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Global macroeconomic sustainability: a dynamic general equilibrium approach

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ABSTRACT. Previous empirical studies assessing sustainability have adopted the weak sustainability indicator (WSI) which measures changes in the stock of physical and natural capital. Whereas these studies have been retrospective, we use a dynamic general equilibrium model to investigate global and regional sustainability over the period 1985–2050, focusing on fossil fuel extraction. Our standard scenario predicts increasing WSI values suggesting global sustainability in all periods to 2050 as, despite a rising world oil price, the introduction of backstop fuels in 2010 provides an alternative source of energy. A more pessimistic scenario examines possible outcomes in the absence of energy saving technological change and backstops fuels. WSI values still indicate global sustainability, though economic growth is only half that predicted by the more optimistic model, and two countries—USA and Brazil—are unsustainable.

1. Introduction

Studies exploring the sustainability of countries or regions have adopted a so-called weak sustainability indicator (WSI) as the basis of one criterion of sustainability. This criterion requires that the values of savings (investment) should be equal to or exceed the sum of the value of manufactured capital depreciation and the value of natural capital depletion and degradation. In other words, the value of the stock of physical and natural capital should not decline over time (Pearce and Atkinson, 1993 and 1995, Proops *et al*., 1999). The use of the WSI rests on the possibility of substitution between man-made and natural capital, and also between different types of natural capital, while the preferable strong sustainability indicator requires that the overall stock of natural capital (and particularly 'critical' natural capital) is non-declining (Turner, 1993). Our limited understanding of the life support functions of ecosystems and problems of valuation make the adoption of this stronger indicator currently infeasible.

Empirical studies have sought to handle the problems of obtaining data

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on natural capital depreciation in two different ways. The approach of Proops, *et al*. (1999) is based on world national income data, covering the period 1980–1990, supplemented by data on non-renewable capital taken from studies for a few countries. The advantages of their approach are, first, that it can explore sustainability on a global basis and, secondly, that it incorporates the 'environmental footprint' of trade. The main disadvantage is that, as undertaken, it does not include wider forms of natural capital. However, the development of 'green' national accounts would remove this disadvantage so that, in the longer term, this approach would provide a useful indicator to help assess whether countries are following sustainable growth paths.

Other studies have assembled a wider range of data on natural resource degradation and depletion for various countries(e.g., Pearce and Atkinson, 1995; Hamilton and Atkinson, 1995). They thus provide a more comprehensive valuation of natural resource changes but, as these studies generally cover only one year and only one country at a time—Hamilton and Atkinson (1995) is an exception—the information is insufficient to suggest whether such countries are adopting sustainable policies. Indeed, Proops *et al.'s* study suggests that some countries/regions can move from an 'unsustainable' result in one (two year) period to 'sustainable' in another, and vice versa.

Both approaches illustrate the weakness of formulating policy objectives in terms of economic growth as conventionally measured. However, while they may shed light on sustainability in recent years, the main questions revolve around whether economies will achieve sustainability or remain sustainable in the much longer run. Sustainable development has been defined as 'continuously rising, or at least non-declining, consumption per capita or GNP, or whatever the agreed indicator of development is' (Pearce *et al*., Blueprint 3, 1993, p. 8). The question then is: 'Can we achieve this in the longer run, given recent economic performance and recognition that non-renewable resources, such as fossil fuels, are by definition non-sustainable?'. In the longer run, population growth and technological change will be important, as will the timing, price and general availability of substitutes for fossil fuels. Existing studies have been retrospective; we look into the future, and our aim is to investigate sustainability using a global applied general equilibrium model to simulate country and regional scenarios for the period 1985–2050. This period provides a realistic planning horizon, bearing in mind that the life of an average power plant is 30 years. We follow the lead of Proops *et al*. (1999) in that our data are based on input–output tables taken mainly from national income accounts. This means that, like them, we cannot incorporate into our analysis degradation or depletion of renewable resources such as forests, soil, fish and other fauna. Instead we focus on fossil fuels, which are the major non-renewable capital resource, and adopt the WSI to explore country, regional and global sustainability.

In certain theoretical models, developed by Weitzman (1976), Aronsson *et al*. (1997) and Bailey and Clarke (1998), it is possible to give the WSI an exact welfare interpretation, as the rate of change of current planner utility, or as a lower bound to this rate of change. This interpretation brings out

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one important aspect of the WSI: that it 'looks' only at the medium run. Environmental disasters or windfalls beyond a certain time horizon are washed out of consideration by discounting. A 'high' or 'low' WSI says something about prospects over the next few years, but hardly reveals whether long-run maintenance of current consumption levels is feasible.

