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Energy Intensity, Greenhouse Gas, and Global Warming

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These notes provide background and a potentially quantifiable model of the economic impacts of energy use which generates greenhouse gas (GHG) emissions and global warming. The focus is on interactions between energy productivity and labor productivity and their spillover effects on the production of GHG. The analysis draws upon the economic development literature regarding models of produced means of production, e.g. machines to make machine for Feldman and Mahalanobis, exports to generate foreign exchange for Chenery, and educational expenditures to enhance human capital for Lucas. GHG emission, in contrast, is a "produced means of destruction." How to deal with it is a pressing global question.

In a bit more detail, global warming is the consequence of three very strong and increasingly contradictory trends. First, emission of carbon dioxide or CO_2, the main driver (for now) of the greenhouse effect, is a direct consequence of using fossil fuels and biomass as the predominant sources of energy for utilization by humans.

Second, people in developing countries worldwide desperately want to increase their real income levels per capita. That necessarily requires growth in real output per unit of labor, or labor productivity. Population growth also enters the equation for overall income (and output) expansion, but if all goes well its energy-use impacts will be less than those of rising per capita incomes. That is, output growth is the sum of growth rates of per capita income and population. If over the next few decades poor countries do have rising per capita income (the historical rate in rich economies is around two percent per year), productivity growth will dominate population expansion.

The third point is that historically a crucial factor supporting rising labor productivity and per capita income has been increasing use of energy. This is an old idea, widely accepted among ecological economists but never fully taken on board by the professional mainstream. It dates back to the 'energetics' movement of the last half of the 19th century (Martinez-Alier and Schlüpmann, 1987; Mirowski, 1989) but not much further.[2] A slightly overstated paraphrase is "The currency of the world is not the dollar, it's the joule" (Lewis, 2007).

Simple algebra can be used to illustrate the issues involved. Let *X* be real output, and assume that the both labor force and population are proportional to a variable *L* (that is, labor force participation rates are stable). Energy use at any time is *E.* Let $\lambda = X/L$ and $\varepsilon = X/E$ stand for labor and energy productivity respectively. If $e = E/L$ is energy intensity then it is easy to see that $e = \lambda/\varepsilon$. Let a "hat" over a variable denote its growth rate, e.g. $\hat{X} = (dX/dt)/X = \dot{X}/X$. It follows that

$$\hat{\lambda} = \hat{\varepsilon} + \hat{e} \qquad (1)$$

or labor productivity growth is the sum of the growth rates of energy intensity and energy productivity. Data exist to illustrate this relationship.

Empirical results

Output is measured in real 1990 dollars at market prices, not in terms of purchasing power parity which is macroeconomically meaningless (Ocampo, et. al., 2009).

To concentrate on global warming, it makes sense to focus on fossil fuels and biomass as the principal energy inputs at a national level. We will assume that energy production from hydro, solar, wind, nuclear power can initially be ignored, since these sources currently represent only a small fraction of global energy use.

Figure 1 presents two scatter diagrams of growth rates of the ratio of annual energy use to employment and labor productivity, for the periods 1970–1990 and 1990–2004 for 12 regional groups of developing economies and the rich countries in the OECD.[3] There appears to be a robust relationship between increasing energy use per worker and labor productivity growth, with a steeper slope and a better fit in the later period. Similar results show up when growth rates are compared at the individual country level. The slope of the relationship in 1990–2004 is around 0.6, suggesting a substantial contribution of more energy use per worker to higher productivity.

Figure 1

Table 1 presents the data in numerical form for the regions and selected countries. A unit of time is necessarily involved – so we are really considering power usage. The numbers are in units of terajoules per worker-year.[4] In 2004, there was evidently a wide range of energy/labor ratios per year – from 0.01 (77 gallons of gasoline) in sub-Saharan Africa to 0.74 (5700 gallons) in Saudi Arabia. The ratio is 0.58

in the US and less than 0.3 in Western European countries, the Asian Tigers, and Japan.

Table 1

Implications for global warming

In the context of global warming, these numbers are not reassuring. For example, if the slope of the relevant future curve as in Figure 1 really is 0.6, then two percent per capita income growth would require the energy/labor ratio to rise at 1.2% per year. Factoring in population growth might raise total energy usage by around two percent annually. In fact, the situation is not quite so dire because the largest non-industrialized groups (notably China, the former USSR, South Asia, and the semi-industrialized economies) report relatively high energy productivity growth. But it still makes sense to ask how current growth rates of energy consumption may feed into the atmospheric stock of carbon dioxide.

As background, Table 2 presents comparisons of energy consumption per worker and carbon dioxide emission per capita for the world and selected countries in 2004. Emissions per unit of energy are in the range of 65–75 metric tons per terajoule in rich countries and somewhat higher in (some) developing and transition economies.

Table 2

One implication is that lower emission levels in the latter are mostly due to smaller energy/labor ratios. The numbers for China, Kenya, Brazil, etc. suggest that there is room for reducing worldwide emissions simply by increasing poor countries' efficiency of carbon utilization, but that major benefits can only come from cutting back on energy use per capita and per unit of economic output.[5]

Rich and poor country trade-offs

Assuming that the CO_2/energy ratio stays constant, Figure 2 illustrates the potential trade-offs.

In the period 1990–2004, energy productivity rose at 1.9% per year in the rich OECD economies and at 2.8% in the rest of the world because of high productivity growth rates (noted above) in some of the larger economies. The downward-sloping line is an isocline showing combinations of energy productivity growth rates that would have been needed to hold the growth rate of total energy use to zero. This scenario represents the initial stages of the “flat path” of carbon emissions that Socolow and Pacala (2006) propose to hold atmospheric CO_2 to less than twice its pre-industrial level.

Figure 2

The prospects are not favorable. Had the energy productivity growth rate in poor countries remained stable, a rate of almost 4.5% per year would have been required in the developed world to hold energy growth to zero.

