$

The profit rate,  $r$ , falls as the labor market tightens if  $\mu_1 > 0$  which also implies that  $r$  falls if  $u$  increases. This response reflects a “profit squeeze” distributive regime (Taylor, 2004). There is a similar squeeze in profitability with  $\mu_2 > 0$  if greenhouse gas concentration,  $G$ , rises. By increasing  $\zeta$  at a given level of productivity, greater capital intensity  $\kappa$  forces the profit rate to fall.

The short run equilibrium, as defined by Eqs. (4) and (5), gives the level and distribution of income,  $u$  and  $r$ .<sup>6</sup> Using these variables we can also solve Eq. (2) for the ratio of gross investment to capital,  $g = I/K$ , which will determine the growth rate of capital stock.

These short run variables are conditional on the levels of the dynamic state variables,  $G$  and  $\zeta$ . After substituting Eq. (4) into Eq. (5), we can determine their direct and indirect influence on the short run variables in the following manner:  $r = r[\zeta, G]$ ,  $u = u[r]$ ,  $g = g[r, u[r]]$ , so that  $u$  and  $g$  are affected indirectly by climate change through its effect on the profit rate.

We assume that the economy is in a profit-led demand regime, i.e.  $\alpha > (s_c - s_w)$ , and a profit-squeeze distributive regime, i.e.  $\mu_1 > 0$ . Under the profit-led/profit-squeeze assumption, the profit rate falls if either of the state variables or output increases. Using subscripts to denote partial derivatives, in Eq. (5) we have  $r_\zeta, r_G, r_u < 0$ . In Eq. (4), output increases with the profit rate,  $u_r > 0$ . In Eq. (2), the investment/capital ratio goes down as well,  $g_\zeta, g_G < 0$ .

Fig. 1 gives a graphical representation of the short-run equilibrium. Output,  $u(r)$ , increases with the profit rate due to the assumption of profit-led demand. The profit rate  $r(u, \zeta, G)$  decreases with output due to the assumption of a profit-squeeze. The intersection of both schedules determines the short run equilibrium, A. Both  $u$  and  $r$  fall in response to an increase in either state variable. In Fig. 1 an increase in the stock of atmospheric carbon to  $G'$  shifts the distribution schedule downward. Both  $u$  and  $r$  are lower in the new equilibrium, B.

Since the focus of this paper is the long run, we abstract from short-to medium-run fluctuations and assume that the demand and distributive variables adjust instantly. In reality, output and distribution adjust in response to each other, giving rise to cyclical patterns in a profit-led/profit-squeeze economy. These cycles of demand and the functional income distribution are usually studied within a Goodwin model (Barbosa-Filho and Taylor, 2006). Work by Kiefer and Rada (2015) suggests that the demand-side effect of  $r$  on  $u$  is weak so that  $u(r)$

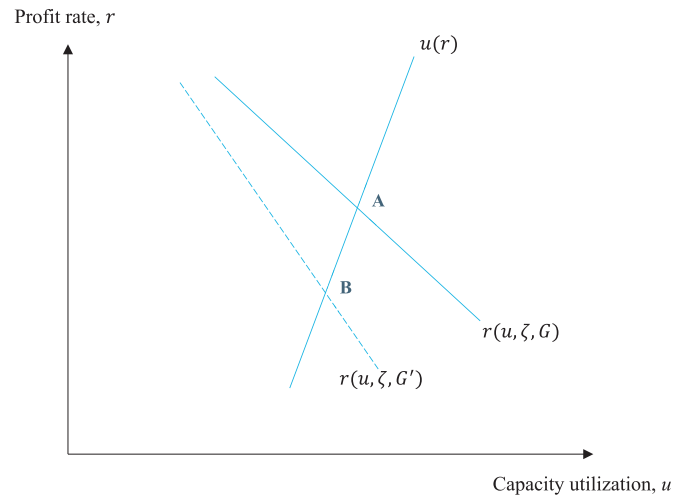


Fig. 1. Short run equilibrium as a function of  $\zeta$  and  $G$ . Higher  $\zeta$  lowers  $r$  and  $u$  and shifts the equilibrium to point B. An increase in  $G$  shifts the system in similar fashion.

schedule in Fig. 1 is steep. This implies that capital utilization will not fall by very much in response to moderate increases in  $\zeta$  and  $G$ .

### 2.2. Long Run Dynamics

In the short run the capital stock, labor productivity, and greenhouse gas concentration are fixed but they evolve over time. Capital increases through net investment, i.e. gross investment minus depreciation. Here we allow for a second climate impact: higher level of greenhouse gases lead to a faster depreciation. To allow for population growth, we work with the capital/population ratio,  $\kappa = K/N$ . Population grows at an exogenous rate,  $n$ . In summary,  $\kappa$  increases according to

$$\dot{\kappa} = \kappa(g - \delta_0 - \delta_1 G - n) \tag{6}$$

with  $\delta_0$  and  $\delta_1 G$  ( $\delta_0, \delta_1 > 0$ ) as the exogenous and climate-change related rates of depreciation and  $g = I/K$  as gross investment from Eq. (2). In standard notation,  $\dot{\kappa} = d\kappa/dt$  and  $\hat{\kappa} = \dot{\kappa}/\kappa$ .

