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Depletion of fossil fuels and anthropogenic climate change—A review

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H I G H L I G H T S

- ► Review of the development of emission scenarios.
- ► Survey of future fossil fuel trajectories used by the IPCC emission scenarios.
- ► Discussions on energy transitions in the light of oil depletion.
- ► Review of earlier studies of future climate change and fossil fuel limitations.

A R T I C L E I N F O

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A B S T R A C T

Future scenarios with significant anthropogenic climate change also display large increases in world production of fossil fuels, the principal CO_2 emission source. Meanwhile, fossil fuel depletion has also been identified as a future challenge. This chapter reviews the connection between these two issues and concludes that limits to availability of fossil fuels will set a limit for mankind's ability to affect the climate. However, this limit is unclear as various studies have reached quite different conclusions regarding future atmospheric CO_2 concentrations caused by fossil fuel limitations.

It is concluded that the current set of emission scenarios used by the IPCC and others is perforated by optimistic expectations on future fossil fuel production that are improbable or even unrealistic. The current situation, where climate models largely rely on emission scenarios detached from the reality of supply and its inherent problems are problematic. In fact, it may even mislead planners and politicians into making decisions that mitigate one problem but make the other one worse. It is important to understand that the fossil energy problem and the anthropogenic climate change problem are tightly connected and need to be treated as two interwoven challenges necessitating a holistic solution.

1. Introduction

Mankind's energy production is the principal contributor to mankind's release of greenhouse gases (GHG), in particular CO_2, to the atmosphere with fossil fuel combustion as the key factor. As a result, anthropogenic GHG emissions and human-induced global warming are fundamentally linked to future energy production. Projections of how the global energy system will develop over the next century are cornerstones in the assessment of future climate change caused by mankind.

The Intergovernmental Panel on Climate Change (IPCC) and many others use climate models that rely on various emission scenarios to depict possible trajectories for future fossil fuel production and their correlating release of CO_2. The Special Report on Emission Scenarios (SRES) (the current set of emission scenarios) was published by the IPCC in 2000 and remains an integral part of climate change modeling, as it has been used by the last IPCC reports (IPCC, 2001, 2007).

As of 2010, world oil production remains around 85 million barrels per day (Mb/d) or 3900 million tons of oil equivalents (Mtoe) annually, with coal and natural gas at 3700 corresponding to 2900 Mtoe per year (BP, 2012). Some scenarios foresee a tenfold increase in world gas production, while others depict future oil production to reach 300 Mb/d by 2100. For example, 16 of the 40 coal scenarios contained in SRES simply grow exponentially until the year 2100 (Patzek and Croft, 2010). Emission scenarios also contain assumptions about future prices, technological developments and many other details related to fossil energy exploitation.

This article reviews the emission scenarios witnessed throughout history, their underlying assumptions on resource availability and future production expectations. Future scenarios with high emissions of CO_2 also display significant increases in world production of oil, natural gas and coal. Can such assumptions

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Table 1
Model names in SRES and developing team behind them.

Abbreviation	Full name	Origin
AIM	Asian Pacific Integrated Model	National Institute of Environmental Studies (NIES), Japan
ASF	Atmospheric Stabilization Framework Model	ICF Consulting, USA
IMAGE	Integrated Model to Assess the Greenhouse Effect	National Institute for Public Health and Hygiene (RIVM), Netherlands
MARIA	Multiregional Approach for Resource and Industry Allocation	Science University of Tokyo, Japan
MESSAGE	Model of Energy Supply Strategy Alternatives and their General Environmental Impact	International Institute of Applied Systems Analysis (IIASA), Austria
MINICAM	The Mini Climate Assessment Model	Pacific Northwest National Laboratory (PNNL), USA

remain justified in the light of the growing body of evidence suggesting that depletion of the world fossil energy resources, primarily oil, is a growing problem? In addition, published critique raised against the fossil fuel projections used by the IPCC is reviewed. Finally, this study compiles recent studies on how fossil fuel constraints may impact anthropogenic climate changes.

1.1. Historical background to anthropogenic climate change

The Swedish Nobel prize laureate Arrhenius (1896) was among the first to theorize about the impact of CO_2 on the earth's climate. However, these ideas were initially met with criticism and fell into obscurity until around the 1950s. Growing concern about mankind's increasing impact on the environment and refined analytical methods revitalized the issue of greenhouse gases after the 1950s. Separate threads of research were pursued by isolated groups of scientists, although an increasing number of studies pointed towards a connection between global warming and anthropogenic emissions of greenhouse gases (Peterson et al., 2008). Mainstream media and politicians largely ignored these results and only expressed concern over these findings much later.

In the 1980s, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) began to investigate the role of carbon dioxide and other emissions. Their interest leads to the establishment of the IPCC in 1988. This new organization became responsible for assessing scientific, technical and socio-economic information relevant for understanding mankind's role in climate change. Their synthesized results have been published in several assessments and special reports over the years (IPCC, 1990, 1995, 2001, 2007). However, these findings are also largely dependent upon a set of assumed trajectories for future fossil fuel production and related emissions.

Various future pathways for society, its energy system and the associated release of greenhouse gases are a cornerstone in the estimation of future climate change. Such outlooks are commonly referred to as emission scenarios and are being used as input into climate models that transform the projected emissions into climatic changes. The IPCC has used a number of emission scenarios throughout its work. The first set was published in 1990, followed by subsequent publications in 1992 and the latest version from 2000. Titles, methods, classifications, assumptions have all changed over time and Girod et al. (2009) reviewed this in more detail.

The 1995 IPCC review of the old emission scenarios recommended that the full range of scenarios should be used as an input rather than just a single scenario. The conclusion was that there was no objective basis on which to assign likelihood to any of the scenarios (SRES, 2000). Meanwhile, a number of other weaknesses were also identified, such as the limited range of carbon intensities, the absence of a scenario with economic closure in the income gap between industrial and developing countries (SRES, 2000), or how the rapid growth in sulfur emissions did not reflect regional and local air quality concerns that might prompt limits

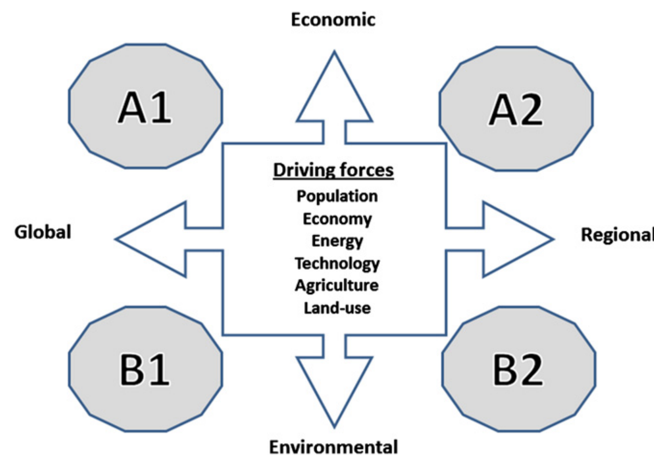

Fig. 1. Schematic illustration of the SRES scenarios with their driving forces and main orientations.

on the future release of sulfur into the atmosphere (Grübler, 1998).

In addition, it was found that all scenarios from 1992 exaggerated recent trends for climate and economic development, leading to correspondingly exaggerated atmospheric GHG concentrations (Gray, 1998). In 1996, the IPCC chose to develop new scenarios and initiated the painstaking process of developing a new set for utilization in future climate change assessments (Nakićenović et al., 1998). This resulted in the current emission scenario set – often known as the Special Report on Emission Scenarios (SRES) – being published in 2000. This report forms the foundation of most recent long-term climate change projections, including those of the Fourth Assessment Report (IPCC, 2007).

