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Comprehensive National Accounting for Carbon Emissions

Abstract

We consider the question of how to integrate carbon emissions in comprehensive national accounts for the purpose of indicating whether countries' development is sustainable. We derive an expression for national saving which includes not only the national effect of current global emissions, but also the future expected paths of emissions nationally and in the rest of the world. We illustrate how the use of our expression for national saving alters the empirical conclusions concerning the sustainability of countries, as compared to the World Bank estimates. Our calculations account for the fact that future prospects of developing countries are more affected by the global carbon emissions than they themselves affect others by their own low per capita emissions. They are thus deemed less sustainable when using our indicator. This information suggests shifting the burden of climate policies away from such countries.

JEL-Codes: C430, D630, O470, Q010.

Keywords: climate change, comprehensive national accounting, carbon emissions.

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1 Introduction

Comprehensive or inclusive national accounting seeks to incorporate all changes in capital stocks that will influence the future prospects of nations, for the purpose of indicating whether their trajectories are sustainable. The World Bank has regularly published accounts that show to what extent the saving behavior of countries indicates that their development is sustainable. Comprehensive national accounting seeks to take into account not only accumulation of reproducible capital, but also the effects in terms of knowledge accumulation, natural resource depletion and environmental degradation (World Bank, 2021).

Some of the emissions leading to environmental degradation are transnational externalities. Carbon emissions are a prime example of this, as the effect of CO_2 accumulation in the atmosphere does not depend on where the CO_2 has been emitted. The purpose of this paper is to investigate how to incorporate carbon emissions in comprehensive national accounts. We limit our analysis to carbon emissions, to allow for a transparent exposition of the principles involved and to enable us to present illustrative estimations of the empirical effects. However, other greenhouse gases can be treated in a similar manner.

In the literature there are essentially two positions on this issue: Hamilton (2012) and the World Bank's *World Development Indicators* estimates take account of the global effects of national emissions as a negative component of national saving, highlighting the responsibility that each country has for *behaving sustainably* by taking account of the consequences of its own emissions. In contrast, Arrow et al. (2012, 2013) argue that the relevant impact on the *actual experienced sustainability* of a national economy is the national effects of global emissions, as this is an exogenous effect on the economy that influences its future prospects. In our analysis we agree with the latter view that the national effects of global emissions are more relevant than the global effects of national emissions when trying to indicate whether the well-being experienced by the people living in an economy is sustainable. In particular, it is the global emissions that affect the economy's ability to generate well-being for its population.

However, our analysis also points to the importance of the future paths of emissions that the economy itself and the rest of the world will follow. If the economy can be expected to follow a pledge (e.g., through the *nationally determined contributions* of the UNFCCC process) to rapidly reduce its own emissions, then it must compensate for future increased mitigation costs by accumulating additional reproducible capital now to ensure that its investment behavior is sustainable, to the extent that these mitigation costs exceed the national benefits of lower future adaptations costs. Likewise, if other countries will continue to increase emissions in the future, current capital investment must increase to compensate for the increased future adaptation costs. In general, pledges and commitments to global and national targets, whether they concern carbon emissions or biodiversity, work like additional constraints on how economies evolve in the future. As we will show, this in turn leads to additional forward-looking terms in the expression of national saving as an indicator of sustainability.

We start out in Section 2 by presenting the concepts of income and saving that underlie the analysis. Then, in Section 3, we present the model in which we derive an expression for national saving for the purpose of indicating an economy's sustainability. This expression includes not only the national effect of current global emissions, but also the future expected paths of changes in emissions nationally and in the rest of the world. We allow for the possibility that net national marginal cost of reducing carbon emissions might be smaller than the sum of the social cost of carbon elsewhere, implying that the climate policies are not globally efficient. We show, however, in Section 4, that our expression for national saving is consistent with the case of globally efficient climate policies. In Section 5 we consider several generalizations, while we, in Section 6 illustrate how the use of our expression of national saving alters the empirical conclusions concerning the sustainability of countries, as compared to the World Bank estimates. We end in Section 7 by offering concluding remarks, with an appendix containing derivations of the national social cost of carbon under discounted utilitarianism.

2 What is income and saving?

In the context of a closed economy with stationary technology, income can be derived from net national product (NNP), measuring the value of the flows of goods and services that are produced by the productive assets of society, while saving equals the value of net investments, being the part of NNP that is not consumed. Income and saving derived in this way have also welfare significance, as established by Weitzman (1976) and later references (e.g., Aronsson, Johansson, and Löfgren, 1997; Aronsson, Löfgren, and Backlund, 2004; Asheim and Weitzman, 2001). Furthermore, NNP (as a cap on consumption) and the value of net investments (being non-negative) can serve as imperfect indicators of sustainability. However, in an open economy — experiencing changing technology, terms-of-trade, and climatic conditions — it might be hard to base income and saving on net product and value of net investments, since much of the return on the sector's assets may derive from expected capital gains or losses. In particular, if a country's productive capacity is reduced as a result of a deteriorating climate, then such dissaving will not be captured by negative net investments. This motivates a brief survey of relevant literature on income concepts, following Asheim and Wei (2009, Sections 2–3).

Income in the tradition of Fisher (1906) and Lindahl (1933, Section II) is defined as interest on wealth, where wealth is the present value of future consumption. Hicks (1946), in Chapter 14 of *Value and Capital*, suggests that "the practical purpose of income is to serve as a guide for prudent conduct" by giving "people an indication of the amount which they can consume without impoverishing themselves", thus, "it would seem that we ought to define a man's income as the maximum value which he can consume during a week, and still expect to be as well off at the end of the week as he was at the beginning." (all quotes from Hicks, 1946, p. 172). As Hicks (1946, p. 174) points out, income as interest on wealth is not an indicator of prudent behavior if the real interest rate is expected to change.[1]

An attractive alternative, suggested by Pemberton and Ulph (2001) and Sefton and Weale (2006), is to associate "as well off" with maintaining the level of dynamic welfare. This signifies that prudent behavior corresponds to non-decreasing dynamic welfare, which can then be used as the indicator for no impoverishment — or sustainable development in current parlance. By combining this approach with an insight first pointed out by Samuelson (1961, pp. 51–52) — namely, that the present value of future changes in consumption measures welfare improvement in a market economy following an optimal path — gives a welfare foundation for defining the present value of future consumption changes as national saving.

Saving as the present value of future changes in consumption is an approximate measure of sustainability in same way as the value of net investments is an imperfect sustainability indicator in the case of a closed economy with constant technology.[2] Adding the value of current consumption to this notion of saving (measured in the same numeraire) leads to a concept of national income

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[1] This observation is nicely illustrated by the Dasgupta-Heal-Solow model (Dasgupta and Heal, 1974, 1979; Solow, 1974) of capital accumulation and resource depletion where the real interest rate is decreasing along a path where capital is accumulated and resource flow diminishes. In this model, income as interest on wealth exceeds both net national product and consumption along an efficient path with constant consumption. Hence, in this setting, the consumers of the economy would impoverish themselves if they were consuming the interest on their wealth.

[2] Such a *genuine saving indicator* (Hamilton and Clemens, 1999) is imperfect as reproducible capital accumulation compensating in value for natural capital depletion is not compatible with sustainable development if the reduced availability of natural capital undermines long-run livelihood, in line with the *strong sustainability* paradigm.

with nice properties, as shown by the following calculations.

Consider a national economy, where $\mathbf{C}$ is a comprehensive vector of consumption flows, implying that all determinants of current well-being are included in $\mathbf{C}$. Let $\{\mathbf{C}(t)\}_{t=0}^{\infty}$ be the path of consumption flows in this economy, and let $\{\mathbf{p}^C(t)\}_{t=0}^{\infty}$ be the corresponding path of market (or calculated) *present value* prices of consumption. The term 'present value' signifies that prices are discounted values. In particular, if relative consumption prices are constant throughout and there is constant real interest rate R, then it holds that $\mathbf{p}^C(t) = e^{-Rt}\mathbf{p}^C(0)$. Differentiation of $\mathbf{p}^C(t)\mathbf{C}(t)$ yields

$$\tfrac{d}{dt}\big(\mathbf{p}^C(t)\mathbf{C}(t)\big) = \dot{\mathbf{p}}^C(t)\mathbf{C}(t) + \mathbf{p}^C(t)\dot{\mathbf{C}}(t)\,.$$

Integrating on both sides under the assumption that $\mathbf{p}^C(T)\mathbf{C}(T) \to 0$ as $T \to \infty$, leads to the following equation:

$$-\mathbf{p}^C(t)\mathbf{C}(t) = \int_t^\infty \dot{\mathbf{p}}^C(\tau)\mathbf{C}(\tau)d\tau + \int_t^\infty \mathbf{p}^C(\tau)\dot{\mathbf{C}}(\tau)d\tau\,.$$

By rearranging this equality we obtain

$$\underbrace{\int_t^\infty \big(-\dot{\mathbf{p}}^C(\tau)\big)\mathbf{C}(\tau)d\tau}_{\text{National income}} \quad = \quad \mathbf{p}^C(t)\mathbf{C}(t) \quad + \quad \underbrace{\int_t^\infty \mathbf{p}^C(\tau)\dot{\mathbf{C}}(\tau)d\tau}_{\text{National saving}}\,. \tag{1}$$

Based on the following arguments, we will interpret the l.h.s. as *national income* at time t and the second term on the r.h.s. as *national saving* at time t.

