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Höök, Mikael

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Future coal production outlooks in the IPCC Emission Scenarios: Are they plausible?

Mikael Höök*

Contact e-mail: Mikael.Hook@fysast.uu.se

* Uppsala University, Global Energy Systems, Department of physics and astronomy, Box 535, SE-751 21, Uppsala, Sweden, webpage: <http://www.fysast.uu.se/ges/>

Abstract:

Anthropogenic climate change caused by CO₂ emissions is strongly and fundamentally linked to the future energy production. The Special Report on Emission Scenarios (SRES) from 2000 contains 40 scenarios for future fossil fuel production and is used by the IPCC to assess future climate change. Coal, with its 26% share of world energy, is a major source of greenhouse gas emissions and commonly seen as a key contributor to anthropogenic climate change. SRES contains a wide array of different coal production outlooks, ranging from a complete coal phase-out by 2100 to a roughly tenfold increase from present world production levels. Scenarios with high levels of global warming also have high expectations on future fossil fuel production.

The assumptions on resource availability are in SRES based on Rogner's assessment of world hydrocarbon resources from 1997, where it is stated that "the sheer size of the fossil resource base makes fossil sources an energy supply option for many centuries to come". Regarding the future coal production it is simply assumed to be dependent on economics, accessibility, and environmental acceptance. It is also generally assumed that coal is abundant, and will thus take a dominating part in the future energy system. Depletion, geographical location and geological parameters are not given much influence in the scenario storylines.

This study quantifies what the coal production projection in SRES would imply in reality. SRES is riddled with future production projections that would put unreasonable expectation on just a few countries or regions. Is it reasonable to expect that China, among the world's largest coal reserve and resource holder and producer, would increase their production by a factor of 8 over the next 90 years, as implied by certain scenarios? Can massive increases in global coal output really be justified from historical trends or will reality rule out some production outlooks as implausible?

The fundamental assumptions regarding future fossil fuel production in SRES was investigated and compared with scientific methodology regarding reasonable future production trajectories. Historical data from the past 20 years was used to test how well the production scenarios agree with actual reality. Some of the scenarios turned out to mismatch with reality, and should be ruled out. Given the importance of coal utilization as a source of anthropogenic GHG emissions it is necessary to use realistic production trajectories that incorporate geological and physical data as well as socioeconomic parameters. SRES is underpinned by a paradigm of perpetual growth and technological optimism as well as old and outdated estimates regarding the availability of fossil energy. This has resulted in overoptimistic production outlooks.

Key words: Emission scenarios, CO₂ emissions, future coal production, peak coal

1. Introduction

The world's primary energy supply is dominated by fossil energy and over 80% is derived from combustion of oil, gas and coal (IEA, 2009). Oil accounts for 34%, coal for 27% and natural gas for 21% (IEA, 2009). The use of fossil fuels is also the dominating source of anthropogenic greenhouse gasses (GHG), particularly carbon dioxide. In 2007, nearly 29 billion tons of CO₂ were emitted due to fossil fuel consumption (IEA, 2009). Around 57% of all global anthropogenic GHGs derive from fossil fuel combustion, with energy supply as the largest contributing sector (Figure 1). Consequently, anthropogenic climate change caused by GHG emissions is strongly and fundamentally linked to future energy production. Studies of the future energy use and production are vital for understanding future GHG emissions.

Among the fossil fuels, coal is the most carbon intensive fuel and causes the largest GHG emissions per energy unit produced. The use of coal is also the most criticised part of the fossil energy sector. Consequently, it is important to inspect what kind of expected coal usage and corresponding emissions that is reasonable in the future.

Figure 1: Shares of total GHG emissions. CO₂ from fossil fuel use is dominating in terms of emissions. This strongly links energy production to GHG emissions and ultimately anthropogenic climate change to assumptions about future fossil fuel production. Derived from: IPCC (2007)

1.1 Aim of this study

Coal is a major source of GHG emissions and an integral part of the world's energy system for the foreseeable future. The IPCC emission scenarios (SRES, 2000) contain a number of outlooks for future coal production. This study aims to investigate those production outlooks and their feasibility, and the paper is mainly reflecting previous studies on coal and the fossil fuel use in the IPCC emission scenarios (Höök et al., 2010a; Höök et al., 2010b).

