Title:

Implications of fossil fuel constraints on economic growth and global warming

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Abstract:

Energy Security and Global Warming are analysed as 21st century sustainability threats.

Best estimates of future energy availability are derived as an Energy Reference Case (ERC). An explicit economic growth model is used to interpret the impact of the ERC on economic growth. The model predicts a divergence from 20th century equilibrium conditions in economic growth and socio-economic welfare is only stabilised under optimistic assumptions that demands a paradigm shift in contemporary economic thought and focused attention from policy makers.

Fossil fuel depletion also constrains the maximum extent of Global Warming. Carbon emissions from the ERC comply nominally with the B1 scenario, which is the lowest emissions case considered by the IPCC. The IPCC predicts a temperature response within acceptance limits of the Global Warming debate for the B1 scenario. The carbon feedback cycle, used in the IPCC models, is shown as invalid for low-emissions scenarios and an alternative carbon cycle reduces the temperature response for the ERC considerably compared to the IPCC predictions.

¹ This study was conducted as an independent academic enquiry and does not necessarily reflect the viewpoints or opinions of any institutions or professional associations that the authors may be directly or indirectly affiliated to.
Our analysis proposes that the extent of *Global Warming* may be acceptable and preferable compared to the socio-economic consequences of not exploiting fossil fuel reserves to their full technical potential.

**Keywords:**

Peak Oil, Global Warming, Economic Growth
1. Introduction

A paradox of global dimensions faces humankind. While energy constraints pose a threat to the global economy, continued extraction and combustion of fossil fuels at current, or increased, rates is now accepted to be the dominant driver of Global Warming (IPCC, 2007a, 136). The development and expansion of alternative energy sources has proven challenging, hence the reluctance of certain major countries to endorse the Kyoto Protocol on reductions of greenhouse gas emissions, notably the USA (UNFCCC, 2008).

Long-term structural scarcity in energy supplies is unprecedented in modern history. To this end, there is no established economic growth theory that explicitly describes the impacts of such energy constraints. Despite awareness that fossil fuel resources are exhaustible, there is no globally accepted benchmark of resource availability for long-term planning purposes. Energy is commonly treated as a limitless exogenous input to economic planning with the result that energy demand is well defined, but disconnected from the physical and logistical realities of supply.

In like manner, the Intergovernmental Panel on Climate Change (IPCC) has identified exponential increases in atmospheric concentrations of CO$_2$ as the dominant forcing agent for global warming (IPCC, 2007a: 136), with the dominant contributor of man-made CO$_2$ emissions being the burning of fossil fuel (IPCC, 2007a: 512). However, the range of scenarios presented for climate futures are not constrained by the possibility that the quantity of recoverable fossil carbon may rule out certain scenarios as physically unrealisable.

The exhaustion of oil and gas commodities has been extensively analysed by Peak Oil proponents (ASPO, 2008). The scientific and deductive merits of Peak Oil theory are well established; the World Energy Council endorses the methodology, declaring the ASPO model as “plausible” (WEC, 2007: 45 to 53). Nevertheless, much uncertainty is still being expressed in the understanding of both the phenomena of Peak Oil and Global Warming:

“…a set of model metrics that might be used to narrow the range of plausible climate change feedbacks and climate sensitivity has yet to be developed.” (IPCC, 2007a: 640)

“…most would appear to agree that peak oil output is not very far away for all of us. It could take place sometime within the next decade or so…” (Ghanem, 2006)
The principles of *Peak Oil* theory are applied in this paper to derive an *Energy Reference Case* (ERC) for the total recoverable reserves of all fossil fuels; liquid, gas and solid. The roles of nuclear and renewable energy sources are also considered in the ERC, to present an integrated energy future. A comparative assessment of the socio-economic threats triggered alternately by *energy scarcity*, or by *Global Warming*, caused by the burning of fossil fuel, is performed in the context of the ERC. The paper thereby facilitates a multidisciplinary synthesis between some of the most important sustainability threats to human society, and motivates a resolution to the paradox posed in the opening paragraph.

As there is still substantial disagreement on the magnitude of geological energy reserves and recoverable resources, the ERC and consequent analysis are likely to be criticised by both energy pessimists and optimists. Nevertheless, we argue that the methods for estimating the total recoverable reserves that we apply to global fossil fuel reserves are robust and are validated by previous case studies. We further argue that these estimates provide stark alternatives that must be considered in deciding how to address the combined challenges of climate change and the ultimate decline of the global carbon-based energy economy. Although the existence of other sustainability threats such as food security, water stress and epidemic diseases are acknowledged, they are beyond the scope of this paper.
2. Production Logistics of Fossil Fuel

Awareness of energy resource depletion stems from work performed by M. King Hubbert in which he used graphical methods to construct a logistic curve for oil production in the lower 48 States (L48) of the USA (Hubbert, 1956). Hubbert proposed a bell-shaped curve to represent the rate of oil production with time, under the assumption that the production rate will be zero at the onset of production and again zero when the reserves are exhausted. Hubbert assumed a symmetrical profile, which implies that peak production is reached once half the recoverable reserves have been extracted (Fig. 1).

![Hubbert's 1956 assessment of L48 oil production](courtesy: Hubbert, 1956)

Based on his most optimistic estimation of conventional oil reserves, Hubbert’s analysis suggested a peak in US L48 oil production would occur in the early 1970s. Hubbert’s assessment proved valid when the US L48 oil production indeed peaked in 1970 (BP, 2007).

The bell-shaped curve, used by Hubbert, is the first derivative of a logistics or s-curve. The basic equation for the logistic function is expressed as (Bannock et al., 2003: 230).

\[
Q = \frac{URR}{1 + e^{-c(t-t_0)}}
\]  

(1)

In the context of the oil production curve, \(Q\) is cumulative production, \(URR\) is the Ultimate Recoverable Reserves, \(t\) is time, \(t_0\) is the time associated with the inflection point where half the URR is recovered and \(c\) is a rate-dependent constant.

With (1) representing cumulative production, the first derivative of \(Q\) with respect to time represents the production rate, \(P\), expressed as
\[
\frac{dQ}{dt} = P = \frac{URRce^{-c(t-t_0)}}{(1 + e^{-c(t-t_0)})^2}
\]  

Eq. (2) has the characteristic bell-shape of the Hubbert-curve in Fig. 1. The production characteristics in (1) and (2) can be linearised as follows.

Substitution of URR from (1) into (2) yields

\[
P = \frac{ce^{-c(t-t_0)}}{(1 + e^{-c(t-t_0)})}Q
\]  

(3)

It follows from (1) that

\[
e^{-c(t-t_0)} = \frac{URR}{Q} - 1
\]  

(4)

Substitution of (4) into (3) yields

\[
P = -c \left( \frac{URR}{Q} - 1 \right)Q + cQ \left( 1 - \frac{Q}{URR} \right)
\]  

(5)

Division by Q in Eq. (5) yields:

\[
\frac{P}{Q} = -\frac{c}{URR} Q + c
\]  

(6)

Eq. 6 represents a linear relationship between the variables P/Q and Q and is the mathematical basis of linearised analysis as used by Deffeyes (2001).

Distortions to the linearised curve occur in the early production life. For actual production data, the ratio of P/Q for the first time interval equals 1 since P = Q for the first unit of production. With increasing production, the curve becomes linear. Once the curve follows a linear relationship, a linear regression through the data points provides an approximation of URR (intercept on the Q axis) while c is the intercept on the P/Q axis. The predicted peak production would be at a cumulative production of half the URR.

The methodology is demonstrated by applying it to oil production in the lower 48 States of the USA in the context of Hubbert’s 1956 assessment. A graph of P/Q vs. Q for the L48 States from 1930 onwards is shown in Fig. 2. The production data shows a discernable trend change starting from 1938 onwards. A linear
regression from 1938 to 1955 projects a URR of 205 billion barrels (Gbl) and a production peak when the cumulative production reaches 103 Gbl. A forecast of future production is required to predict a peak date, since cumulative production in 1955 only amounted to 50 Gbl. An average production growth rate of 4.7% (the average for the five years from 1951 to 1955) yields a cumulative production value of 103 Gbl in 1970.