As discussed in the introduction, labor productivity  $\xi$  is a major source of rising output. What factors determine its growth rate,  $\hat{\xi}$ ? Kaldor emphasized the demand side. Over the years he introduced two versions of a “technical progress function.” In the first  $\hat{\xi}$  is driven by investment which serves as a vehicle for more productive technology (Kaldor, 1957). The second ties productivity growth to the output growth rate  $\hat{X}$  via economies of scale (Kaldor, 1966). To keep the model tractable, we assume that  $\hat{\xi}$  responds to  $\hat{\kappa}$  which is driven by the investment/capital ratio  $g$ . Higher employment may also stimulate labor-saving technical change as in the induced technical change model proposed by Kennedy and von Weizsacker (Kennedy, 1964; von Weizsacker, 1966). As the labor market tightens and the wage bill increases, firms seek more productive operations to save on the increased cost for labor. In growth rate form,  $\hat{\xi}$  evolves according to

$$\hat{\xi} = \gamma_0 + \gamma_1 \hat{\kappa} + \gamma_2 (\lambda - \bar{\lambda}) \tag{7}$$

where  $\gamma_0 > 0$  is the exogenous rate of productivity growth,  $\gamma_1$  and  $\gamma_2 > 0$  capture the effects of capital deepening and labor market tightness, and  $\bar{\lambda}$  is the rate of employment at which no additional productivity investments are undertaken.

For mathematical ease, we will work with the auxiliary variable  $\zeta = \kappa/\xi = \lambda/u$  introduced above. This ratio of capital (relative to population) to productivity provides a natural vehicle to track the system. While  $\kappa$  and  $\xi$  have their own dynamics, they are fixed at a point in time and have to approach a constant growth rate in the long run. They map into  $\lambda/u$ , the employment ratio divided by capital utilization. Using Eqs. (6) and (7), the growth rate equation for  $\zeta$ ,  $\hat{\zeta} = \hat{\kappa} - \hat{\xi}$ , simplifies to

<sup>4</sup> The profit rate and the profit share are related by the identity:  $r = \pi u$ . A positive relationship between  $u$  and  $\pi$  implies a positive relationship between  $u$  and  $r$ .

<sup>5</sup> Climate damage will initially create losses for business owners due to lower profitability. This reasoning motivates our assumption on a negative effect on the profit rate. Through endogenous processes within the economy, business owners can shift some of these losses on to workers by lowering the wage bill. A lower level of profitability lowers growth in income and labor productivity. Rezai et al. (2013) discuss the problems of incorporating climate damages in demand-driven models and how such damages can be interpreted.

<sup>6</sup> The closed-form solution to Eqs. (4) and (5) reads:

$$u = \frac{(\delta_0 + m) + (\alpha_1 - s_c + s_w)(\mu_2 G + \mu_0)}{(s_w - \beta) + \mu_1 \zeta (\alpha - s_c + s_w)} \text{ and } r = \frac{(s_w - \beta)(\mu_0 + \mu_2 G) - \mu_1 (\delta_0 + m)\zeta}{(s_w - \beta) + \mu_1 (\alpha_1 - s_c + s_w)}$$

$$\dot{\zeta} = \zeta [(1 - \gamma_1)(g - \delta_0 - \delta_1 G - n) - \gamma_0 - \gamma_2(\zeta u - \bar{\lambda})]. \tag{8}$$

The stock of atmospheric carbon is the third state variable. Carbon accumulates due to production related emissions and dissipates at a low exogenous rate  $\omega$ . Emissions are determined by the size of the economy,  $X$ , its energy use per unit output (i.e. the inverse of energy productivity,  $\varepsilon = X/E$  with  $E$  as energy use), and the carbon intensity of the energy used,  $\chi$ . Falling effectiveness of mitigation expenditure in curbing production-related fossil fuel emissions is captured by an increasing concave function  $\theta(m)$ . As  $m$  rises, mitigation control becomes less effective according to  $1 - \theta(m)$ .<sup>7</sup> There are also natural emissions  $H_0$  which must enter the accounting.

Most economic models of climate change assume that energy productivity is constant so that, ceteris paribus, emissions are a fixed proportion of output or are changing exogenously along a declining trend. Historically, however, energy use per worker,  $q = E/L$ , tends to increase with labor productivity (Georgescu-Roegen, 1975; Cleveland et al., 1984; Ayres and Warr, 2009; Semieniuk, 2016). Given the identity noted by Taylor (2008)

$$\varepsilon = \frac{X}{E} = \frac{X/L}{E/L} = \frac{\xi}{q}, \tag{9}$$

this empirical pattern implies that the emissions are intimately related to labor productivity i.e. to increase output per worker, energy use per worker has to rise. We capture this relationship by assuming a constant elasticity between energy use per worker and labor productivity:  $\hat{q} = v\hat{\xi}$ , or in level terms at time  $t$ :  $q(t) = [q(0)/\xi(0)^v]\xi(t)^v = C\xi(t)^v$  with  $q(0)$  and  $\xi(0)$  as levels of the variables at time zero. Using identity Eq. (9) we find that  $1/\varepsilon = C\xi^{v-1}$ . Semieniuk (2016) estimated the elasticity  $v$  as being close to unity, the value we adopt in the following discussion.

With emissions responding endogenously to economic growth and the energy need embodied in technological progress,  $G$  evolves according to

$$\dot{G} = H_0 + [1 - \theta(m)]\chi E - \omega G = H_0 + [1 - \theta(m)]\chi N u \kappa C \xi^{v-1} - \omega G. \tag{10}$$

The first equality states that the change in atmospheric carbon is natural plus unabated output-linked emissions minus dissipation at rate  $\omega$  due to biological uptake. The second uses the identities  $E = X/\varepsilon$ ,  $X = N u \kappa$ , and  $\xi = \kappa/\zeta$  and follows from the well-known “Kaya identity” from climate science (Waggoner and Ausubel, 2002). An important aspect of the equation is that atmospheric carbon is an increasing function of the size of the economy,  $X$ , which is at odds with the convention of continued exponential growth of  $G$ . At present the growth rate of  $G$  is around one-half percent per year and climate damage is apparent. Meanwhile  $\kappa$  is increasing at around one or two percent. In Eq. (10) the ratio  $X/G = N u \kappa/G$  is rising with greater population and capital, meaning that the growth rate  $\hat{G}$  is going up. The Malthusian logic of exponential growth shows that with incomplete mitigation ( $\theta(m) < 1$ ) more rapidly increasing climate damage must choke off economic expansion in order to allow for a stabilization of  $G$ ,  $\kappa$ , and  $\zeta$  at a zero growth “stationary state.”