The indicators computed in subsequent sections do not meet the theoretical requirements for the rate-of-change-of-utility interpretation, because of the omitted forms of capital (omitted for reasons explained above), and because valuation of investment and depletion is at (possibly distorted) market prices rather than at the shadow prices of an optimal control model. It is correct, then, to think of WSI's as 'indicators' of general wide-sense investment health; indicators to be supplemented with such other indicators as it is possible to compute. We use them in this spirit, and do not claim (for instance) that WSI $\geqslant 0$ is either a necessary or a sufficient criterion for 'sustainability', however defined. As well as the levels, the movements of the indicators over time are of interest, though of course the omitted-variables issue means that these too should be interpreted with caution.

We proceed as follows. In the next section we describe the model we use for simulations. In section 3 we report scenarios which incorporate different assumptions about technological change and the introduction of renewable energy and, in the final section, we draw some conclusions.

2. The OECD model GREEN[1]

In order to track the movements of a WSI in the presence of technological progress and population growth, we use a global dynamic applied general equilibrium model developed by OECD to study the costs of abating carbon dioxide. This **G**ene**R**al **E**quilibrium **EN**vironmental model (GREEN) consists of 12 regional sub-models, 11 producer and four consumer sectors, and various primary factors (a full list is provided in appendix table 1). The simulation period is from 1985 to 2050 and is broken into five-year intervals up to 2010 and two 20-year intervals thereafter.

The key features which determined our choice of this model for our study include:

- global coverage and extensive regional breakdown;
- bilateral trade linkages between all regions for energy and produced tradeable goods;
- detailed modelling of energy sectors, covering both fossil and renewable fuels;
- endogenous world oil price.

GREEN derives its dynamics from fossil fuel depletion, productive capita accumulation and the putty/semi-putty specification of technology, and it is on these aspects that we focus in this section. Further information about GREEN, its data sources and parameter values will be found in the

[1] This section draws on material from Burniaux, Nicoletti and Oliveira-Martins (1992) and van der Mensbrugghe (1994).

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appendix. Alternatively, Burniaux, Nicoletti and Oliveira-Martins (1992) provide a more extensive discussion of the model.

The energy sector in GREEN covers the three primary fossil fuels (coal, crude oil and natural gas), two secondary fuels (refined oil and electricity) and two backstop technologies. One of these backstops is carbon based, obtained from coal or oil shale, while the other is a carbon-free backstop, e.g., nuclear fusion, solar or wind. Apart from basic fuel production, where (with the exception of electricity) all inputs are employed in fixed proportions (the Leontief technology), intermediate and final production is mainly modelled by nesting constant elasticity-of-substitution (CES) functions. Substitution between energy and a composite input of capital and fixed factors, and between labour and a composite capital/energy fixed factor can occur at subsequent stages. The adoption of a putty/semi-putty technology means that energy can be complementary to capital and the short run and substitutable in the long run. It also has the advantage that capital can be divided into old and new vintages, allowing the incorporation of adjustment costs into the investment process, so that new capital is assumed to be perfectly mobile across sectors, while old capital is partially mobile and less easy to substitute than new. Capital market rigidities are particularly noticeable in the energy sectors where, for example, capital in the form of power stations has few alternative uses (the new Tate Gallery extension being an exception!). Consequently equilibrium rental values for old capital may be lower than for new capital goods and may differ across sectors so that the supply of old capital (i.e. divestment) is not pre-determined but depends on the ratio of rental values of old and new capital.

Coal reserves are assumed to be infinite within the model's time horizon of 2050. The two key parameters of the resource depletion sub-model which determines potential supply of oil and gas are, first, the rate of discovery (i.e. conversion of unproven reserves to proven) and, secondly, the rate of conversion (i.e. extraction converting proven reserves into potential supply) which is region specific. These parameters determine the production profiles which may initially increase over time if new discoveries exceed extraction. In the long run, however, all regions must face declining profiles as oil and gas resources are exhausted. The conversion rate, or level of unproven reserves, is price sensitive. Higher oil and gas prices provide an incentive to increase extraction and intensify exploration, while lower prices may lead producers to delay exploitation of proven reserves. Energy exporting countries may supply less than their potential if prices are low, but producers in other regions are assumed always to supply at potential.

The modelling of foreign trade in GREEN is particularly convenient for our study as each bilateral trade flow between country/region is separately specified. For each tradeable good, including coal and gas, imports are derived from demands of producers and consumers, and import demand depends on the relationship between domestic and world prices. The Armington assumption (that imports from different countries are imperfect substitutes and countries face downward-sloping demand curves for exports) is adopted for all goods except crude oil, which is assumed to be homogeneous across regions, implying a single real world price. The oil

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price is endogenous, being determined by the marginal costs of suppliers in the energy-exporting LDCs region (other producers being price-takers), given world demand for oil. Domestic oil prices, however, may vary across countries and regions as they are deflated by the real exchange rate. This is defined, in each area, as the ratio of a weighted average of domestic primary factor prices to the *numéraire* of the model, which is the price of labour in the United States. Coal and natural gas prices are determined by the supply elasticities of their respective resource bases. These fuels are heterogeneous across regions because their transportation costs are greater than those of oil.

