Inclusive Wealth estimates for sustainable development assessment : a comparative approach to Genuine Savings and Comprehensive Wealth

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Abstract

In the wake of mounting environmental and social challenges, there is a renewed global interest in understanding development trajectories of the past, as a guide for sustainable future ones. Inclusive wealth measures such as Genuine (or Adjusted Net) Savings can be used to assess the sustainability of these paths. Still, despite a growing number of contributions related to various aspects of development paths, the use of Genuine Savings remains limited. One reason for this could be the existence of two empirical measures translating the theoretical notions of inclusive wealth and investment. Another potential culprit is the limited exploration of the forces driving Genuine Savings variations. We use a composite model to simulate both empirical measures of inclusive investment in a controlled environment and discuss the observed discrepancies between them. We then conclude on the merits of both measures and offer suggestions as to how practitioners could add inclusive investment to the routine tools used for development paths assessment.

Keywords : *Genuine Savings (GS); integrated assessment model (IAM); lifecycle impact assessment (LCIA); sustainability; policy analysis, structural change*

Introduction

The 2015 agreement in Paris, since signed by 160 countries, set a milestone for the global fight against climate change. Ratifying countries are now supposed to achieve their agreed goals in terms of carbon emission reductions, setting their economies on a new transition path towards low carbon development for any development stage.

Assessing the performance of economies along such a path is challenging, as all dimensions of development and their contribution to well-being ought to be considered. To this end, The World Bank (2006, 2011) and the United Nations (2012, 2014) have been pushing for the extension of national accounts along the line of comprehensive wealth accounting (Dasgupta, 2009). A comprehensive accounting of all assets engaged in the development/transition towards a low carbon economy enables the computation of Genuine Savings (GS) per capita, an indicator assessing the sustainable of the development path over all dimensions (IWR 2014).

The field of comprehensive wealth assessment and accounting has been expanding over more than 40 years, from the early models of resource accounting in the 1970's (DHSS, 1974), through the first country level estimates in the early 1990's (Pearce and Atkinson 1993) to the broad studies of the mid 2000's (World Bank 2006, UNEP 2014). These many contributions are now structured around two methods to compute GS. Although the theoretical underpinnings are similar, those methods generate different empirical translations of the same welfare measure.

More problematic for practitioners, these two methods have been picked up by the World Bank and the United Nations, resulting in two different sets of accounts being available to assess country level sustainability. This might result in confusion as to how the measures should be used and what they represent. It is also still not clear how the inevitable biases of wealth estimates might actually alter Genuine Savings. Resting on different assumptions, one might be, for example, especially sensitive to an unexpected fall in commodities prices, will the other could be overly sensitive to population growth rate estimates.

The aim of this contribution is therefore to compare estimates of Genuine Savings based on the World Bank and the United Nations methodology and assess how sensitive they are to estimation biases. As comprehensive national accounts are so far limited, any attempt to produce Comprehensive Wealth and Genuine Savings estimates will face severe data limitation.

To compare the two methods, we use the Integrated Assessment Model developed in Dupuy et al. (2017). This model is, to our knowledge, the only model combining a RICE model, a LIME3 life cycle assessment model and a set of shadow prices to compute Genuine Savings over a 100 years' time-horizon. Unlike previous models, this model is forward looking, enabling us to estimate Genuine Savings under real world data limitations but in a perfectly determined planning horizon, modelled on current UN projections regarding population and climate change.

In the first section of the paper we provide some theoretical grounding for our test, stressing the relevant variables to observe for an ideal GS estimator. We then present our modelling framework and our estimates. We conclude with a discussion on the merits of both and recommendation on the best possible methodology and data sources to build GS estimates.

1. A model economy to forecast GS over a century

Unlike past contributions which estimated present Genuine Savings based on past data (see Greasley et al., 2014), our testing strategy is based on a forward-looking model for the world economy over the next century. This allows us to test the performance of the two main empirical computation methods in a controlled environment with perfect foresight.

Representative agent

Our modelling strategy is based on an Integrated Assessment model (IAM) combining a RICE model for climate change assessment with the LIME Life Cycle Impact Assessment (LCIA) model. For a detailed description see Dupuy et al. (2017). The World economy is divided into n regions, each region j composed of identical individuals, maximising utility through the consumption of a composite good:

$$U\left(c_{j,t}\right) = \begin{cases} \frac{c_{j,t}^{1-\eta}}{1-\eta} (\eta \neq 1) \\ \log c_{j,t} \, (\eta = 1) \end{cases} \quad (1.1)$$

Where $U\left(c_{j,t}\right)$ is the per capita utility of consumption in region j at time t. The parameter η is the elasticity of the marginal utility of consumption.[1] Total Regional Utility in t $U\left(C_{j,t}\right)$, is obtained by multiplying individual utility by ${N_{j,t}}$[2], the exogenously given population number for region j in time t. We then sum regional total utility for all future time periods s over the time horizon T to obtain intertemporal well-being in t $V_{j,t}$:

$$V_{j,t} = \sum_t^T N_{j,s} U\left(c_{j,s}\right) \rho^{(s-t)} \quad (1.2)$$

…where ρ is the pure rate of time preference, reflecting how future generations' well-being is taken into account. Each region is assumed to produce a single commodity, which can be used for either "generalized" consumption or investment as economic variables. The generalized consumption includes not only traditional market purchases of goods and services but also non-market ones like enjoyment of the environment. Finally, regional-level intertemporal well-being V_t is maximised at the aggregate level via the function W_t in equation (3.3):

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[1] It also represents the curvature of the utility function, or the rate of inequity aversion, measuring the extent to which a region is willing to reduce the welfare of high consumption generation and to improve that of low consumption generation.

[2] The given population number, $N_{j,t}$, is taken from the SSP-2 scenario in order to coherently analyze climate change mitigation. The number is the largest among the 5 SSP scenario families (van Vuuren et al., 2012), somewhat higher than UN's (2003) mid projection, but still close to the central level compared with high- and low- projections.

$$Max\ W_t = \sum_j^n Neg_j V_{j,t} \quad (1.3)$$

W_t[3] is the objective function weighted sum of social welfare, $V_{j,t}$ for region *j* by Negishi weight, Neg_j[4]. The use of Negishi weights means the distribution on well-being is kept constant over time, preventing convergence in consumption levels.

Production

Gross Output is determined by a nested production function, with capital, labour and natural resources as inputs:

$$F(A_{j,t}, K_{j,t}, H_{j,t}, EL_{j,t}, NE_{j,t}, M_{j,t}, LR_{j,t}) \quad (1.4)$$

Where $A_{j,t}$ is the exogenously given total factor productivity term, $K_{j,t}$ is physical capital, $H_{j,t}$ is human capital, $EL_{j,t}$ is electricity, $NE_{j,t}$ is non-electric energy, $M_{j,t}$ denotes non-fuel mineral resources, and $LR_{j,t}$ denotes land resources.

