

Oil Depletion Model

Understanding the Model

The Association for the Study of Peak Oil and gas (ASPO), and the founders of it, have for years tried to collect data concerning world oil production, discovery, and reserves. A huge problem has been to continuously try to improve the data in order to have a reliable base for modelling depletion and to determine the date of peak production and the beginning of decline. The existing public data is by ASPO considered to be unreliable and in some cases even intentionally misleading. (This is further explained below in the paragraph about the OPEC “quota war”.) Therefore, there is a necessity to use all potential, including confidential, sources and the contacts with people who are, or have been, in the business, in order to get the data considerably more reliable. The building of the model has been ongoing for 10 years. More details, new information, and new insights are obtained over time, which calls for adjustments of the model. No major revision to the basic principle has been needed, as the model provides an adequate base for answering questions raised about oil production, discovery, and reserves.

There are at least two different ways of looking at depletion of oil. Firstly, through the eyes of the natural scientists, with practical experience of the oil business, which have taught them to observe nature and to utilise the laws of physics. Secondly, those classical economists, who do not see resource limitations happen in an open market. This updated model is based on accumulated knowledge and experience of people who have had drilling and exploration throughout the world as their profession.

Oil Classification

With the intention of modelling various sorts of oil and gas as accurately as possible, different properties have to be taken into consideration separately. Examples of properties that differ are the depletion profile, how it exists in nature, and the costs and characteristics of the oil or gas. These are different ways of describing, for instance, physical constraints limiting production, such as production capacity from a source, the means of production from the source, and the distribution capacity to the market. Therefore, oil and gas in the model are separated into different categories. Terms as *conventional* and *unconventional* are commonly used as category descriptions. In this model the term *regular oil* is used to avoid confusions. The category *regular oil* is defined as crude oil excluding the following categories:

- Oil produced from Coal and Shale
- Oil produced as Bitumen¹
- Heavy Oil – Oil with an API² -gravity <17,5^{o3}

¹ A generic name for various viscous or solid mixtures of native hydrocarbons, which have lost most of their gaseous material, e.g. Asphalt. Clark, Audrey N. Penguin Dictionary of Geography, Penguin Group, 1998. [Reference](#). Alternatively, the hydrocarbons are young and have yet to mature to light oil. Selley, R.C.;1998; Elements of Petroleum Geology; Academic Press ; USA. [Reference](#).

² A measure of the density of liquid petroleum products, expressed in degrees. Derived from:

$$API \text{ Gravity (deg rees)} = \frac{141,5}{\text{Specific Gravity}} \cdot (-131,5) \text{ Ford, J. Drilling Engineering, Institute of}$$

Petroleum Engineering, Heriot-Watt University, 1999. [Reference](#)

- Extra Heavy Oil – Oil with an API-gravity $<10^4$
- Polar Oil – Oil produced from polar areas, e.g. Alaska and Siberia.
- Deepwater Oil – Oil produced from underneath the ocean floor at water depths >500 metres
- Natural Gas Liquids (NGL), produced from gas fields and gas plants

These categories, read *non-regular oils*, are also important and are of course not excluded from the model, but treated separately due to the different characteristics explained above. There are great difficulties to define accurate boundaries between the different categories in the data available. To date, regular oil has been the dominating part in world oil production according to official numbers, and will most probably continue to be in the future. Therefore, regular oil will be controlling the peak of all production and is for that reason the focus of this study. Gas-liquids are particularly tricky. Gas brought up from gas-capped oilfields can condense when reaching the surface, becoming *condensate*. The condensate is mixed with the oil and is therefore treated accordingly in the model. When the liquids are condensed from gas in gas fields or produced from gas plants they belong to a separate category, since the condensates in this case will deplete in relation to the gas and not the oil. This is in the model determined by looking at the discovery of both oil and gas. Condensate from gas fields greater than 5000 Tcf (trillion cubic feet) is excluded and treated as non-regular oil.

One thing that should be explained early is what in this report is meant by the expression *reserves*. *Reserves*, or *proved reserves*, are described as “the *estimated* quantity of oil or gas which geological and engineering data demonstrate with *reasonable certainty* to be recoverable from known reservoirs under *existing economic and operating conditions*.” Morehouse D.F.; 1997; The Intricate Puzzle of Oil and Gas “Reserves Growth”; Natural Gas Monthly July 1997; Energy Information Administration; USA. [Reference](#). The *reasonable certainty* in the case of the oil depletion model is what people working in the area call the *P50*, i.e. a 50% certainty.

Backdating

Backdating is an important approach considering discovery, used in this model and by ASPO in general. An oilfield is considered found by the first borehole producing oil. All oil ever produced from that field, regardless of economic or technical circumstances, are backdated to the date of the discovery borehole. By using backdating the actually falling discovery trend becomes evident. Furthermore, the trend can be extrapolated and give a good estimate of what is yet to discover.

Oil Production

In order to, as accurately as possible, predict the future oil production for different countries, these are divided into groups describing their relation to the important parameter *midpoint of depletion*. The midpoint is defined as the year when the country has produced half the amount of oil that it can ultimately produce, from both known and unknown fields. The parameter *depletion rate* is described as the rate

³ Private communication Campbell C.J. 2003. [Reference](#).

⁴ Rogner H-H. An Assessment of World Hydrocarbon Resources, Annual Review of Energy and the Environment, 1997. [Reference](#).

between how much oil is produced one year and the total amount of oil yet to produce prior to that same year. The three main groups are as follows:

1. Countries that have past their midpoint of depletion – future production is expected to decline at the current depletion rate.
2. Countries that have not yet reached its midpoint of depletion – future production is assumed to be flat or to rise to the midpoint, decided independently for each country. After the midpoint, production will decline at the midpoint depletion rate. These assumptions have little effect to the overall outcome of the model, as most countries are already close to their midpoint.
3. Countries playing a swing role. The *swing countries* include the five major oil-producing countries of the Middle East (Abu-Dhabi, Iran, Iraq, Kuwait, and Saudi-Arabia including the Neutral Zone, owned jointly by Kuwait and Saudi Arabia). The *non-swing countries* are therefore all other oil producing countries. The production from the swing countries is assumed to make up the difference between production from the rest of the world, within the countries' modelled physical limits, and world demand under alternative scenarios. The amount of oil each swing country is allowed to produce is based on their share of the amount left to produce among the OPEC countries (see table 1). Still, the countries' individual past midpoint depletion is considered. Saudi Arabia is considered as a swing producer within the region, making up the difference between the regional total production and what the individual countries can produce according to the model.

Production Scenarios

There are five alternative scenarios of world demand considered in the model, but the emphasis is put on the base case scenario. The five scenarios are shown in figure 1, and explained below.

1. Very high scenario – World demand and production of regular oil is assumed to increase by 2% annually, until the swing countries' share of production reaches 40%. Thereafter, demand and production is assumed to be flat until the same share exceeds 50%, after which it starts to decline at that year's depletion rate.

World Oil Production

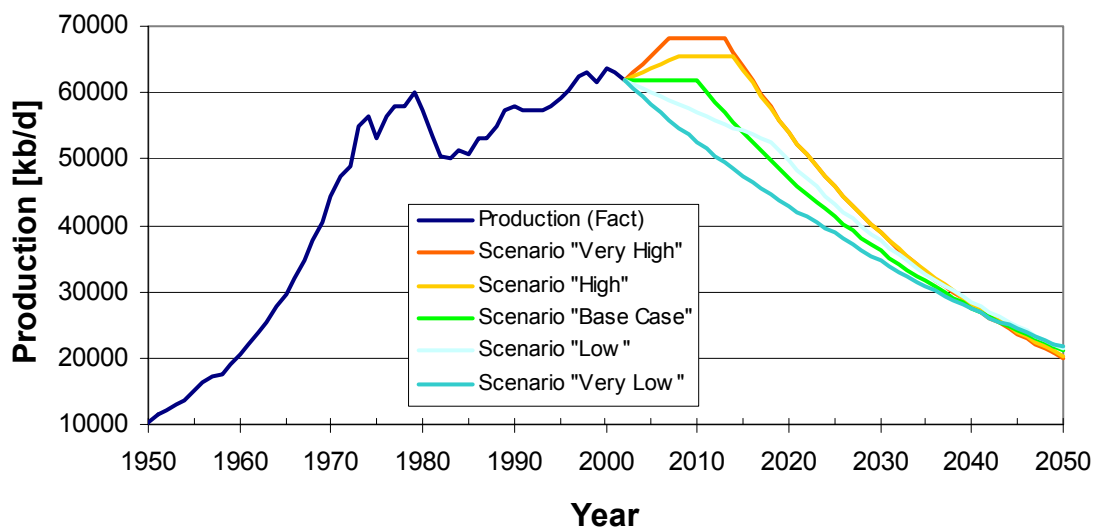


Figure 1. The world oil production up to date and the five scenarios of world oil production and consumption described in the oil depletion model.