It follows from the reasoning of Samuelson (1961, pp. 51–52) that $\int_t^\infty \mathbf{p}^C(\tau)\dot{\mathbf{C}}(\tau)d\tau$ — the present value of future changes in consumption — measures welfare improvement in a market economy following an optimal path. A more general statement of this result is proven in Appendix A of Asheim and Wei (2009, Proposition 4). In particular, we need not assume that the dynamic welfare is discounted utilitarian. Moreover, by allowing for the possibility that the prices are calculated, we need not assume that the economy implements a welfare maximizing path of consumption flows through an intertemporal market equilibrium.

This provides the welfare foundation for defining $\int_t^\infty \mathbf{p}^C(\tau)\dot{\mathbf{C}}(\tau)d\tau$ as national saving. Then, if national income is to serve as a guide for prudent conduct in the sense that dynamic welfare improves if and only if national consumption is smaller than national income, we obtain that national income equals $\mathbf{p}^C(t)\mathbf{C}(t) + \int_t^\infty \mathbf{p}^C(\tau)\dot{\mathbf{C}}(\tau)d\tau$. By (1), this expression can be transformed to $\int_t^\infty \big(-\dot{\mathbf{p}}^C(\tau)\big)\mathbf{C}(\tau)d\tau$, which can be interpreted as the present value of future interest on consumption.

If an economy implements a path with constant instantaneous well-being and the vector of consumption prices $\mathbf{p}^C(t)$ is at any time proportional to the contributions that the various consumption flows make to instantaneous well-being, then it follows that $\mathbf{p}^C(t)\dot{\mathbf{C}}(t) = 0$ at all times. Hence, national income equals the value of consumption and shows that this concept of income serves as a guide for prudent conduct also in this special case.

The analyses of Sefton and Weale (1996) and Weitzman (2003, Chapter 6) show that such a concept of national income equals net national product in a closed economy with a stationary technology. In particular, if the technology is stationary and the economy realizes a competitive equilibrium, then it follows from Dixit, Hammond, and Hoel (1980, proof of Theorem 1) that

$$\mathbf{p}^C(t)\dot{\mathbf{C}}(t) + \tfrac{d}{dt}\big(\mathbf{p}^K(t)\dot{\mathbf{K}}(t)\big) = 0\,,$$

where $\{\mathbf{K}(t)\}_{t=0}^{\infty}$ is the path of the vector of capital stocks in this economy and $\{\mathbf{p}^K(t)\}_{t=0}^{\infty}$ is the corresponding path of market (or calculated) present value prices of net investment flows.

Integrating on both sides under the assumption that $\mathbf{p}^K(T)\dot{\mathbf{K}}(T) \to 0$ as $T \to \infty$, entails that the following equation holds for all t:

$$\int_t^{\infty} \mathbf{p}^C(\tau)\dot{\mathbf{C}}(\tau)dt = \mathbf{p}^K(t)\dot{\mathbf{K}}(t)\,.$$

Combined with (1) we obtain:

$$\underbrace{\int_t^{\infty} \big(-\dot{\mathbf{p}}^C(\tau)\big)\mathbf{C}(\tau)d\tau}_{\text{National income}} \quad = \quad \underbrace{\mathbf{p}^C(t)\mathbf{C}(t) + \mathbf{p}^K(t)\dot{\mathbf{K}}(t)}_{\text{Net national product}}\,. \tag{2}$$

Hence, national income as defined through (1) equals net national product under the assumptions of the technology being stationary and the economy realizing a competitive equilibrium.

However, the fact that real national economies experience technological progress, changing terms-of-trade, and a changing climate makes equation (2) less useful in empirical applications. In such settings, we argue, it seems more straightforward to base the notion of national saving directly on the present value of future changes in consumption — as in equation (1) — and derive expressions in terms of the value of net investments and the influence of exogenous factors on this basis. This is how we proceed in the subsequent section.

3 Model

We present a simple model designed to clearly illustrate principles for how to incorporate carbon emissions in national accounts for the purpose of defining national saving as an approximate measure of national sustainability. Based on the theoretical background presented in Section 2, we do so by associating national saving with the the present value of future changes in consumption. Furthermore, to highlight the effects of incorporating carbon emissions, we abstract from other issues that complicate comprehensive national accounting by assuming no technological progress, no population growth, and only one consumption good. The issues of improving technology, growing population, and changing terms-of-trade must, however, be faced before bringing these principles to empirical application and will be addressed in Section 5.

Consider a national economy i whose net production depends on its stock of reproducible capital K_i, its carbon emissions E_i, and the accumulated stock S of CO_2, and where production can be split into domestic consumption C_i and accumulation of reproducible capital $\dot{K}_i$:[3]

$$F(K_i, E_i, S) = C_i + \dot{K}_i \, . \tag{3}$$

Assume that the concave and differentiable production function F is positively related to K_i and E_i and negatively related to S, implying that the partial derivatives of F satisfy $F_K > 0$, $F_E > 0$, and $F_S < 0$. We can interpret F_E as i's marginal cost of mitigation and $-F_S$ as i's marginal cost of adaptation. Hence, the equation of motion for K_i is:

$$\dot{K}_i = F(K_i, E_i, S) - C_i \, . \tag{4}$$

Assume that the equation of motion for S is:

$$\dot{S} = E_i + E_{-i} - \delta S \, , \tag{5}$$

where E_{-i} is total emissions in the rest of the world. The stocks at time 0, $K_i(0)$ and $S(0)$, as well as the path, $\{E_{-i}(t)\}_{t=0}^{\infty}$, of rest-of-the-world (ROW) emissions are exogenously given. A *path*

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[3] Instead of assuming that the stock S affects only output, we could have assumed that the accumulated CO_2 stock also influences well-being directly. The model can also be generalized to incorporate natural resource input. Such a generalization is presented in subsection 5.2 and applied in the empirical analysis of Section 6.

$\{C_i(t), E_i(t)\}_{t=0}^{\infty}$ for economy i satisfies the two equations of motion as well as the exogenously given initial stocks and the ROW emission path.

Assume that economy i implements the path $\{C_i(t), E_i(t)\}_{t=0}^{\infty}$, where, at each $t \geq 0$, $E_i(t)$ denotes economy i's forecasted emissions. This forecast might build on economy i's *nationally determined contributions* (NDCs) in the UNFCCC process. Let $\{\pi_i(t)\}_{t=0}^{\infty}$ denote the path of present value shadow prices of i's consumption, where we do need to discuss whether economy i maximizes a discounted utilitarian welfare function or have an objective function that also takes into sustainability constraints.[4] The essential assumption is that $\{C_i(t)\}_{t=0}^{\infty}$ maximizes $\int_0^{\infty} \pi_i(t) C_i'(t) \mathrm{d}t$ over all consumption paths $\{C_i'(t)\}_{t=0}^{\infty}$, given the emission path $\{E_i(t)\}_{t=0}^{\infty}$.

This determines the capital path $\{K_i(t)\}_{t=0}^{\infty}$ as well as paths $\{p_i^E(t)\}_{t=0}^{\infty}$ and $\{p_i^S(t)\}_{t=0}^{\infty}$ of present value shadow prices, where, at each $t \geq 0$,

$p_i^E(t)$ is the net national marginal cost of reducing national emissions, and

$p_i^S(t)$ is the national social cost of carbon (SCC),

having the property that, at each $t \geq 0$, $(K_i(t), E_i(t), S(t))$ maximizes

$$\pi_i(t) F(K_i, E_i, S) - p_i^S(t) \left(E_i + E_{-i}(t) - \delta S\right) - p_i^E(t) E_i + \dot{\pi}_i(t) K_i - \dot{p}_i^S(t) S \,. \tag{6}$$

Indeed, by (4) and (5) combined with the maximization of (6) imply that, at any $T > 0$,

$$\begin{aligned}\int_0^T \Big(\left(\pi_i C_i' - p_i^E E'\right) - \left(\pi_i C_i - p_i^E E\right) \Big) \mathrm{d}t \;&\leq \int_0^T \Big(\frac{\mathrm{d}}{\mathrm{d}t}\left(\pi_i K_i - p_i^S S\right) - \frac{\mathrm{d}}{\mathrm{d}t}\left(\pi_i K_i' - p_i^S S'\right) \Big) \mathrm{d}t \\ &= \pi_i(T) \left(K_i(T) - K_i'(T)\right) - p_i^S(T) \left(S(T) - S'(T)\right)\end{aligned}$$

for all paths $\{C_i'(t), E_i'(t)\}_{t=0}^{\infty}$ of consumption and emissions. In particular, $\{C_i(t)\}_{t=0}^{T}$ maximizes the present value of consumption between 0 and T, provided that the requirement that emissions between 0 and T be equal to $\{E_i(t)\}_{t=0}^{\infty}$ is fulfilled, when the capital stock at T is no smaller than $K_i(T)$ and the CO_2 stock at T are no greater than $S(T)$.