With the values of c and URR established from the analysis in Fig. 2, the production curve (2) can be constructed. The predicted production curve is superimposed on actual production data in Fig. 3. The agreement is striking in the context of understanding URR and predicting the date of peak production.

Fig. 2. Logistic curve assessment for oil production in the lower 48 States of the USA (source data: Campbell, 2002). “Linear” denotes the points used for the regression curve.
Fig. 3. Actual and modelled oil production for the US L48 States. [Source data: (Campbell, 2002)].

Because the selection of the number of regression points is subjective, an analysis with an increasing number of regression points was done to demonstrate sensitivity. The result of this analysis is shown in Fig. 4. The predictions converge as the number of regression points increases to six and beyond, despite the dynamic behaviour in the actual production data.

Fig. 4. Sensitivity analysis for the number of regression points used in estimating the intercept point, URR.
Application of the methodology to gas production is demonstrated for the case of Indonesia in Fig. 5 and Fig. 6 with units in billion cubic metres (Bcm). Strahan (2008: 41) demonstrated that the same principles apply to UK coal production.

![Logistic curve assessment for gas production in Indonesia](image1)

**Fig. 5.** Logistic curve assessment for gas production in Indonesia. [Source data: (BP, 2007)].

![Gas production trends for Indonesia](image2)

**Fig. 6.** Gas production trends for Indonesia. [Source data: (BP, 2008)].
3. Global Oil

Sources for global oil production data are listed in Table 1. Averages are used where more than one source is available. Fig. 7 shows the linearised logistic curve assessment for global oil production.

**Table 1. Data sources for global oil production.**

<table>
<thead>
<tr>
<th>Period</th>
<th>Average of Sources</th>
<th>Data Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1900 to 1929</td>
<td>Rodrigue, not dated</td>
<td>Reproduced from graph.</td>
</tr>
<tr>
<td>1930 to 1964</td>
<td>Rodrigue, not dated</td>
<td>Reproduced from graph.</td>
</tr>
<tr>
<td></td>
<td>Campbell, 2002</td>
<td>Table</td>
</tr>
<tr>
<td>1965 to 1970</td>
<td>Rodrigue, not dated</td>
<td>Reproduced from graph.</td>
</tr>
<tr>
<td></td>
<td>Campbell, 2002</td>
<td>Table</td>
</tr>
<tr>
<td></td>
<td>BP, 2007</td>
<td>Table</td>
</tr>
<tr>
<td>1971 to 2006</td>
<td>Campbell, 2002*</td>
<td>Table</td>
</tr>
<tr>
<td></td>
<td>BP, 2007</td>
<td>Table</td>
</tr>
</tbody>
</table>

* Data in Campbell, 2002 has projections to 2050

![Logistic curve assessment for global oil production](image)

**Fig. 7.** Logistic curve assessment for global oil production [Source data: See Table 1].
The cumulative production to 2006 is 1132 Gbl. Assuming that future production will meet consumption, the IEA (2007) projections, extrapolated to 2014 at an annual growth of 2%, predicts that cumulative production will reach URR/2 = 1341 Gbl by 2014.

Fig. 7 implies that the proven reserves in 2006 were \((2682 - 1132) = 1550\) Gbl, compared to 1208 Gbl reported by BP (2007). Global production model predictions (2) are shown superimposed on actual production data in Fig. 8.

The production function smoothes out the perturbations of the oil crises in the 1970s, generally believed to have been caused by geopolitical tension. An alternative viewpoint is reflected in US senate hearings in 1974, and again in 1979, where concerns were raised that production rates from the Saudi Arabian oilfields were unsustainable, and that continued mismanagement of the fields would have led to premature decline and poor recovery (Simmons, 2005: 377 - 384).

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**Fig. 8. Global oil Production trends and projections. One barrel of oil = 5.729 GJ (BP, 2007). [Source data: See Table 1]**

ASPO's Peak Oil analysis is based on the aggregation of detailed country-level assessments (Campbell, 2002) that are considered more accurate than the integrated approach used here. The ASPO model includes non-conventional oil, such as Venezuelan heavy crude and Canadian oil sands (Campbell, 2002), with values that are nominally comparable to those projected by institutional authorities (IEA, 2006: 92 to 93).
The logistic curve predictions are considered adequately representative of future production trends and sufficiently robust for the purposes of this paper, which is to highlight normative dependencies – a higher degree of accuracy is neither important nor achievable given the quality of available data.
4. Global Gas

Sources for global gas production data are listed in Table 2. The linearised logistic curve assessment for global gas production with units in trillion cubic meters (Tcm) is shown in Fig. 9.

Table 2. Data sources for global gas production

<table>
<thead>
<tr>
<th>Period</th>
<th>Sources</th>
<th>Data Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1930 to 1969</td>
<td>Campbell, 2002</td>
<td>Table</td>
</tr>
<tr>
<td>1970 to 2006</td>
<td>BP, 2007</td>
<td>Table</td>
</tr>
</tbody>
</table>

* Data in Campbell, 2002 has projections to 2050

The cumulative production to 2006 is 84 Tcm. Future gas production is assumed to grow at the same rate as the average rate of the five years preceding 2006. At this rate, cumulative production would reach URR/2 = 162 Tcm by 2027. Demand growth of gas could, however, accelerate after Peak Oil occurs.

In accordance with Fig. 9, the remaining proven reserves in 2006 were (324 − 84) = 240 Tcm, compared to an official value of 181 Tcm reported by BP (2007). The production function in (2), superimposed on actual production data and ASPO projections, are shown in Fig. 10. As for the case of oil production, the logistics curve is used in the ERC to maintain consistency across the various fossil fuel sources.
Fig. 9. Logistic curve assessment for global gas production [Source data: See Table 2].

Fig. 10. Global gas production trends and projections. One cubic meter of gas = 0.0360 GJ (BP, 2007). [Source data: See Table 2].
5. **Global Coal**

Sources for global coal production data are listed in Table 3. Coal production is measured in *millions of tons* (Mt) and *billions of tons* (Gt).

**Table 3. Data Sources for Global Coal Production.**

<table>
<thead>
<tr>
<th>Period</th>
<th>Sources</th>
<th>Data Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1820 to 1953</td>
<td>Hubbert, 1956</td>
<td>Reproduced from graph.</td>
</tr>
<tr>
<td>1954 to 1980</td>
<td>IEA, 2003</td>
<td>Data listed in table for hard coal production. Values for total coal production in this date range was estimated by growing the 1953 value by the same annual percentages as hard coal production.</td>
</tr>
<tr>
<td>1981 to 2006</td>
<td>BP, 2007</td>
<td>Table</td>
</tr>
</tbody>
</table>

Table 4 lists the global coal reserves for different categories. Differences in values between sources are the effect of poor data quality and differences in classification (WEC, 2007). Reserves declined from 935 Gt in 2001 to 847 Gt in 2005 (production was only 26 Gt) because of refinements in the categorisation of reserves and not as a result of revisions (WEC, 2007). Despite this downward adjustment in reserves, recent trends in production show notable increases from 2002 (Fig. 11).

**Table 4. Coal reserves and production data (Mt).**

<table>
<thead>
<tr>
<th>Source</th>
<th>Year</th>
<th>Proved Recoverable Reserves</th>
<th>Production</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Year</td>
<td>Hard Coal</td>
</tr>
</tbody>
</table>
Fig. 11. Recent trends in coal production [Source data: (BP, 2008)].

The linearised logistic curve assessment for global coal production is presented in Fig. 12. Cumulative production to 2006 equates to 285 Gt. The regression curve yields a URR of 1671 Gt, equating to remaining reserves of 1386 Gt, 64% higher than the official reserves. The energy scenario that includes the case of 64% overestimation in coal reserves, referred to as Coal Plus, is used in the economic and climate change sections for comparative analysis. The linear regression curve for coal is regarded as upward biased because of production trends since 2002, which are considered as unsustainable.
Three scenarios of global coal production, superimposed on the actual production data, are shown in Fig. 13. The three scenarios correspond to the linear regression curve, a URR of 1126 Gt (to correspond to the official remaining reserves of 847 Gt, see Table 4) and the average between these two curves. The average curve in Fig. 12 has a URR of 1400 Gt, which equates to remaining reserves of 1115 Gt (nearly 25% higher than the official reserves). The Average [1400 Gt] case (Fig. 13) is used in the ERC.
Coal production statistics are generally reported in tons delivered, which include the mass of non-combustible material. The energy-based projection of coal consumption has to be adjusted to compensate for declining coal quality. In the USA, there has been a decline of 3.6% per decade in energy content of coal throughout the second half of the 20th century (Fig. 14).