2. High scenario – World demand and production of regular oil is assumed to increase by 1% annually. As in the very high scenario, a demand and production plateau is assumed during the time the swing countries' share of production is between 40 – 50%. Thereafter decline starts at the year the share exceeded 50% and at the depletion rate of that year.
3. Base Case scenario – World demand and production of regular oil will be flat until 2010. Thereafter, the demand upon the swing countries will exceed their production capability, which brings their swing role to an end. The following production is assumed to decline at the depletion rate of 2010.
4. Low scenario – World demand and production of regular oil is assumed to decrease by 1% annually until the swing countries' share exceeds 50% and thereafter decline at that year's depletion rate.
5. Very low scenario – World demand and production of regular oil is assumed to decrease by 2% annually until the swing countries' share exceeds 50% and thereafter decline at that year's depletion rate.

Oil Reserves

Modelling the production and discovery of each country was started by collecting data from the journals *World Oil* and *Oil & Gas Journal*. Reported proven reserves was evaluated and adjusted with the purpose of removing the non-regular oils where identification of these was possible. The number was also adjusted to eliminate greater anomalies due to the OPEC "quota war" in the late 1980s. Most OPEC countries increased their reserves extremely from one year to the other, mainly in order to increase their production share. These increases can be seen in table 1. The numbers are then adjusted to give a more reasonable estimate of the amounts in reality

left to produce from known fields, according to ASPO members⁽⁵⁾. A qualitative estimate is also made regarding what is ultimately to be produced from each country. The estimate is mainly based on previous discovery pattern, which is used to forecast future drilling activity and discovery.

It is an iterative process that requires common sense and great input from people with experience in this field to facilitate reasonable estimates despite all the conflicting information. Several of the resulting graphs were used to try and create even better estimates, which produce new graphs and so forth.

Table 1: This table shows OPEC countries' yearly reported reserves in Gb from 1980 to 2002. Blue numbers show unaltered reserves for many years in a row. Yellow fields show the extremely increased reserves from one year to the other, described in the text as the OPEC "quota war". Yearly published reserve data from Oil and Gas Journal.

	Abu Dhabi	Dubai	Iran	Iraq	Kuwait	Neutral Zone	Saudi Arabia	Venezuela
1980	28	1,4	58	31	65	6,1	163	18
1981	29	1,4	58	30	66	6	165	18
1982	31	1,4	57	30	65	5,9	165	20
1983	31	1,4	55	41	64	5,7	162	22
1984	30	1,4	51	43	64	5,6	166	25
1985	31	1,4	49	45	90	5,4	169	26
1986	30	1,4	48	44	90	5,4	169	26
1987	31	1,4	49	47	92	5,3	167	25
1988	92	4	93	100	92	5,2	167	56
1989	92	4	93	100	92	5	170	58
1990	92	4	93	100	92	5	258	59
1991	92	4	93	100	95	5	258	59
1992	92	4	93	100	94	5	258	63
1993	92	4	93	100	94	5	259	63
1994	92	4	89	100	94	5	259	65
1995	92	4	88	100	94	5	259	65
1996	92	4	93	112	94	5	259	65
1997	92	4	93	113	94	5	259	72
1998	92	4	90	113	94	5	259	73
1999	92	4	90	113	94	5	261	73
2000	92	4	90	113	94	5	259	78
2001	92	4	90	113	94	5	259	78
2002	92	4	90	113	94	5	259	78

Model Structure

Main Structure

The whole model is built on spreadsheets within the software Microsoft Excel. There is one Excel file for each region of the world and in every file (read region) there is one spreadsheet for each country. The regions, and the countries included therein, can be seen in table 1 and figure 1. Furthermore, three regions have constellations of countries describing e.g. smaller regions of production. These constellations can be

⁽⁵⁾ e.g. Campbell, C.J. and Laherrère, J.H. See www.hubbertypeak.com for more information on them.

seen as the group of underlined countries, listed in the third column in the same table. Every file has got another four spreadsheets in common:

- One regional spreadsheet where all the data from each country in that region are summed.
- One summary spreadsheet where the central data from every country are summarised and displayed.
- One spreadsheet containing graphs for every country, constellation and for the region as a whole.
- One spreadsheet listing all the giant oil fields⁶, and their sizes, in each region by country.

There are also a number of spreadsheets in some of the regions depicting individual calculations needed in order to obtain appropriate data for certain countries. For instance in the file '*SODM-Middle East Gulf.xls*' there is one spreadsheet describing the five scenarios of the future world oil production, or consumption, described earlier. These scenarios distinguish what effect the world production/consumption will cause to the production of the Middle East Gulf countries. This is explained earlier as the *swing role*. Other additional spreadsheets explain e.g. the production of deep oil in Latin America and Africa and the oil production from the different fields in Alaska.

Spreadsheet Structure

At the top of each country's spreadsheet the name and the region it belongs to are displayed. The different regions the world has been divided into in this model can be seen in figure 2. The header also informs about what version it is and the last date it was revised. The version is determined by the year of the most recent production, i.e. if the last obtained production data is of 2002, the version becomes 2002. The following group of cells is a summary of the central data in the spreadsheet as well as trends and comparisons. Below that the main data of production, discovery, and wildcats⁷ is listed by year from 1930 through 2050. Data on production, discovery, and wildcats before 1930 are summed into the field '*Pre-1930*'. For every year up until the most recent the numbers put in are known from, amongst others, ASPO's archives and journals such as *World Oil* and *Oil & Gas Journal*. The columns these data are put into are:

⁶ An oilfield with reported reserves larger than 0,5Gb. [Reference](#)

⁷ An exploration well drilled in an area where no oil or gas has been produced. Ford, J. Drilling Engineering, Institute of Petroleum Engineering, Heriot-Watt University, 1999. [Reference](#)

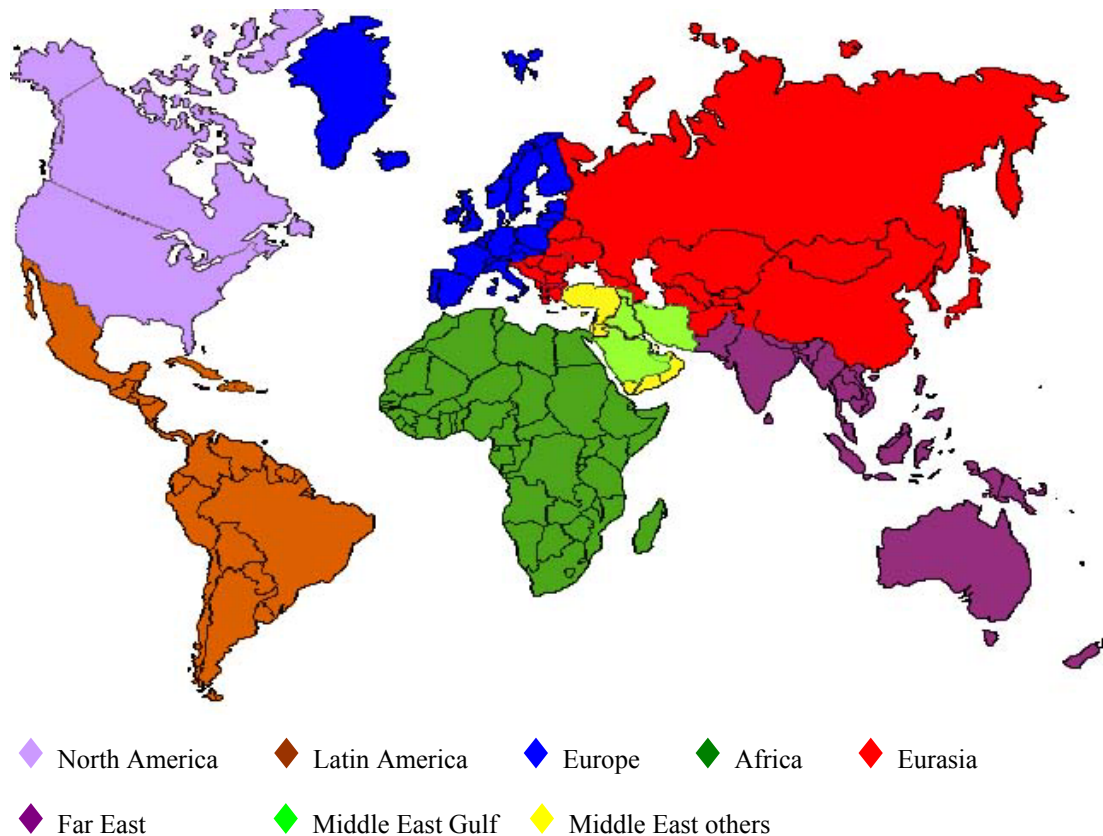


Figure 2: The world has been divided into different regions in the model, as each region, and its countries, has their own Excel file.