The maximization of (6) is a competitiveness condition in the tradition of Malinvaud (1953),

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[4] In the discounted utilitarian case, $\{C_i(t)\}_{t=0}^{\infty}$ maximizes $\int_0^{\infty} U(C_i') e^{-\rho t} dt$ over all consumption paths $\{C_i'(t)\}_{t=0}^{\infty}$, given the emission path $\{E_i(t)\}_{t=0}^{\infty}$, where U is a continuous, increasing and concave utility function, and $\rho > 0$ is a positive utility discount rate. Since F is concave, this implies that $\{C_i(t)\}_{t=0}^{\infty}$ maximizes $\int_0^{\infty} \pi_i(t) C_i'(t) \mathrm{d}t$ over all consumption paths $\{C_i'(t)\}_{t=0}^{\infty}$, given the emission path $\{E_i(t)\}_{t=0}^{\infty}$, where, for each $t \geq 0$, $\pi_i(t) = U'(C_i(t)) e^{-\rho t}$.

leading to the following three first-order conditions:[5]

$$\pi_i F_K + \dot{\pi}_i = 0\,, \tag{7}$$

$$\pi_i F_E - p_i^S - p_i^E = 0\,, \tag{8}$$

$$\pi_i F_S + p_i^S \delta - \dot{p}_i^S = 0\,. \tag{9}$$

First-order condition (7) means that there exists no profitable arbitrage for capital when $K_i(t)$ maximizes (6) w.r.t. K_i given the path of present value shadow prices of i's consumption. First-order condition (9) signifies that the path of national SCC p_i^S is determined such that there exists no profitable arbitrage for carbon when $S(t)$ maximizes (6) w.r.t. S given this path, yielding that

$$p_i^S(0) = -\int_0^\infty \pi_i(t) F_S(K_i(t), E_i(t), S(t)) e^{-\delta t} \mathrm{d}t \tag{10}$$

equals the present value of future national adaptation costs. Finally, first-order condition (8) entails that the net national marginal cost p_i^E of reducing national emissions is determined as the difference between the marginal cost of mitigation and the national SCC when $E_i(t)$ maximizes (6) w.r.t. E_i. We can interpret p_i^E as the weight that economy i assigns to the negative effects of its emissions in the rest of the world.[6]

We do not, at this stage, assume that the net national marginal cost of reducing national emissions equals the sum of national SCCs elsewhere. This would have constituted a condition for global efficiency by equating the national marginal cost of mitigation with the global SCC. Rather, we are particularly interested in the more realistic situation where countries do not take fully account of the costs of their emissions elsewhere.

The first-order conditions allow us express current consumption changes in terms of changes in the present value of net investments in capital and carbon as well as the net national cost of changes in national emissions and the national SCC of changes in emissions elsewhere:

$$\pi_i \dot{C}_i = \pi_i F_K \dot{K}_i + \pi_i F_E \dot{E}_i + \pi_i F_S \dot{S} - \pi_i \ddot{K}_i \qquad \text{(by (4))}$$

---

[5] These first-order conditions can also be derived in the discounted utilitarian case discussed in footnote 4.

[6] In the special case where p_i^E remains equal to zero for all countries i, their climate policies correspond to a Nash equilibrium of a game where countries only care about their own well-being. Conversely, a positive p_i^E implies that country i does not best reply (in terms of national well-being) to the emission policies of other countries.

$$
\begin{aligned}
&= -\dot{\pi}_i \dot{K}_i + p_i^E \dot{E}_i + p_i^S \dot{E}_i - p_i^S \delta \dot{S} + \dot{p}_i^S \dot{S} - \pi_i \ddot{K}_i \qquad \text{(by (7)–(9))} \\
&= -\dot{\pi}_i \dot{K}_i + p_i^E \dot{E}_i - p_i^S \dot{E}_{-i} + p_i^S \ddot{S} + \dot{p}_i^S \dot{S} - \pi_i \ddot{K}_i \qquad \text{(by (5))} \\
&= -\dot{\pi}_i \dot{K}_i - \pi_i \ddot{K}_i + \dot{p}_i^S \dot{S} + p_i^S \ddot{S} + p_i^E \dot{E}_i - p_i^S \dot{E}_{-i} \qquad \text{(by rearranging terms)} \\
&= -\frac{\mathrm{d}}{\mathrm{d}t}\big(\pi_i \dot{K}_i\big) + \frac{\mathrm{d}}{\mathrm{d}t}\big(p_i^S \dot{S}\big) + p_i^E \dot{E}_i - p_i^S \dot{E}_{-i}\,.
\end{aligned}
$$

Assuming that $\pi_i(T)\dot{K}_i(T) \to 0$ and $p_i^S(T)\dot{S}(T) \to 0$ as $T \to \infty$ hold as transversality conditions and the improper integrals converge, we get the following expression for economy i's national saving:

$$
\underbrace{\int_0^\infty \pi_i \dot{C}_i \mathrm{d}t}_{\substack{\text{Approximate}\\ \text{measure of}\\ \text{national}\\ \text{sustainability}}} = \pi_i(0)\dot{K}_i(0) - \underbrace{p_i^S(0)\dot{S}(0)}_{\substack{\text{National SCC}\\ \text{of global CO}_2\\ \text{accumulation}}} + \underbrace{\int_0^\infty p_i^E \dot{E}_i \mathrm{d}t}_{\substack{\text{PV of future net}\\ \text{national benefit}\\ \text{of increasing}\\ \text{national emissions}}} - \underbrace{\int_0^\infty p_i^S \dot{E}_{-i} \mathrm{d}t}_{\substack{\text{PV of future}\\ \text{national SCC of}\\ \text{increasing}\\ \text{ROW emissions}}}\,. \tag{11}
$$

The four terms on the r.h.s. constitute a national sustainability indicator. Hence, for this sustainability indicator to be non-negative, the value of net capital investments must compensate for the national cost of current global CO_2 accumulation, the present value of the net national cost associated with future reductions in national emissions, and the present value of the national SCC of future increases in emissions elsewhere. The fourth of these terms reflects that the technology from economy i's perspective is not stationary but influenced by the future emission policies in the rest of the world. The third term captures the net cost to economy i associated with reducing emissions more than it would have chosen to do for purely selfish national interests.

4 Global efficiency

In Section 3 we have not imposed the assumption that the emission policies of the individual countries lead to efficiency at the global level. Requiring global efficiency amounts to an additional assumption beyond the assumptions already made, namely that each country follows an efficient consumption path, given the constraints imposed by the exogenously given national and ROW emission paths. We turn now to the case of global efficiency, with the purpose of showing that the expression for national saving as an approximate measure of sustainability is consistent with the case where the policies of the individual countries add up to a policy that is globally efficient.

Assume that the set of economies in the world is $\mathcal{I} = \{1, 2, \ldots, I\}$, where $F_i(K_i, E_i, S)$ now denotes the production function of each $i \in \mathcal{I}$, implying that we have the following equations of motion for the I individual capital stocks $\big(K_i\big)_{i\in\mathcal{I}}$:

$$\dot{K}_i = F_i(K_i, E_i, S) - C_i\,, \quad i \in \mathcal{I}\,, \tag{12}$$

while the equation of motion for S can be rewritten as:

$$\dot{S} = \sum\nolimits_{i\in\mathcal{I}} E_i - \delta S\,, \tag{4$'$}$$

As before that the stocks at time 0, $\big(K_i(0)\big)_{i\in\mathcal{I}}$ and $S(0)$, are exogenously given. A *vector of paths* $\big(\{C_i(t), E_i(t)\}_{t=0}^{\infty}\big)_{i\in\mathcal{I}}$ for the global economy satisfies the $I+1$ equations of motion as well as the exogenously given initial stocks.

Assume furthermore that there exist paths $\{\pi_i(t)\}_{t=0}^{\infty}$ of present value prices for all countries $i \in \mathcal{I}$ such that $\big(\{C_i(t), E_i(t)\}_{t=0}^{\infty}\big)_{i\in\mathcal{I}}$ maximizes

$$\int_0^{\infty} \Big(\sum\nolimits_{i\in\mathcal{I}} \pi_i(t) C_i'(t)\Big)\, \mathrm{d}t \tag{13}$$

over all vectors of paths $\big(\{C_i'(t), E_i'(t)\}_{t=0}^{\infty}\big)_{i\in\mathcal{I}}$. As before, along time $\{\pi_i(t)\}_{t=0}^{\infty}$ is the path of present value shadow prices for economy i's consumption. In addition, the fact that (13) is maximized over all vectors of paths means that $\big(\{C_i(t), E_i(t)\}_{t=0}^{\infty}\big)_{i\in\mathcal{I}}$ is globally efficient (in the sense that one country cannot gain without another losing) with, at each $t \geq 0$, $\pi_i(t)/\pi_j(t)$ being a relative welfare weight of consumption in economies i and j. Such relative welfare weights equal unity if the utilities of the countries are subjected to Negishi weighting.

A globally efficient vector of paths determines a path of $\{p^S(t)\}_{t=0}^{\infty}$ of present value shadow prices, where, at each $t \geq 0$, $p^S(t)$ is the global social cost of carbon (SCC), having the property that, at each $t \geq 0$, $\big(K_i(t), E_i(t), S(t)\big)_{i\in\mathcal{I}}$ maximizes

$$\sum\nolimits_{i\in\mathcal{I}} \pi_i(t) F_i(K_i, E_i, S) - p^S(t)\Big(\sum\nolimits_{i\in\mathcal{I}} E_i - \delta S\Big) + \sum\nolimits_{i\in\mathcal{I}} \big(\dot{\pi}_i(t) K_i\big) - \dot{p}^S(t) S\,. \tag{14}$$

Then (12) and (4$'$) combined with the maximization of (14) imply that, at any $T > 0$,

$$\begin{aligned}\int_0^T \Big(\sum\nolimits_{i\in\mathcal{I}} \pi_i \big(C_i' - C_i\big)\Big)\mathrm{d}t \;&\leq \int_0^T \Big(\frac{\mathrm{d}}{\mathrm{d}t}\Big(\sum\nolimits_{i\in\mathcal{I}} \pi_i K_i - p^S S\Big) - \frac{\mathrm{d}}{\mathrm{d}t}\Big(\sum\nolimits_{i\in\mathcal{I}} \pi_i K_i' - p^S S'\Big)\Big)\mathrm{d}t \\ &= \sum\nolimits_{i\in\mathcal{I}} \pi_i(T)\big(K_i(T) - K_i'(T)\big) - p^S(T)\big(S(T) - S'(T)\big)\end{aligned}$$

for all vectors of paths $\big(\{C'_i(t), E'_i(t)\}_{t=0}^{\infty}\big)_{i\in\mathcal{I}}$. Hence, $\big(\{C_i(t), E_i(t)\}_{t=0}^{T}\big)_{i\in\mathcal{I}}$ maximizes the present value of consumption, weighted by the welfare weights, between 0 and T, when the capital stocks at T are no smaller than $\big(K_i(T)\big)_{i\in\mathcal{I}}$ and the CO_2 stock at T are no greater than $S(T)$.