Alternatively, with a constant energy productivity growth rate in the rich countries, energy productivity growth of almost five percent per year would have been needed in the poor ones. The growth rates of the energy/labor ratio corresponding to these cases for rich and poor countries are -2.5% and -2.3% respectively. A flat path could also be achieved with a worldwide energy productivity growth rate of about 3.5%, (i.e. 3.5% in both developed and developing countries). This would imply a growth rate in the energy/labor ratio of about -1.5% in rich countries and about -1% in poor countries.

By way of contrast, the Kyoto targets called for (roughly) an annual one percent reduction in energy use for the rich countries, implying that their energy productivity growth rate would have to be about four percent. If (hypothetically) the Kyoto targets were met, we can calculate the impact on world energy growth using the following equation for the worldwide growth rate of energy consumption:

$$\hat{E} = \theta\left(n_R + \hat{\lambda}_R - \hat{\varepsilon}_R\right) + (1 - \theta)(n_P + \hat{\lambda}_P - \hat{\varepsilon}_P) \qquad (2)$$

where the subscripts R and P stand for rich and poor countries respectively, n_R and n_P are their respective rates of population growth, and θ represents the share of the rich in world energy use (about 45 percent in 2004). The achievement of Kyoto targets would reduce growth of worldwide fossil energy consumption from 1.1% percent to 0.65% per year, well above the flat path.

Compared to the historical data summarized in Table 1, the rates of change in energy/labor ratios required to achieve a flat path look extremely optimistic. The required changes in growth rates are on the order of 100 percent of the historical growth rates themselves – a large adjustment by any standard! The only countries that are now in the required range of energy/labor growth rates are stagnant with negligible or negative labor productivity growth. And in the recent period, there has been no significant downward trend in energy/labor ratios in rich economies.

It is also possible that CO_2/energy ratios could decline, either due to a significantly higher proportion of non-carbon energy sources (solar, wind, hydro, nuclear, etc.) or to the introduction of effective carbon capture and storage technology. Socolow and Pacala (2006) include these possibilities as potential contributors to a flat path of carbon emissions. Unless there are truly dramatic changes in these areas, however, the requirements for changes in energy/labor ratios would not be much less drastic than those outlined above.

"Medium Term" analysis

To complement these numerical illustrations it makes sense to take an analytical look at future prospects, over a climatic "medium term," most appropriately measured in a time frame of decades.

Let *G* stand for the atmospheric concentration of CO_2, currently on the order of 380 ppmv (parts per million by volume). Concentration per capita (or GHG intensity) can be expressed as $\gamma = G/L$. With labor productivity as $\lambda = X/L$ we have $\chi = \lambda/\gamma = X/G$ as a measure of output per unit of atmospheric carbon.[6]

Standard analysis of sources of growth suggests that most expansion of real output per capita is due to increases in labor productivity. To simplify initially we assume that productivity growth $\hat{\lambda}$ is the *only* source, so that real global GDP grows at a rate $\hat{X} = \hat{\lambda} + n$ with *n* as the rate of worldwide population growth.

The appendix sets out the equations of a stripped-down growth model built around the dynamics of λ and γ. The latter is in fact a produced means of destruction of labor productivity.

Along the lines discussed in connection with Figure 1, it is assumed that productivity growth is an increasing function of the growth of energy intensity or $\hat{e}$. Following Rezai, et.al. (2010) $\hat{\lambda}$ is supposed to fall when there is faster growth $\hat{\gamma}$ of CO_2 concentration per capita. The relevant "loss function" becomes more severe with a *lower* level of χ (from above, the ratio of output to atmospheric CO_2).

The expansion of CO_2 concentration depends on total energy use, which rises with higher labor productivity (because it increases output) and falls if energy productivity goes up. GHG accumulation can be reduced by expenditures on carbon mitigation and also by (slow) natural dissipation. Higher expenditure on mitigation is assumed to have decreasing returns in reducing carbon emission. The growth rate of concentration per capita $\hat{\gamma} = \hat{G} - n$ can be shown to converge to zero, i.e. $\hat{G} = n$ at a steady state.

As illustrated immediately below the growth rate of productivity (under plausible assumptions) will adjust toward the growth rate of concentration per capita, i.e. $\hat{\lambda}$ tends toward $\hat{\gamma}$, or $\hat{X}$ toward $\hat{G}$. Shifts in $\chi = X/G$ permit this convergence. Realistically or not, most formal economic growth models converge to a steady state of this sort. Their "transient" dynamics are strongly influenced by the characteristics of the steady state.

In the present case, an additional crucial consideration is that a climate catastrophe may be inevitable unless the absolute level of atmospheric carbon becomes constant or decreases. In the world of the model this can *only* occur if the population growth rate *n* becomes zero or negative. Natural dissipation and/or mitigation might then make total CO_2 decrease, along with the level of real GDP.

Figure 3 shows how the dynamics works out. Because growth rates of both GHG intensity ($\hat{\gamma}$) and productivity ($\hat{\lambda}$) depend on $\chi = \lambda/\gamma$ it becomes a natural "state variable" with $\hat{\chi} = \hat{\lambda} - \hat{\gamma}$. The "GHG intensity growth" curve corresponds to equation (A-1) in the appendix. It shows that $\hat{\gamma}$ is an increasing function of χ, essentially because more output creates more emissions.

The "Productivity growth" curve represents equation (A-3). It is concave because for lower values of χ (higher values of the ratio G/X) productivity growth drops off sharply because of the loss function mentioned above.

Equation (A-4) for $\hat{\chi}$ shows that the growth model is stable under a plausible upper bound on the elasticity of the loss function with respect to χ. As illustrated in Figure 3, the dynamics resembles that of the Solow-Swan growth model. There is a stable equilibrium level of χ at point A, and a potential instability at B due to the steepness of the loss function. At a full equilibrium, as observed above, it will be true that $\hat{X} = \hat{G} = n$.

Figure 3

The model differs from Solow-Swan, however, because the two schedules shift over time. Growth in GHG intensity decreases when energy productivity rises, and increases when labor productivity goes up. On balance, the data in Table 1 suggest that the GHG intensity curve may be shifting upward (largely because of rapid labor productivity growth in South, Southeast, and East Asia).