We assume that all transfers of production factors across regions happen through investment and divestment: there is no lump sum transfers of capital, making it effectively immobile. Physical capital accumulation and depreciation happens only through the usual equation of motion:

$$K_{j,t+1} = (1-\delta)K_{j,t} + I_{j,t} \quad (1.5)$$

…where δ is the annual rate of capital depreciation. In line with our representative agent assumption, we take population growth and technological change to be exogenous. Technological change in the model is divided in two parts: the exogenously given TFP and the evolution of the mix of inputs used in the production process.

$$A_{j,t+1} = A_{j,t}/(1 - ga_{j,t}) \quad (1.6)$$

$A_{j,t}$ the TFP coefficient is determined every period based on the exogenous TFP growth rate $ga_{j,t}$. Capital accumulation and natural resource inputs are then determined by maximizing the discounted utility flow over time constrained by the technology mix (the production function). Net output is the given by:

$$Y_{j,t} = F_{j,t} - TC_{j,t} - EXT_{j,t} \quad (1.7)$$

The Net Output equation (1.7) ties together the three components in figure 1 together:

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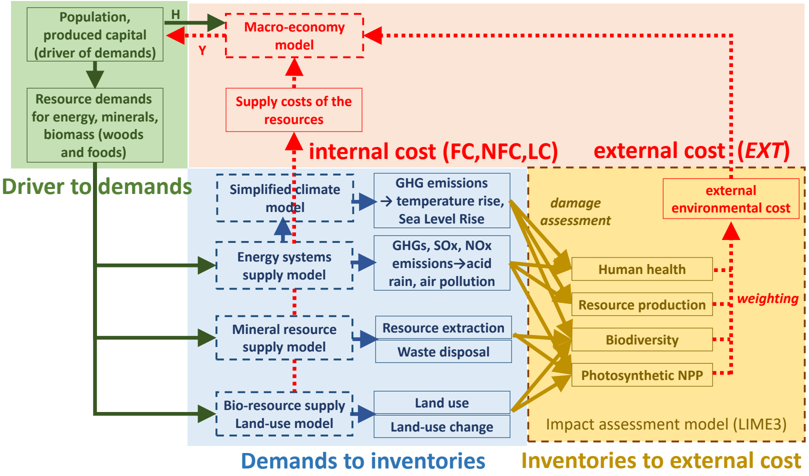
[3] $t \geq 0$, with time steps of 10 years from 2010 to 2150. We use steps of ten years to give enough time for the changes to happen in real life, following the World Bank view on Wealth accounting.

[4] The Negishi technique is referenced from Nordhaus and Yang (1996).

Figure 1.1: The structure of the model



The macroeconomic model in the red box determines Gross Output based on the cost of resource acquisition $TC_{j,t}$ determined in the blue box. Available Output is then reduced by the estimation of an external cost of production $EXT_{j,t}$ determined by the LCIA model (yellow box) to get Net Output $Y_{j,t}$. Further details on $TC_{j,t}$ and $EXT_{j,t}$ are provided below. There is interregional trade of the final good and trade is not balanced. Thus, the accumulated trade surplus/deficit of each region is not necessarily zero in any period, the final period included. The budget constraint for the representative agent in each region is therefore:

$$Y_{j,t} = C_{j,t} + I_{j,t} + M_{j,t} - X_{j,t} \text{ (1.8)}$$

With $M_{j,t}$ the imports and $X_{j,t}$ the exports. Interregional trade is then balanced globally:

$$\sum_j^n M_{j,t} = \sum_j^n X_{j,t} \text{ (1.9)}$$

As trade is not constrained to be balanced at any time, exogenous constraints reflecting the feasible evolution of consumption and investment are imposed every period for every region j. Net Output is allocated between generalized consumption $C_{j,t}$ and investment in physical capital $I_{j,t}$, so as to maximise aggregate (world level) well-being W_t. The level of $Y_{j,t}$ selected is associated with a cost and a level of environmental impact in the blue and yellow parts of the model.

Costs of production

The total cost of production TC_t comes from the three models of resource balance in the blue box (figure 1). These models tie together supply and demand to generate *inventories*. These inventories are then used as factor endowments in the production function $(EL_{j,t}, NE_{j,t}, M_{j,t}, LR_{j,t})$ while their direct cost of extraction/production is accounted for in TC_t (see equation 2.7). The climate model is adapted from the RICE 2010 model (Nordhaus, 2010). Description of the energy model and the land use model can be found in previous contributions (Tokimatsu et al., 2016a, Tokimatsu et al., 2017).

For simplicity, each model generates one final total cost, the product of cost minimization using dynamic linear programing. $FC_{j,t}$ is the production cost of fuel, $NFC_{j,t}$ the cost of non-fuel resources and $LC_{j,t}$ the cost of land resources. Formally:

$$TC_{j,t} = FC_{j,t} + NFC_{j,t} + LC_{j,t} \text{ (1.10)}$$

The external cost of production EXT_t comes from the LCIA model LIME3 in the yellow box in figure 1. While the overall cost of extraction $TC_{j,t}$ is a direct consequence of the demand for natural capital, there are other impacts associated with environmental degradation. These impacts are determined against endpoints that represents societal goals associated with sustainability. The inventories generated by the resource balance models form the basis of the impact assessed here. The external cost is computed as:

$$EXT_{j,t} = \sum \quad MWTP_{j,t} \sum \quad DR_{j,t}\, Inv_{j,t} \text{ (1.11)}$$

The external cost, is best understood as a stock/impact/value relationship. $Inv_{j,t}$ (stock) are inventory releases, which can be expressed as a function of N_t (e.g., CO2 emissions via transformation of energy resources stock changes, land cultivation and waste disposal by mining, and disposal of mineral resources). $DR_{j,t}$(impact) is a function to express the dose-response relation (or cause-effect chain) (Itsubo et al., 2014; Tang et al., 2014, 2015a, 2015b; Yamaguchi et al., 2016) that relate damages at the four endpoints to their causes, expressed as $Inv_{j,t}$.[5]

$MWTP_0$ is a set of Marginal Willingness to Pay (MWTP) associated with endpoints. We use MWTP instead of estimating a damage function as the estimation of an aggregated function is ill-suited to our disaggregated modelling structure. See Itsubo et al (2016), Tokimatsu et al. (2016), Murakami et al (submitted) and Kolstad et al. (2014) for more details.

2. Inclusive wealth estimates: Theory, past results, issues and application in our framework

a. Theory

A comprehensive presentation of the framework behind Inclusive Wealth can be found in Hanley et al. (2015). The welfare significance of wealth and the rate of change in wealth is grounded in standard utility theory. Consider intergenerational well-being, V_t, as expressed in equation (2.1) by using instantaneous utility, U_t, and the utility discount rate ρ:

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[5] Three examples are illustratively provided. Impacts on human health by global warming are expressed by relative risk increase due to global mean temperature rise ($T(t)$) (Tang et al., 2015a). Economic impacts of land loss by sea level rise (SLR) ($SLR(t)$) similar to those assessed by Fankhauser (1998) and Tol (2002a, b). Land use and land-use change are caused by biomass and food production, which can be expressed generally as $LU(t)$. $T(t)$ and $SLR(t)$ are obtained from the same formulations in RICE 2010, total carbon emissions from fossil fuel combustion in energy systems (Tokimatsu et al., 2016a), carbon released from land-use change (Tokimatsu et al., 2017), and exogenously given non-CO2 GHGs.

$$V_t = \int_t^{\infty} U_t C(s) e^{-\rho(s-t)} ds \; (2.1)$$

Sustainable development can then be defined as non-declining well-being over time, $\frac{dV}{dt} \geq 0$. Formally, Inclusive Wealth can be defined from Hanley et al. (2015) as:

$$IW_t = \; p_t K_t + w_t H_t + n_t N_t \; (2.2)$$

Where IW_t is Inclusive wealth valued using the SP p_t, w_t and n_t of the three capital stocks. Inclusive Savings are then:

$$IS_t = p_t \frac{dK_t}{dt} + w_t \frac{dH_t}{dt} + n_t \frac{dN_t}{dt} \; (2.3)$$

The welfare implication of IS and IW have been established through a series of contributions in the literature. The "dynamic average utilitarianism" reading is presented in Dasgupta and co-authors (2001, 2003, 2004, 2009, 2012). It is then used by the United Nations in the Inclusive Wealth reports (2012, 2014). These contributions show that the rate of change in IW is associated with the rate of change of intergenerational well-being V. Therefore, should the rate of change of Inclusive Wealth evaluated at shadow price in t be non-negative, the considered economy is deemed sustainable.