A second point is that by raising capital utilization  $u$ , higher labor productivity increases the demand for energy. Discussions on limits to growth and proposals for “de-growth” must recognize the endogeneity of technological progress and how income is generated in capitalist societies for their policy implications to be relevant.

<sup>7</sup> In our modeling we follow the DICE model of Nordhaus (2014) in assuming a continuum of available energy generating processes which increase in price as their emitted carbon content falls. We abstract from the complexities that the transition to a carbon-neutral energy sector implies. Importantly, we assume that full mitigation is feasible at relative low cost. We also abstract from the varying abilities of energy sources to provide usable work for economic processes (Ayres and Warr, 2009; Hall et al., 2014).

### 2.3. Dynamic Behavior and Steady States

In the absence of adverse effects of climate change, the economy would approach balanced growth in the long run with all relevant variables increasing at the same constant rate (Taylor et al., 2017). Climate change can force such reassuring dynamics to break down. To see why, we focus initially on the differential Eqs. (6) and (8) for increases in  $\kappa$  and  $\zeta$ . Will they converge to a steady state with  $\dot{\kappa} = 0$  and  $\dot{\zeta} = 0$ , and what are the characteristics of this “attractor”? An implicit assumption is that the population growth rate  $n$  is constant (possibly equal to zero at a stationary state).

As pointed out in connection with Fig. 1, the short-run variables  $g$  and  $u$  entering Eqs. (6) and (8) both decrease when  $\zeta$  and  $G$  rise. Because capital scales the system, the equations do not depend explicitly on  $\kappa$ . In Eq. (6) signs of responses are  $\dot{\kappa}_\kappa = 0$ ,  $\dot{\kappa}_\zeta < 0$ ,  $\dot{\kappa}_G < 0$ . In Eq. (8) the partial derivatives are  $\dot{\zeta}_\kappa = 0$  and  $\dot{\zeta}_G < 0$ . From the discussion of Fig. 1, the impact of  $\zeta$  on  $u$  in Eq. (8) is likely to be small, so that the derivative  $\dot{\zeta}_\zeta = d\dot{\zeta}/d\zeta < 0$ .

Assume for the moment that climate change is irrelevant to growth. Such would be the case under full mitigation of all emissions or after a permanent transition to renewable energy, with  $G$  falling back to its pre-industrial level  $G_0$  discussed below. The economy approaches a balanced growth path with a stable ratio of  $\kappa$  to  $\xi$ . The growth rate follows from the implied short run equilibrium, Eqs. (4)–(6).<sup>8</sup>

If  $\theta(m) < 1$  in Eq. (10), greenhouse gas accumulation cannot be ignored. With  $\dot{G}_\kappa > 0$  a higher level of economic activity increases atmospheric carbon concentration and balanced growth may break down. For a given level of  $G$ , two steady state conditions follow from Eqs. (6) and (8) with  $\dot{\kappa} = 0$  and  $\dot{\zeta} = 0$ ,

$$g - \delta_0 - \delta_1 G - n = 0 \tag{11}$$

and

$$(1 - \gamma_1)(g - \delta_0 - \delta_1 G - n) - \gamma_0 - \gamma_2(\zeta u - \bar{\lambda}) = 0. \tag{12}$$

Both are implicit equations between  $G$  and  $\zeta$ . In the jargon they are “nullclines” summarizing combinations of the state variables that hold  $\dot{\kappa} = 0$  and  $\dot{\zeta} = 0$ . Points of intersection of nullclines define overall steady states, if they exist.

Fig. 2 gives a graphical representation. The effect of  $G$  on  $\dot{\zeta}$  is negative due to increased depreciation and slower capital accumulation so Eq. (12) has a negative slope in the  $(G, \zeta)$  plane. Along this nullcline a higher  $G$  would be associated with lower  $\zeta$ . The small arrows signal how  $\zeta$  evolves. For example, if it lies above the nullcline then  $\zeta$  decreases ( $\kappa$  grows less rapidly than  $\xi$ ) until  $\dot{\zeta} = 0$ .

Eq. (6) is a relationship among three variables —  $\kappa$ ,  $G$ , and  $\zeta$ . It can be interpreted in at least two ways. If  $G$  is held constant,  $\zeta$  is set by Eq. (12) while  $\kappa$  has to be determined from Eq. (6) as a function of  $G$  and  $\zeta$ . In Fig. 2 different levels of  $\kappa$  are plotted along contour lines. Since capital stock growth is reduced by higher levels of both state variables, lines further toward the right correspond to lower, and eventually negative, levels of  $\kappa$ .

A stable configuration of the nullclines is shown in Fig. 2. In Eq. (8)  $\dot{\zeta}$  is not strongly affected by  $G$  so the nullcline has a shallow slope. In Eq. (6)  $G$  has a stronger negative impact than  $\zeta$  on  $\kappa$  so the contour lines are relatively steep. Under such circumstances, a high level of  $G$  is associated with relatively low levels of  $\zeta$  and  $\kappa$  along the isocline for  $\kappa$ . In other words, higher GHG concentration leads to slower growth in the long run. With a low  $\zeta$ , productivity is high relative to capital implying that employment is low and the profit rate high.