1.2. The special report on emission scenarios

The SRES writing teams outlined four different narratives to be used as storylines for the future. Six modeling teams (Table 1) generated quantifications of the narratives that laid the foundation of the 40 different scenarios contained in SRES. The scenarios can be divided into four families, each exploring different variants of global and regional development and their implications for global greenhouse gas emission. SRES storyline titles are simply named A1, A2, B1, and B2. They are characterized by global-regional focus and economic–environmental orientation and can be placed in a two-dimensional figure (Fig. 1). No scenario should be considered as a "*business-as-usual*", even though the A1 family is often used as an example of how continued global focus on economic growth might evolve. It is also imperative to emphasize that none of the scenarios contain additional climate initiatives such as GHG reduction schemes or adaptations to the expected climate change. No disaster scenarios were considered and possible surprises, such as new world wars or economic downturns, were also disregarded.

Table 2
Key features in different scenario families and groups. Adapted from SRES (2000).

Family	A1				A2	B1	B2
Subgroup	A1C	A1G	A1	A1T	A2	B1	B2
Population growth	Low	Low	Low	Low	High	Low	Medium
GDP growth	Very high	Very high	Very high	Very high	Medium	High	Medium
Energy use	Very high	Very high	Very high	High	High	Low	Medium
Land-use changes	Low to Medium	Low to Medium	Low	Low	Medium to High	High	Medium
Resource availability	High	High	Medium	Medium	Low	Low	Medium
Technological development	Rapid	Rapid	Rapid	Rapid	Slow	Medium	Medium
Change favouring	Coal	Oil & Gas	Balanced	Non-fossils	Regional	Efficiency	"Dynamics as usual"

Hjerpe and Linnér (2008) described this as utopian thought with built-in linear logic.

The future is described as significantly wealthier than the current world in each of the four main narratives and their corresponding scenario families. There has been a significant discussion around the use of Market Exchange Rates (MER) or Purchasing Power Parity (PPP) as it can lead to significant economic differences in the long time scales used. For example, McKibbin et al. (2007) quantifies that MER terms can result in more than 40% higher emission projections compared with using PPP figures. Castles and Henderson (2003), Tol (2006), and van Vuuren and O'Neill (2006) expand further on this topic.

Van Ruijven et al. (2008) confer the actual models and their underlying concepts. The simplified substitution-based concept known as the "*energy ladder*" is applied consistently, and so is also the environmental Kuznetz curve (a U-shaped relation between economic development and environmental impact). However, van Ruijven et al. (2008) also acknowledge that SRES relies on limited amount of socioeconomic and energy data when only depicting the world in four large regions, i.e. OECD90, Asia, Africa+Latin America, and the so called REF-region consisting of countries undergoing economic reform. With more regions and improved data, it is likely that the dynamics of real world development could be more accurately captured.

All scenarios belonging to the same family were qualitative and quantitative adjusted to match the features of the narrative storyline. Overall, harmonization of 26 scenarios made them share assumptions for global population and gross domestic product (GDP) growth (SRES, 2000; Sivertsson, 2004). Although the scenarios share a few basic assumptions, they can differ substantially in other aspects, such as availability of fossil-fuel resources, resulting GHG emissions, the rate of energy-efficiency improvements, and the extent of renewable energy development.

The remaining 14 scenarios are different versions of the narratives with alternate assumptions for economic and population growth projections. These variations reflect the modeling teams' choice as an alternative to the harmonized scenarios. Marker scenarios are another form of scenario, which is considered by the SRES writing team to be the most illustrative scenario of a particular storyline. SRES (2000) and Höök et al. (2010a) contains more detailed descriptions of the scenario families, even though the main qualities of each storyline can be found in Table 2.

1.3. Scenario probabilities in SRES

SRES (2000) presents 40 scenarios with different developments for the global energy system and the manmade greenhouse gas emissions. These scenarios are founded on literature reviews, development of emission narratives, and quantification of the narratives with the help of six integrated models from different countries. Four specific drivers for CO_2 emissions, namely population; economic activity (gross domestic product or GDP) per capita; energy intensity (primary energy consumption per unit of GDP); and carbon intensity (CO_2 emissions per unit of energy) are identified by the IPCC (Pielke et al., 2008). SRES illustrates that future emissions, even in the absence of any explicit environmental policies, very much depend on how economies and technologies are structured, the energy sources that are preferred and how people use available land area as well as the choices that people make.

IPCC claim that the scenarios "*represent pertinent, plausible, alternative futures*" and derive from a descriptive and open-ended methodology that aims to explore alternative futures (SRES, 2000). The emission scenarios are neither predictions nor forecasts, even though they are commonly used as such. In addition, no probabilities or likelihoods are assigned to any of scenarios since and all of them are considered equally plausible. This condition was a requirement made by the Terms of Reference (SRES, 2000).

The absence of likelihoods in SRES triggered critique (Schneider, 2001, 2002; Webster et al., 2003) highlighting that decision-makers and policy analysts necessitate probability estimates to be able to assess the risks of climate change impacts resulting from these scenarios. The SRES team (Grübler and Nakićenović, 2001) countered by claiming that social systems (important in emission scenarios) are fundamentally different from natural science systems and are largely dependent on the choices people make.

Morgan and Keith (2008) reviewed available findings on scenario analyses and uncertainty and found that the "*equal probability*"-approach often lead to systematic overconfidence and bias. Jones (2001) concluded that equally valid scenarios cannot be realistic, since the range is due to a combination of component ranges of uncertainty, and thus the extremes of this range must be less probable than the central estimate. It has also been argued that the equal probability of each emission scenario is a rather odd postulation and even may be seen as an attempt to assign unjustifiably high weight to extreme outcomes (Höök et al., 2010a; Patzek and Croft, 2010). Clearly, the way uncertainty is handled and the suitability of assigning subjective probabilities to scenarios is a matter of lively debate and an important, but unresolved challenge in the application of climate scenarios (Dessai et al., 2007; Groves and Lempert, 2007; Schenk and Lensink, 2007; van Vuuren et al., 2008; Lemos and Rood, 2010).

Emissions scenarios serve as input to various climate models, where the latter depict how the climate may change under various assumptions for future anthropogenic emissions. From society's perspective, some outcomes are certainly more desirable than others. However, the equal probability assumption can act as a potential obstacle. Planners and engineers, who need to make decisions based on the impacts of climate change, must have a grasp of the inherent uncertainties in the guiding projections as well as the probabilities of the different outcomes. Walsh et al. (2004) and Green et al. (2009) provide additional discussion regarding this.

2. Fossil fuels in the global energy system

Since the dawn of the industrial revolution, fossil fuels have been the driving force behind the industrialized world and its economic growth. Fossil energy has grown from insignificant

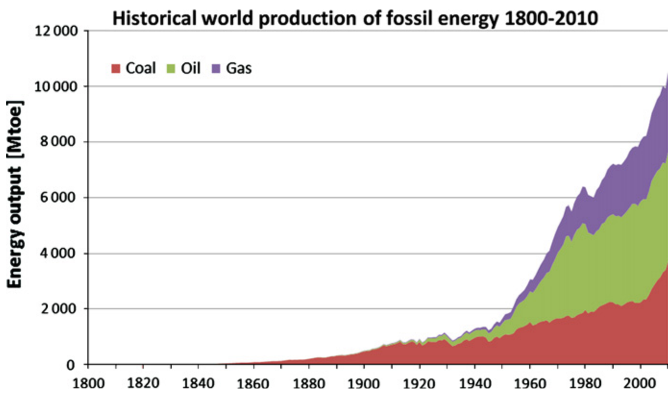

Fig. 2. Global production of fossil energy from 1800 to 2010. Adapted from Höök et al. (2012).

levels in 1800 to an annual output of nearly 10,000 million tons of oil equivalents (Fig. 2). At present, about 80% of all primary energy in the world is derived from fossil fuels with oil accounting for 32.8%, coal for 27.2% and natural gas for 20.9% (IEA, 2011). Combustible biomass and waste (10.2%), nuclear power (5.8%) and hydroelectric dams (2.3%) are the largest contributors to the global energy system after fossil energy, but they account for only a minor share of the global primary energy supply (IEA, 2011). Only 0.8% of the world's primary energy is derived from geothermal, wind, solar or other alternative energy sources. More specifically, wind power accounted for only 0.2% of the global primary energy supply with its 23 Mtoe contribution in while direct solar energy accounted for 0.1% with a 12 Mtoe output (SRREN, 2011).