The core of sustainable development is the trade-off between consumption and investment in an intergenerational setting with irreversible decision regarding the use of exhaustible resources and the environment (Solow 1974). Assessing whether the economy is making resources available for development in time t, or whether agents are consuming a sustainable amount of resources in t is theoretically equivalent at shadow prices (see Hanley et al., 2015 for further details).

Empirically though, observing past and current consumption prices on the one hand and assessing the value of capital stocks used for production on the other are two different approaches. The first is conventionally termed *outcome-based sustainability*, the second *capabilities-based sustainability* and they rest on different observations and different assumptions (Hanley et al., 2015).

The *outcome based* approach seek to produce an indicator of sustainability based on one equity criterion: per capita consumption over time should be determined so as to get a distribution of consumption possibilities that is equitable over space and time, constrained by the available wealth and technology.

From the early contributions associated with the DHSS model (Dasgupta, Heal, Solow, Stiglitz), Hartwick (1977) and others have offered various rules for sustainable reinvestment to sustainably expand wealth and the production sets of economies, in line with equity considerations. The literature extensively discussed whether increasing consumption, both in volume and in value was ethically defensible (Solow 1974, Dasgupta & Heal 1979). The conclusion was that the only ethically defensible position is to maintain consumption constant in value terms over time.

They conclude (see for example Asheim 2003) that very strong assumptions are needed to build a sustainability indicator that have a welfare implication. It seemed therefore unlikely that a strong outcome-based Inclusive Savings measure could be build. The literature on green NNP (Asheim, 2007) illustrates this, as the measure gradually lost support and audience. Still, Arrow et al. (2012) have brought forward a *Comprehensive Wealth (CW) and Comprehensive Investment (CI)* setting that is the final avatar of this tradition.

Since building from scratch an outcome-based measure was challenging, authors starting with the Repetto et al. (1989) report have been mostly focusing on an empirical *capabilities-based* measure for Inclusive Savings, designed to work from existing national accounts and available dataset and guide their expansion. From Pearce and Atkinson (1993), Hamilton (1994), to the latest efforts of Greasley et al. (2014) have been expanding accounts and datasets to build estimates of *Genuine Savings* from capital stocks. See Hanley et al. (2015) for a review.

The distinction between capabilities (GS) and outcome based approaches (CI) to wealth accounting and Inclusive Savings computation is real and help explain the two clearly identifiable streams in the literature coexisting from the early 90's onwards.

These approaches are nonetheless more complementary than substitutes. As Inclusive Savings is a forward-looking indicator, it relies on assumptions regarding population and institutional dynamics, Total factor productivity trend and shocks and sudden critical juncture regarding the substitutability of capital stocks. What matters to your topic is that as a result of this division, different assumptions and sources have been used to build the two existing sets of indicators, resulting in potentially different predictions. The population and technical change dynamics especially could be estimated in different ways.

More generally, how much structure is brought on Inclusive Savings has an obvious impact on the results. The World Bank method is based on the setting offered by Ferreira et al. (2008) used in Greasley et al. (2014). Two methods can be used, one for a constant population growth rate, one for a varying rate:

$$GS = \frac{\dot{K}}{N} - F_R r - \gamma\omega \text{ (2.4)}$$

Where GS is a function of γ the population growth rate, N the population size, $\dot{K}$ the annual rate of change in produced capital, ω is per capita wealth and $F_R r$ is the shadow value of per capita natural capital extraction.

The formula to compute GS used by the Inclusive Wealth report team can be found in the 2014 IWR report, based on the contribution from Arrow et al. (2012):

$$Comp.Wealth = P_{pc} * PC + P_{hc} * HC + P_{nc} * NC$$
$$\Delta Comp.Wealth = P_{pc} * \Delta PC + P_{hc} * \Delta HC + P_{nc} * \Delta NC$$

With PC, HC and NC produced capital, human capital and natural capital respectively, and the P_i their associated prices. This formulation is then amended for capital gains, accounted for separately: oil capital gains, carbon damage and total factor productivity generating an adjusted wealth index.

This short review highlights a series of questions that should be raised when assessing a sustainability indicator:

1. Consumption/investment trade-off (investment being delayed consumption): Does the indicator rests on a smooth consumption path, with constant consumption or not? How well does the measure captures the importance of maintaining and expanding wealth for sustainability?
2. Does the indicator rely on optimality and more generally on the specification of a given economic structure or Resource Allocation Mechanism (RAM)?
3. How are population dynamics taken into account?
4. How are technological change and capital gains from trade integrated?
5. The treatment of substitutability: how large are the movements in reliance on one stock, and how robust is the indicator to it? How much is made to take into account boundary problems of limited substitutability.

The controlled environment of our model will allow us to see whether there are significant differences in the behavior of GS measures with respect to these questions. We now show how we adapted both methods to our modelling framework.

b. GS and CI in an Integrated Assessment Model

We have described our economy and the theoretical underpinnings of Inclusive Savings. We can now follow the method suggested by the World Bank (2006) to compute adjusted net savings (Genuine Savings), and the method proposed by Arrow et al. (2012) to compute inclusive wealth.

The representative agent maximises consumption over time, managing capital stocks and wealth to this end. We do not constrain this program further with the explicit addition of investment rules. GS are computed after optimisation every period, as they would be in real life conditions. Therefore, unless otherwise specified, all equations presented here yield values based on the results from our simulations, and are not integrated in our model.

A first adaptation from the theoretical setting above is the discrete time formulation for the social welfare $\bar{V}$ function in 2.1. Our utility functions are defined at the regional level, with $\bar{V}$ being determined by the social discount rate ρ, the population in the region N[6] and the individual instantaneous utility level *u*:

$$\bar{V}_{j,t,T} = N_{j,t} * U_{j,t} + \left(\frac{1}{1+\rho}\right) * N_{j,t} * U_{j,t+1} + \cdots + \left(\frac{1}{1+\rho}\right)^{(T/10-1)} * N_{j,t} * U_{j,t+(T/10-1)} \quad \text{[utility units]}. \ (2.8)$$

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[6] In line with the literature, N is exogenous. Calibration of the population dynamics is presented below.

$$\equiv \sum_{\varepsilon=0}^{(T/10-1)} \left(\frac{1}{1+\rho}\right)^{\varepsilon} * N_{j,t} * U_{j,t+\varepsilon}$$

T is the truncation year, picked to be 30 years. As indicated in equation 1.3, global welfare W is then computed summing regional welfare $V_{j,t}$ using Neigishi weights, as in the RICE model. Regional consumption levels are therefore the only endogenous variable entering the formulation of social welfare, in line with the theoretical formulation in 2.1. The other time-varying series, population N, is exogenous.