Bringing in dynamics of  $G$ , if  $\theta(m) = 1$  in Eq. (10), then  $\dot{G}$  is driven solely by natural or pre-industrial emissions. As  $G$  decreases  $\kappa$  would speed up, raising steady state  $\zeta$  and shifting the equilibrium point  $S_p$  to

<sup>8</sup> Taylor et al. (2016) present the details of a similar demand-driven model of endogenous productivity and wealth distribution.

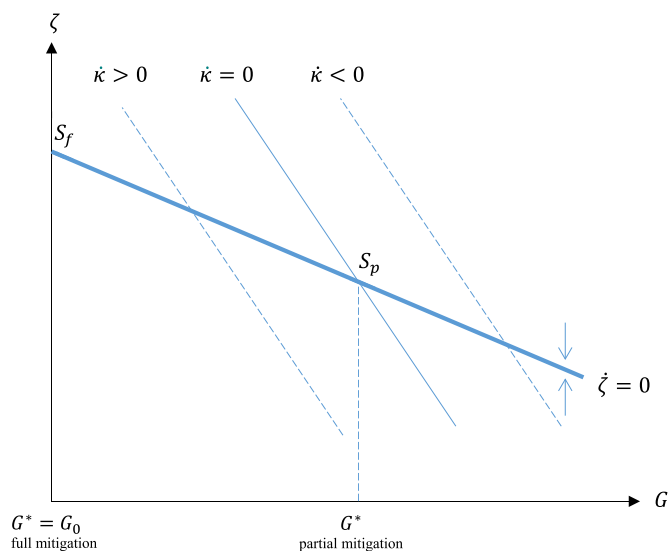


Fig. 2. The heavy lines are nullclines for  $\kappa$  and  $\zeta$ , with a steady state at point  $S_p$ . Contour lines for  $\dot{\kappa}$  as a function of  $G$  and  $\zeta$  are lightly shaded, with lower levels of  $\dot{\kappa}$  along contours further to the right.

the left. With a small  $\omega$ , climate damage would abate, over centuries, moving toward the “full mitigation” equilibrium  $S_f$  in Fig. 2, at which steady state  $G^*$  reaches a sustainable pre-industrial level  $G_0 = H_0/\omega$ .

In the far more realistic case of partial mitigation with  $\theta(m) < 1$ , both  $\zeta$  and  $G$  can arrive at steady states illustrated by the intersection of the nullclines Eqs. (11) and (12) or point  $S_p$  in Fig. 2. Steady state  $\kappa$  has yet to be determined. That's where the GHG accumulation Eq. (10) comes in. We already observed that the partial derivatives of  $\dot{G}$  with respect to  $\zeta$  and  $G$  are negative. With  $\dot{G}_G < 0$ , Eq. (10) is a locally stable differential equation. In a Malthusian touch,  $\dot{G}$  increases with population  $N$ . Unless mitigation can rise indefinitely to offset growing population the implication is that ultimately the system must arrive at a stationary state with  $\dot{G} = \dot{\kappa} = \dot{\zeta} = n = 0$ . The level of  $\kappa$  follows from the nullcline for  $\dot{G} = 0$  which is

$$[1 - \theta(m)]\chi N u \kappa C \zeta^{v-1} - \omega G = 0. \tag{13}$$

Because as discussed in connection with Fig. 2,  $\dot{\kappa}_G < 0$  there is inherent cyclicity between  $\kappa$  and  $G$ . Such cyclical dynamics imply an overshooting of levels of atmospheric carbon and the likelihood of a climate crisis to halt economic growth.

A final question is whether the three-dimensional system is stable overall. As discussed below, with plausible numerical values the model can converge to a stationary state. As background, qualitative judgment helps clarify the process. At a stationary state, on the assumptions we have made the system's Jacobian takes the form

	$\kappa$	$\zeta$	$G$
$\dot{\kappa}$	0	$\dot{\kappa}_\zeta < 0$	$\dot{\kappa}_G < 0$
$\dot{\zeta}$	0	$\dot{\zeta}_\zeta < 0$	$\dot{\zeta}_G < 0$
$\dot{G}$	$\dot{G}_\kappa > 0$	$\dot{G}_\zeta < 0$	$\dot{G}_G < 0$

Local stability is determined by three “Routh-Hurwitz conditions.” The first is that the Jacobian should have a negative trace. It is satisfied on our assumptions. The second is that the determinant should be negative. This condition is satisfied as long as the nullclines take the form in Fig. 2. The third condition is difficult to verify qualitatively. It states that the sum of the three principal sub-determinants must exceed the ratio of the determinant to the trace. As verified by the simulation results just below, it is likely to hold unless there is particularly strong feedback between the concentration of atmospheric carbon and the

employment-utilization ratio.