This study will not venture into any form of climate change effects or spend any time reviewing or commenting the issue of man-made climate change. Such studies have already been made by others (Kharecha and Hansen, 2008; Brecha, 2008; Nel and Cooper, 2009). Instead, the focus will be strictly placed on the plausibility of future coal production trajectories. However, if assumptions regarding the most dominating source of GHG are shown to be flawed it will naturally have repercussions on the validity of the climate change projections derived from models using those emission scenarios as input. The fundamental guiding principle in modelling – garbage in, garbage out – should always be held dear.

2. Background to SRES

The World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) established the Intergovernmental Panel on Climate Change (IPCC) in 1988. Its task is to assess scientific, technical and socio-economic information relevant for understanding anthropogenic climate change. The results have been published in several assessment reports and some special reports over the years (IPCC 1990; 1995; 2001; 2007). The IPCC has been using a set of scenarios, describing future development of society and emissions, to assess future climate change. The first set was published in 1990, followed by subsequent sets in 1992 and 2000. Titles, methods, classifications, assumptions have all changed over time and this has been reviewed by Girod et al (2009).

All of the scenarios from 1992 were found to exaggerate one or more current climate and economic trends, leading to correspondingly exaggerated atmospheric greenhouse gas concentrations (Gray, 1998). Revisions were obviously needed and work was undertaken to develop new scenarios. The current scenario set is called the Special Report on Emission Scenarios (SRES) and were published in 2000. It is the basis for the majority of all long-term climate change projections, including those of the Fourth Assessment Report (IPCC, 2007).

SRES is built on 40 different scenarios and evaluations of the associated GHG emissions. The scenarios are based on literature reviews, development of narrative storylines and the quantification of these story lines with the help of six integrated models from different countries. SRES illustrates that the future emissions, even in the absence of explicit environmental policies, very much depend on the choices that people make, how economies are structured, which energy sources that are preferred and how people use available land resources. IPCC state that “*they represent pertinent, plausible, alternative futures*” and derive from a descriptive and open-ended methodology that aims to explore alternative futures (SRES, 2000). The emissions scenarios are later used as an input to various climate models to depict how the climate may change under various assumptions of future anthropogenic emissions.

The emission scenarios are neither claimed to be predictions nor forecasts, even though they are commonly used as such. Additionally, no probabilities or likelihoods are assigned to any of the scenarios. All scenarios are equally sound and valid, which was required by the *Terms of Reference* (SRES, 2000). The equal probability of each emission scenario has been described as a rather peculiar assumption (Höök et al., 2010a). In any event, this cannot be the case, 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 (Jones, 2001). The IPCC emission scenarios have been criticized for its inability to assign probabilities to the projections (Schneider, 2001; 2002). Additional discussion on the communicative issues and uncertainties within SRES can be found in Schenk and Lensink (2007).

Fossil fuel combustion, the main source of anthropogenic GHG emissions, as well as future production, can be modelled by probabilistic methods (Kontorovich, 2009). This makes claims of equal probability for both high and low resource/production scenarios appear questionable. “*Equally valid scenarios*” rather materializes as an attempt to assign unjustifiably high weight to more extreme visions compared to reasonable outlooks.

2.1 Scenario overviews

Each of the participating modelling teams behind the emission scenarios used computer models and experience considering long-range development of economic, technological and environmental systems to generate quantifications of the storylines, which develop the different scenarios. To simplify the procedure of depicting alternative future developments, each of the four scenario families is described by a specific storyline. The writing teams formulated the storylines in a process that identified driving forces, key uncertainties, possible scenario families and their logic (Höök et al., 2010a). Within each scenario family different variations of global and regional development and their implications for global greenhouse gas emission are explored. There is no business-as-usual scenario or disaster scenario and it was also decided that possible surprises, such as a new world war or major depression, should not be considered. This has been described as a built-in linear logic and utopian thought (Hjerpe and Linnér, 2008).