Changes in social welfare indicate sustainability and would therefore be the most theoretically rigorous indicator. Since our experimental modelling framework allows us to track social welfare levels, we use the rate of change in social welfare as our benchmark sustainability indicator:

$$DM_{j,t,T} = \left(\frac{\bar{V}_{j,t+1,T}}{\bar{V}_{j,t,T}}\right)^{0.1} - 1[\%/\text{yr}]. \ (2.10)$$

The annual changes in $\bar{V}$ are derived from the decennial changes between the 10-year time intervals. We then adjust DM for population growth $\frac{\Delta N}{\Delta t} = n$ and technological change $\frac{\Delta A}{\Delta t} = \tau$[7]

$$DMn_{j,t,T} = DM_{j,t,T} - n_{j,t} \ (2.11)$$
$$DMnt_{j,t,T} = DM_{j,t,T} - n_{j,t} + \tau_{j,t} \ (2.12)$$

$DMnt_{j,t,T}$ (hereinafter DM for simplicity) will be our benchmark indicator, showing directly how well-being changes over time. We then compute GS following the method used by the World Bank (World Bank 2011). The method focuses on the definition of comprehensive investment as in equation 2.5:

$$GS_{j,t} = (I_{j,t} - \delta K_{j,t}) + (Im_{j,t} + Ie_{j,t}) - \sum \ nr_{j,t} * q_{j,t} \ - \sum \ SP_{j,t} * Inv_{j,t} \ (2.13)$$

In line with the theoretical definition in equation 2.3, GS is the rate of change in capital stocks, at current shadow prices. $I_{j,t}$ is investment in physical capital, $\delta K_{j,t}$ is the depreciation of physical capital, $Im_{j,t}$ is investment in health capital[8], $Ie_{j,t}$ investment in human capital,

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[7] In a model that mimics the theoretical setting associated with equation 2.1 to 2.3, the shadow price of population as an asset and the shadow price of technical change should be readily observable. As our framework builds on the RICE model, it still considers population and technical change as exogenous, in line with Arrow et al. (2012). For this reason, we cannot derive from our framework a shadow price for N_t and A_t. We therefore follow Arrow et al. (2012) in adjusting our measures for population growth and total factor productivity. As both rates of change are constant, the simple subtraction of $n_{j,t}$ and $\tau_{j,t}$ suffices.

[8] This stock and the respective investment are added in our computations to the World Bank methodology based on the suggestion of Arrow et al. (2012).

$\sum \quad nr_{j,t} * q_{j,t}$ is the depletion of exhaustible resources (natural capital) and $\sum \quad SP_{j,t} * Inv_{j,t}$ is the indirect impact on well-being of natural capital depreciation (environmental degradation). These values are calculated form our simulation results using the following formulas:

- $I_{j,t} - \delta K_{j,t}$ is determined by equation 1.5 presented above.
- $Im_{j,t}$ is estimated using a power function that was defined using The World Development Indicators (WDI) in 2004. GDP values are then entered into that function to estimate the value of investment in medical expenses per capita. This per capita value is then multiplied by the population size in time t to obtain the total investment value.
- $Ie_{j,t}$ is estimated using a linear function that was defined using WDI in 2004. $Y_{j,t}$values are then entered into that function to estimate the value of investment in education per capita in year t. This per capita value is then multiplied by the population size in time t to obtain the total investment value.
- $q_{j,t}$ and $Inv_{j,t}$ are natural resources stocks and inventories obtained from the LIME3 and RICE components of our model.

The shadow prices associated with produced, human, health and natural capital are the optimal prices obtained from our model. $SP_{j,t}$ prices are computed as the rate of change in global well-being when the relevant inventory varies, over the change in well-being when consumption varies:

$$SP_{j,t} \equiv \frac{\partial W / \partial Inv_{j,t}}{\partial W / \partial C_{j,t}} = \frac{Winv_{j,t}}{WC_{j,t}} \ (2.14)$$

$Inv_{j,t}$ is also taken straight from the model results as in equation 1.11.

We have two sets of shadow prices $nr_{j,t}$ and $SP_{j,t}$ for our two types of natural capital flows, *direct* flows from inventories and *indirect* flows from endpoints. We do not compute shadow prices for produced and human capital, we directly add the full investment value. Our GS estimates are computed based on a 10-years step.

It should also be noted that due to the structure of our model (summarised in equations 1.7 and 1.8), only $I_{j,t} - \delta K_{j,t}$ is derived directly form the optimisation process. The other investment values are subtracted form the final level of consumption, based on net output.

The intuition is as follows: the representative agent set the level of net investment in produced capital which yields the available produced capital stock in t $K_{j,t}$. During this first step, a gross level of consumption is set, from which investment in human capital and health capital should be deducted. The agent has no control over this lump sum subtraction to gross consumption, as it is an amount exogenously set, proportionally to $Y_{j,t}$. The actual value of consumption is this net amount.

We can now define Genuine Savings as the rate of change in total wealth, by first computing total wealth using the World Bank (2011) method:

$$W_{j,t,T}^{PHA/WB} = \int_t^T C_j(t)e^{-\rho(s-t)}ds \quad (2.15)$$

Where ρ is equal to 1.5, C is defined as sustainable consumption, that is C minus $Im_{j,t}$ and $Ie_{j,t}$. Gross Genuine Savings is therefore:

$$\Delta W_{j,t+1,T} = \left[(I_{j,t+1} + Im_{j,t+1} + Ie_{j,t+1} - \delta K_{j,t+1}) - \sum \; nr_{j,t+1} * q_{j,t+1} - EC_{j,t+1}\right] / W_{j,t,T}^{PHA/WB} \quad (2.16)$$

Which shows how wealth has increased between t ant t+1. We then adjust this rate of change for population growth and technological progress (both exogenous in our model):

$$\Delta Wnt_{j,t+1} = \Delta W_{j,t+1} - n_{j,t+1} + \tau_{j,t+1} \, [\%/t] \quad (2.17)$$

…With $\eta_{j,t+1}$ the population growth rate[9] and $\tau_{j,t+1}$ the technological progress growth rate. $\Delta Wnt_{j,t\pm1}$ is the notation for our final, fully adjusted rate of change in wealth, or "GS rate".