- Production [kb/d]
- Number of Wildcats
- Discovery
 - Giant oil fields
 - Oil
 - Condensate
 - Gas

The other columns are calculated from these data, for instance in the *Cumulative* columns, the data is summed for each year in order to get the cumulative amount. To convert numbers into other units, simple conversion factors are used, see (1) below.

$$1 \text{ kb/d} = 1 \cdot 10^3 \text{ barrels/day} = 365 \cdot 10^3 \text{ barrels/year} = 3,65 \cdot 10^4 \text{ Gb/a} \quad (1)$$

Furthermore, the column *Yet-To-Produce* is simply the countries' or the regions' *Ultimate* with the cumulative production for that year subtracted. Another very interesting parameter included in this model is the *Depletion Rate*, explained earlier. There is another column at the end of the spreadsheet explaining the *peak lag* in years between the peak of discovery and the peak of production. The numbers are used to plot the discovery pattern on top of the pattern of production in order to make an assumption about future production based on the discovery to date.

Table 2. A description of the different regions of the world, used in the model, and the countries therein. Some regions have other groups of interest described in the rightmost column, these are smaller internal regions of production. The blue coloured countries are all members of OPEC.

Region	Countries	Underlined Group
Africa	Algeria, Angola, Cameroon, Congo, Egypt, Gabon, Libya, Nigeria, Sudan and Tunisia.	
Eurasia	Albania, Azerbaijan, China, Croatia, Hungary, Kazakhstan, Romania, Russia, Turkmenistan, Ukraine and Uzbekistan.	Former Soviet Union (F.S.U.)
Europe	Austria, Denmark, France, Germany, Italy, Netherlands, Norway and the United Kingdom.	North Sea
Far East	Australia, Brunei, India, Indonesia, Malaysia, Pakistan, Papua-New Guinea, Thailand and Vietnam.	
Latin America	Argentina, Bolivia, Brasil, Chile, Colombia, Ecuador, Mexico, Peru, Trinidad and Venezuela.	
Middle East Gulf	Abu Dhabi, Iran, Iraq, Kuwait, Neutral Zone and Saudi Arabia.	Swing Countries
Middle East (Other)	Bahrain, Dubai, Oman, Qatar, Sharjah, Syria, Turkey and Yemen.	
North America	Canada and the USA	
Other	Small and future producers. ⇒ Afghanistan, Ajan, Bangladesh, Barbados, Belarus, Benin, Bulgaria, Cambodia, Chad, Congo (Zaire), Cuba, Czech Republic, Equatorial Guinea, Ethiopia, Falkland Islands, Georgia, Ghana, Greece, Guatemala, Ireland, Israel, Ivory Coast, Japan, Jordan, Kyrgyzstan, Latvia, Lithuania, Madagascar, Malaysia/Thailand, Moldova, Mongolia, Morocco, Mozambique, Myanmar, Namibia, New Zealand, Niger, Philippines, Poland, Ras al Khaimah, Senegal, Serbia, Slovakia, Somalia, South Africa, Spain, Suriname, Sweden, Switzerland, Taiwan, Tajikistan, Tanzania and Timor Gap.	
Unforeseen	Unforeseen oil that is yet to find.	

Hubbert Curve

At the bottom of each spreadsheet numbers for the *Hubbert curve* and the *creaming curve hyperbola* are calculated and presented. The Hubbert curve explains the theoretical oil production cycle. This is under the assumption of production without economical or political restraints. The area beneath the Hubbert curve is the same as the area beneath the predicted production curve, since they are both based on the ultimate amount of oil each country can produce. The Hubbert curve H is explained below.

$$H = 4 \cdot \frac{PP}{2 + e^{-b(t-tp)} + e^{b(t-tp)}} \quad \text{where} \quad \begin{cases} PP = \text{Amount at peak production [Gb]} \\ U = \text{Ultimate amount to be produced [Gb]} \\ b = \text{Coefficient} = 4 \cdot \frac{PP}{U} \\ t = \text{Year of interest} \\ tp = \text{Year of peak production} \end{cases}$$

Creaming Curve Hyperbola

The creaming curve hyperbola is fitted in with the creaming curve, where cumulative wildcats are plotted against cumulative discovery. The hyperbola theoretically describes the amount of oil discovered per drilled wildcat. The discovery per drilled wildcat can be approximated by this hyperbola under the assumption that the largest fields are found first. Extended to e.g. twice as many wildcats as the present number, the hyperbola can give a good estimate of the amount of oil that will ultimately be produced by a country or region. The curve C is explained below. Further information and description about the curves and formulas can be found on www.hubbertpeak.com.

$$C = \frac{D_{tot} \cdot D_{1/2}Wc}{2 \cdot D_{1/2}Wc - D_{tot} + \frac{Wc_{tot}(D_{tot} - D_{1/2}Wc)}{Wc_{cum}}}$$

$$\text{where} \quad \begin{cases} D_{tot} = \text{Total amount discovered [Gb]} \\ Wc_{tot} = \text{Total amount of wildcats drilled} \\ D_{1/2}Wc = \text{Amount discovered at half the } Wc_{tot} \text{ [Gb]} \\ Wc_{cum} = \text{Cumulative amount of wildcats drilled the year of interest} \end{cases}$$

The following chapter describes 40 different emission scenarios from the Intergovernmental Panel on Climate Change SRES, and their assumptions and uncertainties.

In order to describe possible future emissions and their driving forces, the Intergovernmental Panel on Climate Change (IPCC) developed a set of four scenario families. Altogether these families comprise 40 scenarios described in IPCC's Special Report on Emissions Scenarios – SRES. To simplify the procedure of depicting alternative future developments each of the four scenario families is described by a specific storyline. Each of the six participating modelling teams used computer models and experience considering long-range development of economic, technological, and environmental systems to generate different quantifications of the storylines, which develop the different scenarios. The different modelling teams can be seen in table 3. All scenarios derived from the same storyline constitute the scenario family. Each scenario future is described by a storyline based on the following variables:

- Demographic
- Social
- Economic
- Technological
- Environmental
- Policy

Table 3. The six modelling teams that developed the 40 SRES scenarios. Both the abbreviations and the teams' origins are explained.

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

Storylines were formulated by the writing team in a process that identified driving forces, key uncertainties, possible scenario families, and their logic. Within each

family different scenarios explore variations of global and regional developments and their implications for greenhouse gases (GHG). There is no *business-as-usual* or *disaster* scenario and it was also decided that possible *surprises* would not be considered. However, a future considered as negative by some people may be seen as positive by others. The storylines represent scenario families that can include both success and failure, depending on the viewpoint of the beholder. So-called disaster scenarios typically involve large-scale environmental or economic collapses, and extrapolate current unfavourable conditions and trends in many regions. Many of such scenarios suggest that catastrophic developments may draw the world into a state of chaos within one or two decades. In such scenarios GHG emissions might be low because of low or negative economic growth, but it seems unlikely they would receive much attention in the light of more immediate problems. Hence, SRES does not analyse such futures.

The titles of the storylines have been kept simple: A1, A2, B1, and B2. They are shown very straightforwardly as a two-dimensional tree (Figure 3). The two dimensions shown indicate the global – regional and the economic – environment orientation, respectively. The A1 storyline branches out into several groups of scenarios, for instance one that explores fossil-intensive developments in the energy system. The separation into different scenario groups was introduced to the A1 scenario described by its high growth with high technology nature, in which differences in alternative technology developments account for large differences in future GHG emission levels. Because of this the A1 scenario family requires more explanation than the other three.

The four storylines and scenario families describe future worlds that are generally wealthier compared to the current situation. They range from very rapid economic growth and technological change to high levels of environmental protection, from low to high global populations, and low to high GHG emissions. Furthermore, they do not include additional climate initiatives such as policies to limit GHG gases or to adapt to the expected global climate change. These four scenario families are also representative of a broad range of scenarios found in the literature, but not based on any of them in particular.

Taking into consideration the immense development during the last century, it is hard to imagine what the next century will be like. Therefore, the main characteristics of each storyline assume a distinctly different direction for future developments. These are summarised in table ##.

- The A1 storyline and scenario family describes a future world of very rapid economic growth, low population growth, and the rapid introduction of new and more efficient technologies. The key schemes are convergence among regions, capacity building, and increased cultural and social interactions, with a significant reduction in regional differences in per capita income. The storyline branches out into several groups of scenarios, for instance one that explores fossil-intensive developments in the energy system.
- The A2 storyline and scenario family describes a very heterogeneous world. The key scheme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in high population growth.