The SRES storyline titles have been kept simple: A1, A2, B1 and B2. They can be shown very straightforwardly in a two-dimensional tree, which shows the global-regional focus and the economic-environmental orientation (Figure 2). Closer description of the scenario families can be found in SRES (2000). The four storylines and scenario families describe future worlds that are wealthier compared to the current world. It is important to notice that they do not include additional climate initiatives such as policies to limit GHG gases or to adapt to the expected climate change. Each scenario has a number of driving forces, such as population, economy, technology, energy, land-use, and agriculture. Different preferences and priorities lead to a huge variety of corresponding GHG emissions.

The A1 storyline and scenario family describes a future world of very rapid economic growth, low population growth and the rapid implementation of new and more efficient technologies. The key plots are convergence among regions, capacity building, and increased cultural and social interactions with a significant reduction in the difference in per capita income. The A1 family is the largest and branches out in several subfamilies, each exploring an alternative future with different preferences.

The A2 family contains visions of a very heterogeneous world. The key scheme is self-reliance and preservation of local identities and cultures. Fertility patterns across the globe converge very slowly, which results in high population growth. Economic development is primarily focused on regional growth and per capita economic growth and technology change is more fragmented and slower than in other scenario families.

The B1 scenario family describes a convergent world with the same low population as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the implementation of clean and resource-

efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

Finally, the B2 scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It results in a world with moderate population growth, intermediate economic growth and less and more diverse technological change than in the B1 and A1 storylines. B2 is oriented toward environmental protection and social equity, but also focuses on local and regional initiatives.

Figure 2. Schematic illustration of the SRES scenarios. The four scenario families are shown, very simplistically, as branches of a two-dimensional tree. Each scenario is based on a common specification of the main driving forces such as population, economy, technology, energy, land-use and agriculture. Adapted from SRES (2000)

All qualitative and quantitative properties of scenarios belonging to the same family were set to match the corresponding features of the underlying storyline. Together, 26 scenarios were harmonized to have the same assumptions about global population and GDP development. The remaining 14 scenarios explore alternative interpretations of the four scenario storylines, such as different rates of economic growth and variations of population growth (Sivertsson, 2004; SRES, 2000). The main characteristics of the scenarios are presented in Table 1.

Table 1. Main characteristics of development in different scenario families and groups, as applied to harmonized scenarios. Adapted from SRES (2000)

Family	A1				A2	B1	B2
<i>Subgroup</i>	<i>A1C</i>	<i>A1G</i>	<i>A1I</i>	<i>A1T</i>	<i>A2</i>	<i>B1</i>	<i>B2</i>
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-medium	Low-medium	Low	Low	Medium-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”

3. Future coal supply in SRES

Resource availability in SRES (2000) is built around the works of Rogner (1997) and Gregory and Rogner (1998), and relies on them for detailed discussion of the estimated hydrocarbon amounts. Closer discussion on fossil fuel availability can be found in SRES (2000) and Sivertsson (2004). The message of Rogner (1997) is that the vast unconventional hydrocarbon occurrences and historically observed rates of technology change would allow hundreds of years with availability of fossil energy with low long-term costs, i.e. not significantly higher than the market price of the 1990s. Rogner (1997) also states that additional occurrences beyond the common resource base makes fossil fuels appear as an almost unlimited energy source. In summary, main point of Rogner (1997) is that *“the sheer size of the fossil resource base makes fossil sources an energy supply option for many centuries to come”*, provided that economy and technological progress are favourable.

For coal, Rogner (1997) highlight the many fluctuations in world reserve and resource assessments. A more holistic compilation of the fluctuations can be seen in Tables 2-6 or Figure 3. There is no discussion about the historical trends in global reserve and resource assessments in the work of Rogner (1997), in contrast to Höök et al. (2010b). Table 2 and 3 show some dramatic changes in the estimated in situ resources in the published assessments by WEC and BGR.

Rogner’s overview is also very brief in comparison with oil and gas, mostly calling out to Federal German Institute of Geosciences and Natural Resources (BGR) as the main source. The total coal resource is placed at 6 246 Gtoe, which would equal 8744 Gt of coal (assuming 30 GJ/ton coal). Nearly 60% of all coal is found in the most uncertain category.