Coal is assumed to contain 28 GJ of energy per ton up to 2006, after which it starts to decline at 0.18% per year to reach 24 GJ per ton by 2100. It is estimated that underground coal gasification has the potential to add 565 Gt, which would be consistent with the *Coal Plus* case.
Fig. 14. Coal quality trends in the USA [Source data: (EIA, 2006)].
6. Nuclear Energy


Primary uranium production supplied only 60% of reactor fuel requirements in 2004, with the balance coming from secondary sources such as civilian and military stockpiles (OECD and IAEA, 2006: 60). Reactor requirements for 2004 were for 67320 tons of uranium (tU) to fuel 369 GWe of installed capacity. Primary production of uranium would have to increase considerably to meet increasing demand as secondary stockpiles are depleted.

Concerns have been raised that uranium resources may not be adequate to supply nuclear reactor demand in the future (IAEA, 2001; OECD and IEA, 2006: 75). The International Atomic Energy Agency (IAEA, 2001: 58) considered different resource categories as Reasonably Assured Reserves (RAR), non-attributed RAR (RAR of which the source could not be determined), Estimated Additional Reserves (EAR) of category I and II, representing two different uncertainty classes, and Speculative Reserves (SR). EAR-II and SR represent undiscovered reserves. The study shows that if uranium were to be supplied to meet reactor demand in a high growth scenario, production of the combined resources in RAR, non-attributed RAR, EAR-I and EAR-II would peak in 2030. Institutional viewpoints of uranium abundance only take the resource base into account and do, in general, not explicitly account for production logistics associated with the geological distribution of ore grades such as assessed by Deffeyes (1980) and EWG (2006).

Estimated nuclear generating capacity by 2025 is between 449 and 533 GWe (requiring 100760 tU), which equates to an average annual growth of 1.9% (OECD and IAEA, 2006: 10). Recent estimates are that nuclear energy could expand by between 0.9 and 2.8% per year to 2030 (IAEA, 2007: 53), but the earlier studies mentioned above indicate that the primary uranium requirements for this high growth case cannot be met with any degree of certainty.
Fast breeder reactors have the potential to unlock the fertile $^{238}\text{U}$ and $^{232}\text{Th}$ as sources of fissile nuclear energy. Logistically, a rapid transition to breeding technologies would lock up the majority of fissile material in inventories, including $^{235}\text{U}$, which is the current source of nuclear power in the majority of reactors. A large inventory is required in the breeding cycle because of breeder reactor physics, the long doubling times of 10 to 20 years, reactor throughput and reprocessing. This dilemma was foreseen by Hubbert (1956), who did not anticipate the development of nuclear energy along a path that would exhaust naturally occurring fissile $^{235}\text{U}$ in moderated reactors.

This paper assumes that breeder technology will not relieve medium-term energy constraints imposed by fossil fuel depletion, but that it would offset the exhaustion of $^{235}\text{U}$ beyond 2030. The high growth case (OECD and IAEA, 2006) of 1.9% is assumed as plausible to 2030 in a business as usual case and will be used in this study. The contribution of nuclear energy, used in this study, is illustrated in Fig. 15.

![Fig. 15. Global nuclear energy trends and projections [Source data for historical trend: (BP, 2007)].](image)

Primary energy supply from nuclear is calculated by considering a thermal conversion efficiency of 33% to produce electricity. While considerable refinement is possible to this assumption, considering potential advances in reactor design, it is considered adequate for the purposes of this paper given the uncertainties expressed above.
7. Renewable Energy

Renewable energy technologies are regarded as low quality energy sources compared to fossil fuel and nuclear, in the sense that the energy is relatively dispersed. Views on the viability of large-scale renewable energy are still divided and range from firm beliefs that renewable energy has the potential to provide all of mankind’s energy requirements to beliefs that the potential is limited to the supply of approximately 260 EJ/year (Niele, 2005: 126), compared to the approximately 400 EJ energy consumed globally in the year 2000.

The IEA (2004) presented data to reflect the total “realisable” renewable energy potential per year for electricity generation as approximately 108 EJ/year. Apart from hydro-electricity, accurate time series data for other renewable sources are not readily available and renewable energy technologies are anticipated to gain momentum only in the 21st century (IEA, 2004: 430). Data and assumptions for renewable energy trends are listed in Table 5.

Table 5. Data sources and assumptions for renewable energy**.

<table>
<thead>
<tr>
<th>Period</th>
<th>Sources</th>
<th>Data Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1950 to 1964</td>
<td></td>
<td>Hydro growth of 7% based on growth from 1965 to 1966 (see BP, 2007 below).</td>
</tr>
<tr>
<td>1950 to 1970</td>
<td></td>
<td>Extrapolation of other*** renewable growth of 8.5% for 1971 to 2002 (see IEA, 2004 below).</td>
</tr>
<tr>
<td>1965 to 2002</td>
<td>BP, 2007</td>
<td>Table for hydropower.</td>
</tr>
<tr>
<td>1971 to 2002</td>
<td>IEA, 2004 (Reference Case)</td>
<td>Other*** renewable calculated based on 55 Mtoe* in 2002 and 8.5% growth from 1971 to 2002.</td>
</tr>
<tr>
<td>2003 to 2030</td>
<td>IEA, 2004 (Reference Case)</td>
<td>Projected growth to 2030.</td>
</tr>
<tr>
<td>2030 to 2100</td>
<td></td>
<td>Extrapolation of renewable energy growth up to a total capacity of 108 EJ per year (see IEA, 2004 above).</td>
</tr>
</tbody>
</table>

* Million tons of oil equivalent.
** Biomass and waste is excluded
*** Other includes all sources other than hydro

The contributions of biomass and waste are excluded because their contributions to economic growth are considered as limited and they are not projected to have proportional growth compared to other renewable sources (IEA, 2004: 430).
The contribution of renewable energy, used in the ERC, is illustrated in Fig. 16.

Fig. 16. Global renewable energy trends and projections. [Source data: See Table 5].
8. Energy and Economic Growth

Establishing the causal links between energy consumption and economic growth is important in this study in order to interpret the effects of energy constraints on economic growth. Long-term structural constraints in the availability of energy commodities, as formulated above, are unprecedented in modern history.

The energy-economy link is often omitted from economic growth formulations, such as the Solow model, for which the production function, with the inclusion of multi-factor productivity, is shown in (7) in the Cobb-Douglas form.

\[ Y = F(A, K, L) = A(t)K^{\alpha}L^{1-\alpha} \]  

where \( Y \) is output in GDP, \( A \) is multi-factor productivity, \( K \) is capital, \( L \) is labour and \( \alpha \) is a variable with a value between 0 and 1.

The second component of Solow’s model is expressed in (8) (Jones, 2002: 23).

\[ \frac{dK}{dt} = \rho Y - \delta K \]  

where \( \rho \) is the savings rate and \( \delta \) is the capital depreciation rate.

Consideration of energy commodities as a factor of production raises the question of whether it is an essential resource. A factor of production is considered as essential if output falls to zero in the absence of the resource. An essential resource would be rendered inessential if alternative resources are discovered or synthesised (Dasgupta and Heal, 1974: 4).

Most texts on economic growth theory treat exhaustible resources as inessential with substitution for capital. While the principle of substitution has merits for fossil fuel commodities, it is not the commodity itself that is essential in production, but the energy it delivers. Although the role of energy may have been neglected because of the relative abundance of fossil fuels during the 20th century, there are important historical perspectives that highlight the importance of energy in human development.

The importance of energy as an essential ingredient to life on earth is well established in the physical sciences, both in terms of biological energy, and as a primary enabler of industrialisation. This was recognised by Ludwig Boltzmann in the 1800s, postulating that energy is the “… object of contention in the life-
struggle …” (as quoted by Lotka, 1922: 147). Lotka proposed a Darwinian premise for human development, postulating that mankind has been unconsciously following the laws of nature in the pursuit of energy.