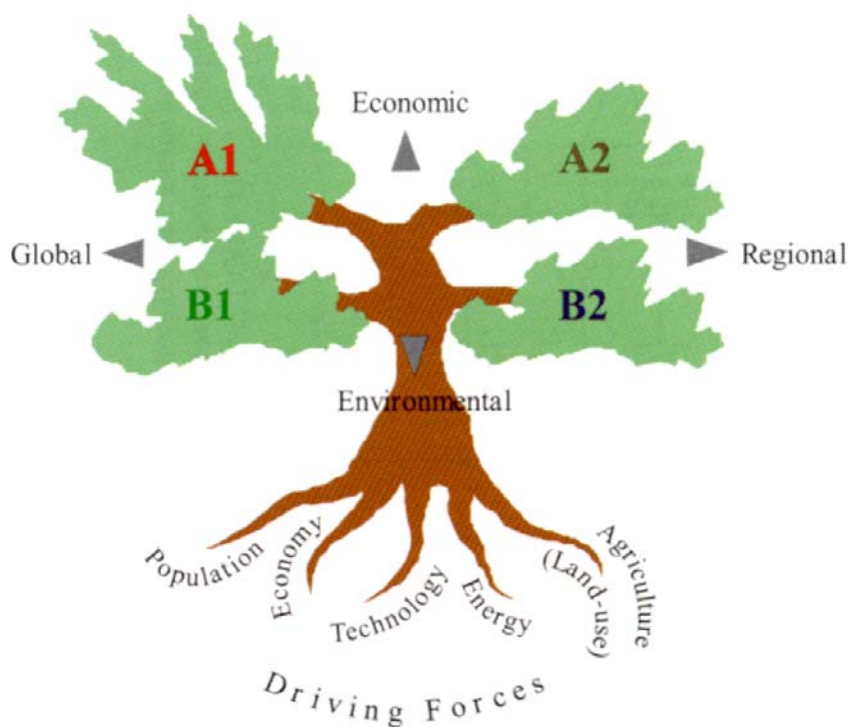


Figure 3. Schematic illustration of SRES scenarios. The four scenario “families” are shown, very simplistically, as branches of a two-dimensional tree. Each scenario family is based on a common specification of some of the main driving forces. The A1 storyline branches out into several groups of scenarios to illustrate that alternative development paths are possible within one scenario family. The figure is taken from IPCC’s Special Report on Emissions Scenarios (SRES).

Reference.

Economic development is primarily regionally oriented and per capita economic

growth and technological change are more fragmented and slower than in other storylines.

- The B1 storyline and scenario family describes a convergent world with the same low population growth 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 introduction 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.
- The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with moderate population growth, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

Table ##. Main characteristics of development in the different scenario families and groups, as applied to harmonised scenarios.

Family Scenario group	A1				A2	B1	B2
	A1C	A1G	A1	A1T	A2	B1	B2
Population growth	Low	Low	Low	Low	High	Low	Medium
GDP growth ^(a)	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-med.	Low-med.	Low	Low	Medium-High	High	Medium
Resource availability ^(b)	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 and dematerialisation	“Dynamics as usual”

^(a) GDP = Gross Domestic Products

^(b) Resource availability of conventional and unconventional oil and gas.

All the qualitative and quantitative features of scenarios belonging to the same family were set to match the corresponding features of the underlying storyline. Together, 26 scenarios were *harmonised* to have the same common assumptions about global population and GDP (Gross Domestic Product) development. Although the scenarios share a few common assumptions they differ quite substantially in others. These

assumptions are e.g. availability of fossil-fuel resources, the rate of energy-efficiency improvements, the extent of renewable-energy development, and the resulting GHG emissions. The remaining 14 scenarios explain alternative interpretations of the four scenario storylines, such as different rates of economic growth and variations in population projections. These variations reflect the modelling teams' choice as an alternative to the *harmonised* scenarios. Another form of scenarios is the marker scenario, which are considered by the SRES writing team to be the most illustrative scenario of a particular storyline but are neither more nor less likely than any other scenario.

Scenario storylines

A1 Storyline and Scenario Family

The A1 storyline is described by rapid and successful economic development, where regional average income per capita converges, which means that current distinctions between poor and rich countries eventually disappear. The main dynamics are:

- Strong dedication to market based solutions
- High savings and dedication to education at the household level.
- High rates of investment and improvement in education, technology, and institutions at the national and international levels.
- International mobility of people, ideas, and technology

The change to economic convergence is a result from advances in transport and communication technology, shifts in national policies on immigration and education, and international cooperation in the development of national and international institutions that improve productivity growth and technology diffusion. These scenarios are dominated by an American or European entrepreneurial, progress-oriented perspective where technology, especially communication technology, plays a significant role. They underline market-oriented solutions, high consumption of products and services, advanced technology, and intensive mobility and communication. Three of these High Growth scenarios in the A1 family, generated with the MESSAGE model, are developed together with World Energy Council (WEC). In the A1 scenario family the trends in population growth are directly linked to the economic trends, as wealth is related to long life and small families (low mortality and low fertility). Global population grows to about nine billion by 2050 and declines to about seven billion by 2100.

Energy and mineral resources are rich in this scenario family as rapid technological progress reduces the amount of resources required for the same level of production and it increases the economically recoverable reserves. Furthermore there is an average annual decrease in the rate of final energy intensity (energy use per unit of GDP). Environmental improvements are valued and rapid technological progress makes it possible to use natural resources for other purposes than they are used for today. In this storyline the concept of environmental quality changes from present weight on conservation of nature to active management of natural and environmental services, which increases the ability of ecosystems to recover from disturbances. High

incomes also translate into high car ownership, growing suburbs, and dense national and international transport networks.

In the rapid changing world, which the A1 scenario family describes, several scenarios indicate uncertainty in the development of energy sources and conversion. Some scenario groups describe a carbon-intensive future comparable to the development strategy of countries that at present have abundant domestic coal resources. Other scenario groups describes an increasingly dependence on unconventional oil and gas resources. A third group of scenarios describes a future shifting towards renewable energy sources possibly also towards nuclear energy. A fourth group (including the A1 marker) predicts a diverse set of technologies and supply sources, with technology improvements and resource assumptions such that no single energy source is exceedingly dominant. These groups depict futures with a significantly different amount of GHG emissions, from the carbon-intensive to the decarbonisation paths, they vary as much as all of the other driving forces across the other SRES scenarios.

A2 Storyline and Scenario Family

The A2 scenario family represents a differentiated world that is, compared to the A1 storyline, characterised by lower trade flows, relatively slow capital stock turnover, and slower technological change. This future also depicts self-reliance in terms of resources and less weight on economic, social, and cultural interactions between regions. People, ideas, and capital are considered less mobile so that technology diffuses more slowly than in the other scenarios. With the weight on family and community life, fertility rates decline relatively slowly, which makes the A2 population the largest among the storylines with 15 billion people by 2100. Global average income per capita in A2 is low compared to other storylines.

The A2 scenario is a more heterogeneous world compared to A1 considering technological change. It is more rapid than average in some regions and slower in others, as industry adjusts to local resource capacity, culture, and education levels. Regions with richer energy and mineral resources become more resource-intensive economies. Other regions, poor in resources, put emphasis on minimising import dependence through technological innovation in order to improve resource efficiency and make use of alternative inputs. The resource availability in different regions mainly determines the fuel mix used. High-income but resource-poor regions shift towards advanced post-fossil technologies, such as renewable or nuclear energy, while low-income resource-rich regions generally rely on older fossil technologies.

Because of the significant food requirements in the A2 world, agricultural productivity is one of the main focus areas for innovation and research, development, deployment efforts, and environmental concerns. Global environmental concerns are relatively weak, although attempts are made to bring regional and local pollution under control and to maintain environmental consideration.

B1 Storyline and Scenario Family

The B1 future describes a future containing a high level of environmental and social consciousness combined with a globally consistent approach to a more sustainable development. Environmental awareness might increase as clear evidence that impacts of natural resource use and global and regional pollution cause a serious threat to the continuation of human life on earth. In this storyline, governments, businesses, the media, and the public increase their interest in the environmental and social aspects of development. Technological change plays an important role.

The B1 storyline has a balanced economic development and efficient efforts to achieve fair income distribution. Although B1, as A1, describes a fast-changing and convergent world, the priorities differ. The B1 world invests a large part of its gains in improved efficiency of resource use (dematerialisation), equity, social institutions, and environmental protection. In some places in the B1 world, people may not achieve the main social and environmental intentions of the mainstream. Vast income redistribution and probably high taxation levels may negatively affect the economic efficiency and functioning of world markets. Specific efforts are made to increase resource efficiency to achieve the goals stated above. Systems of incitements, combined with advances in international institutions, allow the rapid diffusion of cleaner technology. Legislations are adopted to reduce material wastage by maximizing reuse and recycling. The combination of technical and organisational change generates high levels of material and energy saving, as well as reduction in pollution.

Global population reaches nine billion by 2050 and declines to about seven billion by 2100. This is a world with high levels of economic activity and important and intentional progress towards international and national income equality. Global income per capita is significantly lower than in A1. Of this income, more is spent on services than on goods, on quality rather than quantity, because the emphasis on material goods is less and also resource prices are increased by environmental taxation.

As conventional oil and gas resources decline, the B1 storyline describes a relatively smooth transition to alternative energy systems. The B1 world strives towards post-fossil technologies and during the transition conventional and unconventional gas is used significantly since natural gas is the cleanest fossil resource. The push towards post-fossil technologies is mainly driven by environmental concerns.

Because of the high environmental consciousness and institutional effectiveness in the B1 storyline, environmental quality is high, as most potentially negative environmental aspects of rapid development are anticipated and effectively dealt with locally, nationally, and internationally. For instance, air pollution from one country harming another is basically eliminated in the long term. Cities are compact and designed for public and non-motorised transport, with suburban developments strictly controlled. Strong incentives for low-input, low-impact agriculture, along with maintenance of large areas of wilderness, contribute to high food prices and much lower levels of meat consumption than those in A1. These hands-on local and regional environmental processes and policies lead to relatively low GHG emissions, even without specific restrictions to decrease climate change.