Rogner (1997) places the coal reserves at 1 003 Gtoe, equalling 1404 Gt of coal (assuming 30 GJ/ton coal). This is strikingly higher than the latest global reserve estimates of 826 Gt (WEC, 2009; BP, 2010). Even the latest estimate from the BGR (2009) only places total coal reserves at 503 Gtoe or 997 Gt. A full compilation of historical world coal reserve estimates can be seen in Tables 4 and 5. Rogner’s data can only be called outdated and should be replaced with more recent studies and preferably also a discussion of the historical trends in coal supply estimates. The global coal reserves reported by World Energy Council (WEC) contain a declining trend since late 1980s (Table 4). On the other hand, the BGR data does not show this

trend (Table 5). However, the BGR has been known to exaggerate coal reserves compared to the national agencies that provide the reports used by the WEC (Höök et al., 2010b).

Table 2. *Total resource estimates in Gt for selected countries and the world as published by the WEC. Data source Höök et al. (2010b)*

	USA	China	India	FSU	Australia	South Africa	Germany	Poland	UK	Indonesia	World
1924	5 398	996	79	n.a	166	56	423	19	190	n.a	7 398
1929	3 829	1 213	79	489	166	58	423	n.a	190	n.a	n.a
1937	2 893	10 113	26	611	171	214	427	68	306	n.a	16 025
1948	2 897	n.a	n.a	n.a	n.a	90	n.a	n.a	n.a	n.a	n.a
1974	2 925	1 000	83	5 714	199	44	317	61	163	3	10 754
1976	3 600	n.a	86	6 948	372	93	n.a	n.a	190	3	11 724
1980	1 073	1 463	115	6 007	860	93	295	186	190	19	13 476
1986	1 570	2 737	115	5 502	785	133	332	197	186	23	11 990
1989	1 570	1 094	245	5 487	821	122	332	198	378	6	10 052
1992	1 570	954	245	5 487	821	122	241	207	378	64	10 236
1995	1 216	954	286	5 487	817	126	269	223	190	64	10 567
1998	1 570	n.a	n.a	4 141	454	126	308	74	n.a	n.a	n.a
2000	1 321	n.a	n.a	n.a	435	116	308	65	n.a	n.a	n.a
2004	1 564	n.a	n.a	n.a	431	115	100	170	n.a	46	n.a
2007	1 560	n.a	290	n.a	n.a	115	50	56	n.a	57	n.a

Table 3. *Total resource assessments in Gt as published by the BGR. Year 1980 is seen as identical to the WEC report from the same year. Data source Höök et al. (2010b)*

	USA	China	India	FSU	Australia	South Africa	Germany	Poland	UK	Indonesia	World
1976	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	14 185
1980	1 073	1 463	115	6 007	860	93	295	186	190	19	13 476
1988	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	11 610
1993	1725	935	201	5493	861	155	380	194	447	42	10 994
1998	1478	766	166	5499	371	55	371	168	227	18	9 636
2001	1 122	668	163	2 217	194	5	264	144	190	24	5 424
2004	1 090	1 090	259	2 295	298	164	88	70	5	11	4 668
2005	1 058	1 090	292	2 326	305	164	91	101	7	65	6 039
2006	1 359	4 367	252	2 915	194	49	85	179	190	27	9 554
2007	6 720	4 367	230	2 931	148	29	83	179	187	24	15 511
2008	8 120	5 509	278	4 336	359	31	191	401	188	93	20 767

Table 4. Recoverable reserve estimates in Gt for selected countries and the world as published by the WEC. Data source Höök et al. (2010b)

	USA	China	India	FSU	Australia	South Africa	Germany	Poland	UK	Indonesia	World
1924	5 398	996	79	n.a	166	56	423	19	190	-	7 398
1929	3 829	1 213	79	489	166	58	423	n.a	190	n.a	n.a
1937	n.a	n.a	5	309	9	8	109	15	130	n.a	691
1948	n.a	n.a	n.a	n.a	n.a	22	n.a	n.a	n.a	n.a	n.a
1974	182	80	12	136	n.a	11	65	23	4	1	591
1976	199	n.a	13	n.a	63	18	64	n.a	45	0	n.a
1980	182	140	84	233	59	33	60	39	45	1	882
1986	264	n.a	n.a	245	66	58	80	43	5	n.a	839
1989	215	731	63	241	91	55	80	40	4	3	1 598
1992	241	115	63	241	91	55	80	41	4	32	1 039
1995	241	115	70	241	91	55	67	42	3	32	1 032
1998	247	115	75	225	90	55	67	14	2	5	984
2000	250	115	84	225	82	50	66	22	2	5	984
2004	247	115	92	222	79	49	7	14	0	5	909
2007	243	115	56	222	77	48	7	8	0	4	847
2009	238	115	59	222	76	30	7	8	0	4	826