2.1. Importance of future energy systems for emissions

Fossil fuels will remain the backbone of the world's energy system for all foreseeable time, given their present dominance. Furthermore, global reliance on fossil energy brings about an associated problem, namely associated emissions. In fact, energy production is the dominating source of CO_2 and other GHGs. Roughly 70% of all anthropogenic GHG emissions derive from the energy sector (Fig. 3), with the largest contribution made by CO_2 from fossil fuel combustion. In 2008, nearly 30 billion tons of CO_2 were emitted from fossil fuel consumption and this has doubled since 1970 (Fig. 4). Global warming and climate change caused by GHG emissions are strongly linked to fossil energy production and utilization. Consequently, examining likely and possible trajectories of the future energy systems are vital for understanding future climate change caused by mankind.

SRES (2000) contains a significant spread for future emissions (Fig. 5). It can be noted that these projections are notable smaller than IEAs historical CO_2 emission trends as seen in Fig. 4. It can be argued that SRES underestimated emission trends, but van Vuuren and O'Neill (2006) also show that global CO_2 inventories can differ by more than 15% depending on source and methodology. However, all studies agree that fossil fuel use is the most significant emission source.

There is a growing body of evidence indicating that there will be challenges with supplying enough fossil energy for continued growth of economies and related emissions. Energy insecurity, i.e. the welfare impact of either physical unavailability of energy or prices that are not competitive or are overly volatile, has often been identified as a major challenge for the world in the 21st century together with anthropogenic climate change (Curtis, 2007; McCartney et al., 2008; Moriarty and Honnery, 2009; Fantazzini et al., 2011). How are

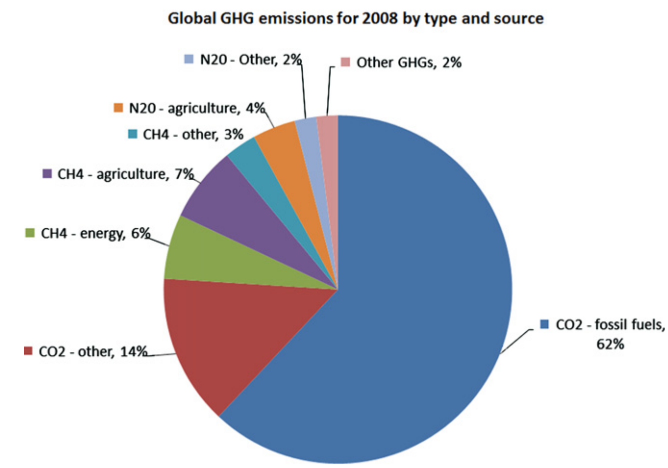

Fig. 3. Global anthropogenic GHG emissions by type and source. Data taken from IEA (2010).

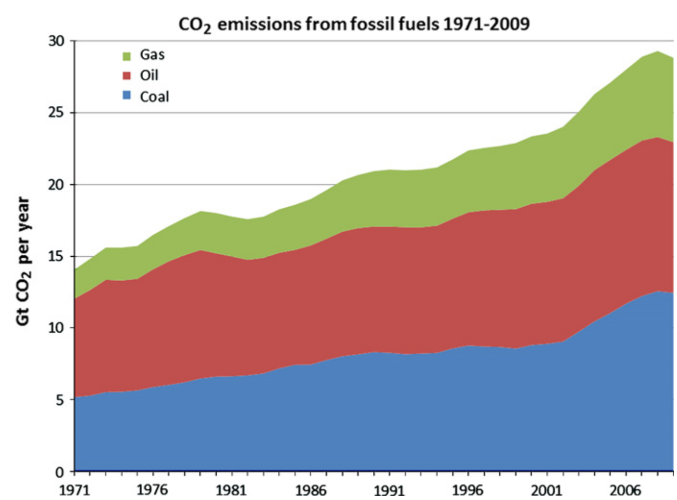

Fig. 4. CO_2 emission trends from 1971 to 2009 by fuel. Data taken from IEA (2010).

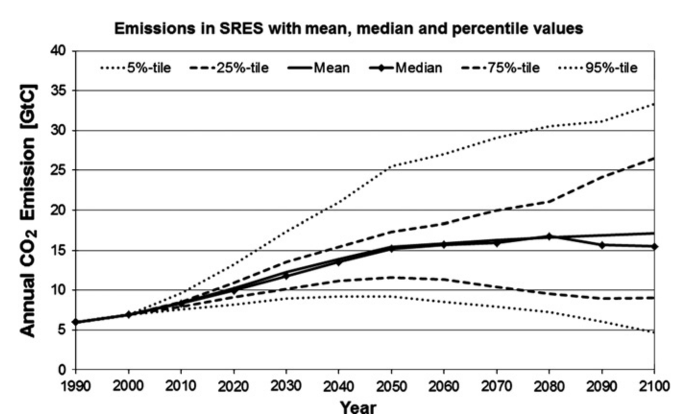

Fig. 5. CO_2 emission for the 40 SRES scenarios together with mean, median and percentiles. Adapted from Sivertsson (2004).

hydrocarbon depletion and anthropogenic climate impact through GHG emissions related?

Despite alertness about fossil fuel depletion as well as understanding about the finite supply of oil, gas and coal, the issue of physical resource availability has not been widely discussed in long-term outlooks used to assess the risk of anthropogenic climate change. In fact, energy is often seen 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 (Nel and Cooper, 2009). As a result, SRES (2000) contains a set of scenarios not compatible with the possibility that the implied recoverable volumes and extraction rates of fossil fuels are physically unreasonable or even unachievable. Peak oil and fossil fuel depletion have received little attention from the climate change debate, despite its relevance for future anthropogenic emissions (Kharecha and Hansen, 2008; Czúsz et al., 2010). In many ways, extreme climate change projections are commonly built on the assumption that there will be essentially no issue at all with future supply of fossil energy.

3. Fossil fuel projections in SRES

Fossil fuels are the dominating GHG source and, consequently, assumed availability and future production paths are vital for projecting manmade changes to atmospheric concentration of CO_2 and climate. However, the underlying assumptions and data sources in SRES (2000) are old or even outdated. This has to do with the one-sided view on fossil fuel availability expressed by the works that SRES relies on, chiefly relying on economic models rather than geological and technical estimates (Höök et al., 2010a).

Rogner (1997) and Gregory and Rogner (1998) are the main sources for details regarding fossil fuel availability for SRES (2000). Rogner (1997) draws his conclusions from compiling a number of hydrocarbon resource estimates prior to 1997, derived from sources such BP, World Energy Council, German Federal Institute of Geosciences as well as academic studies. Especially, additional occurrences beyond the common resource base, so called "*unconventional hydrocarbons*" such as tar sands and gas hydrates, are seen as important by Rogner (1997). These occurrences are claimed to be capable of making fossil fuels appear as an almost unlimited energy source, under the caveat that economic and technological development are favorable. Rogner (1997), and thereby SRES (2000), conveys the notion that "*the sheer size of the fossil resource base makes fossil sources an energy supply option for many centuries to come*." More specifically, the low long-term costs are worth mentioning, as the fossil energy cost is assumed to be not significantly higher than typical 1990s market price (i.e. spot prices of around 17 dollars/barrel).