To trace through the implications, the first thing to observe is that currently $\hat{G}$, the growth rate of CO_2 concentration, is on the order of 0.5% per year, well less than the trend growth of world output. In terms of the model, the current value of χ must lie somewhere between points B and A in Figure 3. Because the productivity schedule is above the GHG intensity schedule for values of χ in that range, $\hat{\lambda} > \hat{\varphi}$ and χ is rising over time. An upward shift in the GHG intensity curve would dampen this trend (worsening global warming), as would a possible downward drift in the Productivity growth curve.

Policy implications

With these observations as background we can turn the policy implications. The most immediate one follows from the nature of growth based on produced means of production or destruction. All dynamic optimization models indicate that means of production should be produced early in a plan, i.e. first concentrate on producing machines for Mahalanobis, exports or import substitutes to earn hard currency for

Chenery, or teachers for Lucas. The reason is that the fruits of these early efforts will support production over a longer time span.

For a produced means of destruction such as atmospheric carbon, the implication is that mitigation efforts should begin early. They would shift the GHG schedule downward, causing χ to rise. The degree of decreasing returns to mitigation could serve as a guideline about the extent to which the effort should be pursued.

Similar reasoning suggests that slower population growth and more rapid growth in energy productivity also shift the GHG schedule downward, with a resulting increase in χ.

If early mitigation is desirable, how should it be paid for? Output in the model at hand is fixed by productivity and population in the short run. Saving can be viewed as increasing physical capital *K* as a form of infrastructure. New capital goods may also stimulate productivity directly by embodying better technologies. To capture this possibility a term such as $+\nu\hat{K}$ could be added to equation (A-3) for $\hat{\lambda}$.

The growth rate $\hat{K}$ of the capital stock as shown in equation (A-5) in the appendix depends on the saving rate *s* and a capital utilization rate $u = X/K$. Over time utilization can vary freely over a "reasonable" range of values as *K* changes with respect to the level of *X* coming from productivity growth. Under plausible assumptions *u* will converge to a steady state.

Spending on mitigation can be seen as a specific use of a fraction μ of total saving *sX*. The effort becomes less effective at the margin, the higher the value of μ. At the same time faster capital stock growth from more saving can raise the productivity growth rate $\hat{\lambda}$. In the model's "short run" of a decade or so an increase in the saving rate would shift the GHG locus in Figure 3 downward by permitting more spending on mitigation. It would shift the productivity locus upward. On both counts $\chi = X/G$ would tend to rise because the numerator would go up and the denominator fall.

There has been a lot of discussion in the literature about whether the present population cohort has to "sacrifice" resources to overcome a GHG "externality." Foley (2009) argues convincingly that this question is incorrectly posed. In microeconomic terms an externality can only be properly defined if the economy is operating efficiently in all other aspects. The presence of GHG means that the global economy operates "inside" its production possibility frontier. Moving toward the frontier by increasing mitigation would create a surplus which could permit both present and future generations to gain. The former could invest less in conventional capital and use those resources both to increase consumption and to undertake mitigation. The latter would benefit from a better allocation involving less conventional capital offset by reductions in GHG. The optimal growth model reported by Rezai, et. al. (2010) illustrates how Foley's arguments apply.

In the present model with the linkage between capital stock growth and productivity growth in force, a lower saving rate (reversing the thought experiment described above) would make $\chi = X/G$ tend to fall with *G* increasing and *X* going down. However, an increased mitigation effort could move the GHG intensity locus downward enough to offset these shifts.

Another distributive conflict pivots around how to allocate the cost of mitigation between rich and poor countries. As in equation (A-2) it is easy to decompose worldwide GHG expansion into contributions from rich and poor countries. Figure 4 is an exaggerated hypothetical illustration about how the contributions might change as overall output increases. The solid lines represent “business as usual” (or BAU). For “low” (or late 20th century) levels of *X* most GHG emission comes from rich countries and the contribution of poor countries is small. For “high” (mid 21st century?) with BAU the situation changes, as poor countries contribute most of the growth of GHG.

The dashed lines show a mitigation scenario in which the poor country contribution drops off notably on the assumption that decreasing returns to mitigation are less onerous in economies which use relatively low levels of energy in production, often under conditions of low efficiency. Trade-offs about how and where mitigation should be pursued immediately arise.

On the whole, poor countries import ‘modern’ technologies previously created in advanced economies. The key policy question in this regard is whether in the near future rich country energy/labor ratios can be reduced (or energy productivity increased relative to labor productivity) substantially by technological innovation and social rearrangements.[7] If such innovations work out, then perhaps they can be passed to developing economies soon enough to enable them to maintain positive per capita output growth with only slowly increasing or (better) decreasing energy/labor ratios.

If such a growth pattern does not prove to be possible, then the three contradictory trends mentioned at the outset will inevitably collide. Only 16 percent of the world's population now lives in the rich countries which account for 45 percent of world energy use. Both shares are declining. Unless the advanced economies find the means to reduce their own energy-labor ratios substantially (and unhistorically) and pass the techniques along to the rest of the world, the consequences of colliding income growth, energy use per capita, and global warming trends are unforeseeable but may well be catastrophic indeed.

Appendix

Using notation already defined in the text, this appendix sets out the equations behind the growth scenarios depicted in Figures 3-xX. Defining $\dot{G}$ as dG/dt, the increase in atmospheric CO_2 concentration can be written as

$$\dot{G} = \alpha E - \beta(\mu)sX - \xi G = [(\alpha/\varepsilon) - \beta(\mu)s]X - \xi G \quad .$$

Carbon emission rises with energy use according to the coefficient α. Let *s* be the saving rate from output and μ the share of saving devoted to mitigation. The function $\beta(\mu)$ gauges the effectiveness of mitigation in reducing emission. Presumably it will be concave. The coefficient ξ reflects the slow natural dissipation of atmospheric CO_2.