The pivotal role of energy in human development is well captured by White (1949: 364 to 365) who considered culture as an organised, integrated system, and loosely distinguished three subsystems namely energy, sociological and ideological systems. White described the energy/technological system as “… [physical] instruments, together with their means of use, by means of which man … is articulated in his natural habitat”.

White (1949: 365) saw the technology system as primary in importance because it is the agent by which mankind attains the means of survival (food, shelter, defence). In this context, White (1959: 56) formulated his law of cultural development as follows:

“Culture advances as the amount of energy harnessed per capita per year increases, or as the efficiency or economy of the means of controlling energy is increased, or both.”

The three dominant components in White’s law are the quantity of energy consumed, the efficiency with which it is consumed and per capita utility derived from the consumption of energy. These ideas are consistent with contemporary thoughts on human development and energy economics and form a central theme in the economics section of this paper.

Studies on the depletion of exhaustible resources include, but are not limited to, fossil fuel. Failure to distinguish clearly between energy and other resources could impact on the validity of conclusions because of assumptions regarding the essentiality of resources. Although Hoteling’s (1931) publication, The Economics of Exhaustible Resources, is seen as a landmark publication on the topic (Mitra, 1980), publication of Limits to Growth (Meadows et al., 1972) sparked renewed interest in sustainable development (Pezzy and Toman, 2002). Central ideas from economic papers on sustainability include (For example: Dasgupta and Heal, 1974; Solow, 1974; Mitra, 1980; Pezzy and Toman, 2002; Jones, 2002: 174 to 189):

- An optimum program for the economic cycle of [“Capital Formation” - “Utilisation of Exhaustible Resources” - “Economic Output” - “Consumption”] exists.
In an optimum program, economic output increases or can be sustained indefinitely as gains in capital accumulation is larger or equal to the effects of declining resources.

The viewpoint that the factor share of energy in economic output is declining is supported in contemporary economic thought (see for example Jones, 2002: 186). Total Primary Energy Consumption (TPES) has developed a decoupling trend with respect to economic growth, as measured by Gross World Product (GWP) since 1979 (Cleveland et. al., 2000) – see Fig.23 in Section 10. Decoupling of energy from economic growth is highly desirable, not only for reasons explained above, but also because of negative environmental consequences associated with energy consumption.

The decoupling effect was studied by Adams and Miovic (1968) who observed that energy elasticity with respect to GDP (energy coefficient) is generally smaller than unity for industrialised countries. Using an energy-based production function (9) that accounts for energy efficiency to calculate useful work for different fuel types, Adams and Miovic calculated energy coefficients of up to 1.4. They found that energy coefficients are not static, but evolve with changes in fuel mix and technology improvements.

\[
Y = F(E_u, K, L) \text{ with } E_u = \sum \mu_i E_{thi} \quad (9)
\]

where \(E_u\) is useful work, \(i = \text{Coal, Gas, Petroleum and Electricity}\), \(\mu_i\) is the fuel efficiency and \(E_{thi}\) is the thermal energy equivalent of the fuel. Useful work is the product of energy efficiency and TPES. A large percentage of TPES is lost in energy conversion processes and end-use losses such as friction or heat.

Nguyen (1984) calculated temporal and country level trends in energy coefficients using refinements to the Adams and Miovic methodology. He concludes: “… conventional measures of energy consumption underestimate the energy services derived”.

A number of more recent studies further refined the use of energy metrics in economic growth. Cleveland et al. (2000) found that most of the decoupling is eliminated when energy is adjusted for quality. The term energy quality refers to the specific attributes of an energy source such as energy density, cleanliness, capacity to do useful work, suitability for storage and conversion amongst others.
Cleveland et al. (2000) reported that energy consumption causes GDP growth in a multivariable Granger causality test if energy quality is taken into consideration.

The relationship between marginal product and price has been calculated by Kaufmann (1994) for various sources of energy in the US economy. Kaufmann demonstrated that petroleum is the highest quality fossil fuel, producing up to 3.45 times more GDP per thermal equivalent unit than coal. This is consistent with Adams and Miovic’s 1968 results.

Using a similar approach to Adams and Miovic (1968), Ayres et al. (2007: 638) reproduced GDP growth in the USA between 1900 and 2000 to a high degree of accuracy by considering useful work as a factor of production together with capital and labour, thereby eliminating the exogenous contribution of Total Factor Productivity (TFP) in a Solow-based growth model such as (7).

The use of price-based metrics is deliberately avoided because of the conclusion drawn by Pezzy and Toman (2002) stating, “… without sustainable prices, we cannot know whether the economy is currently sustainable; but without knowing whether the economy is sustainable, currently observed prices tell us nothing about sustainability ….”
9. An Explicit Energy-Based Economic Growth Formulation

An explicitly energy-based production function is required to predict the consequences of long-term structural constraints in the availability of energy commodities on economic growth. The production function in (10) is proposed, capturing all the essential components of White’s law and the studies above (Adams and Miovic, 1968; Kaufmann, 1994; Cleveland et al., 2000; Ayres et al. 2007).

\[ Y = A_0 e^{\alpha t} \sum_{i} \left[ \mu_{eq,i}(t) E_{Th,i} - \xi_i(t,E_i) \right] \]  

(10)

with \( A_0 e^{\alpha t} \) an exponential growth function related to human ingenuity to improve end-use technology and to derive utility from available resources, \( \alpha \) is a growth exponent, \( t \) is time, \( i = \text{Coal, Gas, Oil, Nuclear and Renewable} \), \( \mu_{eq} \) is an equivalent energy efficiency coefficient for each fuel type \( i \), \( E_{Th} \) is the thermal energy content of each fuel type and \( \xi \) is a function representing the energy cost for obtaining the energy commodities.

Temporal trends in energy efficiency are derived by considering a logistic or s-curve of efficiency improvement for each fuel type (11). Efficiency improvement is not only derived from technology improvement, but also by changing the modes in which fuels are used, for example, by growing the percentage of gas used in electricity generation thereby increasing its productivity in the economy in terms of delivering motive power and driving electronic equipment (Adams and Miovic, 1968; Kaufmann, 1994).

\[ \mu_{eq} = \mu_0 + \frac{\mu_1}{1 + e^{c(t-t_0)}} \]  

(11)

Eq. (11) represents a logistic curve with a zero offset to account for long-term (outside the time scales of this assessment) and past incremental efficiency improvements with \( \mu_0, \mu_1, c \) and \( t_0 \) as constants.

The purpose of \( \xi \) is to account for declining Energy Profit Ratios (EPR or the energy return on energy invested) as the various energy commodities approach depletion (Gever et al., 1987: 63-73). Capital stock requirements are expected to increase with declining EPR, declining mineral ore grades and scarcity of plastics and chemical feedstock (derived from petroleum). Renewable energy and nuclear has lower EPR compared to fossil fuel (Gever et al., 1987: 70). The role of EPR
is neglected in this study by omitting the $\xi$-term in (10). $\mu_{eq}$ is therefore seen as upward biased with respect to the future availability of useful energy (11).

Capital is treated as a catalyst for energy consumption. In this context, capital accumulation is considered essential to expand and maintain the stock of energy consuming capital required for production of both economic output and energy commodities, to research and improve the efficient use of energy, to implement technology improvements by infrastructure renewal and so on. Since time-series data for capital stock are not readily available, assumptions are made regarding the role of capital in the future as follows:

- Capital-energy trends established in the latter half of the 20th century represent an equilibrium condition. In the absence of energy constraints, economic growth is not constrained and capital formation and economic growth will continue along the established balanced growth path.

- Capital depletion would impact proportionally on energy consumption leading to proportional changes in economic output.

The formulation of the impact of capital stock is discussed in the next section.