As fuel reserves are drawn down, the only substitutes will be those emanating from backstop technologies. When they come onstream, GREEN's two backstops are available in all regions at the same time and at the same price. Hence, they are not traded and their prices are exogenous, capping the level to which the price of conventional fossil fuels can rise. Supply is infinite as they are renewable (e.g. solar energy) or from coal or oil shale which, it is assumed, will not be depleted within the timescale adopted for the simulations. Carbon-based backstops are considerably less expensive than carbon-free technologies, and the extent to which backstops can penetrate fuel markets depends on their prices relative to those of conventional fuels.

Consumer/household choice is modelled through a static version of the extended linear expenditure system. For each country/region, a single representative household is assumed to allocate optimally its disposable income between four categories of consumer goods (see appendix table 1) and saving. Savings are independent of the rate of reproduction of capital. Household income comes from labour, capital, rents of fixed factors, crude oil and backstops, and from government transfers net of taxes. There is no forward looking behaviour, and the simulation periods are linked through factor accumulation equations which can be either exogenous (e.g., labour supply) or endogenous (capital supply and resource depletion). Saving is determined simultaneously with the demand for consumer goods, and drives investment, which is not modelled explicitly. Aggregate investment is derived as a residual and is equal to the sum of personal saving, capital depreciation, government sector net balance and foreign flows of capital. Capital depreciation is at a constant, region-specific rate, the rates being calculated on the basis of 1985 data.

3. The simulations

In this section we report the simulation values generated by GREEN for $W(t)$, defined as $W(t)$ = {value of gross investment} − {value of depreciation of manufactured capital} − {value of fossil fuel—coal, oil and gas—extraction}, the valuation being in 1985US$bn. We follow Proops *et al*. (1999) in also monitoring a dimensionless counterpart, namely $\rho(t) \equiv W(t) / GDP(t)$. In interpreting these two measures for the world economy and its regions, we should bear in mind that we value only decreases in exhaustible natural capital in the form of fossil fuel and, like Proops *et al*. (1999) we do not value other changes in natural capital.

The choice of parameter values for our baseline model is standard for

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GREEN and was used in other studies (see Burniaux, Nicoletti and Oliveira-Martins, 1992). Calculating the economic depreciation of fossil fuel extraction, according to the El Serafy method or the Hotelling Rule (see Hartwick and Hageman, 1993), raises problems. As explained in the previous section, in GREEN neither savings nor investment are determined by an interest rate and thus we cannot adopt the El Serafy method. The Hotelling rule requires knowledge of fuel prices, which we have, and marginal costs which are not available for all fossil fuels. Available data on marginal costs are limited and, moreover, reflect current values whereas our simulation takes us up to 2050 by which time we would expect marginal costs to have risen. After careful consideration we decided to report the total value of fossil fuel extractions (net of taxes and subsidies) as we felt this approach was preferable to others in that it provides complete transparency.[2] These values therefore overestimate economic depreciation and, hence, all simulation values of ρ are underestimates. Where our estimates of ρ are negative, we report the estimated depreciation (as a proportion of total value) that would be necessary for a change of sign.

Scenario 1: baseline

Scenario 1, our baseline scenario, reports world values of W and ρ which are positive for all simulations periods from 1985 to 2050—see table 1. Gross investment rises strongly throughout the period, the increase in the value of the manufactured capital stock easily dwarfing the value of the loss of fossil fuel resources. The real growth rate starts at about 3 per cent and decreases to about 2.5 per cent by 2050 (with world population growing at about 1.1 per cent).

The figures for the regional breakdown in 1985 and 2050 are shown in table 2. Examining first the values for 1985 we can see W and ρ are positive

Table 1. *Scenario 1: W(t) and ρ(t) for the world economy (1985 US$bn)*

	GWP	*Gross investment*	*Depreciation* K_M	*Depletion* K_N	*W*	ρ
1985	11,581	2,450	1,491	896	63	0.0054
1990	13,396	3,165	1,724	984	457	0.0341
1995	15,590	3,867	1,969	1,003	895	0.0574
2000	18,215	4,670	2,265	1,058	1,347	0.0740
2005	21,058	5,523	2,574	1,141	1,809	0.0859
2010	24,333	6,537	2,967	1,391	2,180	0.0896
2030	41,474	11,796	4,927	1,908	4,962	0.1196
2050	66,802	19,579	7,894	2,649	9,036	0.1353

Notes: GWP = Gross World 'Domestic' Product
Depreciation K_M = depreciation of manufactured capital
Depletion K_N = extracted fossil fuels
W = Gross investment − Depreciation K_M − Depletion K_N
ρ = W/GWP (dimensionless)

[2] Regional/country values for gross investment, depreciation of man-made capital and natural capital are given in appendix table 4.