As with (6), the maximization of (14) is a competitiveness condition in the tradition of Malinvaud (1953). It leads to the following $2I+1$ first-order conditions:

$$\pi_i F_{iK} + \dot{\pi}_i = 0\,, \qquad i \in \mathcal{I}\,, \tag{15}$$

$$\pi_i F_{iE} - p^S = 0\,, \qquad i \in \mathcal{I}\,, \tag{16}$$

$$\textstyle\sum_{i\in\mathcal{I}} \pi_i F_{iS} + p^S\delta - \dot{p}^S = 0\,. \tag{17}$$

For each country i, first-order condition (15) means that there exists no profitable arbitrage for capital when $K_i(t)$ maximizes (14) w.r.t. K_i given the path of present value shadow prices of i's consumption. First-order condition (17) signifies that the path of global SCC is determined such that there exists no profitable arbitrage for carbon when $S(t)$ maximizes (14) w.r.t. S given this path. Finally, for each country i, first-order condition (16) entails that the marginal cost of mitigation equals the global SCC when $E_i(t)$ maximizes (14) w.r.t. E_i.

These first-order conditions allow us express the welfare weighted value of current consumption changes in terms of changes in the present value of net investments in capital and carbon:

$$\begin{aligned}
\textstyle\sum_{i\in\mathcal{I}} \pi_i \dot{C}_i &= \textstyle\sum_{i\in\mathcal{I}} \pi_i F_{iK}\dot{K}_i + \sum_{i\in\mathcal{I}} \pi_i F_{iE}\dot{E}_i + \sum_{i\in\mathcal{I}} \pi_i F_{iS}\dot{S} - \sum_{i\in\mathcal{I}} \pi_i \ddot{K}_i \qquad \text{(by (12))}\\
&= -\textstyle\sum_{i\in\mathcal{I}} \dot{\pi}_i \dot{K}_i + p^S \sum_{i\in\mathcal{I}} \dot{E}_i - p^S\delta\dot{S} + \dot{p}^S\dot{S} - \sum_{i\in\mathcal{I}} \pi_i \ddot{K}_i \qquad \text{(by (15)–(17))}\\
&= -\textstyle\sum_{i\in\mathcal{I}} \dot{\pi}_i \dot{K}_i + p^S\ddot{S} + \dot{p}^S\dot{S} - \sum_{i\in\mathcal{I}} \pi_i \ddot{K}_i \qquad \text{(by (4}'\text{))}\\
&= -\textstyle\sum_{i\in\mathcal{I}} \dot{\pi}_i \dot{K}_i - \sum_{i\in\mathcal{I}} \pi_i \ddot{K}_i + \dot{p}^S\dot{S} + p^S\ddot{S} \qquad \text{(by rearranging terms)}\\
&= -\frac{\mathrm{d}}{\mathrm{d}t}\Big(\textstyle\sum_{i\in\mathcal{I}} \pi_i \dot{K}_i\Big) + \frac{\mathrm{d}}{\mathrm{d}t}\big(p^S\dot{S}\big)\,.
\end{aligned}$$

Assuming that $\pi_i(T)\dot{K}_i(T) \to 0$, for $i \in \mathcal{I}$, and $p^S(T)\dot{S}(T) \to 0$ as $T \to \infty$ hold as transversality conditions, we get the following expression for global saving:

$$\underbrace{\int_0^{\infty}\Big(\textstyle\sum_{i\in\mathcal{I}} \pi_i \dot{C}_i\Big)\,\mathrm{d}t}_{\substack{\text{Approximate}\\ \text{measure of global}\\ \text{sustainability}}} = \textstyle\sum_{i\in\mathcal{I}} \pi_i(0)\dot{K}_i(0) - \underbrace{p^S(0)\dot{S}(0)}_{\substack{\text{Global SCC}\\ \text{of global } CO_2\\ \text{accumulation}}}\;. \tag{18}$$

The two terms on the r.h.s. constitute a global sustainability indicator. Hence, for this sustainability indicator to be non-negative, the value of net capital investments must compensate for the global cost of current global CO_2 accumulation,

If the vector of paths $\left(\{C_j(t), E_j(t)\}_{t=0}^{\infty}\right)_{j \in \mathcal{I}}$ is globally efficient, then it holds that, for each economy $i \in \mathcal{I}$, $\{C_i(t)\}_{t=0}^{\infty}$ maximizes $\int_0^\infty \pi_i(t) C_i'(t) \mathrm{d}t$ over all consumption paths $\{C_i'(t)\}_{t=0}^{\infty}$, given the vector of emission paths $\left(\{E_i(t)\}_{t=0}^{\infty}\right)_{i \in \mathcal{I}}$. This means that, for each $i \in \mathcal{I}$, there exist paths $\{p_i^E(t)\}_{t=0}^{\infty}$ and $\{p_i^S(t)\}_{t=0}^{\infty}$ of present value shadow prices such that first-order conditions (8) and (9) are satisfied. Comparing these conditions with first-order conditions (16) and (17) above, implies that, under the assumption of global efficiency,

$$p^S = \sum\nolimits_{j \in \mathcal{I}} p_j^S \,, \tag{19}$$

$$p_i^E = \sum\nolimits_{j \neq i} p_j^S \,. \tag{20}$$

Hence, the global SCC equals the sum of the national SCC and, for each economy i, the net national marginal cost of reducing national emissions equals the sum of the other economies' national SCC.

It is straightforward to check that, by summing the l.h.s. and r.h.s. of (11) over all economies $i \in \mathcal{I}$ and using (19) and (20), we obtain (18). Hence, the expression for national saving as an approximate measure of sustainability is consistent with the case where the policies of the individual countries add up to a policy that is globally efficient. However, even in the case where national emissions policies are designed to be globally efficient, the expression of national saving as an approximate measure of sustainability must include the terms that depend on future changes in emissions, both nationally and in the rest of the world. The reason is that burdens relating to CO_2 mitigation and adaptation need not be equally distributed among the I economies (Borissov and Bretschger, 2022). Hence, some economies might have a greater need of accumulating capital to compensate for the future mitigation and adaptation burden.

5 Generalizations

To make the principles of carbon accounting transparent, we have in Sections 3 and 4 assumed no technological progress, no population growth, and only one consumption good, thereby abstracting from issues of improving technology, growing population, and changing terms-of-trade. In this section we indicate how our analysis can be generalized in these various directions.

5.1 Transfers

Climate negotiations might allow for transfers between economies, designed to distribute the burden of climate policies in a more equitable manner. If $\{T_i(t)\}_{t=0}^{\infty}$ is the path of net transfers that economy i is expected to receive, then its equation of motion for K_i is changed to

$$\dot{K}_i = F(K_i, E_i, S) + T_i - C_i \,,$$

and routine calculations lead to following expression for economy i's national saving:

$$\underbrace{\int_0^\infty \pi_i \dot{C}_i \mathrm{d}t}_{\substack{\text{Approximate}\\ \text{measure of}\\ \text{national}\\ \text{sustainability}}} = \pi_i(0)\dot{K}_i(0) - \underbrace{p_i^S(0)\dot{S}(0)}_{\substack{\text{National SCC}\\ \text{of global CO}_2\\ \text{accumulation}}} + \underbrace{\int_0^\infty \pi_i \dot{T}_i \mathrm{d}t}_{\substack{\text{PV of future}\\ \text{changes in}\\ \text{net transfers}}} + \underbrace{\int_0^\infty p_i^E \dot{E}_i \mathrm{d}t}_{\substack{\text{PV of future net}\\ \text{national benefit}\\ \text{of increasing}\\ \text{national emissions}}} - \underbrace{\int_0^\infty p_i^S \dot{E}_{-i} \mathrm{d}t}_{\substack{\text{PV of future}\\ \text{national SCC of}\\ \text{increasing}\\ \text{ROW emissions}}} \,.$$

Clearly, if the present value $\int_0^\infty \pi_i \dot{T}_i \mathrm{d}t$ of changes in net transfers is positive, then the requirement on capital accumulation needed to satisfy the national sustainability indicator is relaxed. As the sum over net transfers over all economies $i \in \mathcal{I}$ equals zero at each t, including transfers has no effect on the expression (18) for global saving under the assumption of global efficiency, provided that Negishi weighting ensures that all relative welfare weights of consumption equal unity.