It is worth noticing that Gregory and Rogner (1998) specifically mention the "*pessimistic*" view on ultimate recoverable resources, represented by geologists such as Campbell. This is contrasted by the "*optimistic*" side, headed by economists. However, limits to future supply is quickly dismissed by Gregory and Rogner (1997) as new technologies and changing economic conditions could – in theory – make enormous amount of hydrocarbon molecules available in the Earth's crust available for utilization. In essence, IPCC and SRES has chosen to disregard the issues of resource depletion and the concept of physical limits based on little more than economic beliefs (Höök et al., 2010a; Valero and Valero, 2011).

3.1. A background to hydrocarbon depletion

All deposits of fossil fuels are limited either physically or economically, thus making them finite and non-renewable natural resources. This originates from the simple fact that it takes millions of years for fossil fuels to accumulate while the deposits are extracted rapidly, making it impossible for the rate of creation to keep up with the rate of extraction. More generally, if the extraction rate is faster than replenishment rate the resource will be finite in the sense that it will eventually be depleted (Höök et al., 2010c).

The issue of depletion and overexploitation of natural resources are not recent concerns. Discussion has been taking place for quite some time, hailing back to the 18th century where Malthus (1798) discussed the impact of growing exploitation of natural resources in an environment with limited capacity to sustain an ever increasing populace. Similar reasoning was later expressed by Verhulst (1838) who found that any population subject to growth would ultimately be bounded by a saturation level (usually described as the carrying capacity) determined by the environment. Later on, Jevons (1856) foresaw limits to the growth of British coal production as a consequence of limited availability of workable coal. In the 1950s, Hubbert (1956) was among the first to develop a framework for describing and predicting production curves of finite resources, primarily focused on oil. He also accurately predicted the peak of US oil production in 1970s.

Possible limits to growth and how it would affect society were explored through system dynamics by the Club of Rome in the infamous report entitled "*The Limits to Growth*" (Meadows et al., 1972). In retrospect, 30 years of reality actually coincides well with the "*standard run*" scenario (Turner, 2008). However, sustained false statements – mainly from economists – discredited the report in the public debate. Its call for sustainability and fundamental policy changes simply went by relatively unnoticed (Turner, 2008). As life after the oil crisis of the 1970s returned to normal many of the issues raised concerning resource depletion were simply forgotten.

In late 1990s, Colin Campbell and Jean Laherrere, two petroleum geologists formerly working in the oil industry, examined reported reserves and extrapolated discovery curves (Campbell and Laherrère, 1998). Their results indicated that the world was running out of cheap and abundant oil and that a maximum production rate of oil could occur somewhere around 2010. Many subsequent studies have pointed to similar time intervals (Bentley and Boyle, 2007). Aleklett and Campbell (2003) covered more issues and created an updated model for oil depletion along with a first expansion into natural gas. The issue of peak gas and peak coal was also raised in the wake of the peak oil debate. Once again, these works became targets for doomsday accusations and claims of undue pessimism, mostly from economists.

3.2. Fossil fuel production outlooks in SRES

Total primary energy production from fossil fuels in the SRES outlooks range from a mere 50% increase from year 2010 in the B1 family to over 400% in the A1 family (Figs. 6–9). The individual SRES projections for oil, gas and coal can be found in Höök et al. (2010a), while this study only presents aggregated fossil energy production trajectories. By 2100, most of the ultimate reserves of conventional oil, gas and coal will be depleted (Höök et al., 2010a). What happens after 2100 is not discussed in SRES (2000) and several scenarios simply end with high production levels. Altogether, not a single one of all 40 scenarios in SRES (2000) is envisioning a future society with remarkably less fossil fuel dependence than at present.

One can also make some important observations from the arithmetic of growth. Every time a growing production doubles it takes more than all that has been used in all the preceding growth (Bartlett, 1993, 1999, 2004). Taking the average fossil energy production of A1 as an example (Fig. 6), it is projected that the global production of fossil energy in 2040 will be approximately twice as much as in 2010. In other words, it is stated that during these 30 years the world will produce and consume more fossil energy than the total that has been consumed since the dawn of

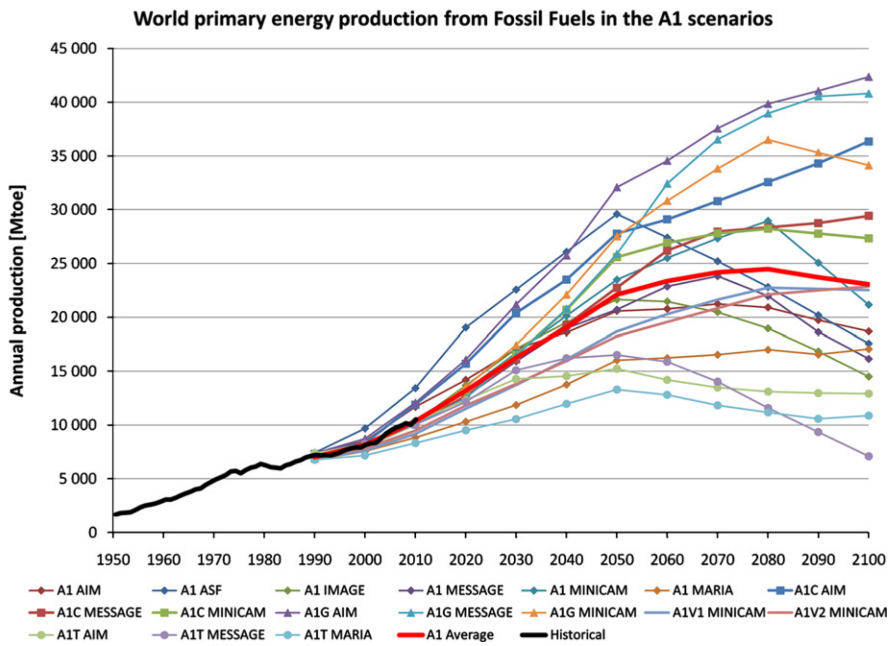

Fig. 6. World primary energy production from fossil fuels in the A1 family.

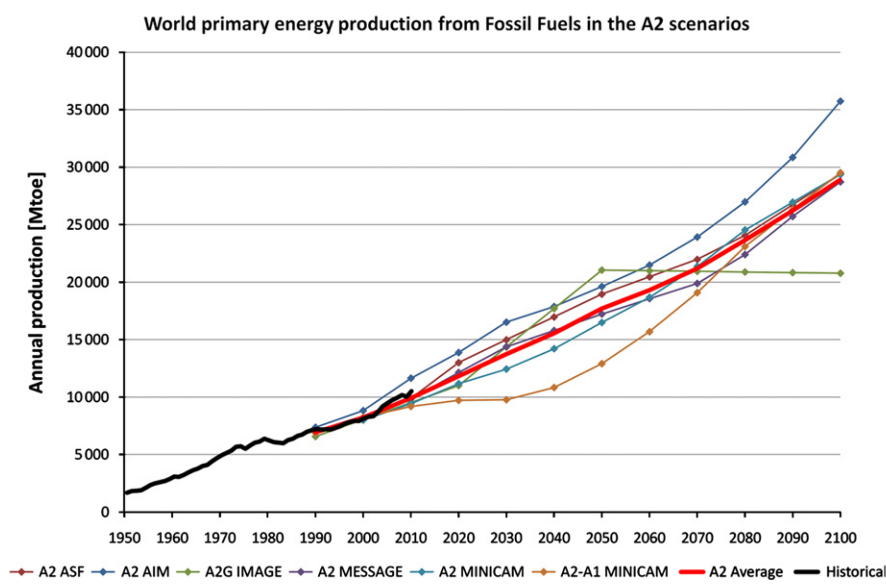

Fig. 7. World primary energy production from fossil fuels in the A2 family.

the industrialized age. This is actually quite mind-bending when stated in this way as opposed to the simplistic long-terms trends with an exponential growth of a mere percent or so annually. The amount of miners, equipment, permits, investments, regional issues and social acceptance needed to achieve this huge task is not discussed in SRES in any detail as everything is just aggregated into four large world regions.