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Table 2. *Scenario 1: W and ρ for regions of the world*

Region	*1985*			*2050*		
	W	ρ	*Rank*	*W*	ρ	*Rank*
World	63	0.0054		9,036	0.1353	
United States	−17	−0.0046	8	951	0.0545	12
Japan	171	0.1348	2	1,808	0.1846	4
European Union (EU)	103	0.0462	4	1,462	0.1507	7
Other OECD (OOECD)	29	0.0373	6	453	0.1475	8
Former Soviet Union (FSU)	−158	−0.2482	12	588	0.2541	1
European economies in transition (EET)	−6	−0.0233	9	221	0.1865	3
Energy exporting countries (EEX)	−120	−0.1146	11	1,161	0.1577	6
China	20	0.0457	5	906	0.1837	5
India	6	0.0357	7	251	0.1279	9
Dynamic Asian economies (DAE)	39	0.1507	1	651	0.2329	2
Brazil	20	0.1060	3	193	0.0900	11
Rest of world (ROW)	−25	−0.0408	10	390	0.0955	10

for all regions except the USA, Former Soviet Union (FSU), east European Economies in Transition (EET), Energy Exporting Countries (EEX) and Rest of World (ROW). However, bearing in mind our earlier comments that we overestimate depreciation of natural resources, we note that for the USA and EET natural resource depreciation (as a percentage of the values reported) would have to exceed 88 and 82 per cent respectively for the value of ρ to remain negative. The other regions with negative ρ, ROW, EEX and FSU, are all unusual in being the only regions where the value of fossil fuel extraction exceeds the value of manufactured capital depreciation. For these regions, if economic depreciation (as a proportion of the total value of fossil fuel extraction) were to exceed 67, 50 and 24 per cent respectively, ρ would change sign. We conclude, therefore, that in 1985 only EEX and FSU may be 'unsustainable' as indicated by ρ.

Unfortunately the regional breakdowns adopted by GREEN and Proops *et al*. (1999) differ but, where we can compare regions, our results are very similar. Their world values for W and ρ in 1984 and 1986 and ours for 1985 are virtually identical and we both find that Japan ranks highly (in our simulation exceeded only by the Dynamic Asian Economies). Proops *et al*. report negative ρ values for FSU in 1980 and 1982 and that it is marginally sustainable in 1984 and 1986, while the USA is unsustainable in 1982 and 1986 and marginally sustainable in 1984. They find EET sustainable in all periods.

We now turn to our simulation values for 2050. Here, W and ρ are positive for all regions but rankings have changed. The high values of ρ for FSU, EET and the Dynamic Asian Economies (DAE) are surprising and we must interpret these with caution as they are the result of very high savings ratios which are partly an artefact of model construction. The

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extended linear expenditure system, adopted by GREEN to model consumer behaviour, assumes that a subsistence minimum quality of each good is purchased. As income increases, the impact of this subsistence quantity decreases and, where a region becomes richer over time, the savings parameter will tend towards a fixed parameter. This effect is particularly strong in the long term when the budget share assigned to saving has a high value in the initial model calibration. We must conclude, therefore, that while the FSU and EET economies will grow over time, it is not likely that they will top the ranking for 'sustainability' by 2050.

Other results worth noting are that the USA has now the lowest ρ value and that Brazil has fallen from third place to next to bottom. Brazil's economy grows at the high average of 3.8 per cent per annum but, in achieving this growth, only 6 per cent of its initial oil reserves remain.

So far we have not taken into account whether a country or region consumes its own fossil fuels or whether it imports them. If a country imports fossil fuels (e.g. USA) or exports them (e.g. EEX), then this is likely to change the value of W and ρ as it is the country which consumes the fossil fuels which leaves an 'environmental footprint', and it is this country which needs to invest to offset the natural resource depreciation, and not the exporter. We need, therefore, to extend our analysis to consider the effects of 'direct' trade in fossil fuels. By use of the term 'direct', we mean to exclude the use of a resource in the production of other export goods. A careful treatment of the *total* amount traded would strictly speaking require an approach such as that of Proops *et al*. (1999), who use input–output methods to perform the requisite accounting in an appropriate manner. Our approach, however, has the advantage that GREEN contains explicit information about the trade in fossil fuels, whereas Proops *et al*. have to deduce what they can about these from extraction data and the total value of *all* traded goods.

Table 3 shows the effects of trade in 1985 and 2050 after adjusting W and ρ according to net exports of crude oil, gas and coal. Comparing the table 3 1985 values for W and ρ with those in Table 2, we see that the adjustment has had no significant effect on the FSU. However, as we would expect, the EEX have moved positively in the rankings from eleventh to sixth place as their high rate of depletion is attributed not to themselves but to other parts of the world. Major net importers have moved negatively: USA from eighth to tenth and the EU from fourth to seventh place. Japan is now the most positively ranked region, even when its high level of fuel imports is taken into account.