5.2 Multiple consumption and capital goods

The generalization to multiple consumption and capital goods are straightforward, following Dixit, Hammond, and Hoel (1980), by replacing the production function (3) by a set of feasible set of 6-tuples $(\mathbf{C}_i, \mathbf{K}_i, \dot{\mathbf{K}}_i, E_i, S, \dot{S})$ which depends on the sum of emissions E_{-i} elsewhere.[7] This leads to the following expression for economy i's saving:

$$\underbrace{\int_0^\infty \mathbf{p}_i^C \dot{\mathbf{C}}_i \mathrm{d}t}_{\substack{\text{Approximate}\\ \text{measure of}\\ \text{national}\\ \text{sustainability}}} = \mathbf{p}_i^K(0)\dot{\mathbf{K}}_i(0) - \underbrace{p_i^S(0)\dot{S}(0)}_{\substack{\text{National SCC}\\ \text{of global CO}_2\\ \text{accumulation}}} + \underbrace{\int_0^\infty p_i^E \dot{E}_i \mathrm{d}t}_{\substack{\text{PV of future net}\\ \text{national benefit}\\ \text{of increasing}\\ \text{national emissions}}} - \underbrace{\int_0^\infty p_i^S \dot{E}_{-i} \mathrm{d}t}_{\substack{\text{PV of future}\\ \text{national SCC of}\\ \text{increasing}\\ \text{ROW emissions}}} \,, \qquad (21)$$

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[7] By letting some of these capital goods correspond to natural resources, this generalizes our analysis to the case where resource inputs are required for the production of output. Indeed, the empirical analysis of Section 6 uses World Bank's genuine saving, which includes resource depletion.

where $\{\mathbf{p}_i^C(t)\}_{t=0}^{\infty}$ and $\{\mathbf{p}_i^K(t)\}_{t=0}^{\infty}$ are paths of vectors of present value prices of consumption and capital.

5.3 Technological progress

In the approach of the previous subsection, the feasible set of 6-tuples $(\mathbf{C}_i, \mathbf{K}_i, \dot{\mathbf{K}}_i, E_i, S, \dot{S})$ depends on the sum of emissions E_{-i} elsewhere, which will change over time. This formulation can also allow for exogenous technological progress by letting the set of feasible 6-tuples depend directly on time. By including time as an additional stock, eq. (21) will be amended through the inclusion of an integral of forward-looking terms that measures the current effect of future technological progress, as shown by Pezzey (2004, Props. 5 and 6) and Weitzman (1997). Furthermore, if the set of feasible 6-tuples for each economy i is tied together with the rest of the world by markets for consumption and capital investment, then each economy i will experience terms-of-trade effects that can similarly be captured by an integral of forward-looking terms (Vincent, Panayotou, and Hartwick, 1997).

Endogenous technological progress is taken account of by the analysis of subsection 5.2 if produced knowledge is a private and proprietary good. At the other extreme, where produced knowledge is freely available to everyone, we can apply the techniques of the present paper to account for such knowledge, based on the observation that carbon emissions as a global negative externality is analogous to freely available knowledge as a global positive externality. We do not pursue this generalization in the current paper.

5.4 Population growth

Up to now we have assumed that population within each economy is constant. While endogenous population growth raises issues of population ethics that we do not want to address in this paper, we can easily allow for population that changes exogenously over time. If $\{N_i(t)\}_{t=0}^{\infty}$ is the path of population that economy i is expected to have, then its equation of motion for K_i is changed to

$$\dot{K}_i = F(K_i, N_i, E_i, S) - C_i \,,$$

where F is positively related to N_i, implying that the partial derivative of F w.r.t. N_i satisfies $w_i = F_N > 0$. The analysis above combined with the results in Asheim, Hartwick, and Yamaguchi

(2023) leads to the following expression for economy i's national saving:

$$\underbrace{\int_0^\infty \pi_i \dot{c}_i N_i \mathrm{d}t}_{\substack{\text{Approximate}\\ \text{measure of}\\ \text{national}\\ \text{sustainability}}} = \pi_i(0)\dot{K}_i(0) - \underbrace{p_i^S(0)\dot{S}(0)}_{\substack{\text{National SCC}\\ \text{of global CO}_2\\ \text{accumulation}}} - \underbrace{\int_0^\infty \big(\pi_i c_i - w_i\big)\dot{N}_i \mathrm{d}t}_{\substack{\text{PV of future consumption}\\ \text{needed to maintain } c\\ -\text{ contribution of}\\ \text{increased population}}} + \underbrace{\int_0^\infty p_i^E \dot{E}_i \mathrm{d}t}_{\substack{\text{PV of future net}\\ \text{national benefit}\\ \text{of increasing}\\ \text{national emissions}}} - \underbrace{\int_0^\infty p_i^S \dot{E}_{-i} \mathrm{d}t}_{\substack{\text{PV of future}\\ \text{national SCC of}\\ \text{increasing}\\ \text{ROW emissions}}},$$

where $c_i = C_i/N_i$ denotes per capita consumption. Since $\pi_i c_i > w_i$, as additional people consume more than they contribute at the margin, an increasing population tightens the requirement on capital accumulation needed to satisfy the national sustainability indicator.

6 Empirical estimates

In this section, we put the theory to use for the purpose of seeing how much it would change sustainability assessments of select countries. Specifically, we use main equation (21) in Section 5 without assuming that countries take full responsibility of their current emissions. In other words, the marginal cost of mitigation need not equal the global SCC. We shall now study the terms on the r.h.s. of (21) in turn.

6.1 Data and assumptions

Genuine saving (excluding carbon emission). The first term on the r.h.s. of equation (21), $\mathbf{p}_i^K(0)\dot{\mathbf{K}}_i(0)$, is the value of changes in the (multiple) capital stocks. For the purpose of our exercise, we interpret it as changes in all capital stocks other than carbon, and use *genuine saving* as its surrogate. Formally referred to as *adjusted net saving* by the World Bank's *World Development Indicators*, genuine saving is constructed by the country's gross saving, deducted by consumption of fixed capital, yet adjusted for the accumulation of human capital and the depletion of natural capital (fossil fuels, mineral resources and metals, and forest resources), as well as carbon (and particulate matter) emissions. Thus, we use genuine saving *before* being adjusted for carbon (and particulate matter) emissions.

It is worth highlighting that the World Bank does account for *current* and *national* carbon emission, valued at the *global* SCC, based on the model of Hamilton and Clemens (1999). As discussed in the introduction, accounting for the country's current carbon emission is consistent with the idea that the country takes full responsibility of the consequences of emission by say, offsetting or emission trading (Hamilton, 2012). However, as we have discussed, this idea is not consistent with the purpose of indicating national sustainability. Instead, what needs to appear is the second term $p_i^S(0)\dot{S}(0)$ on the r.h.s. of equation (21), the estimation of which we turn to now.

National SCC of current global carbon accumulation. The number of tons of CO_2 emitted globally can be simply used for $\dot{S}(0)$, abstracting from the effect of the oceans as a carbon sink (in line with the conclusions drawn by Dietz and Venmans, 2019). We use the historical carbon emission excluding LUCF (land use change and forestry) from *Climate Watch Historical GHG Emissions* data by World Resources Institute.[8]

The marginal price of this emission, $p_i^S(0)$, expresses the portion of the unit SCC that has a domestic incidence in country i. In a similar accounting of local consequences of the global carbon concentration, Arrow et al. (2012) use Nordhaus and Boyer's (2000) study to apportion global carbon damage to the countries under study. The U.S., India, Brazil, China and Venezuela were assumed to bear 9%, 5%, 2%, $< 1\%$, and $< 1\%$, respectively, of global carbon emission damage. However, it is now known that lower-income countries carry much more of global SCC, with both India and China having a share of at least 5% in all the models compared in Tol (2019a).

Ever since the well-known model of Nordhaus and Yang (1996), a number of integrated assessment models have shown regionally downscaled results of outputs and carbon emissions. However, there seems to be only a few studies, and thus very little consensus on what constitute national SCC. For instance, Nordhaus (2017) suggests allocating global SCC to regional SCCs by using the share of the present value of future regional outputs with the discount rate of 5%. This could be in line with the recent literature of simple formula for SCC in an analytical IAM (Dietz and Venmans, 2019), which underscores the role of current output in determining SCC. More recently, Ricke et al. (2018) show national SCCs for a number of scenarios, arguing that India, China, Saudi Arabia and the U.S. bear disproportional shares of global SCC. In a critical reexamination of their result, Tol (2019a) argues that introducing nonzero income elasticity of climate change damage would significantly change the distribution of global SCC to national SCCs. In his estimate, China, India, and Africa put together account for around two thirds of global SCC, while high-income countries

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[8] Available online at: https://www.climatewatchdata.org/ghg-emissions. We should also note that the World Bank (WB) accounts only for carbon emission damage from fossil fuel use and the manufacture of cement, "estimated to be USD40 per ton of CO_2 (the unit damage in 2017 US dollars for CO_2 emitted in 2020) times the number of tons of CO_2 emitted," while we include all carbon emission only excluding LUCF. This difference in scope is related to the argument that a sustainability indicator should keep track of real change in well-being, rather than the responsibility of emitters.

bear trivial shares. Moreover, as Tol (2019a) illustrates, there are several debatable methodological issues. For example, Burke, Hsiang, and Miguel (2015) use quadratic impact function that is regressed on past whether data and assume that temperature change, rather than its level, affects economic growth. Also, they assume that weather shock affects economic growth rate, rather than its level (Newell, Prest, and Sexton, 2021). Consequently, Ricke et al. (2018), which depends on Burke, Hsiang, and Miguel (2015), might particularly underestimate national SCCs in northern regions. As is salient in recent episodes of forest fires, negative national SCCs in such regions might not capture non-consumption aspects of climate change damage, including disamenity, morbidity and premature mortality costs, and damage to ecosystem and natural capital. Notwithstanding their limitations, we use the central result of Ricke et al. (2018), which is the median estimate with growth adjusted discounting (with the pure rate of time preference of $\rho = 2\%$ and the elasticity of marginal utility of $\eta = 1.5$) for SSP2/RCP6.0 scenario and the short-run Burke, Hsiang, and Miguel (2015) methodology. Table 1 gives an overview of the share of national SCCs out of global SCC across studies, in which the Ricke et al. (2018) study is adopted in our exercise.