Dividing both sides of this equation by *G* gives

$$\hat{G} = [(\alpha/\varepsilon) - \beta(\mu)s]\chi - \xi \quad .$$

It follows that

$$\hat{\gamma} = [(\alpha/\varepsilon) - \beta(\mu)s]\chi - (\xi + n) \quad . \qquad \text{(A-1)}$$

This equation for the growth rate of CO_2 concentration per capita can be restated as

$$\dot{\gamma} = [(\alpha/\varepsilon) - \beta(\mu)s]\lambda - (\xi + n)\gamma \quad .$$

This differential equation is stable, so that γ will converge to a "quasi-steady state" value

$$\bar{\gamma} = [(\alpha/\varepsilon) - \beta(\mu)s]\lambda/(\xi + n)$$

with $\hat{G} = n$. Of course, so long as energy and labor productivity levels ε and λ are changing over time $\bar{\gamma}$ will be a moving target for γ. It will stable when

$$[(\alpha/\varepsilon) - \beta]\hat{\lambda} - (\alpha/\varepsilon)\,\hat{\varepsilon}) = 0 \ .$$

The rapid labor productivity growth rates for well-performing developing regions in Table 1 suggest that they are driving the worldwide level of GHG accumulation up; the evidence is less clear for the industrialized world.

This line of thought can be pursued one step further. Let $i = R, P$ be an index for rich and poor regions, and define A_i as $A_i = (\alpha_i/\varepsilon_i) - \beta_i(\mu_i)s_i$. Then the overall change in GHG emission becomes

$$\dot{G} = (A_R x_R + A_P X_P)X - \xi G \qquad \text{(A-2)}$$

with $x_i = X_i/X$ where the X_i are regional output levels. This sort of decomposition underlies Figure 4.

The growth of productivity can be described as

$$\hat{\lambda} = \tau - \zeta(\chi)\hat{\rho} + \phi\hat{e}$$

in which τ is a time trend. Faster growth of GHG per capita reduces the growth rate of output per capita according to the loss function $\zeta(\chi)$. As χ *decreases* (so that the ratio of GHG to output goes up), the loss becomes more acute. Finally, growth in energy intensity $\hat{e}$ stimulates productivity growth according to the coefficient ϕ (recall the discussion of Figure 1).

Plugging (A-1) into this equation gives

$$\hat{\lambda} = \tau - \zeta(\chi)\{[(\alpha/\varepsilon) - \beta(\mu)s]\chi - (\xi + n)\} + \phi\hat{e} \quad . \qquad \text{(A-3)}$$

and the growth rate of χ itself becomes

$$\hat{\chi} = \hat{\lambda} - \hat{\rho} = \tau - [1 + \zeta(\chi)]\{[(\alpha/\varepsilon) - \beta(\mu)s]\chi - (\xi + n)\} + \phi\hat{e} \quad . \qquad \text{(A-4)}$$

It is easy to see that the differential equation for $\dot{\chi}$ will be stable if $(1 + \zeta)/\zeta > -\zeta'\chi/\zeta$, i.e. the absolute value of the elasticity of ζ with respect to χ is not "too high". Again, the quasi-steady state value $\bar{\chi}$ will be changing over time as a moving target for χ.

Figure 3 in the text depicts the dynamics of the system based on (A-1) and (A-3).

A quick extension of the model would be to take into account capital accumulation. With output determined by labor productivity exclusively, physical capital is best viewed as providing required infrastructure. New capital goods may also stimulate productivity directly.

To bring these possibilities into play, let *K* be the capital stock and $u = X/K$ be "utilization," which is assume to be able to vary freely within some "reasonable" range, i.e. there are no locally diminishing returns to the use of capital. A simple equation for capital stock growth then becomes

$$\hat{K} = su - \delta$$

with *s* as the saving rate (as above) and δ the rate of depreciation. Using $\hat{u} = \hat{X} - \hat{K}$ and $\hat{X} = n + \hat{\lambda}$ it follows that *u* satisfies a differential equation

$$\dot{u} = u[-su + (n + \delta + \hat{\lambda})] \quad . \qquad \text{(A-5)}$$

Without going into the details, suppose that $\hat{\lambda}$ in (A-3) is also positively affected by capital stock growth and thereby the level of u. If the effect is not too strong, (A-5) will be locally stable with $\partial\dot{u}/\partial u < 0$. The time-derivative $\dot{u}$ will also depend negatively on χ via (A-3). From (A-4) the productivity linkage means that $\dot{\chi}$ will depend negatively on χ and positively on *u.* These signs of partial derivatives lead to the configuration of the phase diagram shown in Figure 5. It could be used to explore long-term developments in a non-optimizing framework.

Figure 5

Notes

1. New School for Social Research. Ideas from Duncan Foley, Jonathan Harris, Codrina Rada, and Armon Rezai are gratefully acknowledged.

2. Leibniz proposed the basic concept of energy around 1680 but it did not take its modern form until the 1840s.

3. The data in this paper were initially presented in Taylor (2009). The country groups are described in Ocampo, et. al. (2009).

4. One joule is the energy required to lift a small (100 gram) apple one meter against the earth's gravity. One terajoule is roughly equivalent to 7700 gallons of gasoline or 31 tons of coal. Alternatively, one watt equals one joule of energy use per second. Dividing terajoules per year by the number of seconds in a year shows that an American worker utilizes 19.3 kilowatts of power to produce his or her contribution to real GDP. An African uses 300 watts.

5. In any case, switching from the current worldwide mix of fossil fuel energy sources to using natural gas (the least carbon-intensive source) exclusively would reduce carbon emissions by only about 15 percent (see Lewis, 2007).

6. The ratio χ can be interpreted as the "velocity" of the turnover of GHG with respect to production. In the model being described a fall in χ (less recycling of GHG) has an adverse effect on productivity growth.