As fossil fuels become scarcer and investment in the capital stock increases, we would expect the fuel trade adjustment to have a diminishing effect on ρ. To investigate this, we compare results for 2050 from scenarios 1 (see table 2) and 2. The conjecture is confirmed: the trade adjustment now makes little difference to the rankings, though, as explained earlier, we must view the high values for FSU, EET and DAE with scepticism.

Comparing changes between 1985 and 2050, reported in table 3, enables us to assess the impact of growth on energy demand and supply. By 2050, gross world product is five and three-quarters times what it was in 1985.

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Table 3. *Scenario 1: W and ρ for regions of the world, adjusted to allow for the effects of trade in fossil fuels (1985 US$bn)*

Region	1985					2050				
	Fossil fuel					Fossil fuel				
	Exports	Imports	Adj. W	Adj. ρ	Rank	Exports	Imports	Adj. W	Adj. ρ	Rank
World	279	279	63	0.0054		906	906	9,036	0.1353	
United States	5	32	−45	−0.0121	10	10	212	750	0.0430	12
Japan	0	44	127	0.0999	1	0	98	1,711	0.1747	4
European Union (EU)	8	73	38	0.0170	7	2	175	1,290	0.1329	8
Other OECD (OOECD)	22	15	37	0.0467	5	36	63	427	0.1390	7
Former Soviet Union (FSU)	4	1	−155	−0.2437	12	87	1	674	0.2914	1
European economies in transition (EET)	2	21	−25	−0.1044	11	6	40	187	0.1578	6
Energy exporting countries (EEX)	143	3	20	0.0192	6	727	2	1887	0.2562	2
China	6	1	25	0.0571	4	6	97	815	0.1653	5
India	1	6	2	0.0096	9	0	21	230	0.1171	9
Dynamic Asian economies (DAE)	0	20	19	0.0730	2	0	78	573	0.2052	3
Brazil	0	8	12	0.0617	3	0	94	99	0.0462	11
Rest of world (ROW)	45	11	9	0.0146	8	30	27	394	0.0964	10

At the start of the simulation the real price of oil falls for two periods and then rises again, exceeding its initial level only in 2010. Thereafter the rise is steep until in 2050 the price is 61 per cent above its 1985 level. The rate of increase is held in check by the introduction of backstop fuels in 2010 though it is not until 2030 that they are consumed in significant quantities; by 2050 they constitute 46 per cent of the total fuel usage.

Most regions respond to the increase in the world oil price by switching to coal and/or backstops. Coal consumption rises in all regions throughout the simulation period and, by 2050, world consumption is four times that in 1985. World gas consumption has risen to two and a half times that of 1985 as the rise in the oil price has led some regions to increase consumption of gas (notably in EEX where reserves are assumed to be infinite within the simulation period, FSU, China, DAE and ROW) so that by 2050 gas stocks are 60 per cent of starting levels. Apart from one region, EEX, where oil usage rises continuously, oil consumption begins to fall quite early in some countries and more sharply in most from 2010 so that by 2050 world consumption is 95 per cent of what it was in 1985 and reserves are at 40 per cent of current levels. The EEX which export 80 per cent of fossil fuel trades, leaving their reserves at 48 per cent of 1985 levels, are the major beneficiaries of the oil price increase and move from sixth in 1985 rankings to second place in 2050.

Japan maintains a high level of sustainability despite having few fossil fuel reserves and a relatively low increase in fossil fuel imports. It manages this by making extensive use of backstop fuels which enter in two forms: one, from coal or oil shale, contains more carbon than coal (the dirtiest fossil fuel)[3] and another which is carbon free (e.g. solar or wind energy). The simulations suggest that Japan would rely heavily on the carbon-free backstop (for electricity generation), being responsible for 63 per cent of world use. Only the USA, the EU and DAE also make significant use of the carbon-free backstop for electricity (17, 9 and 6 per cent respectively) and regions with large reserves of coal, such as China and FSU, switch to these rather than backstops. Substitutes for gasoline are less easily obtained and more regions adopt the carbon backstop (mainly from oil, rather than coal, shale), the main users being USA (17 per cent), EEX (16 per cent), ROW (13 per cent), with Japan, EU and China each taking 11 per cent.

Overall, the rise in the oil price checks the rate of growth. For industrialised countries (USA, Japan, EU, OOECD) this falls from an average of 3.1 per cent (reflecting a high growth rate for Japan) to 2.3 per cent by 2050 (the OOECD experiencing the lowest rate of 1.8 per cent). Developing regions (China, India, DAE, Brazil and ROW) start with an average growth rate of 3.7 per cent, which falls to 3.3 per cent by 2050. The availability of backstops, which by assumption come on stream in all regions in 2010, mitigates the impact of the oil price rise on the industrialised countries and they consume 62 per cent of total backstop energy. Backstops also have a

[3] In the absence of an agreement to reduce carbon emissions, these scenarios (which do not incorporate carbon taxes) suggest a large increase in emissions. We leave to another time an exploration of the effects of a Rio type agreement on emissions and sustainability.