The parameters in (10) were calculated in a mathematical optimisation routine to minimise the error function in (12). A first order error function is considered, opposed to the more commonly used least squares, to suppress short-term trends in the empirical data that are affected by political influences and market imperfections.

$$\text{Error} = \min \sum_{j=1950}^{2006} \left[ \text{GWP}_j - A_0 e^{\mu_1 t_0} \sum_i \left( \frac{\mu_j}{1 + e^{-c(t_t - t_0)}} \right) E_{j0,i} \right]$$  
(12)

Solutions to the different parameters were constrained to realistic ranges with $0 > \mu_i > 0.7; 0.1 > \mu_j > 0.7; 0.004 < c < 0.05$ and $t_0$ as follows: coal – 1880 < $t_0$ < 1960; gas, oil and nuclear – 1930 < $t_0$ < 2020; renewables – 1850 < $t_0$ < 1950. Value-ranges for $\mu$ relate to achievable thermal efficiencies (see for example Adams and Miovic, 1968, for historical efficiency values). Parameter $c$ was constrained by considering the rate of change in efficiency improvement over time and time ranges, by considering historical developments and conceivable inflection points in the logistic curve for various technology options.
Because of the large number of degrees of freedom in (12), the “imperfect” discrete dataset and a deliberately introduced randomness in the optimisation routine, the error function contains a number of minima. It was found in “exhaustive” computer runs of the mathematical optimisation routine that numerical solutions are in close proximity producing similar trends to those in Fig. 17, with backward and forward extrapolations to 1900 and 2100 respectively.

![Graph showing solution to $\mu_{eq}$](image)

**Fig. 17. Solution to $\mu_{eq}$.**

The solution with the minimum error sum (12) found in repeated computer runs is shown in Fig. 17 and will be used in further analysis. Although it is proven here that an explicit energy-based analytical formulation for economic growth exists (see accuracy of curve fit in Fig. 18), the coefficients calculated are not considered as theoretically justified or correct and may be improved by analysing energy specific trends related to EPR (exploration, production, transport, processing, conversion, end-use, etc.), conversion and end-use technologies. Accurate energy specific coefficients may result in an increased error sum, which may require the inclusion of other factors of production to explain residuals, but this is beyond the scope of this paper.

Values of the variables for this solution are listed in Table 6. Differences in equivalent efficiency between fuels reflects the aggregated productivity variation between fuels with *energy quality* related factors such as conversion and associated losses, competitiveness of end-use industries, EPR, elasticity of substitution, scarcity rent, and so on included. Although segregation of these factors is outside the scope of this paper, it should be noted that efficiencies in excess of 0.5 in heat engines are not considered practically achievable on a large scale with current technology and material constraints. The efficiency
improvement trends in Fig. 17 (approaching 0.7 and beyond in the long-term) may therefore break down over the next few decades.

The solution is not valid on a country level because of differences in fuel mix, end-use and trade in energy intensive commodities and manufactured goods. A country level solution can be obtained by calculating the variables in Table 6 from country specific data.

**Table 6. Numerical values for solution to Eq. 12**

<table>
<thead>
<tr>
<th></th>
<th>Coal</th>
<th>Gas</th>
<th>Oil</th>
<th>Nuclear</th>
<th>Renewable</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_0$</td>
<td>0.173</td>
<td>0.075</td>
<td>0.110</td>
<td>0.000</td>
<td>0.655</td>
</tr>
<tr>
<td>$\mu_1$</td>
<td>0.148</td>
<td>0.700</td>
<td>0.560</td>
<td>0.700</td>
<td>0.113</td>
</tr>
<tr>
<td>$C$</td>
<td>0.004</td>
<td>0.050</td>
<td>0.050</td>
<td>0.050</td>
<td>0.017</td>
</tr>
<tr>
<td>$t_0$</td>
<td>1883</td>
<td>2014</td>
<td>2020</td>
<td>2020</td>
<td>1948</td>
</tr>
<tr>
<td>$A_0$</td>
<td>105 045</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\alpha$</td>
<td>5.43E-4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 18 shows a plot of the modelling results against GWP data with backward extrapolation to 1900. The regression coefficient, $R^2$, of the fit equals 0.9989 for the 1950 to 2006 period.

**Fig. 18. Graph of actual and modelled GWP.** [Source data: GDP from 1900 to 1945 interpolated from Maddison (2008); GDP from 1950 to 2003 from Maddison (2008); GDP from 2004 to 2006 from The Conference Board (2008).]
10. Energy-Economic Projections

The energy consumption case, considered for greenhouse gas emissions, assumes that the maximum technical rate at which energy is available is based on the assessments in Sections 3 to 7 above. The sum of energy projections across all sources considered is used as the *Energy Reference Case* (ERC) for further assessment.

The dynamics of capital formation in a sustained energy scarcity scenario (relative to 20th century equilibrium conditions) is unprecedented and there is no unified theory with which to explicitly describe its impact on economic growth. Three cases are derived for this assessment, based on the impact of capital formation relative to balanced growth trends established in the 20th century and beyond. Trends in socio-economics, politics and human behaviour are assumed as imbedded in the balanced growth metrics.

For the purposes of this assessment, the following assumptions are made for conditions that lead to a fundamental deviation from balanced growth, such as energy constraints:

- Financial markets remain functional.
- State legitimacy remains intact in most countries.
- International law prevails.

It is plausible that some of these assumptions are overoptimistic, but they are considered as a meaningful basis for assessment. The three cases considered for assessment are differentiated by the degree to which capital formation competes with consumption, a dynamic that is largely dependent on human behaviour and which is not possible to explicitly quantify. The trends in Fig. 19 are used as a basis to derive the cases.

GWP-AU represents *Gross World Product* (GWP) in a Business As Usual (BAU) case where the basis for BAU is formed by the average trend from 1970 to 2006. The average rate of growth in GWP from 1969 to 2006, calculated from the data in Fig. 18, is 0.0352 (3.52%) per annum. This growth rate gives an exponential growth function as expressed in (13) and shown in Fig. 19.

\[ \text{GWP-AU} = 1.3105 \times 10^7 e^{0.03515(t-1969)} \tag{13} \]

with \( t \) as time in years.
Fig. 19. Economic growth trends.
* GWP-AU is GWP in a business as usual (BAU) case.
** CC-AU gives a BAU breakdown between Capital formation and Consumption.
*** GDP-EC is the GWP as calculated under Energy Constrained conditions in accordance with (10).

Capital formation and consumption are based on the global savings rate as a percentage of GWP (IMF, 2008). The global savings rate averaged 22% of GWP with a minimum of 20% and a maximum of 24% between 1981 and 2007. Jones (2002, 14) presents it as a stylised fact that the ratio of K/Y has been constant in the USA over the last century. Gross capital formation of 22% is assumed as an equilibrium rate that allowed the growth regime (in terms of energy consumption and economic output) experienced over the last number of decades. The CC-AU curve is extrapolated in relation to the GWP-AU by the exponential fit in (14).

\[ \text{CC-AU} = 2.883 \times 10^6 e^{0.03515(t-1969)} \]  

(14)

As mentioned before, the dynamics involved in a fundamental change from the historic growth regime depends on a number of behavioural aspects. Three economic regimes are therefore proposed as follows.

Eq. (10) has constant returns to scale with respect to TPES if equally distributed across energy sources (summation factor in Eq. (10)). Based on the constant economic growth rate and the constant capital formation rate as a percentage of economic growth, the conditions of balanced growth are met with the result that \( \frac{K}{Y} = \beta \) where \( \beta \) is a constant (Jones, 2002: 37). With \( \frac{K}{Y} \) as a constant, \( Y_{i+1}/Y_i = \)
\(K_{i+1}/K_i\), where the subscript \(i\) denotes the year of assessment. Consider (8) applied in a time stepping procedure as follows.

\[
K_{i+1} = K_i + \rho_i Y_i - \delta K_i = K_i (1 - \delta) + \rho_i Y_i
\]

\[
\therefore \frac{K_{i+1}}{K_i} = \frac{Y_{i+1}}{Y_i} = \frac{K_i (1 - \delta) + \rho_i Y_i}{K_i} = (1 - \delta) + \frac{\rho_i Y_i}{K_i} = (1 - \delta) + \frac{\rho_i}{\beta} \tag{15}
\]

The constant \(\beta = K_{i+1}/Y_{i+1} = K_i/Y_i\) is calculated as 0.197 from (15) by considering a constant depreciation rate of 2%, an investment rate of 22% and the average GWP growth rate of 3.52% between 1970 and 2006.