7. The same observation applies to CO_2/energy ratios as well.

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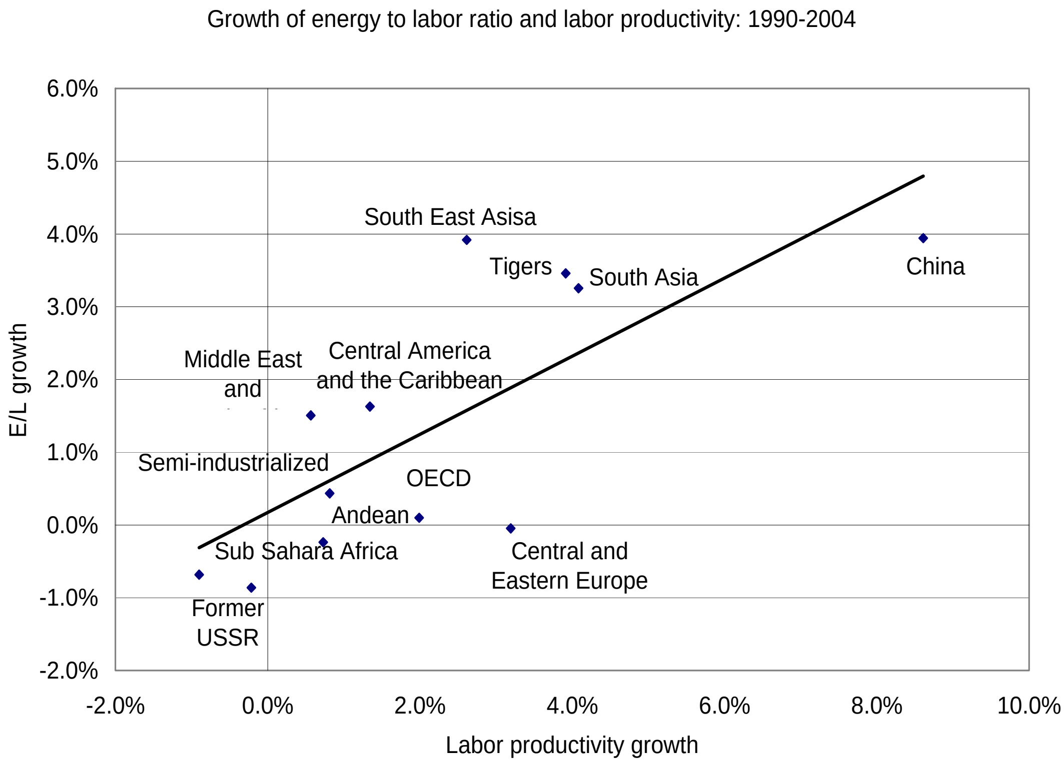

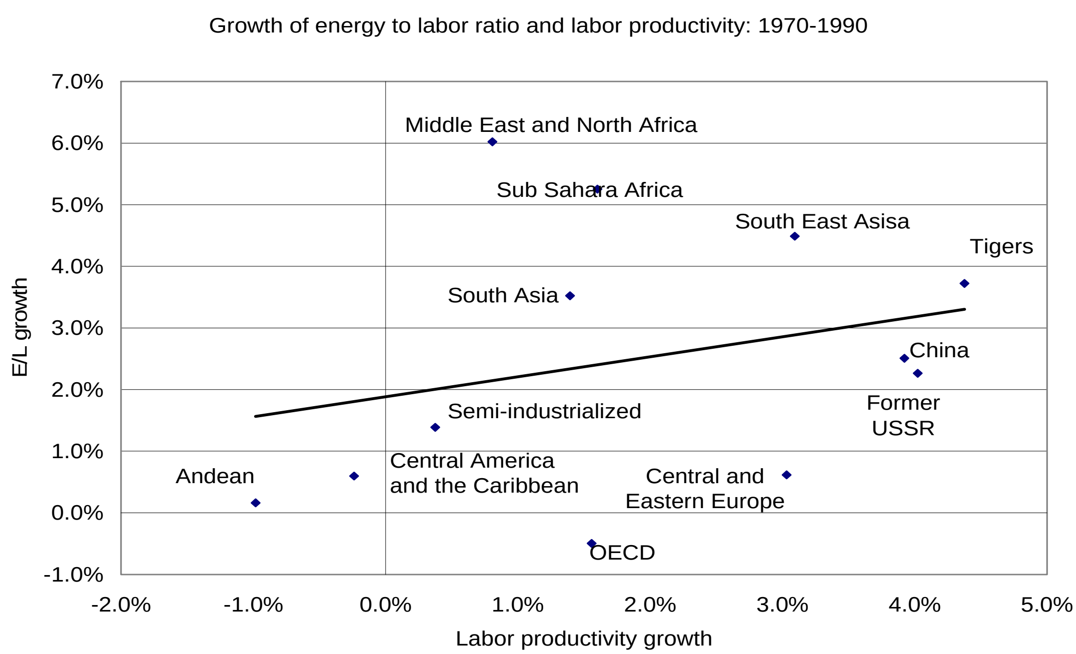

Figure 1: Growth rates of labor productivity and the energy/labor ratio.

1970-1990	Selected OECD	Central and Eastern Europe	USSR* (1989 end year)	Tigers	South East Asia	China	South Asia	Semi-Industrialized countries	Central America and the Caribbean	Andean	Middle East	SubSahara Africa
Growth Rates Energy Productivity	2.1%	2.4%	1.6%	0.6%	-1.3%	1.4%	-2.1%	-1.0%	-0.8%	-1.1%	-4.9%	-3.5%
Growth Rates Labor Productivity	1.6%	3.0%	4.0%	4.4%	3.1%	3.9%	1.4%	0.4%	-0.2%	-1.0%	0.8%	1.6%
Growth Rates E/L	-0.5%	0.6%	2.3%	3.7%	4.5%	2.5%	3.5%	1.4%	0.6%	0.2%	6.0%	5.3%
E/L beginning year (1970)	0.49	0.21	0.26	0.08	0.01	0.02	0.01	0.09	0.04	0.04	0.05	0.0048
E/L end year (1990)	0.45	0.24	0.40	0.17	0.03	0.04	0.02	0.12	0.05	0.04	0.16	0.0133