Table 1: National or regional SCC shares of global SCC across studies (%, USD)

Country	RICE	FUND	PAGE	ADGMO	Nordhaus	Tol	0ϵ Tol	Ricke et al.	
Brazil				2				5.3	24
China	16	8	11	<1	21	12.8	7.6	18.2	83
Indonesia								6.6	30
India	12	5	22	5	9	23.9	2.5	34.9	160
Japan	2	3			3	0.3	8.8	1.6	7
Russia	1	10			3	0.8	1.7	-23.5	-108
EU	12	24	9		15	1.4	27.3		
USA	10	17	7	9	15	0.6	26.1	9.7	45
Middle East	10				7	2.6	4.0		
Africa	11	6	26		3	30.4	2.6		
Latin America	7		11		6	4.3	6.8		
World	100	100	100		100	100	100	100	USD458

Note: Compiled from Nordhaus (2017), Ricke et al. (2018), and Tol (2019a), as well as ADGMO (Arrow et al., 2012). "0ϵ" is the case with 0 income elasticity of climate change damage reported in Tol (2019a), while Tol assumes elasticity of -1.68. Ricke et al. (2018) uses the case of fixed consumption discount rate of 3% for SSP2/RCP6.0 scenario and the short-run Burke, Hsiang, and Miguel (2015) methodology. All the figures are in percentage, except for the last column, which is expressed in USD, from the Ricke et al. (2018) study.

Future national emission path. We now turn to the third, forward-looking term of the r.h.s. of equation (21). There is a great deal of uncertainty in future emission path, $\{E_i(t)\}_{t=0}^{\infty}$, which depends on how the economy evolves in the future, along with their pledges and available technology. Thus far, we have not specified the underlying resource allocation mechanism in formulating our theoretical results, apart from assuming that each economy's investment policy is efficient, given the national and ROW emission paths. However, assuming a suboptimal, realistic path serves our purpose here (Arrow, Dasgupta, and Mäler, 2003; Fenichel and Abbott, 2014), instead of considering idealistic or optimal paths (Hamilton and Clemens, 1999).

Climate Action Tracker (CAT) collates modelled emission pathways for select countries. These pathways are regionally downscaled figures from global emission pathways that correspond to 1.5, 2, 3, and 4 degrees targets. These modelled emission pathways, including the one with the Paris-consistent 1.5 degree target, do not take account of how much countries *should* mitigate and are thus distinct from what CAT calls fair effort sharing of emissions in the future. They are also different from NDCs in general, as the modelled emission pathways are also unrelated to how much countries actually pledge.[9] We thus postulate as the baseline scenario what CAT calls an "insufficient" mitigation pathway which largely correspond to 3°C higher.

Future national mitigation cost. The present-value net national cost of decreasing emission, p_i^E, consists of the mitigation cost net of the national SCC, as in the first-order condition (8). For the national SCC, we use the same source with the second term of the r.h.s. of equation (21). As for the mitigation cost, we first define total mitigation cost, A, as a function of mitigation effort of i at time t, $M_i(t)$, given $K_i(t)$, the background emission $E_i^0(t)$ without mitigation effort, and $S(t)$:

$$A(M_i(t), t) = F(K_i(t), E_i^0(t), S(t)) - F(K_i(t), E_i^0(t) - M_i(t), S(t)),$$

from which the marginal abatement cost (MAC) in dollars can be expressed by the first derivative, $A_M = F_E > 0$. This in turn allows us to derive the net national cost of reducing national emissions by the equation $p_i^E = \pi_i A_M - p_i^S$.

The sheer uncertainty of the future marginal cost of mitigation is mainly generated by future technical progress, as well as future policy uncertainty. One way to assume future mitigation cost is to use the results of integrated assessment models (IAMs) that incorporate climate and economy. Some IAMs balance costs and benefits of future mitigation, while others instead focus on detailed process and technology adoption. In a meta-analysis of 26 IAMs, Kuik, Brander, and Tol (2009) study how relevant factors affect estimates of MAC of carbon dioxide in 2025 and

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[9] According to AR6, "GHG emissions in 2030 implied by nationally determined contributions (NDCs) announced by October 2021 make it *likely* that warming will exceed 1.5°C during the 21st century and make it harder to limit warming below 2°C" (IPCC, 2023).

2050. The authors' metaregression suggests that MAC is significantly negatively affected by the target in carbon concentration in ppm. The mean and median of MAC have been reported to be 24.8 (55.8) and 16.2 (32.2) euro per tCO_2-eq for the year 2025 (2050), respectively.[10] For our purpose of country measurements of sustainability, however, we need to use regionally downscaled MACs. In addition, since their study, the policy target of interest has somehow shifted from GHG concentration to cumulative emissions. This has led to the dramatic increase of the use of carbon budget in policy and academic discourse (IPCC, 2014, AR5). Cumulative emissions correspond to our specification (5) of carbon stock dynamics when the rate of dissipation δ is negligible.

We follow Gollier (2022) in assuming that abatement cost at time t is a quadratic function of mitigation $M_i(t)$ at time t. Hence, total mitigation cost in dollars per tCO_2 is given by

$$A(M_i(t), t) = a(t)M_i(t) + \frac{1}{2}bM_i(t)^2, \tag{22}$$

where $a(t) > 0$ is time-variant and $b > 0$ is time-invariant. Then the MAC becomes

$$A_M(M_i(t), t) = a(t) + bM_i(t) \tag{23}$$

in units of dollar per tCO_2.

As $a(t)$ captures the BAU carbon price (Gollier, 2022), tradable permit price can be directly used for current $a(t)$. Unfortunately, carbon markets around the world are still in their infancy. Given the EU and Chinese carbon market trends over the past few years, we use USD88 and USD8.8 per tCO_2 in the period of 2021-2030 for developed and developing countries, respectively.[11] For the period of 2031-2050, these prices are assumed to decline by 7.25%, in line with Nordhaus (2018)'s assumption on the backstop technology cost decline of annual 0.5%.

To calibrate the second-order time-invariant parameter b in the MAC function (23), we also use the MIT Emissions Prediction and Policy Analysis (EPPA) (Morris, Paltsev, and Reilly, 2012)

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[10] This suggests that the distribution of MAC across models might be heavily skewed to the right, so the authors take logs of both MAC and concentration. They also show that multigas policy incorporating non-carbon GHG may significantly reduce the MAC, in line with recent calls to reduce them (Tanaka et al., 2021; Hänsel et al., 2020). Other factors such as baseline, whether models allow induced technical change, intertemporal optimization, and carbon capture and storage (among others) turn out to be insignificant or less significant.

[11] China's national emission trading scheme (ETS) commenced only in July 2021. Its price, although rising, is still in the order of the magnitude of one-tenth of its EU counterpart. Japan's J-Credit trading trial was implemented in October 2022, where the carbon price was reported to be around USD23.

who provide CGE-based regionally specified MAC curves.[12] Aside from a "core" across-the-board reduction scenario, the authors of the EPPA analysis also show a realistic path of emissions reductions from 2010 to 2050, where developed countries reduce first, followed by developing countries in a gradual manner. Since we use "insufficient" realistic emission pathways from CAT, we accordingly use this more realistic scenario MACs by Morris, Paltsev, and Reilly (2012), who assume 50% reduction at the maximum in 2050, which seems more consistent with the three degree mitigation effort than the Paris-consistent target. Specifically, we use MAC of 20% reduction in each country in 2020. To apply the values to annual figures, b values are divided by 15 years (Gollier, 2022). Assumptions are summarized in Table 2.

Table 2: National marginal mitigation cost assumptions

Country/Region	$a(t)$ 2021–2030	$a(t)$ 2031–2050	b
Africa	8.8	8.2	24.21
EU and UK	88.0	81.6	25.56
Australia	88	81.6	24.86
Brazil	8.8	8.2	17.23
Canada	88	81.6	18.98
China	8.8	8.2	3.80
Indonesia	8.8	8.2	32.75
India	8.8	8.2	11.61
Japan	88.0	81.6	41.28
Russia	8.8	8.2	13.53
Saudi Arabia	8.8	8.2	29.61
United States	88.0	81.6	23.14

Note: The units for $a(t)$ and b are USD/tCO$_2$ and USD/tCO$_2^2$, respectively. b values are taken from Morris, Paltsev, and Reilly (2012).

Future ROW emission path. National sustainability partially depends on how other countries manage their resources in the future (Yamaguchi, 2021). This is the sense in which (11) and (21) capture the ROW emission path in the future. As already mentioned, we focus on the realistic, "insufficient" emission pathways of countries. Likewise, we postulate that the country of interest i anticipates that the ROW also follows this path in the future. We thus use the ROW emission pathways "Pledges and Targets High" from CAT, where approximately 31 Gt-CO$_2$-eq of GHG is expected to be emitted in 2050, that largely correspond to the "insufficient" modelled

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[12] As the authors argue, MAC curves tend to become lower and flatter as time goes by, due to more available decarbonization technologies and path dependency of the mitigation effort. In "core" across-the-board reduction scenario when the reduction policy is started in 2010, MACs in 2010 are higher than MACs in 2020, which are higher in MACs in 2050.

emission pathway.[13] Even if they are deemed insufficient, world emissions are expected to decline in most scenarios, implying that the $\dot{E}_{-i}$ are negative for most countries as we near 2050.

Future national SCC. The shadow price of future changes in ROW emission, p_i^S in (21), represents the present value of future national SCC. One of the key findings of the recent analytic IAM literature is the role of initial output in the SCC. The increasing damage of additional emission in a growing economy might be offset to a certain extent by the growth effect in the consumption discount rate. Using the initial national SCC in 2020 of Ricke et al. (2018), we assume that the present-value national SCC is constant, which might be justified by a constant damage share of output. See Appendix A for a discussion of the future path of SCC.