Table 5. Recoverable reserve estimates in Gt as published by the BGR. Year 1980 is seen as identical to the WEC report from the same year. Data source Höök et al. (2010b)

	USA	China	India	FSU	Australia	South Africa	Germany	Poland	UK	Indonesia	World
1976	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	792
1980	182	140	84	233	59	33	60	39	45	1	882
1988	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	880
1993	282	110	62	48	84	68	53	22	3	6	818
1998	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	806
2001	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	968
2004	283	115	125	206	105	49	7	10	0	5	990
2005	252	115	126	157	107	49	7	10	0	7	935
2006	247	192	96	204	79	49	41	16	0	7	1 019
2007	263	192	74	215	77	29	41	16	0	7	990
2008	263	192	81	215	77	31	41	16	0	4	997

Figure 3. Evolution of the worlds coal reserve and resource estimates made by WEC and BGR since 1924. Adapted from Höök et al. (2010)

4. Modelling future production

All production numbers in SRES (2000) are presented in exajoules (EJ) or zetajoules (ZJ), which are units that are hard to grasp in layman's terms. As a result, we have chosen to convert their figures to more commonly used units. For conversion, we have used 42 GJ as a ton of oil equivalent (toe) and expressed everything in Mtoe or Gtoe.

SRES (2000) assume everything from low to very high resource availability to describe different futures scenarios. The future resource consumption is dependent on future price levels (either assumed as exogenous inputs or determined endogenously in the model) and future technology capable of mining unconventional resources. All the scenario story lines show elements of utopian thinking in particular regarding future technologies capable of decoupling economic growth from energy consumption, how globalization is assumed to even out economic differences and how access to energy is rising in the future (Hjerpe and Linnér, 2008).

Regarding coal, the question is assumed to be only one of economics, accessibility and environmental acceptance. Geological availability and quality issues are simply regarded as non-interesting or solvable with new technology or higher prices. Rogner (1997) stressed the need to have dynamic upper limits and to include both anticipated technology advances and undetermined technological breakthroughs. Simplistic aggregate quantity-cost curves and learning effects are presented as the main articles for modelling energy sources, basically implying that production will “automagically” occur as rising prices makes more and more resources available. However, such an assumption fails to include the complex interaction with other potential energy sources and the fuel demand by society.

Society is dependent on the flows of fossil fuel and the future production is defined through the size of those flows. The size of the tank, i.e. the resource base, is of secondary importance as it is the tap that governs the flow rate and future utilization of fossil fuels in the society. Vast but complicated resources are useless for preventing the coming of a production peak if they cannot be developed fast enough to offset the depletion of “easy” coal. Vast reserve bases have little to do with the likelihood of significant future production, as production is dependent on many more factors than just geological availability. Focusing on future coal reserve levels, while ignoring other factors that affect coal extraction, leads to an incomplete picture for future coal production.

Future coal production will not be entirely determined by what is geologically available, but rather by the fraction of the practically recoverable amounts as well as the demand by consumers. One must remember that society demands energy, not just energy from coal. Hence, if this energy can be obtained less costly and more practically from other energy sources, potentially nuclear power or wind, those will be favored. Increased coal prices do not necessarily lead to increased production, increased reserves, and the transformation of resources into reserves. The price development and feasibility of other energy sources must also be considered, since it is the energy, and not the feedstock that is demanded.

4.1 A1 family

This family features rich energy and mineral resources, while rapid technological progress reduces the amount of resources needed for the same level of production and increases the economically recoverable reserves. The A1 family also has some subgroups that explore variants of this rich and technological future. A1C depicts a coal-focused future where new clean coal technologies, such as sulphur removal, have made coal generally environmental-friendly with the

exception of GHG emissions. A1G describes an oil and gas rich future, with a rapid transition from conventional resources to rich unconventional resources such as methane hydrates. In fact, over 95% of the total gas resources in Rogner (1997) come from methane hydrates (Höök et al., 2010a). A1T describes a non-fossil future where rapid developments of solar and nuclear technologies replace fossil fuels.