To summarize, Rogner (1997) and SRES (2000) go to great lengths to claim that there are enough fossil resources, i.e. hydrocarbon molecules in the crust, to theoretically sustain production for an extended period of time. However, this shows a misinterpretation of the actual problem as well as avoidance of the question at stake—namely future production. Resources are irrelevant for production, unless they cannot be transformed to reserves and commercially exploited. Vast resources have little to do with the likelihood of significant future exploitation, as this is dependent on more factors than just geological availability. It is the flow of fossil energy resources, i.e. production flows, that is demanded and society can only use the amounts that can be exploited and recovered. The size of the tank – the resource base – is of secondary importance as it is the tap that governs flow rate and practical availability for the civilization. Vast amounts of unconventional hydrocarbons are pointless for preventing the coming of a production peak if they cannot be developed fast enough. The world may indeed be awash in hydrocarbon resources as claimed in SRES (2000), but this is simply no guarantee for high production levels in the future.

3.3. Critical concerns over the SRES production scenarios

Since SRES was published in 2000, there have been a number of critical concerns raised over the fossil fuel production outlooks built into the emission scenarios. However, this debate did not become especially widespread. Public debate rather seemed to

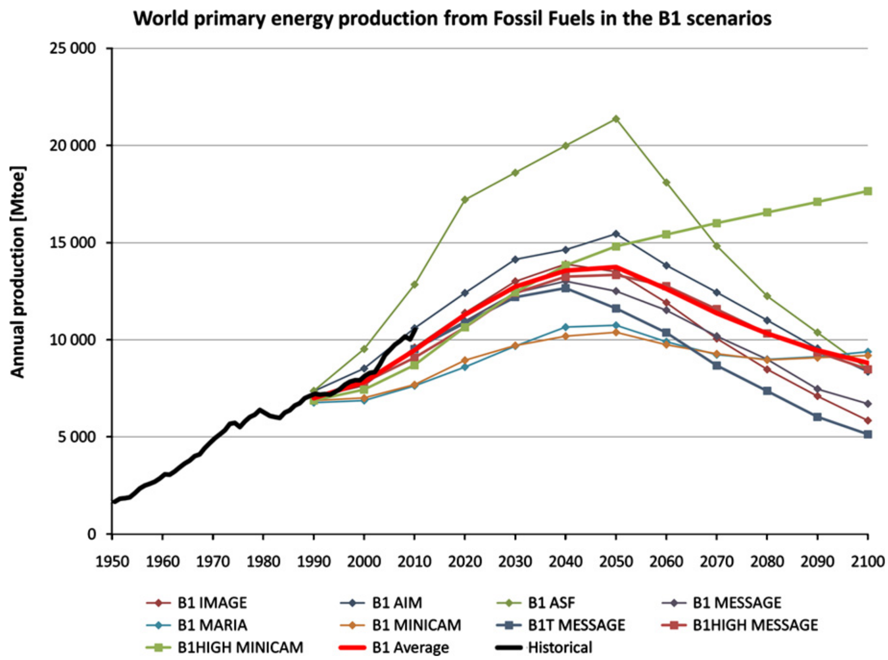

Fig. 8. World primary energy production from fossil fuels in the B1 family.

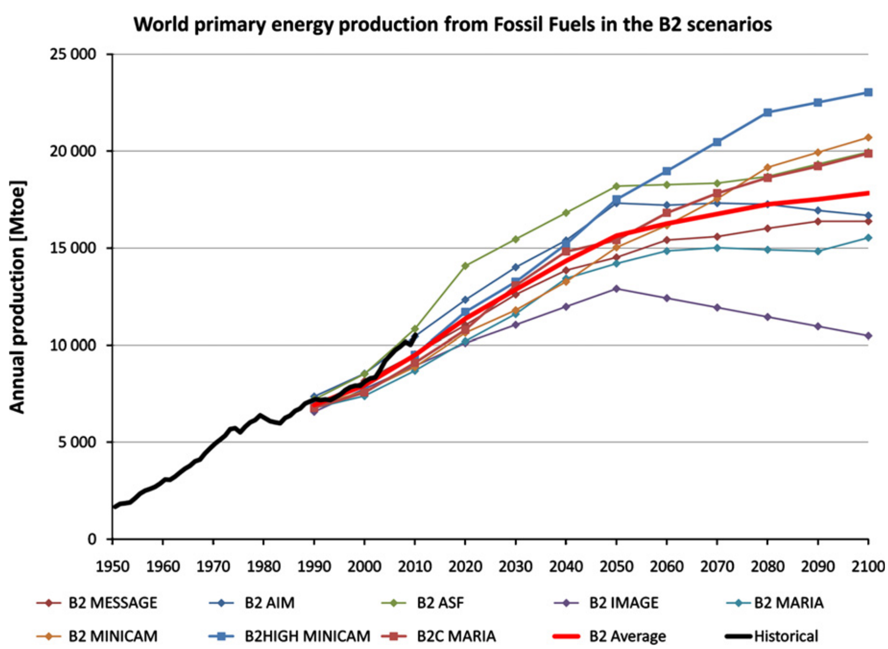

Fig. 9. World primary energy production from fossil fuels in the B2 family.

focus on the results of climate models rather than the underlying assumptions used to derive those outcomes.

One of the first to detect the optimistic production paths were Laherrere (2001, 2002). He compared technical industry data with the SRES projections, thus finding the emission scenarios to be excessively optimistic on future oil and gas supply. This was true for both conventional and unconventional resources. By 2100, the A1G scenarios consume around 14 times more natural gas than in 2000 and Laherrere (2001) even described this as "*pure fantasy*". He concluded that the IPCC assumptions about abundant volumes of cheap oil and gas were in dire need of revision.

Similar ideas was expressed by Aleklett and Campbell, 2003 (Coghlan, 2003), who earlier had questioned the longevity of the world's oil and gas endowment. Sivertsson (2004), who had updated the results of Aleklett and Campbell (2003), later showed a major discrepancy between all 40 SRES scenarios and expected future production and discoveries of gas and oil. The authors of SRES responded to this by claiming that the findings were too "*conservative*" and claimed that there was still plenty of coal to exploit. Thus, the question was largely shifted over to coal.

The investigation of SRES was expanded to include coal by Rutledge (2007). However, the conclusion still indicated that cumulative energy production and CO_2 emissions from coal, oil and gas would be less than any of the IPCC emission scenarios. Different coal production forecasts later indicated that reasonable production profiles were going to be lower than projected in the SRES (Energywatch Group, 2007; Mohr and Evans, 2009; Höök et al., 2010b; Patzek and Croft, 2010).