B2 Storyline and Scenario Family

The B2 world has an increased concern for environmental and social sustainability compared to the A2 storyline. Environmentally aware citizens increasingly influence government policies and business strategies at the national and local levels, with a trend towards local self-reliance and regional decision-making structures and institutions. Human welfare, equality, and environmental protection all have high priority, and they are dealt with through community-based social solutions as well as technical solutions, although implementation rates vary across regions.

Effort is extensively put into education and welfare programs and this reduces mortality and somewhat also fertility. The population reaches about 10 billion people by 2100, consistent with both the UN (United Nations) and IIASA (International Institute of Applied Systems Analysis) median projections. Income per capita grows at an intermediate rate and international income differences decrease, although not as rapidly as in storylines of higher global convergence.

High educational levels usually encourage both development and environmental protection. In the B2 storyline, one of the few common international priorities still left is environmental protection. Nevertheless, strategies to tackle global environment challenges are not of a central priority and are therefore less successful compared to local and regional environmental response strategies. The governments have difficulties designing and implementing agreements that combine global environmental protection, even when this could mean shared economic benefits.

The global emphasis on technological development is less significant in the B2 storyline compared to A1 and B1. Investments in energy research and development continue to decrease globally, and instruments for international diffusion of technology and knowledge stay weaker than in A1 and A2 storylines. Some regions, which have fast economic development and limited natural resources, put specific emphasis on technology development and cooperation on equal conditions.

One particular focus of community innovation is urban and transport infrastructure, and this contributes to a lower level of car dependence and less urban growth. An emphasis on food self-reliance contributes to a shift in dietary patterns towards local products, with relatively low meat consumption in countries with high population densities.

Depending on the availability of natural resources, energy systems differ from region to region. The need for more efficient usage of energy and other resources encourages the development of less carbon-intensive technology in some regions. Environmental policy cooperation at the regional level leads to success in the management of some transboundary environmental problems. Although the global energy system stays primarily hydrocarbon-based to 2100, a gradual transition occurs away from the current share of fossil resources in world energy supply, with a corresponding reduction in carbon intensity.

Translation of storylines into scenario drivers

A1 scenarios

The A1 marker scenario was developed by the AIM modelling team. This first group of A1 scenarios assumes what the modelling teams consider as a balanced progress across all resources and technology from energy supply to end-use. The modelling teams also consider it to assume balanced land-use changes. There are three other

groups of A1 scenarios, which each illustrates alternative paths of the future considering different resource and technology development assumptions:

- *A1C*: clean-coal technologies that are generally environmentally friendly with the exception of GHG emissions.
- *A1G*: an oil and gas rich future, with a rapid transition from conventional resources to rich unconventional resources⁸ including methane clathrates⁹.
- *A1T*: a non-fossil future, with a rapid development of solar and nuclear technologies on the supply side and mini-turbines and fuel cells used in energy end-use applications.

The MiniCAM modelling team also evaluated alternative interpretations of the A1 scenario storyline with different demographic, economic, and energy development patterns (*A1v1*-MiniCAM and *A1v2*-MiniCAM) on top of the alternative technology-resource developments examined in the other A1 scenarios.

A2 scenarios

The A2 marker scenario was developed by the ASF modelling team. An alternative interpretation of the A2 scenario storyline in the form of a delayed development or transitional scenario between the A2 and A1 scenario families was developed by the MiniCAM modelling team here as well (*A2-A1*-MiniCAM).

B1 scenarios

The B1 marker scenario was developed by the IMAGE modelling team. Some of these scenarios explore alternative technological developments (similar to the A1 scenario, e.g. *B1T*-MESSAGE) or alternative interpretations on rates and potentials of future dematerialisation and energy-intensity improvements (e.g., *B1High*-MESSAGE and *B1High*-MiniCAM explore scenario sensitivities of higher energy demand compared to the B1 marker scenario).

B2 scenarios

The B2 marker scenario was developed by the MESSAGE modelling team. Some models (e.g., *B2*-MARIA or *B2High*-MiniCAM) offered additional perspectives of both inter- and intra-model variability in the interpretation of the B2 storyline, particularly with respect to resource availability and technology development assumptions and their resulting impact on GHG emissions.

The role of prices in SRES scenarios

The SRES scenarios were not intended to predict future energy prices, nor were the scenarios intended to predict factors such as future energy taxation. Price information comes into the long-term emission models either in form of scenario assumptions

⁸ Conventional and unconventional resources see regular and non-regular described in the previous chapter describing the oil depletion model.

⁹ Methane hydrates in crystallised formations beneath the ocean floor.

outside the SRES, or it is derived within models based on simple assumptions of price formation mechanisms that are usually based on marginal cost information.

Energy intensities, Energy demand, and Structure of energy use

Energy intensities are, in all marker scenarios, predicted to decline with increasing income levels. Technological change, which is the common source of economic growth and energy intensity improvements, is described to be the main reason for this decline. The SRES 40 scenarios of total world primary energy production, and primary energy production from oil, gas, and coal are shown in figures ### - ###. The numbers needed in order to produce these and the following SRES graphs were downloaded from the internet, from IPCC's homepage. (http://sres.ciesin.org/final_data.html) **Reference.**

A1 scenarios

In the A1 marker scenario, improvements in energy efficiency on the demand side are assumed to be relatively low, because of low energy prices caused by rapid technological progress in resource availability and energy supply technologies. Other A1 scenarios indicate a wide range in energy intensity improvements and resultant energy demand. The range between energy intensity across scenarios is in general larger in the 1990 base year than towards the end of the scenarios simulation. This is a result from alternative estimates and model specifications of non-commercial energy use. The high-income characteristics of the A1 world will make the use of non-commercial energy to decline and later to end altogether. Because of that, differences in energy intensities across models become much smaller. The A1T scenario group explores how the diffusion of a whole host of new energy end-use technologies (e.g., micro turbines and fuel cells) results in significant additional improvements in efficiency and then also higher energy intensity improvements. Furthermore, they generate lower final energy demand at equal or lower energy costs compared to other A1 scenarios.

A2 scenarios

Final energy intensities in the A2 marker scenario improve gradually. It is the product of regional GDP growth and energy intensity improvements that determines the final energy demand across regions. Global primary energy use per unit GDP improves through scenarios over time. This mainly reflects the low per capita GDP growth of this scenario, which translates into low rates of energy intensity improvement. Nonetheless, the resultant energy intensities are comparable to current Western European levels, as are income and energy use per capita. In other words, the scenario describes a global picture by 2100 quite similar to that of Western Europe of today.

B1 scenarios

Energy intensity improvements in the B1 marker scenario result from energy efficiency investments brought about by increases in fuel and electricity prices and technological innovations (including assumptions on taxes and perceived premium values for clean fuels). There is an also rather high rate of energy intensity reduction

towards the end of the timescale, which originates from the specific assumption that less industrialised regions catch-up. The demand for electricity is assumed to rise faster than for non-electricity energy, and may pose one of the capital availability constraints in this scenario. Most scenarios explore the implications for energy demand of less rapid dematerialisation tendencies of the economy, especially for developing countries. However, current knowledge about rates and direction of dematerialisation of economic activities are limited.

B2 scenarios

The evolution of the final energy demand levels and structure in the developing regions follows patterns that are similar to the historical development in the now-industrialised regions of the world. This again is consistent with the “dynamics-as-usual” interpretation of the B2 storyline. Improvements in energy intensity are generally higher in regions far away from the energy-intensity frontier and also faster in those for which the capital turnover rate (i.e., GDP growth) is higher. The trend is towards energy reaching the consumer in more flexible, more convenient, and cleaner forms. This reflects that people with higher income are willing to pay more for more convenient energy forms. Therefore, the final energy mix is characterised by growing importance and dominated of grid-dependent fuels, such as electricity, district heating, and gas. Consistent with the storylines and the higher income levels of A1 and B1, this change in final energy structure is faster in these scenario families than in the other two scenario families. These scenario differences mainly reflect differences in per capita income levels.