Data sources are summarized in Table 3.

Table 3: Data sources

Data	Description	Source
$\mathbf{p}_i^K(0)\dot{\mathbf{K}}_i(0)$	genuine saving excl. CO_2 emissions (current USD)	*WDI*
$p_i^S(0)$	national SCC of global carbon stock accumulation	Ricke et al. (2018)
$\dot{S}(0)$	global carbon stock accumulation	WRI
p_i^E	national marginal mitigation cost of emission	Morris et al. (2012), Gollier (2022)
$\dot{E}_i$	national emission change	*CAT* “insufficient” domestic pathway
p_i^S	PV national SCC of future ROW emission change	Ricke et al. (2018)
$\dot{E}_{-i}$	ROW emission change	*CAT* “Pledges and Targets High”

Note: *WDI*: *World Development Indicators*, *CAT*: *Climate Action Tracker*, and WRI: World Resources Institute's *Climate Watch Historical GHG Emissions.* Genuine saving excluding carbon emission = net national saving + educational expenditure − energy depletion − mineral depletion − net forest depletion.

6.2 Results

The bottom line results are summarized in Table 4 and 5 for a set of countries. First off, we look at the columns (a) and (b) in Table 4 from the World Bank, that record genuine saving (the value of the change in capital assets) and carbon emission as the annual average during the decade 2010–2019. Only Kenya is deemed unsustainable in the unadjusted genuine saving. Carbon emission

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[13] Because countries assessed by the CAT were responsible for 81% of global emissions in 2010 (excluding LULUCF), we lack ROW data only for carbon emissions and thus assume that the share of CO_2 emission excluding LUCF in GHG emission in tCO_2-eq is constant at the 2019 level across time in each country in using the following data: Climate Action Tracker (2022). 2030 Emissions Gap: CAT projections and resulting emissions gap in meeting the 1.5°C Paris Agreement goal. November 2022. Available at: https://climateactiontracker.org/global/cat-emissions-gaps/. The share of CO_2 emission in GHG emission in tCO_2-eq varies across countries. While it falls somewhere in the range of 70-90% in most countries, lower-income, agriculture-dependent countries tend to have a lower share. For example, CO_2 accounts for only 39%, 27%, 38% of GHG emission in Brazil, Kenya, and Nigeria in 2019.

in column (b) WB gSCC is calculated by the number of tons of CO_2 emitted by the country, multiplied by USD40 per tCO_2 across the board. Formally, it captures $[\sum_i p_i^S(0)]E_i(0)$ where $[\sum_i p_i^S(0)]$=USD40/tCO_2. Since the carbon emission damage so computed is smaller than genuine saving by one order of the magnitude, the resulting genuine saving including carbon emission are positive for all major economies excluding Kenya, as in column (a)+(b).

Table 4: Genuine saving adjusted with various carbon accounting and prices (in billion USD)

	(a)	(b)	(a)+(b)	(c)	(a)+(c)	(d)	(a)+(d)	(e)	(a)+(e)
Country	GS	WB gSCC		gSCC		nSCC40		nSCC	
Australia	**116**	-13	**103**	-151	**-35**	-16	**100**	-179	**-63**
Brazil	**202**	-15	**187**	-177	**25**	-72	**130**	-823	**-621**
Canada	**141**	-19	**122**	-220	**-79**	96	**237**	1,094	**1,235**
China	**2,496**	-337	**2,159**	-3,857	**-1,361**	-249	**2,248**	-2,845	**-348**
Germany	**533**	-25	**508**	-291	**242**	36	**569**	414	**947**
UK	**85**	-14	**71**	-160	**-75**	25	**111**	290	**376**
Indonesia	**133**	-17	**116**	-200	**-67**	-90	**44**	-1,027	**-893**
India	**521**	-73	**448**	-837	**-316**	-476	**45**	-5,451	**-4,930**
Japan	**239**	-40	**199**	-463	**-224**	-22	**217**	-250	**-11**
Kenya	**-0.70**	-1	**-1**	-6	**-7**	-12	**-13**	-142	**-143**
Nigeria	**36**	-4	**32**	-44	**-8**	-110	**-74**	-1,254	**-1,218**
Norway	**89**	-1	**87**	-15	**73**	19	**108**	218	**306**
Russia	**201**	-55	**146**	-629	**-428**	321	**522**	3,667	**3,868**
Saudi Arabia	**166**	-18	**149**	-202	**-36**	-32	**135**	-362	**-196**
USA	**1,291**	-173	**1,119**	-1,975	**-683**	-133	**1,159**	-1,518	**-227**
Vietnam	**26**	-7	**19**	-79	**-53**	-24	**2**	-277	**-251**
South Africa	**17**	-15	**2**	-169	**-152**	-19	**-3**	-223	**-206**

Note: Column (a) GS: genuine saving excluding CO_2 emission. Column (b) WB gSCC signifies the CO_2 emission damage calculated by the World Bank (WDI) using $[\sum_i p_i^S(0)]$=USD40/tCO_2 in $[\sum_i p_i^S(0)]E_i(0)$. Column (c) gSCC uses the World Bank methodology of accounting for global SCC of the country but using $[\sum_i p_i^S(0)]$=USD450/tCO_2 in the Ricke et al. study. Column (d) nSCC40 uses national SCC distribution in the Ricke et al. study with the 3% consumption discount rate, but the global SCC is assumed to add up to $[\sum_i p_i^S(0)]$=USD40/tCO_2. Column (e) uses national SCC in the Ricke et al. study. All the columns are annual averages of the period 2010-2019.

Column (c), (d), and (e) for the carbon emission cost, also as the annual average during the decade 2010–2019, suggests that carbon affects national sustainability differently than what the World Bank suggests. Column (c) gSCC signifies the World Bank (WDI) "responsitiblity" methodology, but using $[\sum_i p_i^S(0)]$=USD450/tCO_2 in the Ricke et al. study. This brings most countries on an unsustainable path, as in column (a)+(c), barring Brazil, Germany and Norway. Column (d) nSCC40 uses national SCC *distribution* in the Ricke et al. study, but the global SCC is assumed to add up to around one tenth of Ricke et al. study, $[\sum_i p_i^S(0)]$=USD40/tCO_2 in line with World Bank gSCC, because the magnitude of global SCC figures are still debatable. The resulting column (a)+(d) record negative figures only for Kenya, Nigeria and South Africa, but some regional variance can be observed, as a result of geographical inequality in the distribution of global SCC. Finally, the way column (e) is calculated is theoretically the same with Arrow et al. (2012) but empirically distinct, as we apply recent findings by Ricke et al. (2018) instead of Nordhaus and Boyer (2000). Of particular interest is India, Saudi Arabia, and the U.S., all of which are known to bear a relatively large share of global SCC (see Table 1). This turns half of our sample countries to the unsustainable category, as in the (a)+(e) column. Note that in Canada, Germany, UK, Norway, and Russia, this term is positive because climate change is thought to bring warmer climate in terms of nationally disaggregated SCC in the Ricke et al. study.

Table 5: Sustainability indicator components (in billion USD)

Country	(a) $\mathbf{p}_i^K(0)\dot{\mathbf{K}}_i(0)$	(e) $-p_i^S(0)\dot{S}(0)$	(f) $\int_0^\infty p_i^E \dot{E}_i \mathrm{d}t$	(g) $-\int_0^\infty p_i^S \dot{E}_{-i} \mathrm{d}t$	(a)+(e)+(f)+(g)
Australia	**116**	-179	-7	75	**5**
Brazil	**202**	-823	1	344	**-275**
Canada	**141**	1,094	-21	-454	**761**
China	**2,496**	-2,845	209	773	**634**
Germany	**533**	414	-26	-170	**751**
UK	**85**	290	-5	-122	**249**
Indonesia	**133**	-1,027	1	430	**-462**
India	**521**	-5,451	9	2,288	**-2,632**
Japan	**239**	-250	-50	101	**41**
Kenya	**-0.70**	-142	0	60	**-83**
Nigeria	**36**	-1,254	-3	531	**-690**
Norway	**89**	218	-1	-92	**214**
Russia	**201**	3,667	-91	-1,468	**2,309**
Saudi Arabia	**166**	-362	-1	152	**-44**
USA	**1,291**	-1,518	-149	557	**181**
Vietnam	**26**	-277	0	116	**-135**
South Africa	**17**	-223	-1	93	**-114**

Note: See equation (21). Column (a) GS: genuine saving excluding CO_2 emission. Column (a) and (e), that also appears in Table 4, are annual averages of the period 2010-2019. Column (f) and (g) are the sum of PV for the period 2021-2050.

In Table 5, column (f) shows that the PV of the net national cost of reducing national emissions in the period 2021–2050 cannot be dismissed as well. Note that this term could either be positive or negative, even if future emissions are expected to decline. In Japan, the U.S., and Russia, this term is negative and relatively large compared to the magnitude of genuine saving. In Japan and the U.S., this is caused by large future national mitigation costs that exceed their national SCC.

In Russia, with its estimated negative national SCC, the net national cost of reducing emissions is relatively large because national emission reductions do not only involve mitigation costs but also slow desirable climate change. However, in China, the net national cost of reducing emissions is negative because their national SCC exceeds its mitigation cost.

Column (g), the PV of the national climate costs of changes in future ROW emission change during the period 2021-2050, usually works as a gainer in terms of sustainability, because our scenario depicts a monotone decline in global emissions in the decades to come, no matter how insufficient they are to reach the Paris-consistent target.