### 3. Simulations of a Calibrated Model

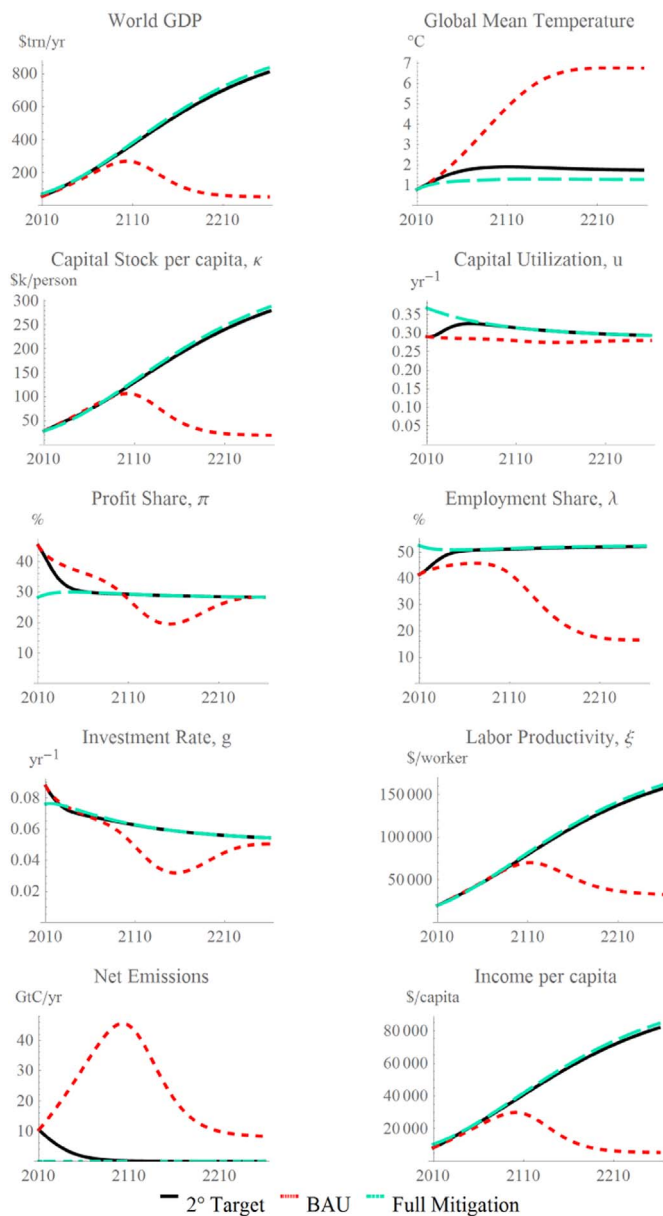
Analytically we have shown that, in the absence of ambitious climate policy, the economy may go through boom-and-bust cycles. In ecology, this behavior is known as predator-prey dynamics. Since output is prey with a slow recovery rate from Eq. (6), the cycles are likely to be damped. In this section we use a parameterized model calibrated to the world economy to study the dynamics numerically. Atmospheric temperature (degrees Celsius) is used instead of CO<sub>2</sub> concentration to measure the impact of global warming. Following Nordhaus (2014), more complicated GHG dynamics replace Eq. (10), making responsiveness of the model a bit “slower” than in our simple specification.<sup>9</sup> Population is assumed to rise from 7 to 9 billion at the end of the century, stabilizing at 10 billion. The exogenous component of labor productivity grows at 1% per year initially but tends to zero over time.

Fig. 3 presents the simulations of growth and climate change for different levels of mitigation. There are three scenarios: (i) “BAU” (red, short-dashed) where no emission abatement takes place, (ii) “2 °C target” (black, solid) has the share of unabated emissions falling 6% per year such that temperature stays within 2 °C, and (iii) Full Mitigation” (green, long-dashed) holds new emissions equal to zero from the start. The cost of the “2 °C” scenario peaks at 3% of GDP at mid-century and falls thereafter. Full mitigation costs significantly more, starting at 6% of GDP initially and falling to 3% by the end of the century and 2% by 2150.

The economy grows at 3% per year initially in all scenarios but the trajectories quickly diverge. In the “BAU” run, rapid growth generates high net emissions which translate into rising global mean temperature, surpassing 4 °C at the end of the century and stabilizing at 7 °C in 300 years. As temperature rises and climate damages increase, the profit rate falls. Investment levels are insufficient to maintain aggregate demand and unemployment results. After this boom-bust cycle, output is back to its current level after 200 years but due to increases in labor productivity, employment relative to population falls from 40% to 15%. With the profit share fairly stable, this shift implies significant redistribution for working households. Those lucky enough to find employment are paid almost three times the current wage rate, but the others have to rely on subsistence income or public transfers. Only in the very long run, as labor productivity falls in response to rampant unemployment, can employment levels recover. But then the same amount of income spreads across more workers, since the overall size of the economy is limited by the climate constraint.

Mitigation allows the economy to avoid stagnation. In the “2 °C target” scenario, fiscal outlays are slowly ramped up. The 2 °C mitigation scenario allows the economy to continue its growth path with steady increases in the income per capita and growing employment. The transition to the steady state with higher levels of capital and lower profit rates is smooth without the disruption of a climate crisis. The full mitigation version does better at controlling warming than the 2 °C scenario, but implies higher cost. Given that the economy of our model is demand-constrained this tax-and-mitigate policy increases output, employment, and growth. This full mitigation scenario, in which all emissions cease immediately, fares better environmentally and economically but is dubious technically and even more so institutionally.

<sup>9</sup> We use the climate dynamics of DICE to increase the comparability of our results. From a scientific perspective a more detailed representation of all greenhouse gases (not just CO<sub>2</sub>) would be desirable. The numerical model also allows for non-linear specifications of climate damages, again, following Nordhaus (2014). The Appendix discusses how the numerical and analytical models differ and provides a complete list of equations and parameter values. Given the assumption that economic institutions will remain constant over the complete time horizon, these simulations like all others have to be deemed illustrative.



**Fig. 3.** Illustrative simulations of the demand-driven model of economic growth and climate change. Climate policy which limits peak warming to 2 °C (black, solid) or 1.3 °C (green, long-dashed) permits the economy to continue its current pattern of exponential growth with increasing levels of income and high levels of employment. Under BAU (red, short-dashed), the economy follow its current pattern for several decade while global mean temperature rapidly increases. Climate damage lowers profitability, output, capital accumulation and employment drastically. In equilibrium, income levels and labor productivity are low while temperature stabilizes at 7 °C.