IPCC's 40 Scenarios of World Primary Energy Produced from Oil

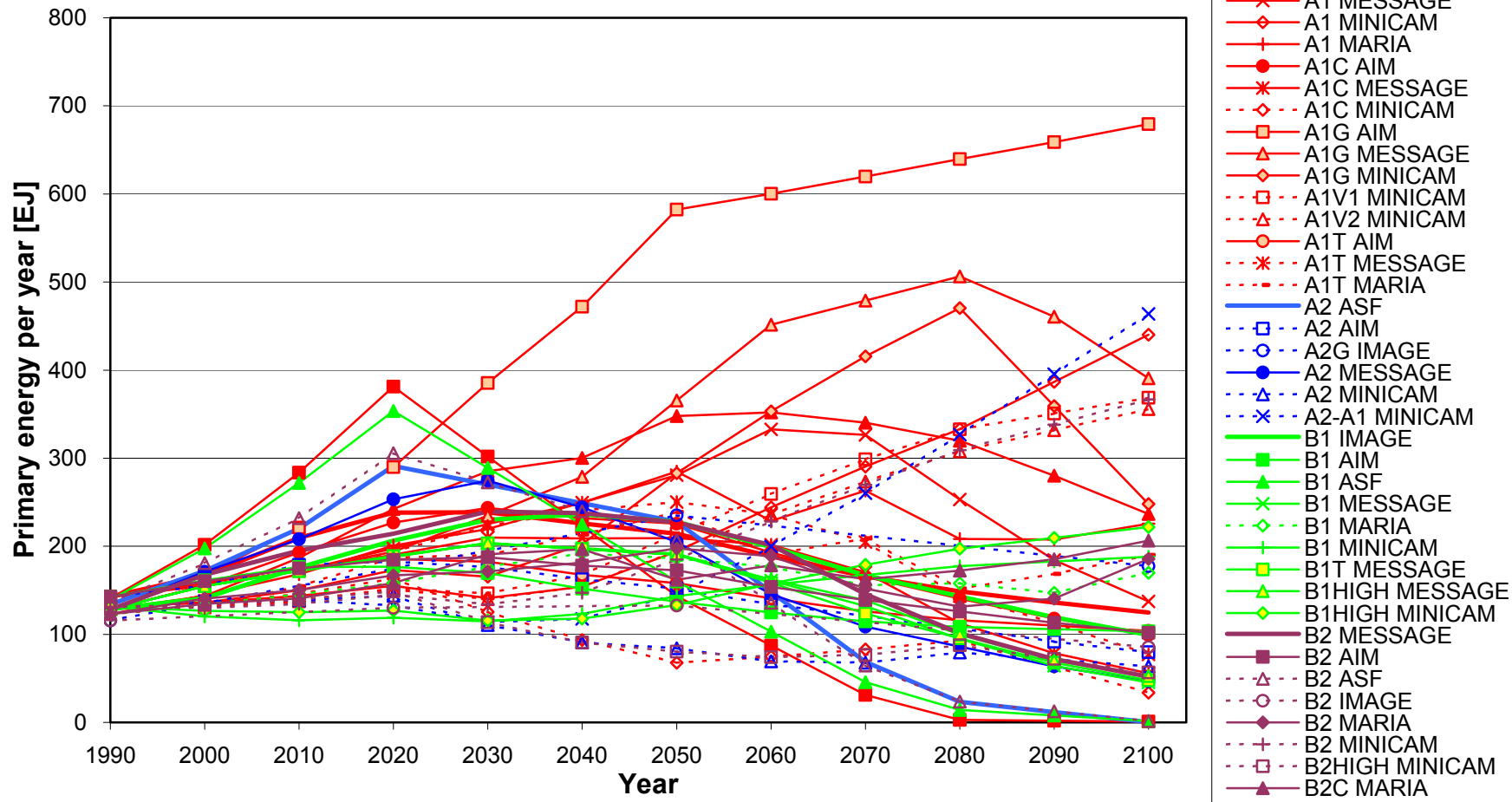


Figure ##. IPCC's 40 scenarios on world primary energy produced from oil 1990-2100.

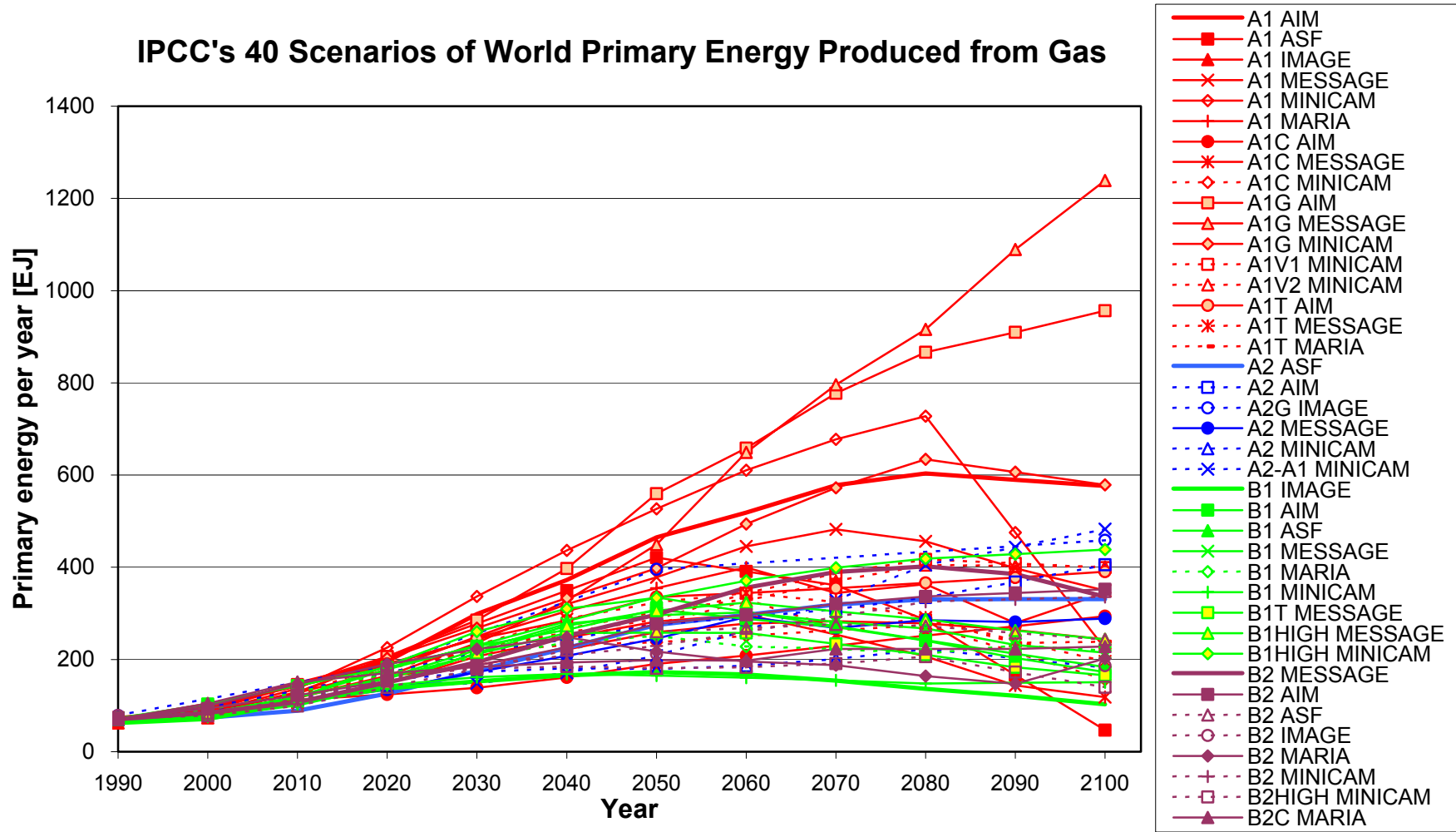


Figure ##. IPCC's 40 scenarios on world primary energy produced from gas 1990-2100.