We can now turn to the method used by Arrow et al. (2012). The method is based on the sum of all assets composing wealth, valued using their shadow prices:

$$W_{j,t,T}^{ADGMO} = Wn_{j,t,T} + Wp_{j,t,T} + Whu_{j,t,\hat{T}} + Whe_{j,t,T} \text{ [trillion in 2000 USD]}, \quad (2.18)$$

We adapted the expressions presented in the Inclusive Wealth reports (2012, 2014) to value these components separately. For physical and natural capitals, we followed the methodology developed by Kunte et al. (1998), using the discounted sum of production given by the amount of produced assets as valued by their shadow prices during the truncation year T. Produced capital is:

$$Wp_{rg,yr,T} = \sum_{\xi=0}^{T/10-1} \left(\frac{1}{1+r_{rg,yr+10\xi}}\right)^{10\xi} \cdot \left(\sum_{nfm}\sum_{\sec} \frac{10 \cdot \left(\left(np_{nfm,\sec,rg,yr+10\xi} \cdot D_{nfm,\sec,rg,yr+10\xi}\right) + \left(np_{nfm,\sec,rg,yr+10\xi+1} \cdot D_{nfm,\sec,rg,yr+10\xi+1}\right)\right)}{2}\right)$$

[trillion in 2000 USD]. (2.19)

Where np is the shadow price of produced capital and D the demand associated with the sector. Natural capital is then the sum of 2 subcomponents:

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[9] As population enters both the maximand and the production function in the macroeconomic model, GS should be adjusted (Dasgupta 2009). The literature offers two methods for this. First, Ferreira et al. (2008) consider future population growth as a form of «capital loss», as future total wealth should be divided amongst a larger number of individuals. GS are amended 2 ways to make up for the capital loss: a reduction of the discount rate and a wealth-based subtraction to the gross GS rate. Second, Arrow et al. (2012) considers exogenous population growth as one of the external dynamics of the economy, just like technological change. The GS amendment is then to subtract the population growth rate in t. As our production based computation of GS savings is the replica of Arrow et al. (2012) method, we use this adjustment. Note that our population growth rate is not constant between 10 years' time steps, but it is constant within those 10 years' intervals.

$$Wn_{rg,yr,T} = Wnm_{rg,yr,T} + Wnbio_{rg,yr,T} \text{ [trillion in 2000 USD]. (2.20)}$$

Those 2 subcomponents can be expressed as:

$$Wnm_{rg,yr,T} = \sum_{\xi=0}^{T/10-1}\left(\frac{1}{1+r_{rg,yr+10\xi}}\right)^{10\xi}\cdot\sum_{mr}\frac{10\cdot\left(\left(nr_{mr,rg,yr+10\xi}\cdot q_{mr,rg,yr+10\xi}\right)+\left(nr_{mr,rg,yr+10\xi+1}\cdot q_{mr,rg,yr+10\xi+1}\right)\right)}{2}$$

[trillion in 2000 USD]. (2.21)

$$Wnbio_{rg,yr,T} = \sum_{\xi=0}^{T/10-1}\left(\frac{1}{1+r_{rg,yr+10\xi}}\right)^{10\xi}\cdot\left(\sum_{bio}\frac{10\cdot\left(\left(nb_{bio,rg,yr+10\xi}\cdot B_{bio,rg,yr+10\xi}\right)+\left(nb_{bio,rg,yr+10\xi+1}\cdot B_{bio,rg,yr+10\xi+1}\right)\right)}{2}\right)$$

[trillion in 2000 USD]. (2.22)

We then present the definition of human capital:

$$Whu_{rg,yr,\hat{T}} = pH_{rg,yr,\hat{T}}\cdot N_{rg,yr} \text{ [trillion in 2000 USD]. (2.23)}$$

$$pH_{rg,yr,\hat{T}} = \exp\left(S_{rg,yr}\cdot\hat{\rho}\right)\cdot\left(\frac{N^{5+S}_{rg,yr}}{N_{rg,yr}}\right)\cdot\int_0^{\hat{T}} wr_{rg,yr}\cdot\exp\left(-\hat{\rho}t\right)dt \text{ [trillion in 2000 USD/cap]. (2.24)}$$

With S the years of schooling, that are a function a production $Y_{j,t}$. Human capital is expressed as the multiplication of educational attainment S, the number of population of the age of 5 plus the average years of the education attainment, and the shadow price valued by the present value of the average labour compensation of human capital received by workers over the expected lifetime working period.

Health capital is simply measured using the elasticity of the VSL in USA with respect to income/output/production per capita in 2000 ($VSL_{USA,2000}$ = 6.3 million USD), as used in Arrow et al. (2012):

$$Whe_{rg,yr} = VSL_{USA,2000}\cdot\left(\frac{GDP_{rg,yr}/N_{rg,yr}}{GDP_{USA,2000}/N_{USA,2000}}\right)^{0.6}. \text{ (2.25)}$$

These four components are then summed to obtain total wealth. The rate of change of wealth is obtained the usual way. Environmental Cost is subtracted from the wealth increase to reflect the capital losses associated with environmental externalities:

$$IW_{j,t,T} = \left(\frac{W^{ADGMO}_{rg,yr+1,T}-EC_{j,t+1}}{W^{ADGMO}_{rg,yr,T}}\right)^{0.1} - 1 \text{ [\%/yr]. (2.26)}$$

This rate of change is then adjusted as always:

$$Iwnt_{j,t,T} = IW_{t,j,T} - n_{j,t} + \tau_{j,t} \text{ [\%/yr] (2.27)}$$

This concludes our presentation of the two alternative GS measures in our setting.

c. Data sources and calibration

The discrete time step of our model is 10 years. There are 10 regions: North America, West Europe, Japan, Oceania, China, East-South Asia (including Association of Southeast Asian Nations (ASEAN) member countries, plus India), the Middle East and North Africa, Sub-Saharan Africa, Latin America, and the former Soviet Union and East Europe. Our population is assumed to be composed of representative agents, its size being estimated based on UN projections from the Shared-Socio Economic Pathways (SSP)-2 scenario (van Vuuren et al., 2012). Population data ($N_{j,t}$) and the reference level ($\overline{Y}_{j,t}$) of the GDP scenario are taken from the SSP database (version 0.9.3) (IIASA, 2015), in which IIASA-WiC Population and OECD GDP are applied.

Regarding the labour population ($L_{j,t}$), we compute the population rate at each time period for each area, based on a medium-scenario population projection by the United Nations (UN 2003, 2011). We subsequently multiply these figures by the population data ($N_{j,t}$). Calibration data for C, I, Y, M, X, in 2010 and δ (set from 7% to 18% per annum) for the respective regions, are obtained from the World Development Indicators (WDI) (World Bank, 2015) and the Global Trade Analysis Projects (GTAP) data base (Purdue University, 2015).

The setting of the initial K value is obtained from the RICE 2010 model (Nordhaus, 2010). We use a nested CES production function inspired by Berndt and Wood (1975), Manne & Richels (1996) in a departure from the usual specification in either RICE -99 or -2010 (Nordhaus & Boyer 2000, Nordhaus 2010). $MWTP_0$ is derived from the discrete choice experiments used in environmental valuation, whose data is obtained from both face-to-face and Internet surveys in G20 and Asian countries. Details of the survey and analysis can be found in Itsubo et al., (2015) and Tokimatsu et al., (2016b).

The utility discount rate, ρ, is assumed to be 1.5 % per annum, in the lower end of the range in the literature (0.1%-5%), (Portney and Weyant, 1999; Stern, 2006; Dasgupta, 2008; Nordhaus, 2007). Regarding the importance of parameter settings in the production function (Maeda and Nagaya, 2013), we reviewed the parameters ε and λ in the literature (Berndt and Field, 1981; Nemoto, 1984; Manne and Richels, 1992; Markandya and Pedroso-Galinanto, 2007). Capital depreciation is set as .07-.18 depending on regions. Since the one-time period of our model is assumed to be 10 years, we use the tenth power of the annual rate in the equation. The income elasticity of substitution over time σ is set as .5 as default from Pearce (2003).