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strong effect on EEX growth which peaks at 5.4 per cent in 2010 and falls to 1.7 per cent by 2050.

Scenario 2: pessimistic

In order to evaluate the importance of technical change and of backstops, our alternative scenario calculates W and ρ under pessimistic assumptions: energy productivity growth in production, consumption, investment and stock-building are all set at 0, and there are no backstop technologies. Even under these assumptions, real GWP shows growth of about 1.0 per cent per annum over the period, with W and ρ increasing over time, though the value of ρ is just over one half of what it was by 2050 in scenario 1—see table 4. The effect of the absence of technological progress in energy use is striking: by 2050, GWP is only one-third of that projected in scenario 1, but fuel usage remains proportionately high with coal consumption at 72 per cent, oil 78 per cent and gas 67 per cent of the 2050 levels projected in the more optimistic scenario. As a result of the slower growth, the oil price has only risen by 25 per cent in 2050, compared with 1985; world oil stocks fall to 45 per cent of initial levels and gas to 67 per cent.

The regional breakdown, given in table 5, reveals that in 2050 the values of ρ are negative for both USA and Brazil, as they are for all periods from 1995. For the USA to be sustainable, as its fuel imports are large, economic depreciation would have to amount to less than 10 per cent of the 2050 total value of fossil fuel extractions. Brazil's fuel imports equal 58 per cent of total saving and exceed the sum of depreciation of both manufactured and natural capital.

For industrialised economies, the average growth rate of 1.2 per cent in 1990 falls to 0.4 per cent in 2050 while the developing countries move from 1.9 to 0.9 per cent. The lower demand for oil reduces the EEX growth rate from 2.4 to 1.8 per cent, but this region is still ranked second in terms of 'sustainability'. Both China and the FSU benefit from extensive coal reserves but, by 2050, these are virtually exhausted in the EU and, with oil reserves down to 18 per cent of initial levels, it has switched from oil to gas and falls from seventh place in scenario 1 to tenth.

The possibility of medium-run GWP growth under pessimistic assump-

Table 4. *Scenario 2: world values for W and ρ, adjusted to allow for the effects of trade in fossil fuels and assuming no technological progress in energy use and no backstop fuels (1985 US$bn)*

	GWP	*Gross investment*	*Depreciation* K_M	*Depletion* K_N	*Adj. W*	*Adj.* ρ
1985	11,581	2,450	1,491	896	63	0.0054
1990	12,623	2,898	1,628	956	314	0.0249
1995	13,663	3,211	1,726	958	527	0.0386
2000	14,671	3,491	1,824	968	699	0.0477
2005	15,628	3,743	1,914	988	841	0.0538
2010	16,533	3,979	2,000	1,009	969	0.0586
2030	19,536	4,742	2,280	1,124	1,338	0.0685
2050	21,582	5,249	2,475	1,180	1,594	0.0738

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Table 5. *Scenario 2: regional values for W and ρ in 2050, adjusted to allow for the effects of trade in fossil fuels and assuming no technological progress in energy use and no backstop fuels (1985 US$bn)*

Region	*Fossil fuel*				*Scenario 2*	*Scenario 1*
	Exports	*Imports*	*Adj. W*	*Adj. ρ*	*Rank*	*Rank*
World	801	801	1,594	0.0738		
United States	5	235	−111	−0.0194	12	12
Japan	0	81	212	0.1129	4	4
European Union (EU)	2	159	114	0.0352	10	8
Other OECD (OOECD)	20	56	97	0.0658	7	7
Former Soviet Union (FSU)	51	1	214	0.2327	1	1
European economies in transition (EET)	3	26	22	0.0626	8	6
Energy exporting countries (EEX)	691	2	766	0.2013	2	2
China	1	23	114	0.1587	3	5
India	0	12	30	0.0767	6	9
Dynamic Asian economies (DAE)	0	42	59	0.1068	5	3
Brazil	0	47	−5	−0.0131	11	11
Rest of world (ROW)	28	117	80	0.0443	9	10

tions illustrates one reason the WSI can hardly be held to measure 'sustainability': current world fossil fuel resources are sufficient to push the real problems of depletion beyond the period when they would worry a time-discounting planner. Nevertheless given its true interpretation as an indicator of some aspects of medium-run investment, it does not misrepresent the facts, namely that there is no *imminent* threat to global growth.

As we explained at the outset, we consider WSI values as one of many possible indicators of sustainability and so, to conclude our analysis, in table 6 we report simulation results for another indicator, GDP per capita.

The values for scenario 1 indicate the GDP per capita would increase in all regions so that by 2050 GWP per capita is 79 per cent higher than in 1985. The world has been 'sustainable' in both scenarios but, under the pessimistic scenario, GWP per capita declines steadily to 2050 when it is only 90 per cent of what it was in 1985. GDP per capita increases in all industrialised countries, EEX and China but declines in the FSU (from 2030), India (from 2000) and ROW (from 1995). Positive values for W and ρ are no guarantee that GDP per capita can be maintained in the medium term.