For coal, future production for this scenario family can be found in Figure 4. Massive increases in world production are generally expected and no peak at all is foreseen prior to 2100 in the average case. The A1C-subgroup includes a tenfold increase in world coal production. The other subgroups tend to rely on other energy sources than coal, with massive increases in global oil and gas production as a result (Höök et al. 2010a). Valero and Valero (2010) found that the proven reserves of coal, oil, and natural gas must increase by at least 56%, 139% and 288% to meet the fuel requirements on the A1-subfamily focused on fossil energy (A1F).

In summary, one can only see that this scenario family is optimistic regarding future coal production and has a built-in assumption that no constraints or limitations will apply to coal extraction prior to 2100. A number of scenarios, such as A1 ASF with an oil peak at 182 Mb/d in 2020 or A1T Maria that phases out coal entirely in the long run, can be ruled out from disagreement with historical data. A number of scenarios shows a peak in coal production around 2050, in agreement with Mohr and Evans (2009) and Höök et al (2010b), but those scenarios also consume unrealistic amounts of oil and gas (Sivertsson, 2004).

Table 3: *Cumulative coal production 1990-2100 in the A1 family*

Scenario name	Coal [Gtoe]
A1 AIM	379.0
A1 ASF	1226.9
A1 IMAGE	533.8
A1 MESSAGE	451.4
A1 MINICAM	494.6
A1 MARIA	201.7
A1C AIM	1627.3
A1C MESSAGE	1151.9
A1C MINICAM	1427.9
A1G AIM	448.2
A1G MESSAGE	509.8
A1G MINICAM	901.4
A1V1 MINICAM	512.5
A1V2 MINICAM	540.8
A1T AIM	294.8
A1T MESSAGE	277.8
A1T MARIA	105.0
A1 AVERAGE	652.1

Figure 4. Projected world coal production the in A1 scenario family. Production ranges from 800 to nearly 27 000 Mtoe by 2100, with an average is 11 000 Mtoe without a peak prior to 2100. Adapted from Höök et al. (2010a)

4.2 A2 family

This family describes a differentiated world which, compared to A1, is characterized by low trade flows, relatively slow capital stock turnover and slower technological progress. This family also depicts self-reliance in terms of resources and less weight on social, economic and cultural interactions between different regions. A2 is often used as the “business-as-usual” family, where economic development continues without environmental concern or major attempts to reduce the gap between rich and poor countries.

Regions with rich mineral and energy supply will develop into more resource-intensive economies. Other regions with fewer resources will focus on minimizing import dependence and improve efficiency or make use of alternative inputs. The resource availability in different regions mainly determines the fuel mix used. High-income but resource-poor regions develop advanced post-fossil technologies while low-income but resource-rich regions generally rely on older fossil technology. The resource availability is generally *rather conservative*, and utilization is largely limited to conventional resources without venturing into the field of unconventional fuels, generally resulting in high coal consumption.

Coal will become the dominant fuel since oil production peaks. From being a mere 25% of the fossil energy in the 2020s, coal grows to over 75% in 2100 (Valero and Valero, 2010). Coal production is projected with generally continue increasing trends throughout the rest of the century resulting in roughly six times higher coal production by 2100 on average (Figure 5). An exponential increase is more or less the general theme. In addition, Valero and Valero (2010)

also found that the proven reserves of oil, natural gas and coal would need to increase by 50%, 140%, respectively 89% in order to meet the projected demand in this scenario family.

The projected outlooks would put enormous pressure on the USA, Russia, China, Australia, India and South Africa as they together hold roughly 90% of the world's coal reserves and resources (Höök, 2010b). For example, major amounts of the Russian coal are located in the Tunguska and Lena basins in central Siberia (Thomas, 2002), and will not realistically be developed for many decades due to limited infrastructure as well as remoteness and harsh climate.

Since 1860, the cumulative world production of coal has been around 165 Gtoe (Ion, 1974, 1979; Jenkins, 1989; Mitchell, 2003; BP, 2010), with 52 Gtoe alone produced in the last 20 years. With this in mind, the A2 family assumes that the cumulative production by 2100 will be many times the total historical output.