Finally, aggregating (a), (e), (f), and (g) gives us a lot murkier set of figures, around half the countries assessed as unsustainable. China, Indonesia, India, Nigeria, and the U.S. all suffer from negative net national SCCs of current emission on the order of trillion dollars, which are not fully compensated for by reductions in future ROW mitigation. However, while China and the U.S. have sufficient saving in other assets to ensure that their overall indicators are positive, Indonesia, India, and Nigeria seem to face an unsustainable path. Another implication from Table 5 is that immediate mitigation contributes to national sustainability by improving both (e) and (g) terms. Also, comparing (f) and (g), the reduced national climate costs as a result of reductions in future ROW emissions more than offsets the mitigation costs of reductions in future national emissions in those countries where climate change brings net costs.

6.3 Sensitivity analysis

Here we report some sensitivity analysis of the empirical estimates. In particular, Table 6 reports results based on the pure rate of time preference of $\rho = 0.05\%$ (the consumption discount rate of $r = 2\%$), $\rho = 1.05\%$ ($r = 3\%$; base case), and $\rho = 3.05\%$ ($r = 5\%$).[14] A higher consumption discount rate turns out to translate into changing sustainability from negative to positive in Saudi Arabia, where climate change does not bring net benefit, a higher consumption discount rate means lower national SCC, weakening both current damage and future benefit. The same reasoning applies to Australia, Brazil, China, and the US.

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[14] The SCC values are also adjusted under different discount rates. Section A in the Appendix develops an SCC under discounted utilitarianism. To convert the SCC value of Ricke et al. (2018), we assume that the consumption discount rate r can be decomposed into the utility discount rate, ρ, and the product of $\eta = 1.5$ and $g = 1.3\%$ in the Ramsey formula, where ρ can be determined as the residual. To convert the SCC consistent with the consumption discount rate of $r = 3\%$ to 2%, for example, we multiply the original SCC with $(0.03 - g)/(0.02 - g)$, following equation (28).

More importantly, it is only in developing countries (Brazil, Indonesia, India, Kenya, Nigeria, Vietnam, and South Africa) that unsustainability is implied for any of the discount rates chosen. The driving force here is, as shown in Table 5, high national SCC that is not fully recovered by future benefit of improved climate, despite relatively low future national mitigation costs. We conclude that national SCC of global CO_2 is much more important than the global SCC for countries with low current per capita emissions.

Table 6: Sensitivity analysis of our sustainability indicator with regard to the consumption discount rate, r (in billion USD)

	$r = 2\%$	$r = 3\%$	$r = 5\%$
Australia	-144	5	62
Brazil	-955	-275	-17
Canada	1,665	761	421
China	-1,730	634	1,582
Germany	1,090	751	625
UK	488	249	159
Indonesia	-1,312	-462	-141
India	-7,132	-2,632	-929
Japan	-173	41	129
Kenya	-200	-83	-38
Nigeria	-1,727	-690	-298
Norway	394	214	146
Russia	5,339	2,309	1,165
Saudi Arabia	-344	-44	70
USA	-1,106	181	705
Vietnam	-364	-135	-48
South Africa	-298	-114	-43

Note: The base case (with $r = 3\%$) result is taken from the (a)+(e)+(f)+(g) column in Table 5.

To be fair, there could be several ways to improve our preliminary analysis. Application to per capita genuine saving in the previous section 5 is both straightforward and important. Both future MAC and SCC are arguably uncertain, and robustness checks should be performed as new evidence arrives. Marginal mitigation cost estimates are quite uncertain, as it is affected, among others, by how fast countries mitigate given pledges and commitments, carbon leakage, past emission effort and path dependency, and other countries' emission effort. Although we carefully choose scenarios and assumptions that are internally consistent, some endogenous interplays might not be captured, such as the effect of past mitigation effort on future level of SCC. They should be studied further in integrated assessment models in the future.

7 Concluding remarks

We have developed an indicator of national sustainability which integrates carbon emissions in a manner that is consistent with the theory of comprehensive national accounting. In addition to including the national SCC of global CO_2 accumulation, the indicator also takes account of the net national cost of future reductions in national emissions and the national SCC of future increases in ROW emissions. Pledges and commitments to global and national targets are additional constraints on how economies evolve in the future, which in turn should appear in the expression of national saving as an indicator of sustainability.

We have illustrated the empirical ramifications of this national sustainability indicator by comparing it to the World Bank estimates, which incorporates carbon emissions by considering the global SCC of current national emissions. Our calculations suggest that developing countries — as India in our estimates — are considered less sustainable when using our indicator. The reason is that the national SCC of global CO_2 accumulation is much more important than the global SCC of national carbon emissions, for countries with low per capita carbon emissions. Another takeaway from our illustrative estimates is that the national cost of future reduction in national emissions might be non-negligible for developed countries — as Japan in our estimates — if they follow through on their pledges for future emission reductions.

On this background we argue that there is a need to change the way in which carbon is incorporated into empirical estimates of national sustainability, to make such estimates more informative of the actual development that different countries will experience when carbon emissions are accounted for. Of course, as our results reflect actual sustainability, we do not claim that countries assessed to be sustainable should not be held responsible. On the contrary, we argue that, by properly estimating how carbon emissions affect different countries, such national sustainability indicators might provide information that is useful in international negotiations about how to share the burden of climate policies. In the UNFCCC process, such burden sharing is implemented by NDCs where contributions are conditional on financial transfers, by the Adaptation Fund, and by the loss-and-damage fund that COP27 recently agreed to establish.

A SCC under discounted utilitarianism

The main purpose of this appendix is to lay a theoretical foundation under discounted utilitarianism for the estimated level and growth of the SCC in the empirical analysis of Section 6. It also serves as guidance for an SCC that can be used for comprehensive national accounting including carbon emissions.

There has been a heated debate on the formulation of carbon damage function (e.g. Burke, Hsiang, and Miguel 2015), but as is increasingly common, we assume that the damage of country i is proportional to the pre-damage aggregate output (Nordhaus, 2018) and linear in the relative temperature (van der Ploeg, Emmerling, and Groom, 2023):

$$D_i = (\bar{\varphi}_i + \varphi_i T)\ Y_i, \tag{24}$$

where $\bar{\varphi}_i$ and φ_i are country-specific parameters, T is the relative temperature, and Y_i denotes the pre-damage gross output. Recent evidence suggests that the temperature is linearly related to cumulative emissions (Matthews et al. 2009; IPCC 2014; Dietz and Venmans 2019), so that we can assume that δ is very small and

$$T = \bar{\xi} + \xi S, \tag{25}$$

where $\bar{\xi}$ and ξ are globally common parameters. In particular, ξ is often referred to as transient climate response to cumulative carbon emission (TCRE), which was coined after the proportionality between cumulative emission and global mean temperature change was found. Using (24) and (25), output net of climate change damage (Nordhaus, 2018) becomes $Y_i - D_i = [1 - \bar{\varphi}_i - \varphi_i(\bar{\xi} + \xi S)]Y_i = F(K_i, E_i, S)$, so i's marginal cost of adaptation reads

$$-F_S = \varphi_i\ \xi\ Y_i. \tag{26}$$

Recall that we have derived the national SCC $p_S^i(0)$ in (10). Exploiting our emission-temperature-damage specification (26) and noting that first-order condition (7) implies

$$\pi_i(t) = \pi_i(0)e^{-\int_0^t F_K \mathrm{d}s}\,,$$

expression (10) can be rewritten as

$$p_i^S(0) = \pi_i(0)\int_0^\infty \varphi_i\ \xi\ Y_i\ e^{-\int_0^t (F_K(K_i(s),E_i(s),S(s))+\delta)\mathrm{d}s}\mathrm{d}t\,. \tag{27}$$

For the purpose of empirical application, suppose further that:

(a) the output growth rate is constant at g_Y, so that $Y_i(t) = Y_i(0)e^{g_Y t}$,

(b) the social objective is discounted utilitarian, where utility U is a continuous, increasing and concave utility function, and $\rho > 0$ is a positive utility discount rate, as in footnote 4, and

(c) the utility function U has constant elasticity $\eta > 0$ of marginal utility, corresponding to $U(C_i) = C_i^{(1-\eta)}/(1-\eta)$ if $\eta \neq 1$ and $U(C_i) = \ln C_i$ if $\eta = 1$, and implying that $U'(C_i) = C_i^{-\eta}$.

Assumptions (b) and (c) imply that $\pi_i(t) = C_i^{-\eta}(t)e^{-\rho t}$ and $\dot{\pi}_i(t) = -(\rho + \eta g)\pi_i(t)$, where g is the consumption growth rate, allowing us to rewrite first-order condition (7) as $F_K = -\dot{\pi}_i/\pi_i = \rho + \eta g$. By also invoking assumption (a), expression (27) of the national SCC can be simplified further:

$$\frac{p_i^S(0)}{\pi_i(0)} = \varphi_i \; \xi \; Y_i(0) \int_0^\infty e^{-(\rho+\eta g+\delta-g_Y)t}\mathrm{d}t = \frac{\varphi_i \; \xi \; Y_i(0)}{\rho + \eta g + \delta - g_Y} \, . \tag{28}$$

This indicates the recent finding in the literature that the SCC is proportional to the output (see van den Bremer and van der Ploeg 2021 for a more general formula including damage uncertainty). The denominator also shows that the growth effect in the consumption discount rate and the growth effect on the SCC offset each other, with a complete offset if $\eta = 1$ and consumption and output grow at the same rate (i.e., $g = g_Y$). The analysis underlying this expression also supports our assumption that the SCC is constant.

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