**4. Discussion by Way of a Conclusion**

This paper supplements existing attempts to integrate economic and geophysical modeling of climate damage by focusing specifically on the impacts of climate change on the demand side of the economy. This is an important aspect because much of the existing literature makes the controversial assumption that economic institutions automatically lead to the full utilization of productive resources, and because many impacts of climate change immediately affect demand and the distribution

**Appendix A**

Numerical simulations are based on an extended model which allows for taxation, non-linear effects of climate change, and a more realistic

of income, which is closely related to demand. Our demand-driven growth framework allows us to study the medium- to long-run impacts of climate damage and mitigation on variables like the utilization rate, unemployment, and wages. The endogenous processes of labor productivity growth, distribution, and employment are essential to our analysis. This allows us to model the economic growth (i.e. growth in income) as an outcome generated in capitalist societies by policies rather than a policy variable itself.

As an anonymous referee for this journal usefully points out, there is a considerable difference in the credibility of the BAU and mitigation scenarios in our simulations. The BAU scenario implies that the world economic/geophysical system will encounter unprecedented conditions, such as a 7 °C average temperature increase, for which we have little or no empirical historical evidence. We present these BAU simulations as a tentative attempt to quantify the unquantifiable, and to identify key points, both economic and geophysical, where major contradictions are likely to occur. These contradictions might involve catastrophic non-linear geophysical responses to extreme economic stresses, but equally well might involve revolutionary changes in the institutions that at present organize world economic production due to geophysical stresses.

We believe our mitigation scenarios are more robust precisely because they stay closer to the range of geophysical and economic conditions about which we have some empirical historical evidence. The main question hanging over the mitigation simulations is how much stress a shift to a low (essentially zero) carbon-dioxide emitting economic regime might put on existing economic institutions. We make the somewhat optimistic assumption that improvements in non-emitting technologies and gradual adoption of carbon-free energy sources will make this transition feasible, if admittedly challenging. The allowances in our mitigation scenarios for direct expenditures on mitigation (our broad concept for all measures to reduce emissions per unit of economic output) are quite large in absolute terms, although at 3–6% of world economic output fairly small in relative terms.

The key point, however, is that mitigation allows the economy to avoid economic stagnation and climate catastrophe, and therefore keeps both economic and geophysical conditions closer to historically known levels. We believe that an important and robust lesson from our modeling exercise is to underline that strong efforts at mitigation of global climate change need not be antagonistic to economic performance or economic interests as measured by the traditional gauges of wage and profit incomes, employment and growth of the output of useful economic goods and services.

The BAU scenario underlines this same conclusion from a somewhat different point of view. If technological options for decarbonization are either unavailable or not deployed, economic output will have to be stabilized by a climate crisis, in ways that will be very unfavorable to traditional economic indicators such as level and growth of output, distribution, and employment. In the mitigation scenarios, the control of CO<sub>2</sub> emissions essential to avoid a crisis beginning a few decades in the future does take place, and our simulations support the conclusion that this level of mitigation can in fact improve economic performance measured by traditional indicators. Environmental and social-economic policy goals are mutually reinforcing so long as serious climate policy is implemented.

Either way, controlling CO<sub>2</sub> is essential to avoid a crisis beginning a few decades in the future. Environmental and social goals are not mutually exclusive so long as serious climate policy is implemented. If technological options for decarbonization are either unavailable or not deployed, output will have to be stabilized by a climate crash.

representation of climate and population dynamics. Notation follows the main text. Our economy is calibrated to 2010 with global output of \$60 trillion and capital stock of \$200 trillion. Population is 6 billion people, employment roughly 3 billion, and global energy use per person about 2.5 kW/person (Semieniuk, 2016). Initial values for the climate system are taken from Nordhaus (2014). The parameters  $g_0$  and  $\Phi$  are calibrated to give  $u = 0.3$  and  $\pi = 0.4$  initially. Taylor et al. (2017) provide supporting data for base year calibration.

Variables

<b>Pop</b>	Population
<b>u</b>	Output – capital ratio: output per capital
<b>ξ</b>	Labor productivity: output per worker
<b>ε</b>	Energy productivity: output per energy unit
<b>λ</b>	Employment share: workers/total population
<b>π</b>	Profit share: share of profits in income
<b>κ</b>	Capital – population ratio: capital per capita
<b>q</b>	Energy per worker
<b>X</b>	Output
<b>g</b>	Investment rate: growth rate of capital
<b>s</b>	Saving rate: share of saving in income
<b>T<sub>atm</sub></b>	Atmospheric temperature
<b>Z</b>	Climate damage, 1 – Z is % lost due to climate change

Parameters

<b>m</b>	Scenario-dependent	Mitigation share (% of GDP)
<b>τ</b>	30%	Tax share (% of GDP)
<b>s<sub>c</sub></b>	70%	Saving propensity out of profits
<b>s<sub>w</sub></b>	5%	Saving propensity out of wages
<b>β</b>	10%	Government expenditure (% of capital)
<b>g<sub>0</sub></b>	– 0.033	Autonomous investment demand (scaled to capital stock), see calibration section below
<b>g<sub>u</sub></b>	0.1	Investment response to higher output
<b>g<sub>r</sub></b>	0.7	Investment response to higher profitability
<b>δ</b>	5%	Depreciation rate of capital
<b>A</b>	2	Employment share elasticity of the profit share
<b>B</b>	2	Climate damage elasticity of the profit share
<b>Φ</b>	0.2792	damage parameter, see calibration section below
<b>n<sub>0</sub></b>	0.015	population parameter, calibrated to give 0.5% initial growth
<b>γ<sub>0</sub></b>	0.01 0.99 <sup>t</sup>	Exogenous productivity growth, falling at 1%/year
<b>γ<sub>1</sub></b>	0.5	Kaldor-Verdoorn effect
<b>γ<sub>2</sub></b>	0.005	Kennedy-Weitzsäcker effect
<b>λ̄</b>	0.5	Goodwin-neutral employment share
<b>ν</b>	1	Elasticity between labor productivity and energy use