Table 4: Cumulative coal production 1990-2100 in the A2 family.

Scenario name	Coal [Gtoe]
A2 ASF	1113.4
A2 AIM	1136.6
A2G IMAGE	514.0
A2 MESSAGE	747.3
A2 MINICAM	1117.5
A2-A1 MINICAM	477.6
<i>A2 Average</i>	851.1

Figure 5. Projected coal production in the A2 family. Adapted from Höök et al. (2010a).

4.3 B1 family

B1 assumed that the capital output ratio of resource exploitation is assumed to rise with increasing depletion, but this is counteracted by learning curve effects. Coal production costs are assumed to rise with increasing depth and rising labour wages but this offset by increased mechanization (for underground mining) and economic scale-up effects.

Coal is significantly lower in the B1 family than in the A1 and A2 families (Figure 6). On average, coal production levels are not dramatically higher than present output. Even though, B1 ASF appears as a rather odd bird with its dramatic deviation from the other scenarios within this family. Other scenarios, such as B1 ASF with an oil production of 170 Mb/d by 2020 or B1 MARIA that features monotonically decreasing coal production after 1990, can also be ruled out due to poor agreement with actual data.

Valero and Valero (2010) saw that this scenario family depletes around 70% of the worlds current coal reserves by 2100. Table 5 gives the cumulative production output to 2100. On average, most of the scenarios reach a maximum production around 2050 (Figure 6). This is in agreement with studies like Mohr and Evans (2009) or Höök et al (2010b).

Table 5: *Cumulative coal production 1990-2100 in the B1 family*

Scenario name	Coal [Gtoe]
B1 IMAGE	313.9
B1 AIM	379.8
B1 ASF	648.6
B1 MESSAGE	161.2
B1 MARIA	77.8
B1 MINICAM	250.1
B1T MESSAGE	154.1
B1HIGH MESSAGE	201.6
B1HIGH MINICAM	305.4
B1 AVERAGE	276.9

Figure 6. Projected coal production in the B1 scenario family. Adapted from Höök et al. (2010a)

4.4 B2 family

Here the available fossil energy is assumed to be conservative. The availability of oil and gas expands only gradually and it not extended much beyond current conventional and unconventional reserves (as of late 1990s). However, coal is assumed to be abundant. Overall this results in relatively limited energy options for the world. Coal production is assumed to be at much higher production levels than present (Figure 7). A tripling of world coal output is the average of this scenario family, while certain individual scenarios can be even more extreme.

Table 6: Cumulative hydrocarbon production 1990-2100 in the B2 family

Scenario name	Coal [Gtoe]
B2 MESSAGE	300.7
B2 AIM	571.6
B2 ASF	785.9
B2 IMAGE	426.9
B2 MARIA	454.0
B2 MINICAM	433.7
B2HIGH MINICAM	1056.1
B2C MARIA	608.7
B2 AVERAGE	579.7

Figure 3: Projected coal production in the B2 scenario family. Adapted from Höök et al. (2010a)

5. Comments on the SRES production outlooks

Generally, the most favourable formations have been exploited first while more challenging and/or undesirable formations have been left. In fact, various studies show that depletion can make up for technological progress in the industry (Livernois, 1988; Tilton, 2003; Rodriguez and Arias, 2008; Topp et al., 2008). In essence, the increased costs resulting from the need to mine less favourable formations, i.e. more complex geology, more remote areas, deeper or thinner coal seams, lower quality hydrocarbons and similar, have been matching the cost reductions done by increased mechanization and introduction of new technologies. However, SRES often disregard such information based on little more than optimistic expectations on new technology.

The main message of Rogner (1997) directly shows misunderstanding of the actual problem as well as avoidance of the key question, namely future production. Society is dependent on fossil fuel flows and future production is about the size of those flows. The size of the tank, i.e. the resource base, is of secondary importance as it is the tap that governs the flow rate and future utilization of fossil fuels in the society. Vast unconventional hydrocarbon resources are useless for preventing the coming of a production peak if they cannot be developed fast enough. Once again it must be stressed that vast resources have little to do with the likelihood of significant future production, as production is dependent on many more factors than just geological availability. The important question for society is not the size of reserves. Rather it is the actual flow of energy that can be obtained from the reserves.