4. Conclusions

We have used a global dynamic general equilibrium model to explore regional and global sustainability over the period 1985–2050. Following the lead of others, we have used the weak sustainability indicator (WSI) but, due to data restrictions, have had to limit our exploration of natural resource depletion to fossil fuel extraction. Our study has enabled us to

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Table 6. *Real GDP per capita under different scenarios*

	1985 GDP per capita		*Change by 2050 relative to 1985*			
			Scenario 1		*Scenario 2*	
	(1985 US$)	*Rank*	*(%)*	*Rank*	*(%)*	*Rank*
World	2,402		179		−10	
United States	15,432	1	281	8	32	3
Japan	10,477	2	697	1	53	2
European Union (EU)	6,920	3	373	6	58	1
Other OECD (OOECD)	6,648	4	154	10	22	6
Former Soviet Union (FSU)	2,298	5	182	9	12	8
European economies in transition (EET)	2,007	6	323	7	28	5
Energy exporting countries (EEX)	1,599	7	148	11	29	4
China	424	11	615	2	12	8
India	242	12	416	5	4	11
Dynamic Asian economies (DAE)	1,501	8	521	3	22	6
Brazil	1,374	9	490	4	8	10
Rest of world (ROW)	707	10	94	12	−14	12

explore the importance of technological progress, the availability of natural resource substitutes (backstop fuels in our case) and population trends.

Different assumptions about the values assigned to key parameters, such as the rate of technological change, population growth, and the cost and availability of backstops, would generate different results. On the assumptions we have adopted, our first simulation suggests that world WSI values would increase over time. However, by 2050 there is evidence that economic growth is slowing down in the face of rising fuel prices despite the availability of backstop fuels on which the industrialised countries increasingly rely. While all regions are 'sustainable' (though, for reasons explained in section 3, we must treat the high values for the former Soviet Union and east European economies in transition with caution), the USA appears to be the least sustainable after direct fossil fuel imports are taken into account. On our results, 'sustainability'—at least over the period of our simulations—does not appear impossible but, of course, this picture might change considerably if we were able to include the depletion of other natural resources, such as soil, forest, fish, etc.

A somewhat different picture emerges in our pessimistic scenario in which there is no energy-saving technological progress and there are no backstop fuels. World WSI values are still positive but gross world product is only about half of what it was projected to be in our more optimistic scenario. Perhaps surprisingly, all regions, except the USA and Brazil, remain sustainable. Nevertheless, growth rates are low compared with those in the other scenario, though those of developing countries are slightly higher than for the industrialised nations.

The WSI is only one possible criterion of sustainability. Though gross

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world product (GWP) increases steadily throughout the simulation period, when we explore the trend in GWP *per capita* we find that, under the pessimistic scenario, this declines from 1990 onwards. By 2050 it is only 90 per cent of what it was in 1985 because population increases are greater in poor than in rich regions.

As fossil fuel reserves diminish, alternative renewable sources of energy will be needed to sustain economic growth. The rising costs of the scarcer fossil fuels relative to the price of such renewables will determine their rate of adoption. Backstops from coal and oil shale are cheaper, and unfortunately dirtier, than carbon-free sources, such as solar and wind power. Using a computable general equilibrium model, our two scenarios illustrate the importance of both the availability of such substitute sources of energy and of the rate of technological progress in energy use. With the advent of green national accounts incorporating data about depletion and degradation of a wider range of natural resources, this approach could help to provide a more comprehensive indicator of long-run sustainability.

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Appendix[4]

The sectoral makeup of GREEN is given in appendix table 1. All sectors are assumed to operate under constant returns to scale and cost optimisation. The simulation period is from 1985 to 2050 and is broken into five-year intervals up to 2010 and two 20-year intervals thereafter. The growth of the global economy over the time is modelled through a sequence of period-related, but intertemporally uncoordinated, flow equilibria. In each region and in each period, equilibrium is characterised as a set of prices of goods and primary factors that equate demand and supply in all corresponding markets. The model's dynamics derive from fossil fuel depletion, productive capital accumulation, and the putty/semi-putty specification of technology. They are calibrated in reach region on exogenous GDP, population growth rates and on given autonomous energy efficiency improvements which are rates of neutral technological progress in energy use. Implied growth rates are calculated for neutral technological progress in the capital/labour/fixed-factor bundle. In counterfactual simulations, this technological progress path is exogenous while GDP growth rates become endogenous.

Data are drawn from various sources. The national input–output tables are supplemented by data from national accounts and IEA energy statistics. Trade matrices are based on Eurostat National Accounts, OECD Foreign Trade Statistics and other sources. The highest resource estimates of yet-to-find fuel reserves have been taken from the Stanford-based Energy Modeling Forum Study No. 12 (EMF 12) entitled 'Global Climate Change: Energy Sector Impacts of Greenhouse Gas Emission Control Strategies'. This was also the source for backstop prices. Other fuel information was taken from IEA forecasts.