Based on the above, (16) is used in a time stepping procedure to calculate changes in capital and GWP growth in a capital constrained regime. When investment is zero, capital, economic output and quantities of energy consumption are assumed to decline at the depreciation rate as research stagnates and technology breakthroughs required for improved efficiency arrest.

\[
Y_{i+1} = \left(1 - \delta\right) + \frac{\rho_i}{\beta} Y_i \tag{16}
\]

As mentioned before, the cases considered are differentiated by the degree and rate at which capital formation is eroded. The actual GWP is assumed as the minimum between Eq. (10) (energy constrained growth) and Eq. (16) (capital constrained growth). The initial constraint is an energy constraint, but there is still sufficient capital available to fully exploit the declining available energy. As economic output declines, excess production declines together with savings and investment so that capital eventually becomes a constraint. Three economic regimes are considered as follows with reference to Fig. 19:

**Low:** The deficit in economic output, with respect to historical equilibrium, is fully absorbed by a decline in capital formation.

**Reference:** The decline in economic output is divided equally between declining consumption and declining capital formation.

**High:** The capital-output ratio, \(K/Y\), remains constant, which implies that the deficit is accounted for by declining consumption. This case assumes that capital formation keeps pace with available energy so that the ERC is fully utilised.
The *High* case is considered as optimistic because of the substantial research and development as well as the higher capital expenditure (compared to historical fossil fuel utilisation) required in nuclear and renewable technologies.

Time series trends for the three cases are presented in Fig. 20 and Fig. 21. It is assumed in this analysis that the UN (2006) population projection stabilizes by 2050 and remains unchanged to 2100.

![Fig. 20. Model results of economic output in 1990 PPP dollars](image)

![Fig. 21. Model results of GWP per capita in 1990 PPP dollars. [Source data: Population, (UN, 2006)].](image)
The *High* case has the best long-term outcome, in terms of economic welfare, and is the only case with a stabilising feedback, but demands an early compromise in redirecting output from consumption to capital formation. Once capital is eroded, it is not considered plausible for the global economy to recover in the light of declining energy availability and a growing global population with increasing consumer needs. The capital demands for the *High* case may in fact be underestimated because of declining EPR in fossil fuel and the higher energy cost, parameter $\xi$ in (10), of nuclear and renewable energy relative to fossil fuel.

Fig. 22 shows *Total Primary Energy Supply* (TPES) for the three cases compared to the maximum technical availability of energy. Although the high resource coal case, *Coal Plus*, in Fig. 13 is not necessarily considered as technically plausible, it is presented in Fig. 22 for comparison. The open squares show the contribution of fossil fuel to TPES in the *Energy Reference Case*.

![Graph showing TPES trends to 2100 in EJ.](image)

**Fig. 22. Primary Energy Supply (PES) trends to 2100 in EJ.**

It is not considered plausible for the *Low* and *Reference* trends in Fig. 21 to continue without a breakdown in some of the assumptions regarding financial markets, state legitimacy and international law. It is further considered as unlikely for the current Western economic paradigm to be sustainable in any of the three cases considered.

The model shows a continuation in the decoupling effect between GWP and TPES discussed earlier. Although the long-term trends in efficiency improvement
(Fig. 17) results in significant decoupling over time (Fig. 23), the degree of decoupling may be overestimated in light of the technology improvements required.

![Chart showing Global Energy and GDP Trends](chart.png)

**Fig. 23.** Global Energy and GDP Trends (After Cleveland, 2000). [Source data: GDP from 1950 to 2003 (Maddison, 2008); GDP from 2004 to 2006 (The Conference Board, 2008); Energy – see tables 1 to 3 and 5 for oil, gas, coal and renewables; nuclear data (BP,2007)]
11. Global Warming

The IPCC concludes in the *Fourth Assessment Report* (AR4) that "Most of the observed increase in global average temperatures since the mid-20th century is very likely [>90%] due to the observed increase in anthropogenic greenhouse gas concentrations" (IPCC, 2007b: 10). Projections of future warming and its consequences depend on several factors, including the future emission rates of anthropogenic greenhouse gases, of which CO₂ from the burning of fossil fuel is the most important.

The remainder of this paper interprets the knowledge base on global warming, compiled by the IPCC in AR4, in the context of available fossil fuel and the ability of the current economic paradigm to utilise it in energy applications.

The simplest model for global mean surface temperature is based on climate sensitivity with respect to radiative forcing (IPCC, 2001: 353-355). The relationship between parameters is expressed in (17):

\[ \Delta T_s = \lambda \Delta F = \lambda \text{RF} \]  

(17)

where \( \Delta T_s \) is the mean surface temperature response, \( \lambda \) is the climate sensitivity parameter, \( \Delta F \) is the *Radiative Forcing* (RF). Although the radiative forcing model lacks the ability to resolve spatially inhomogeneous effects, it is a good estimator for climate response and yields comparative results with most sophisticated global circulation models (GCMs) (IPCC, 2007a: 133; Hansen and Sato, 2004: 16109).

*Radiative Forcing* (RF) represents externally imposed perturbations on the Earth’s energy budget, as attributed to the combined effect from various causes (Table 7).

### Table 7. Radiative forcing contributors. (IPCC, 2007a: 136, 141)

<table>
<thead>
<tr>
<th>Forcing Agent</th>
<th>Radiative Forcing [W m⁻²]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean**</td>
</tr>
<tr>
<td><em>CO₂</em></td>
<td>1.66</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.48</td>
</tr>
<tr>
<td>N₂O</td>
<td>0.16</td>
</tr>
<tr>
<td>Halocarbons</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>------------------------------</td>
<td>---</td>
</tr>
<tr>
<td>Tropospheric ozone</td>
<td>0.35</td>
</tr>
<tr>
<td>Stratospheric ozone</td>
<td>-0.05</td>
</tr>
<tr>
<td>Stratospheric water vapour</td>
<td>0.07</td>
</tr>
<tr>
<td>*Black carbon on snow</td>
<td>0.10</td>
</tr>
<tr>
<td>Land use albedo</td>
<td>-0.20</td>
</tr>
<tr>
<td>*Aerosol (direct)</td>
<td>-0.50</td>
</tr>
<tr>
<td>*Aerosol (albedo)</td>
<td>-0.70</td>
</tr>
<tr>
<td>Contrails</td>
<td>0.01</td>
</tr>
<tr>
<td>Solar irradiance</td>
<td>0.12</td>
</tr>
<tr>
<td>Total</td>
<td>1.84</td>
</tr>
<tr>
<td>Total anthropogenic</td>
<td>1.72</td>
</tr>
</tbody>
</table>

* Caused predominantly by the burning of fossil fuel.
** The confidence intervals are not symmetric.

Although the burning of fossil fuel is generally seen as the dominant driver of climate change because of the high RF caused by the build-up of CO₂, other fossil fuel products have negative RF as shown in Table 7. For this reason, some researchers argue that most of the observed global warming is driven by non-CO₂ gases (fossil RF) (Hansen et al., 2000; Wigley, 1991). In later work Hansen et al. (2007) caution that some of the RF effects of aerosols may be highly non-linear, but confirm their (Hansen et al.) 2000 assessment.

The negative forcing caused by aerosol emissions from the burning of fossil fuel is of particular importance because, while CO₂ is a long-lived greenhouse gas (mean residence time in the atmosphere of decades), aerosols are short-lived species (mean residence times in the troposphere of days or weeks). Reduction or cessation of fossil fuel burning and associated aerosols would lead to a rapid reduction in aerosol-induced forcing and a prompt increase in positive radiative forcing.

Based on the above, a simple radiative forcing model is used to assess mean global surface temperature for the three cases in Fig. 21. Although the model offers no spatial resolution, it is considered adequate for the purpose of this assessment. The following additional assumptions are made in the model:

- Linearity is assumed in the Radiative Forcing (RF) response relationship. The IPCC reports that linearity has been demonstrated for global response (IPCC,
No efficacy factors are used because the contributions of indirect effects are directly included.

- The climate sensitivity parameter, $\lambda$, is 0.413, based on a temperature increase of 0.76 °C (IPCC, 2007c: 36) and a RF of 1.84 W/m² (Table 7).