TFP is calibrated from data sources to fit the scenarios (level of production). The form of function ϕ is increasing, but diminishing in rate ($\phi' = d\phi/dS > 0, \phi'' = d^2\phi/dS^2 < 0$), where ϕ equals 0 when S is 0. Here ϕ' denotes marginal income increase by additional education attainment, corresponding to the coefficient (rate of return); ϕ' was determined using data from various studies (Psacharopoulos, 1994; Hall and Jones, 1999; Psacharopoulos and Patrinos, 2004 Lutz et al., 2007, Barro and Lee, 2010; World Bank, 2015).

We do not follow DICE 2013 for our initial values for the TFP level ($A_{j,0}$) and growth rate ($ga_{j,t}$). We calibrate the TFP growth rate based on the future baseline scenario (SSP-2) to obtain feasible solutions for computation. In some sections we applied historical data from Klenow

(2005). We calculate the TFP to determine not only $A_{j,0}$, but also values over the time horizon from the results of the SSP-2 scenario.

First, we obtain $A_{j,t}$ from the solution of equation (3.7), here in expanded form:

$$\bar{Y}_{j,t} = (A_{j,t}, K_{j,t}, H_{j,t}, EL_{j,t}, NE_{j,t}, M_{j,t}, LR_{j,t}) - (FC_{j,t} + NFC_{j,t} + LC_{j,t}) \quad (4.1)$$

where $\bar{Y}_{j,t}$ is the GDP of SSP-2, and the other choice variables are endogenously calculated in our model. Subsequently, the regression analysis was conducted from the obtained ($A_{j,t}$ to derive the initial level ($ga_{j,0}$) and decline rate ($dela_{j,t}$) of the TFP growth rate. The derived TFP is given as a constant parameter throughout our simulation in the sensitivity analysis.

3. Results

a. Scenarios and simulations

As population growth is the main exogenous variable in our model (and the main force of change with productivity over long time spans) we run our model with 2 different scenarios with respect to population trajectories:

- A first scenario termed Eeff (for economically efficient) pictures population as growing in line with the median Shared Socioeconomic Pathways 2 (SSP-2) proposed by the UN. In this scenario population keeps growing over the period but at a decreasing rate from the middle of the 21st century.
- A second scenario termed "2050const" assumes a constant population from 2050. This scenario is designed to generate constant consumption and therefore compare our sustainability indicators in this theoretically consistent case.

We also present for illustrative purposes a final scenario "BAU" for Business As Usual where the External environmental cost EXT is not subtracted form production in equation 1. 7. This is the scenario where environmental externalities are not internalised, which results in extra room for consumption and a lower burden for resource consumption.

Figure 3.1 shows the trajectory of GDP (Y) in all three scenarios, levels (in Trillion USD) and losses as a percentage compared with BA10.

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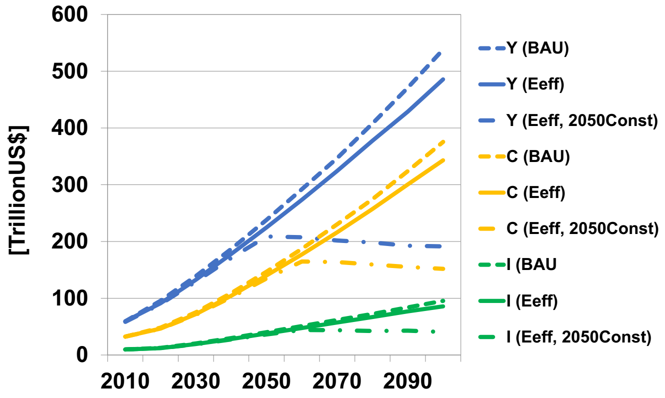
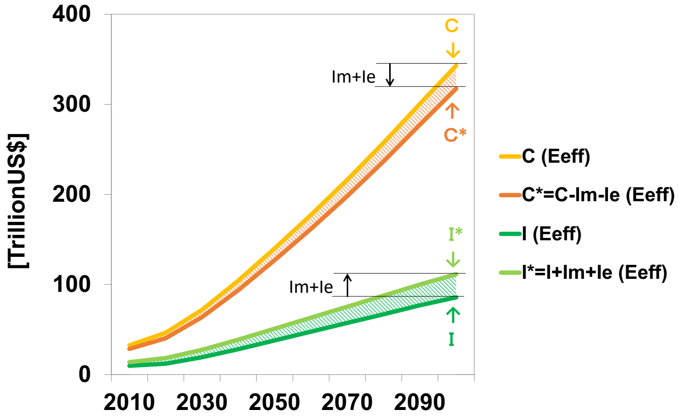
[10] In order to obtain computational feasible solution, endogenously obtained GDP is uncapped in the computation under 2050const scenario; hence the level after 2050 is almost stable but with a little unstable.

Figure 3.1: GDP under all three scenarios



(a) model runs for output, consumption, and investment



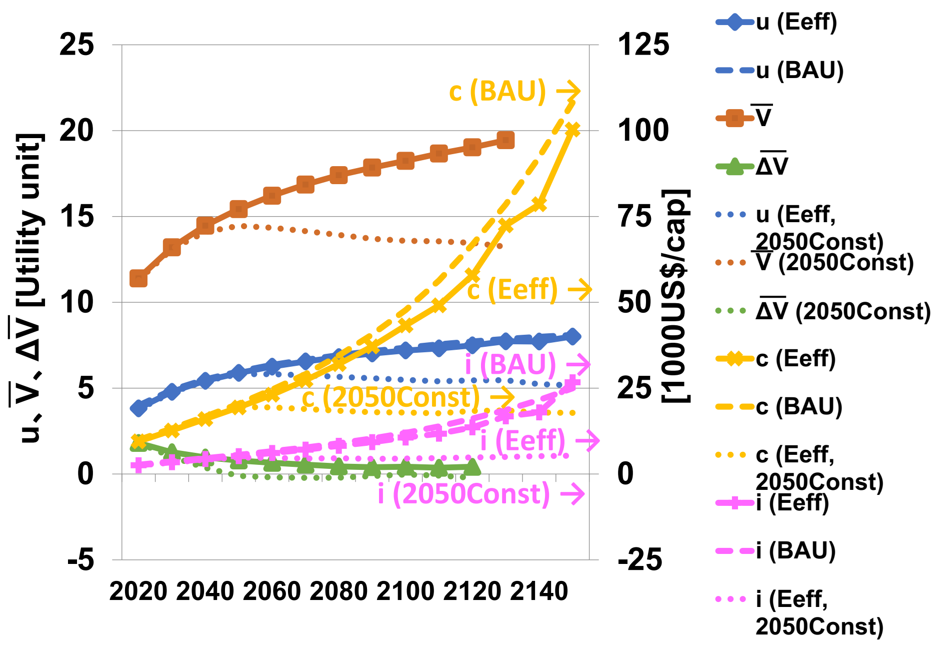
(b) adjusted consumption and investment; C*=C-Im-Ie, I*=I+Im+Ie

The critical variables in our model are displayed in figure 3.1. Figure 3.1 a) shows the trajectory of GDP (Y) in all three scenarios in levels (in Trillion USD). Figure 3.1 b) shows the adjustment of consumption and Investment to obtain effective consumption C* and total investment I*.