In calibrating the model, the important assumptions are those concerning population and GDP growth rates, and technological progress. Population growth rates, listed in appendix table 2, are assumed to be exogenous and are based on World Bank projections. Improvements in energy efficiency can arise in various ways. In addition to end-use energy-saving technical change, energy intensity (i.e., E/GDP) has been declining over time in response to rising energy prices, government regulation and changes in the composition of GDP. Modelling constraints mean that these are combined into one 'autonomous efficiency' parameter, which is introduced into the different sectors. In our simulations the annual value is set at 1 per cent for all regions and sectors. Other important parameters are the elasticities of substitution between energy and other factors, and between fuels. The choice of values, set out in appendix table 3, was made after an exhaustive literature by OECD (Burniaux *et al*., 1992: 74–5).

The model is calibrated on 1985 data but has been updated in 1994 when changes were made to the specification of the model and of the baseline scenario, as well as to data.

[4] This appendix draws on material from Burniaux, Nicoletti and Oliveira-Martins (1992) and van der Mensbrugghe (1994).

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Appendix Table 1. *Main features of GREEN*

Regions	*Producing sectors*	*Consumer goods*	*Primary factors*
United States	**Conventional energy:**	Food and beverages	Primary factors
Japan	Coal mining	Fuel and power	Sector-specific 'old' capital
European Union	Crude oil	Transport and communication	'New' capital
Other OECD	Natural gas	Other goods and services	Sector-specific fixed factors for each fuel
Energy exporting countries	Refined oil		Land in agriculture
China	Electricity, gas and water distribution[1]		
Former Soviet Union	**Backstops:**		
European economies in transition	Carbon based		
Dynamic Asian economies	Carbon-free		
Brazil	**Rest of economy:**		
Rest of World	Agriculture		
	Energy-intensive industry		
	Other industry and services		

Note: [1] Because of data constraints, the electricity sector could not be isolated from the gas and water distribution sectors.

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Appendix Table 2. *Exogenous average population growth rates arising from GREEN's assumptions about population growth*

Region	*Population growth 1985–2050 (percent)*
World	1.1
United States (USA)	0.3
Japan	−0.1
European Union (EU)	−0.1
Other OECD (OOECD)	0.7
Energy exporting countries (EEX)	1.6
China	0.7
Former Soviet Union (FSU)	0.4
India	1.1
European economies in transition (EET)	0.2
Dynamic Asian economies (DAE)	0.8
Brazil	1.0
Rest of World (ROW)	1.9

Appendix Table 3. *Elasticities of substitution*

	All regions	
	Medium term	*Long term*
Energy and other factors of production		
Energy and capital	0	−0.8
Labour and energy/capital	−0.12	−1.0
Inter-fuel elasticities		
Production:		
Conventional fuels	−0.25	−2.0
Conventional vs. backstop		−10.0
Final demand		1.2

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Appendix Table 4. *Basic data for calculating W(t) and ρ(t) (1985 US$bn)*

	1985				*Scenario 1: 2050*				*Scenario 2: 2050*			
Region	*GWP*	*Gross investment*	*Depreciat'n* K_M	*Depl'n* K_N	*GWP*	*Gross investment*	*Depreciat'n* K_M	*Depl'n* K_N	*GWP*	*Gross investment*	*Depreciat'n* K_M	*Depl'n* K_N
World	11,581	2,450	1,491	896	66,802	19,579	7,894	2,649	21,582	5,249	2,475	1,180
USA	3,693	631	503	145	17,446	3,737	2,352	434	6,039	1,034	792	124
Japan	1,266	363	182	10	9,793	3,645	1,421	415	1,876	569	263	13
EU	2,228	474	297	74	9,705	2,954	1,269	223	3,240	747	421	55
OOECD	787	181	108	44	3,072	928	395	79	1,476	369	188	48
FSU	638	145	94	209	2,313	1,136	295	253	920	411	117	131
EET	237	56	26	35	1,185	423	121	81	355	114	37	32
EEX	1,048	232	112	240	7,363	2,508	728	619	3,810	1,075	348	648
China	441	114	43	51	4,930	1,510	409	196	720	228	54	38
India	182	34	18	9	1,963	368	70	47	397	67	15	9
DAE	262	69	27	2	2,794	993	278	64	550	159	55	3
Brazil	186	42	19	4	2,149	455	203	58	392	81	38	2
ROW	614	110	60	75	4,088	923	352	180	1,808	395	149	77

Notes: GWP = Gross World 'Domestic' Product
Deprec'n K_M = depreciation of manufactured capital
Depl'n K_N = total value of extracted fossil fuels (net of taxes and subsidies)

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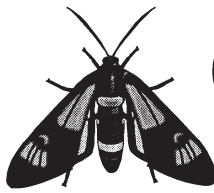
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