In hindsight, empirical observations show that nearly 60 countries have already passed their maximum production levels of oil (Sorrell et al., 2010). A most comprehensive summary of over 500 peer-reviewed studies on oil concluded that a global peak before 2030 appears likely and there is a significant risk of peaking before 2020 (UKERC, 2009). Sorrell et al. (2010) also found that forecasts that delay the peak of conventional oil production until after 2030 rest upon several assumptions that are at best optimistic and at worst implausible. Clearly, the risks associated with future oil supply and how it impacts the global energy system should be given serious consideration.

3.3.1. *Oil and gas production details in SRES*

Another inadequacy in SRES is the lack of discussion surrounding details. For oil, the world has a significant dependence on roughly 300 giant oil fields, accounting for 60% of world oil production (Höök et al., 2009). In comparison, there are 50–70,000 oil fields in the world. Likewise, a significant fraction of the world oil supply is derived from relatively few countries, such as countries around the Persian Gulf. Perturbations and real world dynamics cannot be captured by aggregated modeling approaches that only portray oil production as a global function or in four regions. Consequently, the absence of details regarding future production in SRES is problematic.

Optimistic assumptions are also placed on gas in SRES (2000). To achieve the projected ten-fold increases in global gas production, astronomical investment must be made but this appears unlikely from available long-term policies and planning documents. For gas, methane hydrates are identified as the important long-term supplier in SRES as earlier mentioned. In reality, exploitation of gas hydrates is still far from commercially feasible. Beauchamp (2004) points out that, by any standard, gas hydrates will not come cheap—economically, energetically or environmentally.

There appears to be more or less of a consensus about a global peaking of oil production before 2030 among analysts (UKERC, 2009). Alas, the foundation of future oil supply used by SRES (2000) is outdated and does not reflect the growing knowledge of the last decade. Aggregated models and generalized assumptions appear questionable and should be clarified and reinforced to be considered realistic. Currently, IPCC and SRES (2000) seem far more optimistic about future oil production than the petroleum industry itself. This indeed is a peculiar standpoint.

3.3.2. *Coal production details in SRES*

For coal, the geographical distribution of reserves and resources is very uneven. About 90% of known geological occurrences, both commercially feasible and infeasible, are concentrated to just six countries. In addition, global production is also focused in an only few countries (China alone made up approximately 50% of global coal output in 2011). Studies have also found that the peaking of Chinese coal production might occur relatively soon (Tao and Li, 2007; Mohr and Evans, 2009; Lin and Liu, 2010). It is safe to say that the SRES coal projections would put significant expectations on just a few countries, but detailed studies of the most important coal nations do not indicate that such outlooks are reasonable (Höök et al., 2010b).

Coal-to-liquids (CTL) is assumed to be widely applicable and available at low costs—typically below 30 dollars/barrel and even as little as 16 dollars/barrel in some cases (SRES, 2000). Such assumptions seem rather unsound compared to more recent and updated assessments, which end up around 48–75 US$/barrel (Vallentin, 2008). For example, The B2 MESSAGE scenario projects a CTL production of 32 Mb/d by 2100, which is also higher than global oil production at the same time. Such CTL-capacities would require approximately 10,000 Mt of coal per year—more than current global coal output (Höök and Aleklett, 2010). No details on conversion ratios and other important factors are given in SRES (2000), except for statements on the technological possibilities. Is it really reasonable to expect CTL to become such a vital part of the global energy system based on little more than optimistic visions about technical possibilities?

4. The complexity of energy substitutions

Anthropogenic climate change is an intricate problem arising from complex interactions between three distinct parameters—energy, economics, and environment. Energy is essential for economic growth and the development of society, but also a major factor for mankind's emission of GHGs. The core of the poodle is the realization that these three threads are not separate questions, but rather a single issue that necessitates a holistic treatment. The current stance with energy generally seen as an exogenous input to economic planning, but detached from the reality of supply is not capable of providing the all-inclusive view required to fully depict mankind's interaction with the global climate system. To illustrate this problem, we illuminate some of the complexities found within this interdependent conflux of energy, economics and environmental impacts.

SRES (2000) also portrays the importance of unconventional fossil hydrocarbons, justified by Rogner (1997) and Gregory and Rogner (1998). As an example, the B1 family assumes that massive unconventional oil and gas supplies have a geographic distribution widely different from conventional resources and that will have a major impact on future fuel supply and trade flows. The transition from conventional to unconventional oil and gas is assumed to be smooth in SRES (2000) as new technology allows tar sands, gas hydrates and similar fuels to be exploited. This is justified without quantitative assessments.

4.1. *A question of development pace*

A smooth energy transition requires that alternative energy sources are developed fast enough to offset the expected shortfall of fossil energy due to hydrocarbon depletion. To better understand the scope of this challenge, it is important to have a grasp of how fast conventional hydrocarbons may be declining.

Taking conventional oil as an example, existing production has been found to decline at around 6% annually and this is a commonly accepted figure derived by several studies (Höök et al., 2009; Sorrell et al., 2012). This decrease can be quantified into required new annual production addition of 3 to 7 Mb/d – roughly a new North Sea per year – and this puts some real numbers on what is required just to offset the decline in existing production. Even though unconventional hydrocarbons are available, the important question is what kind of flow rates they can provide.

The attenuation of the peak oil decline requires a sustained growth of more than 10% for unconventional oil production over at least the next 20 years (de Castro et al., 2009). Such sustained growth rates have not been seen for any of the global energy systems in history and are not expected by either of the dominating forecasting agencies, i.e. the IEA or the EIA. Also, Mohr and Evans (2010) found that projected unconventional oil production could not mitigate the peak of conventional oil. Even the BGR (2008), the main data source of Rogner (1997), states that: "*after peak oil, the nonconventional oil production will rather modify the decline in oil supply than close the gap between demand and supply.*"

To conclude, the development pace of unconventional hydrocarbons are essential in offsetting the lost production flows due to peaking of conventional ones. Even if vast amounts of unconventional fossil fuels are available in theory, they must still be developed fast enough to smoothly offset the decline of conventional flows. It is essentially a question of flows, not the size of available resources as society demands and only can use the amounts that are producible.

Fantazzini et al. (2011) also highlight some energy transition risks and pointed to the fact that for the last 150 years society have not transitioned from previous fuel sources to new ones—just adding them to the total supply. Fouquet (2010) investigated energy transitions seen in history and found that the whole innovation chain took more than 100 years and the diffusion phase nearly 50 years for new energy sources. Furthermore, the contribution to global energy supply from new energy systems will be marginal at best—even if their development mimics the most extreme growth rates seen in history (Höök et al., 2012). Consequently, quantitative studies indicate that transitions to unconventional hydrocarbons or renewable/alternative energy will be slow and likely not able to smoothly fill the resulting gap as conventional fossil fuels become depleted.

4.2. Economic consequences of hydrocarbon depletion

Koetse et al. (2008) investigated energy substitutability over long terms and found that the economy could respond with substitution provided that there was abundant capital. The question at stake is therefore what kind of economic repercussions might coincide with a peak production of oil and other hydrocarbons. The economic consequences of a declining supply of fossil energy that must be accounted for when projecting the future development of global energy systems and their future contribution to GHG emissions.

Bardi (2007) showed that resource scarcity frequently increases price oscillations, which often slow an energy source transition. Likewise, Reynolds and Baek (2012) show that peak oil and the theory surrounding oil depletion are important determinants for oil prices. Hamilton (2011) points out 11 of the 12 US Recessions since World War II were preceded by an increase in oil prices. The combination of declining oil production (and thus oil priced high enough to cause recessions), high taxes, austerity measures, more restrictive credit conditions and demographic shifts have the potential to severely constrain the financial resources required for a transition to alternative energy sources. It is also likely that this combination of forces triggers the contraction of the world economy (Hamilton, 2009; Dargay and Gately, 2010).