Initial conditions

<b>Pop</b>	7 billion
<b>κ</b>	200 \$T/7 billion
<b>ξ</b>	60 \$bn/3 billion
<b>q</b>	2.5 kW/person

With definitional identities

$$\lambda[t] = \frac{\kappa[t]u[t]}{\xi[t]}$$

$$u[t] = \frac{X[t]}{\kappa[t]Pop[t]}$$

$$s[t] = s_w(1 - \pi[t]) + s_p\pi[t]$$

$$\varepsilon[t] = \xi[t]/q[t]$$

we can define the short run equilibrium

$$X[t] = m X[t] + (1 - \tau - s[t])X[t] + \beta Pop[t] \kappa[t] + g[t] Pop[t] \kappa[t]$$

$$g[t] = g_0 + g_u u[t] + \alpha u[t] \pi[t]$$

$$\pi[t] = (\Phi Z[t])^B (\lambda[t])^{-A}.$$

Note that in the numerical model, the profit share is a non-linear function of the labor market and climate damages. Aggregate demand now also includes government taxation and non-mitigation expenditure (which is scaled to capital stock rather than GDP to match empirically observed effects of expenditure on output).

Given the short run equilibrium, we can turn to the dynamic equations of the model just below. The first equation is exogenous population growth, which follows logistic growth with maximum population set to 10 billion. With  $n[t] = \mathit{Pop}[t]/\mathit{Pop}[t]$  equal to population growth, the second equation reproduces Eq. (6) from the main text. The last two equations restate Eq. (7) and the energy-labor productivity nexus from the text.

$$\dot{\mathit{Pop}}[t] = n_0 \left( 1 - \frac{\mathit{Pop}[t]}{10} \right) \mathit{Pop}[t]$$

$$\dot{\kappa}[t] = \kappa[t] \left( g[t] - \delta - \frac{\dot{\mathit{Pop}}[t]}{\mathit{Pop}[t]} \right)$$

$$\dot{\xi}[t] = \xi[t] (\gamma_0 + \gamma_1 \kappa[t]/\kappa[t] + \gamma_2 (\lambda[t] - \bar{\lambda}))$$

$$\dot{q}[t] = \frac{q[t] \dot{\xi}[t]}{v \xi[t]}$$

Our climate model is taken from the DICE model (Nordhaus, 2014) and parameterized to an annual scale (Rezai and van der Ploeg, 2017). In the carbon cycle, carbon diffuses between the atmosphere ( $M_{AT}$ ), and the upper ( $M_{UP}$ ) and lower ( $M_{LO}$ ) parts of the oceans following a Markov process. Higher levels of atmospheric carbon increase radiative forcing, which directly increases global atmospheric temperature,  $T_{atm}$ , while some of this additional energy is taken up by the ocean over time, increasing oceanic temperature,  $T_{LO}$ . The exogenous forcing component increases linearly from 0 W/m<sup>2</sup> to 0.45 W/m<sup>2</sup> at the end of the century. Emissions,  $(1 - \theta) \frac{\chi[t] X[t]}{\varepsilon[t]}$ , are calibrated to 10 GtC initially. The dynamics of carbon intensity,  $\chi[t]$ , are also taken from DICE.

$$\begin{pmatrix} M_{AT}[t] \\ M_{UP}[t] \\ M_{LO}[t] \end{pmatrix} = (1 - \theta) \frac{\chi[t] X[t]}{\varepsilon[t]} \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} + \Xi \begin{pmatrix} M_{AT}[t-1] \\ M_{UP}[t-1] \\ M_{LO}[t-1] \end{pmatrix}$$

$$\begin{pmatrix} T_{atm}[t] \\ T_{LO}[t] \end{pmatrix} = Y \begin{pmatrix} T_{atm}[t-1] \\ T_{LO}[t-1] \end{pmatrix} + \Theta \left( \frac{\eta_2 \text{Ln} \left[ \frac{M_{AT}[t]}{M_{AT1750}} \right]}{\text{Ln}[2]} + F_{EX}[t] \right)$$

with

$$\Xi = \begin{pmatrix} 0.981436 & 0.0080939 & -1.123 \cdot 10^{-6} \\ 0.018583 & 0.991397 & 0.0000687 \\ -1.91 \cdot 10^{-5} & 0.0005089 & 0.999932 \end{pmatrix}.$$

$$Y = \begin{pmatrix} 0.970932 & 0.00535475 \\ 0.00184718 & 0.99493 \end{pmatrix}.$$

$$\Theta = \begin{pmatrix} 0.0207734 \\ -0.0002172 \end{pmatrix}.$$

The damage function of DICE is adapted to account for potentially catastrophic losses at high levels of temperature (Ackerman and Stanton, 2012),

$$Z[t] = \frac{1}{1 + 0.00245 T_{atm}[t]^2 + 0.000005021 T_{atm}[t]^{6.76}}.$$

Fig. A.1 plots the mitigation shares (panel a) and the associated mitigation expenditures (panel b). used in the scenarios in Fig. 3.