Other peculiar details can also be found in SRES (2000). One of those things is expectations on coal-to-liquids (CTL) technology. CTL technology costs are assumed to be very low, typically below 30 dollars/barrel and even as little as 16 dollar/barrel in some cases (SRES, 2000). Such assumptions seem rather unsound compared to more recent and updated assessments, which ends up around 48-75 US\$/barrel (Vallentin, 2009). The lack of details regarding CTL conversion ratios have been highlighted by Höök and Aleklett (2009). CTL is assumed to be a vital part of future fuel supply in several scenarios. CTL normally yields 1-3 barrels per ton of coal consumed (Höök and Aleklett, 2009).

For example, the world CTL production (32 Mb/d) by 2100 in the B2 MESSAGE scenario is expected to be higher than the world oil production at the same time. Such a CTL-capacity would alone require more than the present world coal consumption to fuel the synthetic fuel plants, in addition to the amounts needed for “conventional” use of coal in power plants, steel mills and other industries. Can such major expectations on CTL really be made with little more than vague arguments based on technical possibilities?

Patzek and Croft (2010) highlights how 16 of the 40 coal scenarios in SRES simply grow exponentially until the year 2100. Since all scenarios are assigned equal probability, these unreasonable outliers were a weight equal to the more realistic lower scenarios. Patzek and Croft (2010) continues to point out that policy makers tend to focus on the most extreme outcomes, and these outliers have gained severe prominence as inputs to the subsequent climate models. Assigning equal probability to everything ranging from zero coal production to a tenfold increase compared to present levels cannot be a reasonable approach.

In summary, we can only encourage the IPCC to involve more resource experts and natural scientists in future emission scenarios. The current set, SRES (2000), is biased toward exaggerated resource availability and unrealistic expectations on future production outputs.

6. Conclusions

Perpetual economic growth is only an extrapolation from history, not a law of nature. Future depletion and the coming of a production peak are both phenomenological observations as well as results derived from physical models. However, perpetual growth is often held as a fundamental assumption for economists and used as a “rule of thumb” for extrapolation. Perpetual growth cannot be used as an underlying assumption for non-renewable energy sources, such as fossil fuels. Rotty (1979) stated that one should be able to make a more accurate analysis than simply projecting continued exponential growth in attempting to estimate the energy demands of the future. Even former technological and economic optimists are now seeing the end of an era with exponential growth (Ayres, 2006). This is hardly surprising, given the underlying arithmetic properties of growth and how quickly unreasonable values are reached for resource production and consumption even for modest growth rates (Bartlett, 1993, 1999, 2004).

SRES is riddled with future production projections that would put unreasonable expectation on just a few countries or regions. Is it reasonable to expect that China, among the world’s largest coal reserve and resource holder and producer, would increase their production by a factor of 8 over the next 90 years, as implied by the A1C-scenarios? The concentration of the world’s coal reserves and resources to a few countries will result in that a few countries will play the key roles for future production. Many countries will have to rapidly increase their domestic production and consumption by absurdly large factors to fulfil the scenarios presented in SRES.

Resource-constrained modelling based on mathematical geology and historical time series indicate that most production trajectories in the scenarios are overoptimistic (Rutledge, 2007; Mohr and Evans, 2009; Patzek and Croft, 2010; Höök et al. 2010b). Only the B1 family appears to have any constraints on future coal production compatible with academic studies.

Both Smil (2000) and Bezdek and Wendling (2002) point out that long range energy forecasters have made numerous inaccurate projections, mostly in the form of overestimations. Additionally, many inaccurate forecasts were done in good faith with state-of-the-art models, competent researchers and good funding, showing the difficulty of long-range energy forecasting.

It is argued that many SRES scenarios need to be revised, generally downward, regarding production expectations from coal. Several scenarios also agree poorly with reality over the recent years and some can even be ruled out. SRES is underpinned by a paradigm of perpetual growth and technological optimism as well as old and outdated estimated regarding the availability of coal. As a result, future coal production projections in SRES (2000) are exaggerated and so are the resulting emissions. What kind of repercussions this has on the future climate is an open question which needs to be assessed from several different angles.

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