Lutz et al. (2012) explored the macroeconomic consequences of peak oil and found that sharp increases in oil prices due to the nature of the oil market in the short/medium term. The global macroeconomic effects of an increase of the oil price as high as modeled here are comparable to the effects of the financial and economic crises of 2008/2009. Oil exporting countries gained importance in the globalized economy, while importance of oil importing economies decreases. Both Lutz et al. (2012) and Kerschner and Hubacek (2009) found that the transport sector would be firstly and strongly effected, but all other sectors were subjected to indirect impacts through global supply chains.

Interdependencies between fossil fuel production activities also complicate the situation. At present over 95% of the energy in the transportation sector is derived from petroleum (IPCC, 2007). Lin and Liu (2010) note that transportation could account for over 50% of the total coal cost for a consumer. Consequently, increasing oil prices are likely to give increasing coal costs. The globalized supply chains used by virtually all energy technologies are dependent on transports. After peak oil distance will, once again, become increasingly expensive, and oil price may begin to act as a trade barrier for products and implementation of new energy sources (Fantazzini et al., 2011).

To conclude, society may become caught in a struggle with alternating circumstances of insufficient cash flow to handle price spikes and plummeting prices that do not cover cost structures. Fantazzini et al. (2011) and Tverberg (2012) found indications that oil supply problems would be likely to trigger financial problems, thus making substitutions even harder.

4.3. Energy-return on investment

Another factor worth considering is the energy-return-on-investment (EROI) simply referring to the ratio of energy output and the required energy input for an arbitrary energy source. It is only the net energy produced that can be used for non-energy activities in society. The distinction between gross and net energy gain is not that important when having high EROI-values, as the required energy to power the energy production is negligible. Historically, society has been powered by conventional fossil fuels with high EROI—often capable of returning more than 100 times the required energy investment. However, alternative energy sources, such as unconventional hydrocarbons or renewables, generally have lower EROI values. Growth rates of global energy systems have also been shown to correlate to EROI, where energy sources with high EROI tend to grow faster. This could possibly imply that the growth rates seen for fossil fuels in history will not be easily matched by future alternative or renewable energy sources (Höök et al., 2012).

Future GDP-growth requires net energy inputs, hence net energy consumption will grow roughly in parallel. However, depletion of fossil fuels implies that the EROI will diminish. This has already been seen in history (Gagnon et al., 2009; Murphy and Hall, 2010; Grandell et al., 2011). To counter decreasing EROI, gross production of fossil fuels and corresponding CO_2 emissions must grow even faster. Moriarty and Honnery (2010) discuss the ambiguous effects and show that fossil fuel depletion may either help or hinder CO_2 reductions depending on society's response. Finally, Heun and de Wit (2012) found highly non-linear oil price and production cost movements when EROI declined below 10, indicating the underlying connection to economic consequences of switching to alternative fuels with lower EROI.

4.4. Sociopolitical consequences

Others have shown that peak oil is likely to reduce mobility for individuals as well as disrupting urban freight movements (Aftabuzzaman and Mazloumi, 2011). In addition, Krumdieck et al. (2010) found that people living in low-density sprawled urban forms with very few work or resource destinations accessible by public transport, biking or walking, are at a higher risk than people living in concentrated activity areas with integrated land use and transport modes and with closer access to production and work activities. As a result, peak oil could hit certain groups in society harder and lead to increased social tensions.

Furthermore, increasing oil prices due to depletion will increase the amount of oil-related income flowing into autocratic and weakly institutionalized states. Colgan (2012) notes that such states are the most likely sites of future revolutionary governments and highlights that such regimes and large oil incomes are a toxic combination for international peace and security. Consequently, the world might expect further turbulence and political violence in oil-producing regions in the future. It is feasible to assume that increased conflicts will be an obstacle for energy transitions.

It is entirely possible to change the global energy system into something less dependent in fossil fuels. Fuel/energy substitutions can be found in history and are often highlighted in the debate. However, one must read carefully and not overstate the simplicity of an energy transition. Friedrichs (2010) gave examples illustrating that peak oil can throw countries into sociological trajectories not prone to easy energy transitions. Nothing is guaranteeing that the relatively peaceful period currently experienced by the developed nations that is favorable to rapid energy source transitions will continue much longer.

4.5. Summarizing remarks

Sometimes it is claimed that peaking of conventional hydrocarbons would be disastrous for the environment disaster. This is motivated by the established fact that unconventional fossil fuels have much larger emission footprints (Brandt and Farrell, 2007). However, this is only valid if, and only if, unconventional hydrocarbon production becomes a major part of the future energy system. Once again, vast unconventional resources do not "*automagically*" imply high production rates as future exploitation is dependent on more factors than just geological occurrences.

The IPCC scenarios also seriously underestimate technical challenges associated with building a new energy system according to several experts in the field. Pielke et al. (2008) showed that two thirds of all energy efficiency improvements are already built into the scenarios, as they are assuming spontaneous technological change and decarbonization. In addition, they also demonstrated that the assumed rate of decarbonization in 35 of the scenarios agreed poorly with reality in 2000–2010, as the rapid growth of the Chinese and Indian economies actually had increased the global carbon and energy intensities. Smil (2008) also pointed out how the scenarios ignored several key facts about global energy and its future, more specifically the Jevons paradox (Jevons, 1856) which has implied that for the last 150 years all energy efficiency improvements have actually been translated into higher energy use. Finally, Smil (2000) and Bezdek and Wendling (2002) pinpoint that long range energy forecasters have made many inaccurate projections, mostly as overestimations.

The smooth energy transition assumptions built into SRES (2000) are debateable or even questionable. Such idealized substitution mechanisms are likely to oversimplify the complexity of energy transitions, in particular when supply of the dominant energy source (i.e. oil) is declining.

5. Climate impact assessments from fossil fuel constraints

Fossil fuel depletion limits the maximum extent of anthropogenic global warming, although this is challenging to handle in a holistic manner. Energy constraints pose a threat to the economy (Nel and Cooper, 2009), and similarly changes in human energy-related behaviors can lead to a broad range of effects on natural ecosystems (Czúsz et al., 2010). Energy, economy and ecology are seldom seen as three interconnected problems. The lack of widely accepted benchmarks for energy constraints in long-term planning has been a problem often forcing analysts to overlook this factor or oversimplify it into exogenous inputs disconnected from the reality of supply. Consequently, only a relatively limited set of analyses have been investigating the climate changes that limited future production of fossil fuels may have. This review attempts to identify all published papers dealing with this issue.

Doose (2004) discussed fossil fuel limits and how they would impact future anthropogenic climate change. He used a simplistic carbon sink model and a basic Hubbert-type production model and found that it would be unlikely that future atmospheric CO_2 concentrations would rise higher than 650 ppm before falling to 450 ppm by 2150.

Brecha (2008) highlighted that there are both geologic and economic reasons to expect limits in future production and made simplified emission scenarios to explore the consequences. He found that CO_2 concentrations would end up somewhere between 500 and 600 ppm, corresponding to a 2–3 °C temperature increase. This is still above the proposed 2 °C climate ceiling, but far less than the large temperature increases generated by the more extreme scenarios in SRES.

Kharecha and Hansen (2008) used a Bern carbon cycle model and a set of peak oil and gas-compatible emission scenarios to explore the implications of peak oil for climate change. It should be noted that they considered coal to be abundant and capable of increasing production up to 2100 in a business-as-usual outlook, resulting in 550 ppm CO_2 in the atmosphere. Four other scenarios had more constrained coal production profiles, somewhat more compatible with published peak coal projections (Mohr and Evans, 2009; Höök et al., 2010b; Patzek and Croft, 2010; Rutledge, 2011). The CO_2 concentration ended up around 450 ppm for these scenarios and they were found to be largely consistent with current assessments of the cumulative 21st century emissions needed to stabilize atmospheric CO_2 at 450 ppm even after factoring in carbon cycle feedbacks.