Figure 3.2 shows trajectories of per capita consumption c (in yellow), utility u (blue), “instantaneous social welfare” $\overline{V}$ defined as discounted sum over 30 years of multiplying the utility with population (brown), and “time differentiate” in the 10-year time step of $\overline{V}$ ($\Delta\overline{V}$), up to 2150.

c, u, and $\overline{V}$ are continuously increasing under BAU and Eeff scenarios while those are almost stabilized (a little declining especially $\overline{V}$ which includes number of population in declining after 2070). Due to the declining trend of $\overline{V}$ leads to $\overline{\Delta V}$ shows zero or slightly negative.

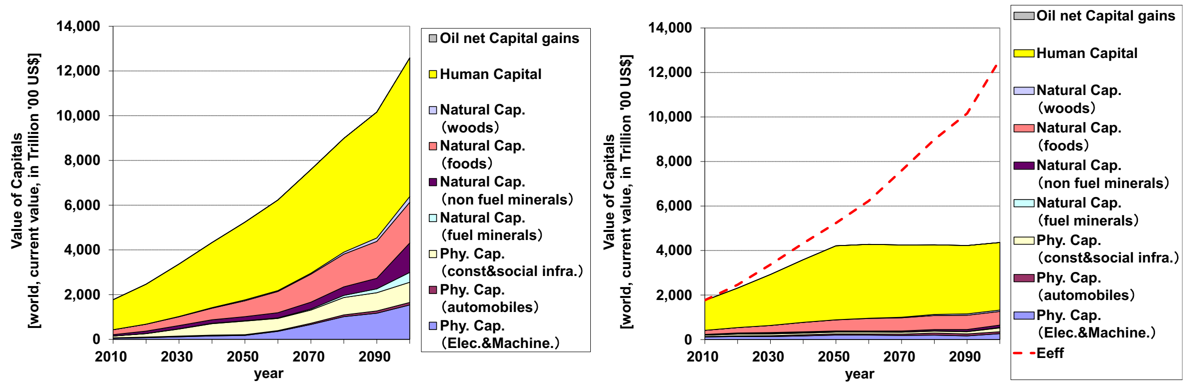
Figure 3.2: Output, consumption and Utility under all three scenarios



c, u, and $\overline{\mathrm{V}}$ are continuously increasing under the BAU and Eeff scenarios while those are almost stabilized (a little declining especially $\overline{\mathrm{V}}$ which includes a population decline after 2070). Due to the declining trend of $\overline{\mathrm{V}}$, $\overline{\Delta\mathrm{V}}$ turns to zero an even slightly in the negatives.

Figure 3.3 shows the accumulation of capital components over time under the two balanced growth scenarios ((a) Eeff, (b) 2050const).

Figure 3.3: Capital stocks in the Eeff and 2050const scenarios



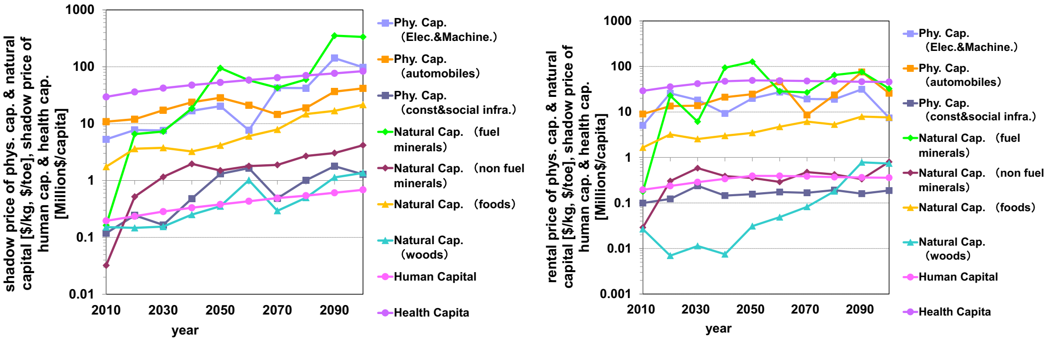
a) scenario Eeff

b) scenario 2050const

The Eeff scenario shows an expected pattern of accumulation, driven by Human capital, Food products and Produced Capital. The 2050const scenario displays a lower trend of capital accumulation while population is still growing, then a quasi-stabilisation from 2050 onwards. Without population growth, our model shows a constant capital stock, so that investment is mostly directed at maintaining existing capital and compensating the ongoing depletion oh exhaustible natural resources (the so-called cake eating economy).

Figure 3.4 finally shows trends of shadow prices over time in both scenarios. All trends are clearly upward slopping in the population growing Eeff scenario. The picture is more mixed in the 2050const scenario, where assets that witness stock increases also see price increases, while others have flat prices over the period.

Figure 3.4: Asset prices over time



a) scenario Eeff

b) scenario 2050const

This concludes the description of our model world economy. The model exhibits the expected behaviour across all three scenarios, with consumption, capital accumulation and utility evolving in line with expectations with respect to the population assumptions.

b. Comparison of GS measures under the different scenarios

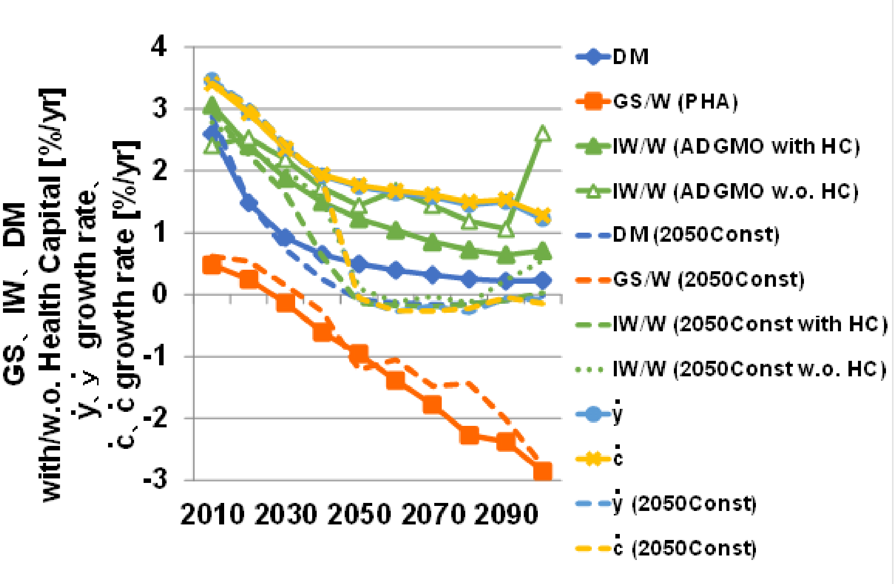
We can now turn to the values computed for GS and CI in this model context. In figure 3.5 we show, each time for both scenarios:

- Values for DM, the rate of change in intertemporal social welfare V
- Values for IW/W, comprehensive investment. This value is computed with and without Health Capital as Health Capital it so far excluded from Genuine Savings.
- Values for GS/W, the rate of change in Genuine Savings.
- Values for the rate of change in consumption and investment levels.

General comments on figure 3.5 gravitate around the common downward trend to all variables. The ranking of indicators also consistently shows Comprehensive Investment CI exhibiting higher rates of savings than the rate of change in social welfare DM and the rate of change in GS. The consumption growth rate follows the output growth rate, both declining.