IPCC's 40 Scenarios of World Primary Energy Production from Coal

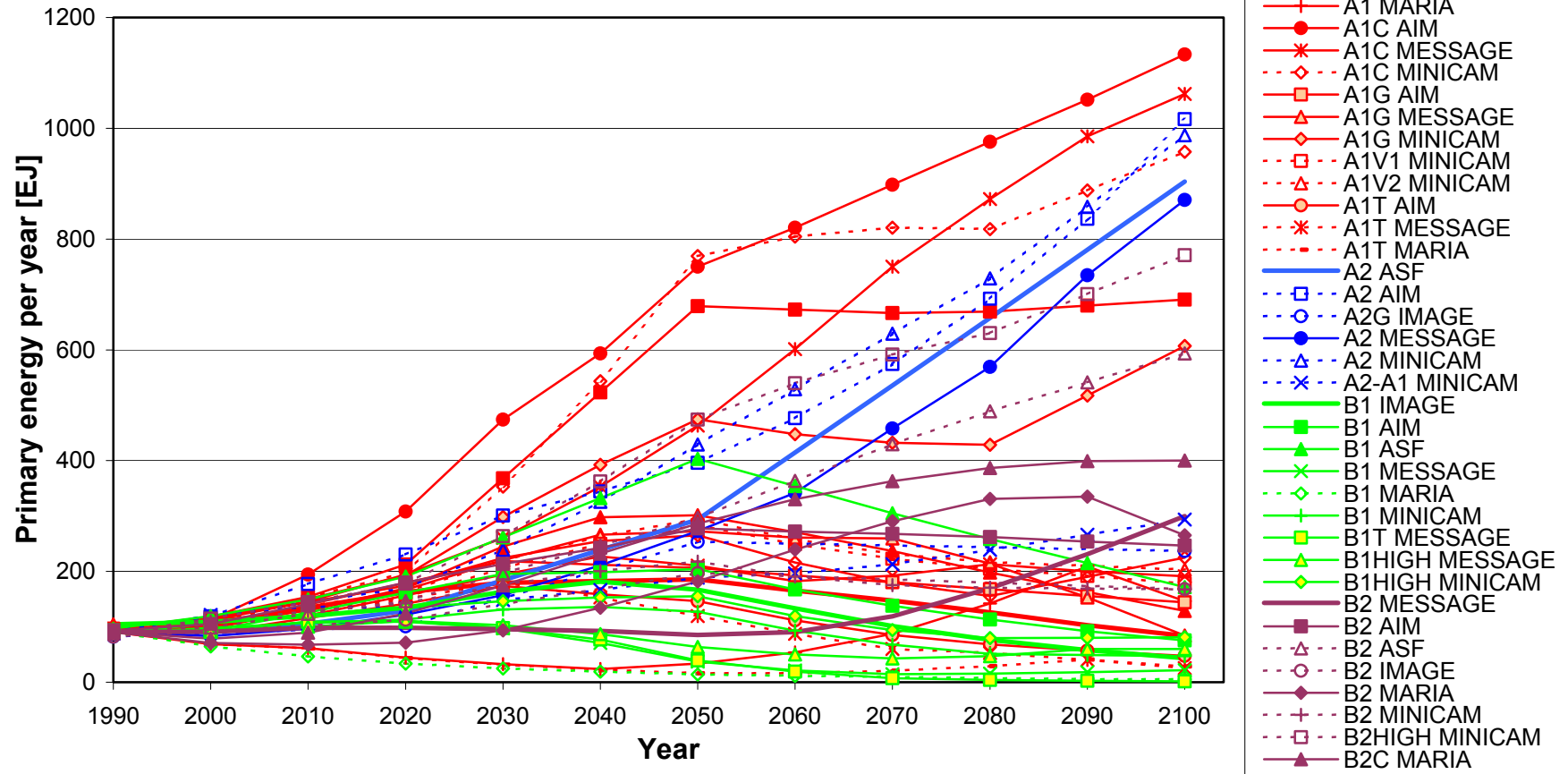


Figure ###. IPCC's 40 scenarios on world primary energy produced from coal 1990-2100.

Resource availability

Resources taken into account by the SRES are existing reserves, resources that have yet not been discovered or that need further techno-economical development to become available, and other occurrences of hydrocarbons in the Earth's crust. Oil, gas, and Uranium occur in deposits that need to be found, and the exploration for new resources is related to the needs for production over the next few decades rather than to a need to define what might ultimately be available for exploration. As a result, the ultimate resource base is uncertain. Coal is a different story, it occurs in layers over wide areas and very little exploration is needed to give an estimate of potentially available resources. The most important uncertainty is whether or not they could be mined with the technologies and economics of today. Finally, the renewable sources of energy depend on technological development and cost reductions in progress.

The conventional oil industry of today is relatively mature and even for the SRES writing team the question is at what point of the 21st century the current reserves will start to run out. Unconventional resources are also available, such as shale oil, bitumen, and heavy oil. They are starting to be used and they will, according to SRES, extend current conventional oil reserves. The gas industry of today is less mature and much more remains to be discovered, especially in areas that today do not have the infrastructure to use gas and exploration has not been motivated in the areas as a result of that. There is also a large amount of unconventional gas discovered, some of which e.g. the US has already put into production. Additionally, huge quantities of natural gas are believed to exist as methane hydrates on the ocean floor and technology development may make it possible to exploit these at some stage. With coal, the question is not of discovery but one of economics, accessibility, and environmental acceptability.

Long-term emission scenarios depend on quantification by formal models, therefore one important distinction that needs to be made is the one between assumptions concerning the ultimate resource base and projected actual resource use. Of course more resources than what is available cannot be used, which gives the model one specified constraint. Actual resource use on the other hand, or what is usually called "call on resources", depends on several other factors represented in models, such as:

- Future price levels
- Assumptions on future technology improvements

It is evident that, in the absence of climate policies, none of the SRES scenarios depicts a premature end to the fossil-fuel age. Invariably, cumulative fossil-fuel use to 2050 (not to mention to 2100) exceeds the quantities of fossil fuels extracted since the onset of the Industrial Revolution, even though the "call on" fossil resources differs significantly among the different scenarios.

A1 scenarios

Energy resources are predicted to be plentiful by assuming a large future availability of coal, unconventional oil, and gas as well as high levels of improvement in the efficiency of energy exploitation technology, energy conversion technologies, and transport technologies. The grades of energy resources used in the model differ on the basis of extraction cost. For A1, large amounts of unconventional oil and natural gas

in assumed. Resource availability and reliance uncertainties are also explored through additional scenario groups within this family. Three of these (*AIC*, *AIG*, and *AIT*) explore more extreme patterns of reliance on particular resources and technologies compared to the more “balanced” tendencies in the original A1 scenarios.

The coal intensive group *AIC* is restricted mainly to conventional oil and gas, which results in among the lowest cumulative oil and gas use of all scenarios. The scenario illustrates the long-term GHG emission implications of quickly running out of conventional oil and gas combined with rapid technological progress in developing coal resources and clean coal mining and conversion technologies. As a result the cumulative coal use is very high.

The group *AIG* assumes oil and gas resources to be plentiful because of the assumed development of economic extraction methods for unconventional oil and gas, including methane clathrates. The high oil and gas extraction mostly reflects current awareness that radical technological change needs to occur to translate a significant part of the resource base of unconventional oil and gas into potentially recoverable resources, a development that needs support by development of non-fossil alternatives. Cumulative coal extraction in *AIG* is relatively low.

As a result of fast technological progress in post-fossil alternatives in the technology-dynamic *AIT* scenario group, the call on oil and gas resources are comparatively modest, quite similar to the *AIC* scenario group. The main difference is that because of the improvements in non-fossil alternatives the call on coal resources remains modest as well.

A2 scenarios

Resource availability assumptions for the *A2-ASF* world are generally rather conservative, essentially that current conventional estimates of petroleum resource availability are not expanded. Unconventional hydrocarbons, such as methane clathrates and heavy oils, do not come into large-scale use. As a result, coal resource use is the highest among the SRES marker scenarios. The A2 marker scenario quantification of oil, natural gas, and coal resource availability reflects the “An Assessment of World Hydrocarbon Resources, Rogner H-H, Annual Review of Energy and the Environment”, 1997. **Reference** estimates for conventional oil and coal resource availability.

Overall there is an increasing reliance on coal resources. The *A2G-IMAGE* scenario assumes that a significant fraction of methane hydrate occurrences become technically and economically recoverable in an A2 world. The opposite end of the resource availability spectrum is explored in the A2-MiniCAM scenarios. First, methane clathrates are assumed not to become available. The call on resources focuses more on coal or unconventional oil and gas. The range of reliance on coal resources is therefore an inverse image of the range of oil and gas resource availability. It is hard to tell what the development will be like, and it is here demonstrated that the uncertainties in fossil resource availability might be much larger than assumed a decade ago.

B1 scenarios

Assumptions on the fossil fuel resource base used in the B1 marker scenario quantification are based on the estimates of ultimately recoverable conventional and

unconventional fossil resources described in Rogner (1997). **Reference.** The capital output ratio of resource exploitation is assumed to rise with progressive resource depletion. The supposed availability of huge non-conventional occurrences of oil and natural gas, with a geographic distribution clearly different from the distribution of conventional oil and gas, has significant implications for fuel supply and trade patterns in the long run.

B2 scenarios

The availability of fossil energy resources in the B2 marker scenario is assumed to be conservative, in line with the gradual change philosophy of the B2 scenario storyline. Therefore, oil and gas availability expands only gradually while coal continues to be abundant. Assumed oil and gas resource availability does not extend much beyond current conventional and unconventional reserves. Through gradual improvements in technology, a larger share of unconventional reserves and some additional resource categories are assumed to become available at improved costs over the 21st century. The availability of oil and gas, in particular, is limited compared to the estimated magnitude of global fossil resources and occurrences. This translates into relatively limited energy options in general and extends also to non-fossil energy options. The largest uncertainties in the A2 scenario family relate to the different interpretations of the more gradual change under a “dynamics-as-usual” philosophy that characterises the B2 scenario storyline. The lower resource-availability assumptions for oil and natural gas lead to a higher reliance on coal and non-fossil alternatives.

Technological Change

As a consequence of the “multi-model approach” used in SRES, detailed improvement assumptions and scenario implementations for individual technologies vary greatly from one model to another. This although the same storyline characteristics were used as guiding principles and many scenarios share similar assumptions on improvement potentials for different technologies. The different technological improvements for each scenario storyline are described in table ##.