- CO$_2$ emissions from land use are assumed to be constant at 1 GtC per year. There is considerable uncertainty on land use emissions, but it is recognised that most emissions are the result of changing land use, such as deforestation, and would not be sustained. For this reason, all the IPCC scenarios assume declining CO$_2$ emissions from land use (IPCC, 2000).

- CO$_2$ emissions from the burning of fossil fuel correspond to the conversion factors in Table 8.

**Table 8. Emission rates for fossil fuel (Marland and Boden, not dated).**

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Emission Rate Kg C / GJ Heat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas</td>
<td>13.78</td>
</tr>
<tr>
<td>Petroleum</td>
<td>19.94</td>
</tr>
<tr>
<td>Hard Coal</td>
<td>24.15</td>
</tr>
<tr>
<td>Lignite and Brown Coal</td>
<td>25.22</td>
</tr>
<tr>
<td>Coal Average</td>
<td>24.69</td>
</tr>
</tbody>
</table>

- The atmospheric concentration of CO$_2$ increases by 1 part per million (ppm) for every 2.12 GtC (7.8 Gt CO$_2$) of airborne CO$_2$ (IPCC, 2007a: 516; Kharecha and Hansen, 2008: 3).

- The biosphere and oceans absorb a large portion of CO$_2$ emissions, referred to as CO$_2$$_{abs}$. Hansen and Sato (2004: 16111) demonstrated a correlation between CO$_2$$_{abs}$ and the following key parameters:
  - The equilibrium concentration of atmospheric CO$_2$ for a given global temperature, $C_{eq}$. $C_{eq}$ increases linearly by 18 ppm per °C and can be calculated from a pre-industrial equilibrium in 1850 of 278 ppm (IPCC, 2007a: 140).
The excess or out-of-equilibrium CO$_2$ in the atmosphere, $\Delta C$, with

$\Delta C = C_{\text{Actual}} - C_{\text{eq}}$

Despite large inter-annual variations, the ratio of CO$_2$$_{\text{abs}}$/ΔCO$_2$ converges to a constant, A, when averaged over time (Hansen and Sato, 2004: 16111). Based on the above, CO$_2$$_{\text{abs}}$ is derived from CO$_2$ emissions (fossil fuel emissions plus 1 GtC per year for land use) and average annual atmospheric concentrations (Fig. 24). The trend in Fig. 24 is assumed valid for atmospheric concentrations of up to 600 ppm, based on Fung et al. (2005) and a graphical interpretation of work by Joos et al. (2001: 900).

The functional relationship for the absorption model is given in (18). The value of A for the linear regression curve in Fig. 24 is 0.03. A sensitivity analysis is performed by considering a lower curve with $A = 0.022$, which reduces CO$_2$$_{\text{abs}}$ by a factor of almost 2/3 compared to empirical data. The value of 0.022 was chosen to match the atmospheric CO$_2$ concentration of the Bern cycle in 2006 as will be discussed later. The two models are referenced as AH(0.03) and AL(0.022). Some of the large deviations, such as the 1998 data point (Fig. 24) can be attributed to specific events such as extensive wildfires coupled with El Niño (IPCC, 2007a: 526).

$$CO_2_{\text{abs}} = A \times (\Delta CO_2)$$

(18)

Fig. 24. Empirical data of CO$_2$$_{\text{abs}}$ against $\Delta CO_2$. [Source data for atmospheric CO$_2$ measured at Mauna Loa from NOAA (2008)].
The Mauna Loa annual average measurements of atmospheric CO$_2$ concentration closely resemble global averages (NOAA, 2008). The Mauna Loa dataset is used because it covers the longest available measurement history.

The efficiency of terrestrial sinks to absorb CO$_2$ is not negatively affected at these moderate levels of atmospheric concentrations as implied by the Bern carbon cycle, used in most IPCC AR4 models (IPCC, 2007a: 213, 790), and by Kharecha and Hansen (2008) as shown in Fig. 24. The Bern carbon cycle model (19) is cumulative with respect to carbon emissions by inducing irreversible atmospheric concentrations at all levels, even for infinite timescales, as shown in Fig. 25. The relationship between excess CO$_2$ and CO$_2_{abs}$, observed by Hansen and Sato (2004) has significant intuitive merits for low to moderate levels of excess CO$_2$ compared to the Bern cycle model.

\[
CF = 0.217 + 0.259e^{-172.9t} + 0.338e^{-18.51t} + 0.186e^{-1.186t}
\]  

(19)

with CF as the remaining airborne fraction of CO$_2$ after time, $t$.

![Fig. 25. Pulse response function for 1 GtC emissions from C$_{eq}$ of the model proposed in this paper compared to the Bern carbon cycle.](image)

- Atmospheric concentrations of N$_2$O increase linearly (IPCC, 2007a: 131). The rate of increase was calculated as 0.685 ppb per year from a base of 319 ppb in 2005 from NOAA (2008) data.
• The RF from CH$_4$ is based on NOAA (2008) data on measured trends in atmospheric CH$_4$ concentrations. Although concentrations are declining, the reasons are not well understood (IPCC, 2007a: 131) and CH$_4$ concentration is assumed to remain constant over the assessment period. RF from stratospheric water vapour, caused by the oxidation of CH$_4$ is also assumed to remain constant.

• The RF from halocarbons is assumed to remain constant. Montreal protocol gas concentrations peaked in 2003 and concentrations are decreasing (IPCC, 2007a: 131), but other sources are emerging.

• Although the primary cause of RF from changes to stratospheric ozone is Montreal protocol gas species, of which concentrations are decreasing, stratospheric ozone is assumed to remain constant over the assessment period.

• RF from tropospheric ozone is assumed to remain constant since there is large uncertainty regarding the magnitude, sign and causes of projections (IPCC, 2007a: 150).

• Solar and ozone RF are introduced linearly over a period of 30 years from 1976 to 2006.

• It is considered acceptable to neglect the RF contributions from land use albedo and contrails, given the minor size and the uncertainties of these forcings.

• The RF from aerosols (-1.2 W/m$^2$) and black carbon (+0.1 W/m$^2$) are assumed proportional to carbon emissions, based on the assumption that all aerosols are either directly linked to the burning of fossil fuel or indirectly by economic activity, which have constant return to scale with respect to energy consumption. Using 2006 as a base year, $RF_F = -1.1 \frac{E_y}{E_{2006}}$, where $RF_F$ is the combined effect of aerosols and black carbon, E is the quantity of carbon emissions from fossil fuel in GtC, and y is the year of calculation.

• Recent publications still express considerable uncertainty about solar irradiance changes (Joos and Spahni, 2008). For this reason, the RF value of 0.12 W/m$^2$ used by the IPCC is assumed to remain constant.
RF for atmospheric concentrations CO$_2$, CH$_4$ and N$_2$O is calculated in accordance with equations (20) to (22) (IPCC, 2001; 358; NOAA, 2008)

\[
RF(\text{CO}_2) = 5.35 \ln \left( \frac{C}{C_0} \right)
\]

\[
RF(\text{CH}_4) = 0.036 \left( \sqrt{M} - \sqrt{M_0} \right) - \left[ f(M, N_0) - f(M_0, N_0) \right]
\]

\[
RF(\text{N}_2\text{O}) = 0.12 \left( \sqrt{N} - \sqrt{N_0} \right) - \left[ f(M_0, N) - f(M_0, N_0) \right]
\]

where atmospheric concentrations of CO$_2$, CH$_4$ and N$_2$O are expressed as C, M and N respectively. The subscript, 0, denotes a reference level. Reference levels are 278 ppm, 700 ppb and 270 ppb for C$_0$, M$_0$ and N$_0$ respectively (NOAA, 2008). The function f is defined in (23).

\[
f(M, N) = 0.47 \ln \left[ 1 + 2.01 \times 10^{-5} (MN)^{0.75} + 5.31 \times 10^{-15} M(MN)^{1.52} \right]
\]

The modelling assumptions described in this section were applied to the three cases in Fig. 21, assuming that reductions in energy consumption relative to the High case are proportionally distributed between energy sources.
12. Carbon Emissions and Climate Response

The 0th-order climate model used here is seen as representative of existing knowledge because of the considerable uncertainty expressed by the IPCC for the various *Radiative Forcing* (RF) components (IPCC, 2007a: 203). The model predicts a weaker climate response for comparative emissions scenarios because of the carbon cycle model used. Observations and modelling results (Fung et al., 2005; Joos et al., 2001), nominally support the proportional relationship, observed by Hansen and Sato (2004: 16111) and used here, for CO₂ concentrations below 600 ppm.