The end of period peak associated with CI without health capital is a puzzle at this stage. Under the 2050const scenario, CI both with and w/o Health Capital drop with DM to reach marginally zero while GS/W shows little difference compared to its values under the Eeff scenario. The fact that the inclusion of Health Capital lowers the rate of change in CI is due to its size: when included is actually smooths the savings rate and brings complementary to other types of assets (see the discussion section below).

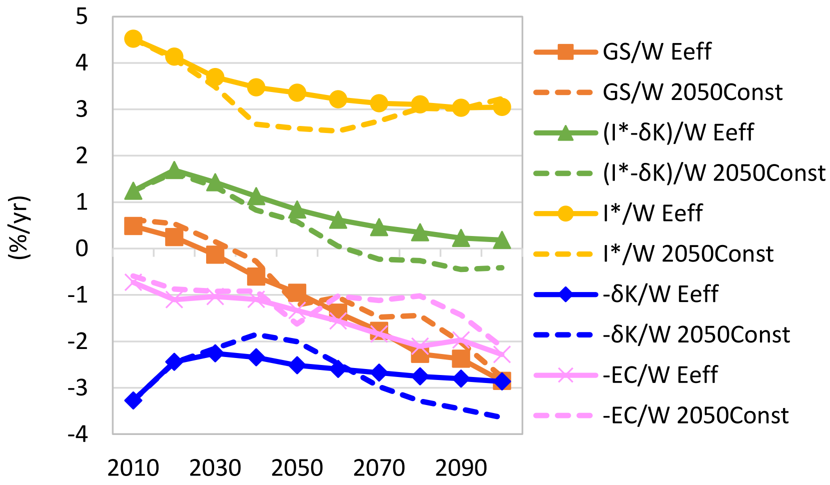
Figure 3.5: Rate of change in all three measures for GS



In figure 3.6 we bring further insight into the behaviour of our inclusive wealth indicators, showing the separate movements of the various GS components. In line with the previous graph, gross investment is falling over the period, with a sharper/lower fall before/after 2050 in the 2050const scenario. This is consistent with the perfect foresight assumption in our model, as the representative agent reduces investment quicker anticipating population stagnation. Then in the face of the same resource constraints, he builds up capital marginally more quickly to end of at a similar rate of gross investment.

This profile produces mirror curves for the depreciation of produced capital (blue curves). As, a result, net investment is effectively negative (respectively marginally positive) in the 2050const (respectively Eeff) scenario. The final component EC/W corresponds to $\sum \; SP_{j,t} * Inv_{j,t}$. It anchors GS firmly in negative territory, although there is a bounce back in the 2050const scenario after 2050 due to the reduced pressure on resources.

Figure 3.6: Various components of wealth as a percentage of the total



4. Discussion

In this section, we briefly discuss the results along two main points.

Consumption, Investment and Utility: structural change.

Our model economy in the Eeff scenario exhibits a decline in the rate of consumption, investment and output growth. Since consumption only yields utility and intertemporal well-being, the representative agent arbitrage away from investment in the early periods. Associated with a fairly high rate of produced capital depreciation, natural resources depletion and environmental impacts this results in a shrinking material productive base.

This part of the model behaviour reproduces accurately the standard feature of a cake eating economy, condemned to declining output and consumption. This feature is clearly portrayed in the 2050const scenario, as consumption is actually declining.

Still, in the Eeff scenario consumption keeps increasing at a declining rate as our representative agent maintains investment in other capital stocks. With a growing population and a reasonably high level of substitutability between capital stocks, the world economy turns to relatively cheap human capital as a source of output. Substitution away from material capital allows utility to keep growing, even at a declining rate.

Our simulations show how, despite falling natural resources stocks and increasing environmental impact, the economy can keep running by shifting its productive base to cheaper assets and different goods.

These observations lead us to call for a broader understanding of the notion of structural change. Structural change is mostly used to describe a change in the sectoral composition of the economy (an increase in the weight of manufacturing matching a fall in the weight of agriculture) or a change in the skill structure of the working population (going from low-skill

to high-skill). In a sustainability context, the notion of structural change can be applied to describe country level evolving reliance on various assets of different nature.
Beyond the traditional *state* description of countries (resource-rich, resource-poor, industrialised, service driven, etc.), a forward looking measure such as inclusive savings interrogates the *dynamic propertie*s of an economy, its ability to transition from one state to another.

Those dynamic properties are contingent to the resource base of the economy, symbolised by its reliance on various capital stocks. In a sustainability context and the associated very long time horizon, the ability of the social planner to maximise utility is contingent on the ease of substitution between assets (Neumayer, 2010), as much as the individual rates of return they yield. It is in this underlying assuming that the two measures differ in their sustainability assessment.

Inclusive Savings : a single measure ?

How well do both measure predict sustainability in this context? Both GS and CI are declining over the time period, but only GS turn negative, as early as 2030. Still, our modelled world economy is allowed to run for more than a century afterwards, without seeing a fall in consumption and utility levels. The introduction of constant population after 2050 is the only hypothesis producing this result.

Are GS yielding a too pessimistic sustainability outlook then? GS turn negative under the combined pressure of falling aggregated investment, low maintenance and increased environmental impact. What GS is not capturing is how the economy is completing this unsustainable production pattern with population based assets such as human and health capital.

CI never turns negative and stays consistently above the rate of change in intertemporal well-being. The trend of the measure is more regular, reflecting an appraisal of the assets that is closer to the actual use by the representative agent. As a result, CI is largely driven by variations in the large stock of human and health capital. By construction, the measure evens out, just like our model economy, the very different states of the various assets mobilised.

The difference between the two measures (computed as they are today), can be summarised through their handling of the joint questions of substitutability and structural change. By construction, GS underestimates the ability of economies to generate utility based on human capital, skills and knowledge. It also underestimates the ability of technical change to reduce reliance on natural capital assets, or at least improve in due time the substitutability of these assets. The more “production based” outlook of GS ends up making it more conservative in ist outlook.

GS seem to have an especially hard time dealing with assets that have a low investment value and a high stock value. It fairs better with more conventional assets where the relationship between investment value and use value is closer to produce capital and natural capital goods. Still, GS offer a more precautionary approach and the prominence given by the measure to various components of natural capital is probably better suited to the needs of the economy.

Conversely, CI embraces more broadly the asset base of the economy and effectively assumes high substitutability between assets. This logic is probably a good fit for knowledge based advanced economies where intangibles play a large role in generating well-being. It probably reflects better the current state of these economies, but is less robust to sudden asset or asset class-specific shocks. These shocks ought to be priced in the shadow prices of these assets.

Inclusive wealth measures of sustainability come from a sound theoretical framework and perform well in empirical studies (Hanley et al. 2015). There is a general trade-off between comprehensiveness and accuracy, where including more assets over a greater number of countries leads to less detailed data and cruder methodologies (especially for shadow prices estimates).

Beyond this general trade-off, practitioners should consider carefully the aim of their study and the structural state of the economy considered, before choosing one the existing measures and/or build new estimates. Comprehensive investment and other outcome based methods that rely on consumption data are a good fit for flexible economies with a relatively even distribution of assets and a regular consumption profile. Genuine Savings and production based methods will fare better in economies undergoing major structural transformation and/or characterised by an uneven distribution of equally important assets (such as industrialising economies).

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