1990-2004	Selected OECD	Central and Eastern Europe	USSR* (beginning year)	Tigers	South East Asia	China	South Asia	Semi-Industrialized countries	Central America and the Caribbean	Andean	Middle East	SubSahara Africa
Growth Rates Energy Productivity	1.9%	3.2%	2.1%	0.4%	-1.3%	4.5%	0.8%	0.4%	-0.3%	1.0%	-0.9%	-0.2%
Growth Rates Labor Productivity	2.0%	3.2%	-0.2%	3.9%	2.6%	8.6%	4.1%	0.8%	1.3%	0.7%	0.6%	-0.9%
Growth Rates E/L	0.1%	0.0%	-0.9%	3.5%	3.9%	3.9%	3.3%	0.4%	1.6%	-0.2%	1.5%	-0.7%
E/L beginning year (1990)	0.45	0.24	0.41	0.17	0.03	0.04	0.02	0.12	0.05	0.04	0.16	0.01
E/L end year (2004)	0.45	0.24	0.37	0.27	0.05	0.07	0.04	0.12	0.06	0.04	0.19	0.01

Table 1: Growth of energy productivity, labor productivity, and the energy/labor ratio.

Data Sources: World Bank Development Indicators 2005 database; Gronningen Center for Growth and Development

	World	US	UK	Sweden	France	Japan
Total CO_2 Emission						
(thousands of metric tons)	27,245,758	6,049,435	587,261	53,033	373,693	1,257,963
Total Energy Consumption						
(thousands of terajoules)	361,849.00	81,762.00	8,926.00	671.00	5,667.00	17,094.00
Employment	2,836,437	140,702	28,008	4,311	24,963	63,290
Population	6,411,145	293,028	60,271	8,986	60,991	127,480
Energy Consumption/Labor	0.13	0.58	0.32	0.16	0.23	0.27
CO_2 Emission/Energy						
Consumption	75.3	74.0	65.8	79.0	65.94	74
CO_2 Emissions/Population	4.25	20.6	9.7	5.9	6.1	9.9

	China	India	Argentina	Brazil	Venezuela	South Africa	Kenya	Saudi Arabia	Poland	Russia
Total CO_2 Emission (thousands of metric tons)	5,012,377	1,342,962	141,786	331,795	172,623	437,032	10,588	308,393	307,238	1,524,993
Total Energy Consumption (thousands of terajoules)	51,339	14,890	2,358	4,880	2,295	4,939	119	5,715	3,745	24,355
Employment	752,000	394,612	14,329	71,058	8,855	19,092	15,110	7,675	13,855	66,407
Population	1,295,734	1,065,071	38,984	183,169	24,765	44,448	33,973	25,796	38,580	143,508
Energy Consumption/Labor	0.07	0.04	0.16	0.07	0.26	0.26	0.01	0.74	0.27	0.37
Carbon Emission/Energy Consumption	97.6	74.0	65.8	79.0	65.94	74	89.0	74.0	73.7	74.7
Carbon Emissions/Population	3.87	1.3	3.6	1.8	7.0	9.8	0.31	12.0	8.0	10.6

Table 2: Carbon dioxide emission and energy consumption in 2004.

Data Sources: Gronningen Center for Growth and Development; 2004 Energy Statistics Yearbook, United Naions; Carbon Dioxide Information Analysis Center, United States Department of Energy

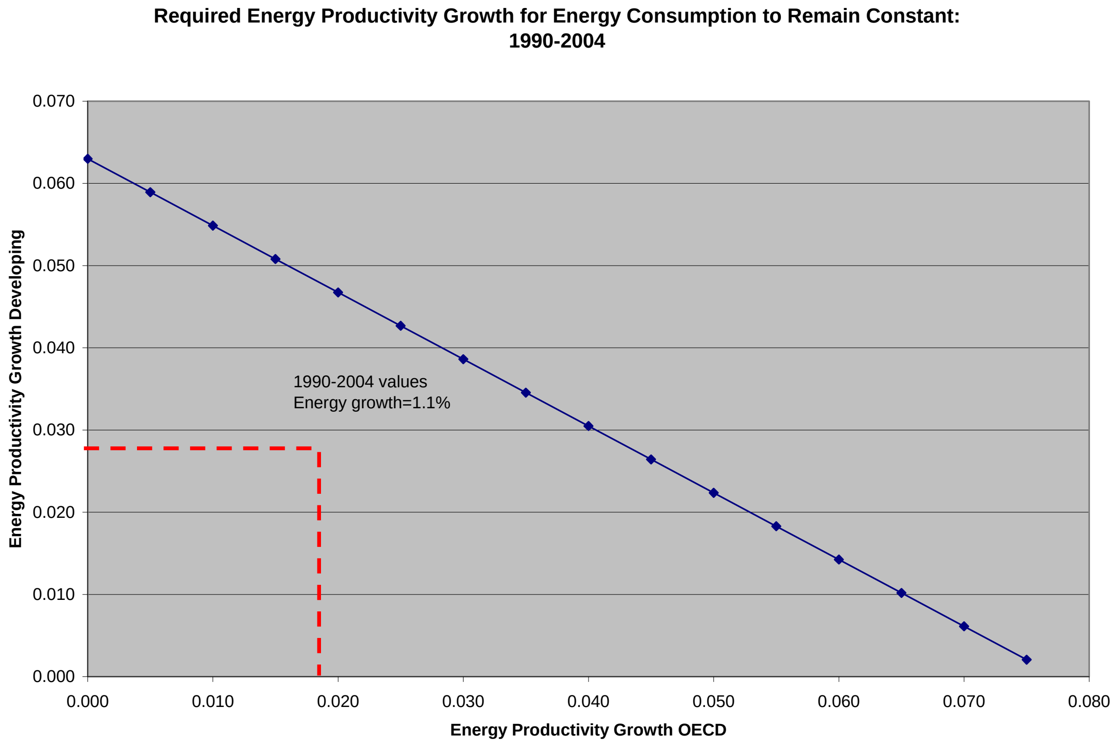

Figure 2: Energy productivity growth rates required to hold overall growth of energy use to zero, 1990-2004