The *High* case of fossil fuel consumption is based on the *Energy Reference Case* (Fig. 23) and conforms approximately to the IPCC B1 scenario (IPCC, 2000). The *High* case is used as a benchmark for the maximum achievable climate change response. Modelling results for the B1 scenario predict a mean global surface temperature anomaly of between 1.25 and 2.25 °C in 2100, relative to 1980 to 2000 average temperature record, for various models (IPCC, 2007a: 803).

The performance of the three carbon response models, AH(0.03), AL(0.022) and Bern, are shown against empirical atmospheric CO₂ in Fig. 26. The AH(0.03) model gives the best fit to measured data while the Bern and the AL(0.022) models both underestimate the absorption of CO₂ by terrestrial sinks and hence overestimate the atmospheric concentration of CO₂.
Fig. 26: Modelled atmospheric concentration of CO$_2$ against measured data and calculated carbon emissions. [Source data for measured atmospheric CO$_2$ from (NOAA, 2008)]. Atmospheric CO$_2$ projections, based on a modelling run from 1900 with non-fossil fuel emission of 0.5 GtC from 1900 to 1950 and 1 GtC from 1950 forward, are shown in Fig. 26. The Coal Plus scenario, based on the AH(0.03) model, is superimposed for comparison. The Bern carbon cycle produces comparable results to the B1 scenario (IPCC, 2007a: 803). An important variable in future climate change is the time that warming is sustained at high temperatures because of slow feedback effects as the deep ocean and ice sheets are affected. Atmospheric CO$_2$ is reduced to below 350 ppm by 2200 in the AH(0.03) model.

![Fig. 26: Modelled atmospheric concentration of CO$_2$ against measured data and calculated carbon emissions.](image)

Fig. 27: Temperature anomalies relative to 1980 to 2000 average temperatures. Mean surface temperature anomalies relative to the 1980 to 2000 average are shown in Fig. 27. Temperature increases are relative to 2000, with an anomaly of approximately 0.25 °C in accordance with IPCC (2007a: 803). All cases, except for the Bern carbon cycle, have peak anomalies below 1 °C. Although the Bern carbon cycle produces a slightly lower temperature anomaly to the B1 scenario, comparison of RF and temperature response trends to other scenarios shows that it can apparently be attributed to a higher climate sensitivity used for the B1 scenario by IPCC (2007a: 803).

Kharecha and Hansen (2008: 9) discuss the “…avoidance of dangerous anthropogenic climate change” and conclude that additional warming beyond
2000 should be limited to 1 °C and that this can be achieved by limiting CO₂ concentration to 450 ppm. Based on this assessment, these levels would not be reached if fossil fuel resources were exploited at their full technical potential.

Global warming mitigation strategies are beyond the scope of this paper. It is, however, important to note that Carbon Capture and Storage (CCS) has a significant energy cost (MIT, 2007) that would inversely impact on the energy efficiency trends shown in Fig. 18 and consequently on the future availability of energy for use in the economy.
13. Summary and Conclusion

An *Energy Reference Case* for the future availability of energy resources is derived by considering logistics analysis of fossil fuel reserves and institutional intelligence on nuclear and renewable energy. Although the methodology used for resource assessment is endorsed by the *World Energy Council*, the validity of the approach is further demonstrated by means of examples. The *Energy Reference Case* differs substantially from some institutional scenarios (such as developed by the *International Energy Agency*) because of production rate constraints imposed by the logistics approach.

The logistics approach followed provides some merits for the inclusion of a high resource case for coal that overestimates official reserves by 64%. The high coal case, referenced as *Coal Plus*, is included in the assessment to point out sensitivities to variations in the energy and emissions cases. The *Energy Reference Case* is deemed optimistic since the methodology overestimates official reserves by approximately 25% for all fossil fuel reserves. It is, however, not unusual for reserves to grow with time. Despite these apparent inconsistencies, the *Energy Reference Case* is considered as a valid benchmark for analysis of economic growth and *Global Warming*.

The economic impact of the *Energy Reference Case* is a significant divergence from 20th century equilibrium growth conditions. Stabilisation of human welfare is only achieved under optimistic assumptions with respect to technology change and human behaviour, demanding a paradigm shift in contemporary economic thought.

The technological assumptions for the *High* case, that assumes full utilisation of the *Energy Reference Case*, are not tangible with today’s knowledge and considerable research and investment of productive resources will be required to develop a sustainable nuclear future, to incrementally develop renewable energy capacity, to offset declining *Energy Profit Ratios* and to improve the efficiency with which energy is converted and utilised.

In light of the above, the energy cost of *Carbon Capture and Storage* may be unaffordable. The authors propose that productive resources, currently directed towards *Carbon Capture and Storage*, may be better utilised to design a sustainable energy future by focussing on issues such as energy efficiency, advanced nuclear fuel cycles, incremental expansion of renewable energy,
sustainable lifestyles, sustainable metropolitan infrastructure, sustainable agriculture and so on.

The nature of human behavioural challenges is considered by the authors to have “tragedy of the commons” characteristics, a phenomenon for which Hardin (1968) argues there are no technical solutions. Significant redesign of the contemporary economic paradigm, possibly by coercive means, may be required to enable a smooth transition to a non-fossil energy future. Hardin argues that society may voluntarily accept coercive practices if it is clear that such practices are in common interest. In this regard, academic discourse on the issues identified in this paper is of critical importance.

Ethical issues regarding equitable distribution of natural capital and burden sharing rules in a resource-constrained world are beyond the scope of this paper. For this reason, this assessment and its conclusions are strictly in a global context and should not be considered as valid in a national or regional context.

Based on the Energy Reference Case, a maximum global average surface temperature response of less than 1°C above 2000 levels is predicted if all the recoverable fossil fuel reserves were combusted without mitigation of CO₂ emissions. Modelling parameters that are compliant with the IPCC models predicts a maximum temperature response of 1.5°C, consistent with IPCC results, but it is argued that these are not valid for the low-emissions scenarios considered here because of the cumulative properties of the Bern carbon cycle in the IPCC models. An alternative carbon cycle is calibrated to empirical data and yields a temperature response of less than 1°C which is regarded as acceptable within the current climate change debate - up to 2°C is accepted by some institutional authorities (European Commission, 2007).

The impact of 1°C in global warming should, however, not be trivialised and may still require considerable adaptation to minimise environmental and socio-economic impacts. For this reason, the conclusion regarding an acceptable temperature response from emissions in the Energy Reference Case is considered as subjective even though it is supported in the Global Warming debate.

This assessment confirms a number of synergies in mitigation strategies for Global Warming and Energy Security. Although energy efficiency is of primary importance, it must be supported by behavioural changes that bring about energy
conservation. Directing the proceeds of energy efficiency towards consumption would lead to undesired erosion of capital in an energy-constrained future and increase the probability of a partial collapse in modern society.

Our analysis indicates that if constraints are placed on the availability of fossil fuel reserves and an alternative to the Bern carbon cycle used, the predicted extent of global warming is changed to a relatively low temperature increase. This highlights the necessity when undertaking climate change modelling to not only reflect the impact of increased emissions, but to also have realistic input data concerning the extent to which fossil fuel reserves will continue to be exploited in the future.

It is acknowledged that as technological changes occur and as new information is obtained the empirical bases of this assessment is likely to change. In this context, it is prudent to assume realistic constraints when undertaking modelling exercises at a global level.

In conclusion, our analysis indicates that the extent of Global Warming, analysed in the context of the Energy Reference Case is considered acceptable in the current climate change debate. Our analysis proposes that the extent of Global Warming may be acceptable and preferable when compared to the socio-economic consequences of not exploiting fossil fuel reserves to their full technical potential.
14. References


under the Intergovernmental Panel on Climate Change (IPCC) emission scenarios. Global Biochemical Cycles 15 (4), 891-907.