Another interesting approach was performed by Meinshausen et al. (2009), which used a comprehensive probabilistic analysis. The climatic consequences of burning all proven fossil fuel reserves were explored by time-evolving distributions of 26 SRES and 21 other scenarios. The conclusion was that it was a significant risk to surpass the 2 °C rise in global temperature due to the cumulative emissions. Victor (2009) raised critique against the proposed measures and highlighted the political problems of a limit to cumulative emissions.

Nel and Cooper (2009) made a complete treatment of fossil energy to better understand its impact on the economy and climate. The emissions were projected to a peak at 11 GtC by 2020 before diminishing to around 6 GtC by 2100. Climate responses were examined with three carbon cycle models, where the Bern model reached atmospheric CO_2-levels of $\sim$540 ppm by 2100 compared to the other models that gave lower atmospheric concentrations. The model with the best fit to historical data peaked at around 430 ppm by 2060 before slowly decreasing. The consequent warming would be limited to about 1 °C above the 2000 level.

The three studies reached somewhat different results and a lot of this can primarily be attributed to different assumptions about climate sensitivity. Zecca and Chiari (2010) criticized Nel and Cooper (2009) for underestimating future warming, but Ward and Nel (2011) defended their position. Zecca and Chiari (2011a) used a simplistic carbon cycle/climate sensitivity model to transform 10 recent fossil fuel forecasts into temperature projections under "*realistic*" fossil fuel production trajectories. It was found that CO_2 concentration could increase up to 445–540 pm with a corresponding temperature increase of 0.9–1.6 °C with respect to year 2000.

Nel (2011) evaluated SRES scenarios against fossil fuel depletion models and proposed attainable trajectories for emissions. In addition, a new parametric carbon feedback model was developed and found to be consistent with empirical data. A radiative feedback model was used for sensitivity analysis to establish a range of reasonable global warming outcomes. Finally, Nel (2011) predicted a maximum atmospheric concentration of CO_2 in the range of 500–560 ppm and a maximum global mean surface temperature increase of 1.5–2 °C relative to year 2000.

Ward et al. (2012) stochastically modeled future emissions and found that high emissions are unlikely to be sustained through the second half of this century, even with the addition of shale oil and other unconventional hydrocarbons. The most frequently occurring model runs typically yielded an overall peak in emissions somewhere between 2040 and 2050, with a corresponding peak emissions rate of 60–70 $GtCO_2$/year. However, these results were not converted into expected temperature increases or average CO_2 concentrations.

Another study by Zecca and Chiari (2011b) expanded the discussion of carbon cycle models, but also found that despite methodological differences analysts arrived to the same important conclusion: *it is likely that fossil fuel depletion will limit the atmospheric CO_2 concentration at levels lower than the ones derived from SRES and normally presented in the anthropogenic climate change debate*. Even though there is still a considerable debate regarding the detailed climate response from fossil fuel limits, one can identify an emerging unity that it will be vital limit for mankind's ability to cause climate change. Whether or not dangerous climate change will occur due to mankind's GHG emissions is still an open question and depends on climate sensitivity and feedback mechanisms as well as fossil fuel availability and future energy trends. The issue is complex and more intra-disciplinary studies are encouraged.

6. Concluding discussions

This far, peak oil and related limits to future fossil energy extraction are nearly absent in the climate change debate (Kharecha and Hansen, 2008). It is certainly about time to change this and stop seeing anthropogenic release of CO_2 as something detached from future energy supply questions. Energy cannot be seen as a limitless input to economic/climate models and remain disconnected from the physical and logistical realities of supply (Nel and Cooper, 2009).

Vernon et al. (2011) found that supply-side constraints may dominate and that scenarios which disregarded such limits are too narrow. The current set of scenarios, SRES (2000), is perforated by optimistic expectations on future fossil fuel production that are improbable and some of the scenarios can even be ruled out as clearly unrealistic. Several scenarios also agree poorly with reality over the recent years and some can even be ruled out due to this mismatch. It can be argued that several SRES scenarios are in need of revision – generally downward – regarding production expectations from fossil fuels.

The utopian thinking in SRES (Hjerpe and Linnér, 2008), is unsubstantiated in the light of recent developments and there are serious issues with the future production modeling. Extraction of fossil energy is dependent on much more than just geological availability. Some scenarios would also place unreasonable expectations on just a few countries or regions. Is it reasonable to expect that China would increase their coal production by a factor of 8 over the next 90 years, as implied by the A1C-scenarios? More detailed studies on China has actually placed the likelihood of a peaking in Chinese production relatively soon (Tao and Li, 2007; Mohr and Evans, 2009; Lin and Liu, 2010). Energy forecasting on a global perspective sometimes overlooks constraints which occur on a smaller geographical level, necessitating more detailed models to better capture the reality of the world's fossil fuel production. Especially a better handling of coal is crucial, as it accounts for both the largest amounts of remaining fossil fuels as well as the largest CO_2 emissions.

SRES (2000) also appears to have missed the growing body of evidence that supports an imminent peaking of world oil production (UKERC, 2009). Needless to say, many of the assumptions used in the IPCC emission scenarios are outdated and in dire need of re-evaluation. Although, they are not outside the realm of extreme possibilities, they are certainly not reasonable as a sound projection compatible with historical trends and recent developments in the field of fossil fuel forecasting. The current stance, where SRES (2000) is much more optimistic about future oil supply than the oil industry and other agencies attempting to forecast future oil supply with high levels of accuracy puts the IPCC in a rather odd or even awkward position. Although development of new emission scenarios is underway, there is still a long road left before they are finished and have been widely implemented within the climate forecasting branch.

The extreme scenarios with high temperature increases can only be obtained by disregarding supply constraints and projecting continued exponential growth in fossil fuel extraction until 2100. The validity of the climate change projections obtained from climate models can be no more than the soundness of the input, i.e. the emission scenarios, that was used to derive those estimates. It can only be stated that the golden rule of modeling – "*garbage in – garbage out*" – should always be held dear.

The extent and timing of peak oil and other impending peaks are not clear, but it is obvious that these events will have a significant impact on mankind's future release of CO_2 given the importance of fossil fuels as a source of anthropogenic emissions. While continued improvement of the understanding of climate mechanisms is being pursued, it is equally important to refine and evaluate the input that is being used in the climate models. It is unlikely that future anthropogenic emissions can be realistically projected without proper understanding of energy system developments, and neither can the future climate change caused by manmade activities. The reviewed studies found quite different results for global warming and GHG concentrations, despite all using fossil fuel constraints. There is still room for improvement and additional refinement of modeling is strongly encouraged. However, the general conclusion is still that fossil fuel constraints will limit anthropogenic climate impact towards the low-medium outcomes presented by the IPCC reports.

There are several feedback and climate mechanisms that can potentially cause severe changes in the climate at lower CO_2 concentrations than expected by the IPCC (2007). Consequently, the peaking of fossil fuels should not be seen as something that automatically solves the issue of anthropogenic climate change. Availability and future production paths will, however, put a limit on mankind's ability to emit GHGs and this must be factored into the climate change projections. The current situation, where climate models largely rely on emission scenarios detached from the reality of supply and its inherent problems is problematic. In fact, it may even mislead planners and politicians into making decisions that mitigate one problem but make the other one worse. It is important to understand that the fossil energy problem and the anthropogenic climate change problem are tightly connected and need to be treated as two interwoven challenges necessitating a holistic solution.

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