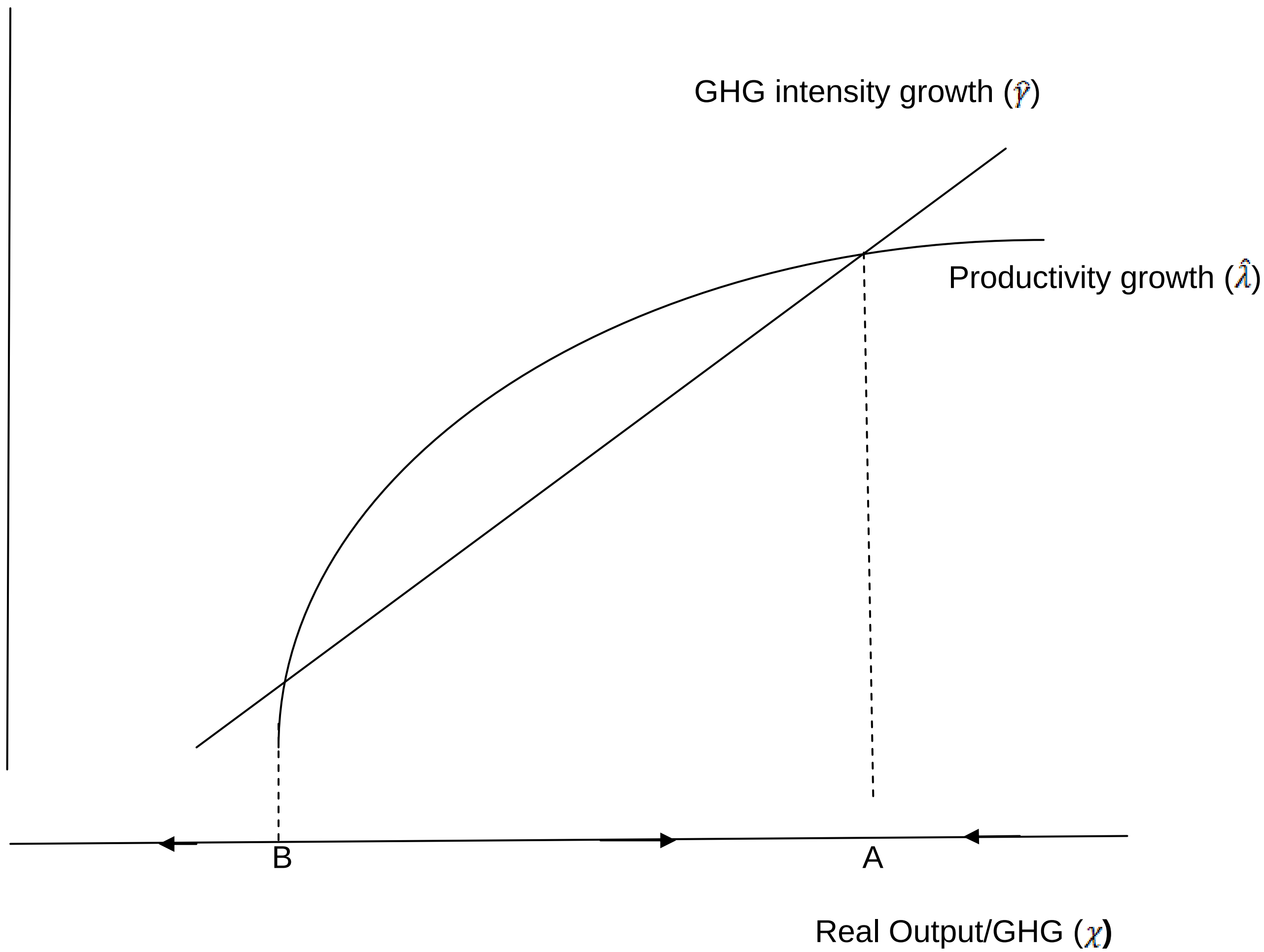

Figure 3: "Medium term" greenhouse gas accumulation dynamics

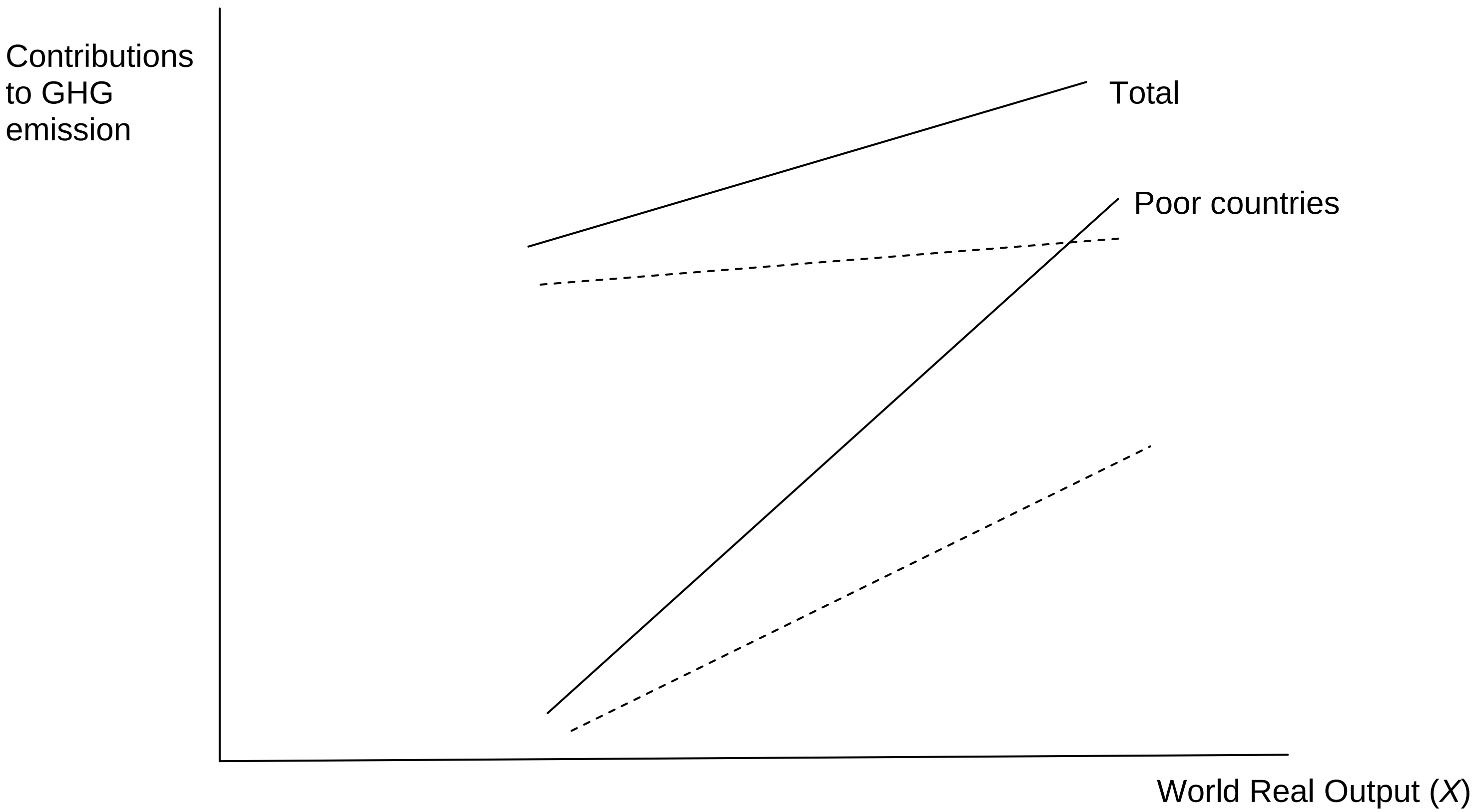