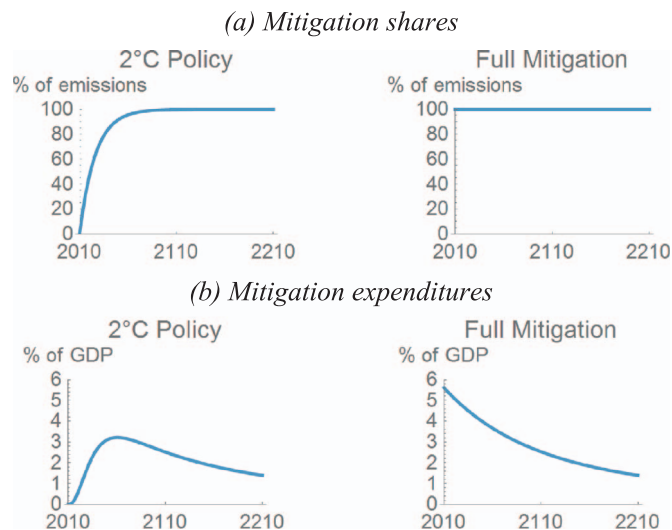


Fig. A.1. Mitigation shares and expenditures for the two mitigation scenarios.

## References

- Ackerman, Frank, Stanton, Elizabeth, 2012. Climate risks and carbon prices: revising the social cost of carbon. *Economics* 6 (2012-10).
- Ayres, Robert U.B., Warr, Benjamin, 2009. *The Economic Growth Engine: How Energy and Work Drive Material Prosperity*. Edward Elgar Publishing, Cheltenham.
- Barbosa-Filho, Nelson H., Taylor, Lance, 2006. Distributive and demand cycles in the U.S. Economy – a structuralist Goodwin model. *Metroeconomica* 57, 389–411.
- Cleveland, Cutler, Constanza, Robert, Hall, Charles, Kaufmann, Robert, 1984. Energy and the U.S. Economy: a biophysical perspective. *Science* 225 (4665), 890–897.
- Domar, Evsey D., 1946. Capital expansion, rate of growth, and employment. *Econometrica* 14, 137–147.
- Foley, Duncan K., 2012. Dilemmas of economic growth. *East. Econ. J.* 38, 283–295.
- Georgescu-Roegen, Nicholas, 1975. Energy and economic myths. *South. Econ. J.* 41 (3), 347–381.
- Goodwin, Richard M., 1967. A growth cycle. In: Feinstein, C.H. (Ed.), *Socialism, Capitalism, and Growth*. Cambridge University Press, Cambridge.
- Hall, Charles, Lambert, Jessica, Balogh, Stephen, 2014. EROI of different fuels and the implications for society. *Energy Policy* 64, 141–152.
- Harrod, Roy F., 1939. An essay in dynamic theory. *Econ. J.* 49, 14–33.
- Kaldor, Nicholas, 1957. A model of economic growth. *Econ. J.* 67, 591–624.
- Kaldor, Nicholas, 1966. *Causes of the Slow Rate of Economic Growth of the United Kingdom: An Inaugural Lecture*. Cambridge University Press, Cambridge UK.
- Kennedy, Charles, 1964. Induced bias in innovation and the theory of distribution. *Econ. J.* 74, 541–547.
- Kiefer, David, Rada, Codrina, 2015. Profit maximizing goes global: the race to the bottom. *Camb. J. Econ.* 39, 1333–1350.
- Lavoie, Marc, 2014. *Post Keynesian Economics: New Foundations*. Edward Elgar, Northampton MA.
- Nordhaus, William, 2014. Estimates of the social cost of carbon: concepts and results from the DICE-2013R model and alternative approaches. *J. Assoc. Environ. Resour. Econ.* 1, 273–312.
- Rezai, Armon, Stiglitz, Sigrid, 2016. Ecological Macroeconomics: Introduction and Review. *Ecol. Econ.* 121, 181–185.
- Rezai, Armon, van der Ploeg, Frederick, 2017. Climate policies under climate model uncertainty: max-min and min-max regret. *Energy Econ* (forthcoming).
- Rezai, Armon, Taylor, Lance, Mechler, Reinhard, 2013. Ecological Macroeconomics: An application to climate change. *Ecol. Econ.* 85, 69–76.
- Semieniuk, Gregor, 2016. Fossil energy in economic growth: a study of the energy direction of technical change, 1950–2012. In: University of Sussex: SPRU - Science Policy Research Unit Working Paper 2016-11.
- Smith, Adam (1776) *The Wealth of Nations*, New York: Modern Library (reprint; 1994).
- Solow, Robert M., 1956. A contribution to the theory of economic growth. *Q. J. Econ.* 70, 65–94.
- Taylor, Lance, 2004. *Reconstructing Macroeconomics: Structuralist Proposals and Critiques of the Mainstream*. Harvard University Press, Cambridge, MA.
- Taylor, Lance, 2008. energy productivity, labor productivity, and global warming. In: Harris, Jonathan M., Goodwin, Neva R. (Eds.), *Twenty-first Century Macroeconomics: Responding to the Climate Challenge*. Edward Elgar, Northampton MA.
- Taylor, Lance, Foley, Duncan K., Rezai, Armon, 2016. Demand drives growth all the way. In: *SCEPA Working Paper No. 2016-04*, . [http://www.economicpolicyresearch.org/images/docs/research/economic\\_growth/2016-4\\_Demand\\_Drives\\_Growth\\_All\\_The\\_Way.pdf](http://www.economicpolicyresearch.org/images/docs/research/economic_growth/2016-4_Demand_Drives_Growth_All_The_Way.pdf).
- Taylor, Lance, Rezai, Armon, Kumar, Rishabh, Barbosa, Nelson, Carvalho, Laura, 2017. Wage increases, transfers, and the socially determined income distribution in the USA. *Rev. Keynesian Econ.* 5, 259–275.
- Waggoner, Paul, Ausubel, Jesse, 2002. A framework for sustainability science: a renovated IPAT identity. *PNAS* 99, 7860–7865.
- von Weizsäcker, Carl, 1966. Tentative notes on a two-sector model with induced technical progress. *Rev. Econ. Stud.* 33, 245–252.