Figure 4: Hypothetical contributions to GHG emission

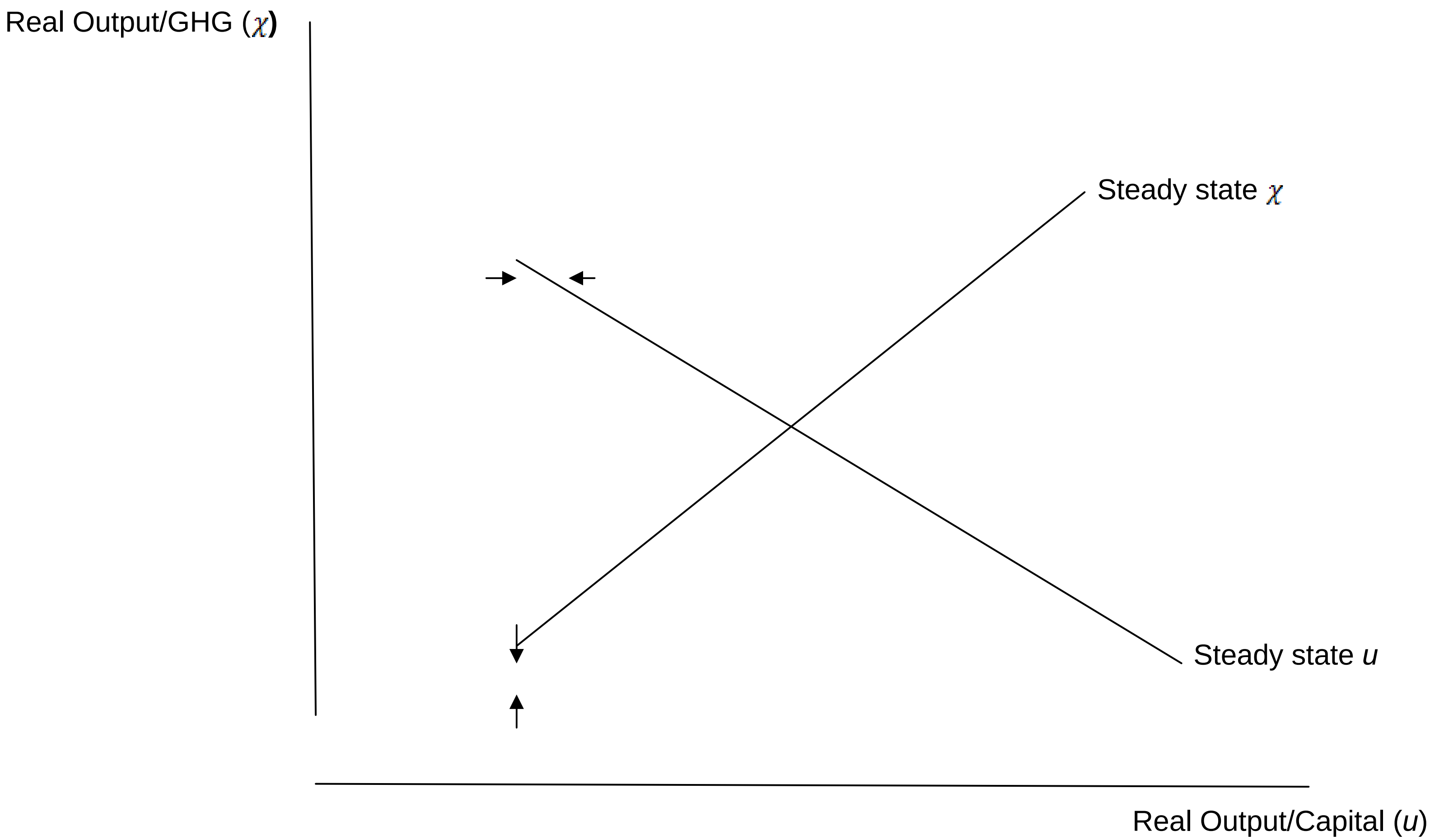

Figure 5: Long term phase diagram for capital utilization and GHG concentration