The A1 marker scenario describes the “balanced” technology development group of A1 scenarios, it assumes significant innovations in energy technologies, which improve energy efficiency and reduce the cost of energy supply. Consistent with the A1 scenario storyline, such improvements occur across the board and neither favour nor penalise particular groups of technologies. A1 assumes, in particular, drastic reductions in power-generation costs, through the use of solar, wind, and other modern renewable energies, and significant progress in gas exploration, production, and transport. Alternative scenario groups explore path-dependent scenarios in which technologies evolve on equally largely exclusive development paths. The historical **Table ##.** Summary of technology improvements for extraction, distribution, and conversion technologies assumed in the SRES scenarios. The classification examines technology dynamics across the four marker scenarios and the four A1 scenario groups relative to each other. Note that rates can be heterogeneous among world regions. A1 scenarios

Scenario	Coal	Oil	Gas	Non-fossil
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A1	High	High	High	High
A1G	Low	Very high	Very high	Medium
A1C	High	Low	Low	Low
A1T	Low	High	High	Very high
A2	Medium	Low	Low	Low
B1	Medium	Medium	Medium	Moderate-high
B2	Low	Low-medium	Moderate-high	Medium

experience up to now has generally been this way that particular energy technologies (such as the steam engine and after that the combustion engine) have kept out other technological alternatives. These scenario groups describe alternative spectra of technology dynamics in the domains of unconventional oil and gas, coal, as well as post-fossil technologies.

In the *A1G* scenario group, technological change enables a larger fraction of the large occurrences of unconventional oil and gas, including oil shales, tar sands, and especially methane hydrates to be tapped. High technological learning and cost reduction effects could lower unconventional oil and gas extraction costs by approximately 1% per year and conversion technology costs about 2%. The lower costs would still probably not be sufficient to tap significant fractions of unconventional resources such as gas clathrates. For the *A1G* scenario group, substantial improvements and extensions of the present pipeline grids and entirely new natural gas pipelines systems from Siberia and the Caspian to South East Asia, China, Korea, and Japan after 2010/2020 would be needed. Since unconventional oil and gas resources are distributed unevenly geographically, the scenario implies both capital-intensive infrastructure investments and exceptional large-scale gas and oil trade flows. There is also little pressure to develop non-fossil alternatives in such scenarios, so costs of non-fossil alternatives remain comparably high, even after significant technological improvements.

The *A1* marker and the *A1T* scenarios assume drastic reduction in cost for solar, wind, and other renewable energies. *A1C* assumes lower coal costs and emphasises coal exploitation technology progress and the introduction of advanced coal-fired power generation technology, such as integrated gasification combined cycle (IGCC). *A1G* assumes lower oil and gas costs than other *A1* scenarios. The cost of nuclear power is assumed to be the lowest in *A1G* and *A1T*, and the highest in *A1C*.

Improvements in energy efficiency on the demand side are assumed to be comparatively lower in the *A1* scenario family, except for the *A1T* scenario, where the low energy prices give very little incentive to improve end-use energy efficiencies.

In the dynamic technology scenario group *A1T*, technological change, driven by market mechanisms and policies to promote innovation, favours non-fossil technologies and synfuels¹⁰, especially hydrogen from non-fossil sources. Liquid fuels

¹⁰ Synthetic fuels derived from alternative fossil fuels like oil shale, tar sand, and gasified coal.

from coal, unconventional oil and gas resources, and renewable resources are assumed to become available at less than US\$30 per barrel and falling.

A2 scenarios

The A2 scenario family includes slow improvements in the energy supply efficiency and relatively slow convergence of end-use energy efficiency in the industrial, commercial, residential, and transportation sectors between regions. A combination of slow technological progress, more limited environmental concerns, and low land availability because of high population growth means that the energy needs for the A2 world are satisfied primarily by fossil (mostly coal) and nuclear energy. However, in some cases regional energy shortages force investments into renewable alternatives, such as solar and biomass.

B1 scenarios

Consistent with the general environmentally conscious and resource-conservation thrust of the B1 scenario storyline, technological change is largely directed at improving conversion efficiency rather than costs for fossil technologies. It is assumed that subsidies on coal for electricity generation are removed entirely. A specific feature of the marker scenario is that it treats non-fossil electricity generation technologies as highly generic, for instance, it does not distinguish between nuclear, solar, or wind-power generation technologies. Cost decreases are anticipated once non-fossil options penetrate on a large scale. Liquid bio fuels are produced in small amounts in almost all regions. In all regions a gradual transition occurs from fossil fuels to non-fossil options in electric-power generation, because of rising fuel prices and declining specific investment costs for fossil alternatives. The shift would start in resource-poor industrialised regions such as Japan and Western Europe, but is somewhat tempered by rising conversion efficiencies of fossil-fuelled power plants. One of the factors that constrain the use of natural gas in the scenario is the assumption that only a limited part of the transport market is open to competition from non-liquid fuels. Also, the market share of coal in industry is fixed exogenously in some regions, to reflect the decreasing environmental and social attractiveness of the more “dirty” coal.

B2 scenarios

The B2 scenario storyline also predict important future improvements of technologies, although in a more moderate way than in A1 or B1 scenarios. Cost improvements are also more modest because of the regionally fragmented technology policies assumed to characterise a B2 world. Therefore, technology spreading effects and benefits from shared development costs are more limited in the scenario. The high emphasis of environmental protection at the local and regional levels is reflected in faster development and diffusion of energy technologies with lower emissions, including advanced coal technologies, nuclear, and renewable energies. As conventional oil supplies decrease, initially high-cost synfuels from coal and also bio fuels are introduced as substitutes. Conventional coal technologies undergo the lowest aggregate rates of improvements in the scenario and are subject to increasing controls of social and environmental externality (mining safety and sulphur emissions). Increasingly, therefore, only advanced coal technologies are set up.

Comparatively small variations in relative technology characteristics such as cost and efficiencies can lead to wide differences in scenario outcomes. For instance, changing the relative economics between coal and nuclear in the two MARIA scenarios results in a difference of more than 200GtC cumulative emissions over the 21st century.

Prospects for future energy systems

In the energy systems models used to generate the scenarios reported in the SRES, the entire energy systems structure is represented from primary energy extraction, through conversion, transport, and distribution, all the way to the provision of energy services. Primary energy harnessed from nature (e.g., coal from mine, hydropower, biomass, solar radiation, produced crude oil, or natural gas) is converted in refineries, power plants, and other conversion facilities to give secondary energy in the form of fuels and electricity. This secondary energy is transported and distributed (including trade between regions) to the point of final energy use. Final energy is transformed into useful energy (i.e., work or heat) in appliances, machines, and vehicles. Finally, application of useful energy results in delivered energy services (e.g., the light from a light bulb, mobility, etc.).

Important differences exist in accounting conventions on how to calculate the primary energy equivalent of particularly renewable and nuclear energy. To assure comparability of model results, the SRES writing team agreed to adopt as a common accounting methodology the direct equivalent method for all non-thermal uses of renewable and nuclear energy. The primary energy equivalence of these energy forms is accounted for at the level of secondary energy, that is, the first usable energy form available to the energy system. For instance, the primary energy equivalence of electricity generated from solar photo-voltaics or nuclear power plants is set equal to their respective total electricity output. It is not set equal to the heat that would have to be generated burning fossil fuels to produce the same amount of electricity as generated in a photo-voltaic cell or nuclear reactor (as used in the so-called “substitution” accounting method). This common SRES accounting convention must be borne in mind when comparing the primary energy-use figures from the SRES with those of other studies.

By the early 1970s, 56% of global primary energy use was based on oil and gas. From the early 1970s to 1990, the global primary energy structure has changed little. Efforts have been made though to substitute for oil imports, which have led to an increase in the absolute amount of coal used and to the introduction of non-fossil alternatives in the OECD countries (Organisation for Economic Cooperation and Development), e.g., nuclear energy in France and Sweden. Rapid growths in energy demand and coal use, particularly in Asia, have outweighed structural change in the OECD countries.

Scenarios B1, B2, *AIT*, and to some extent *AIB* follow a trend towards increasing shares of zero-carbon options in the long term. *AIG* more or less follows an oil-gas line of equal share that continues the current dominance of oil and gas in the global energy balance far into the 21st century. Scenarios in the *AIC* group, on the other hand, indicate a near doubling of coal's share in primary energy use.

A1 scenarios

The most significant change in the long-term primary energy mix in the A1 marker scenario is the fast market penetration of (new) renewable energy. Its share increases from a current 3% (excluding traditional non-commercial biomass use) to some 66% by 2100. Given the assumption of rapid technology progress, the cost of modern renewable energy technologies (solar, wind, commercial biomass, etc.) decline significantly in the long-term. Such low costs could make solar energy the largest primary energy source by 2100. In the meantime, the shares of coal and oil decrease from 25% and 36% in 1990 to 12% and 15%, respectively, by 2050 and thereafter continuing either because of depletion of conventional oil resources or because of fast market penetration of post-fossil technologies. Gas increases its market share initially (from 20% 1990 to 33% by 2050) and declines thereafter, but still remains an important market share (24%) by the end of the 21st century. Nuclear energy is mainly a temporary substitute technology, its share increases from 2% in 1990 to some 10% by 2050, and declines to 4% by 2100 because its economics increasingly fall behind those of new renewable energies.

A2 scenarios

Major global trends in the A2 marker scenario include an increase in the coal share (from 29% in 1990, through 30% by 2050, to 53 % in 2100) and a reduction in the share of conventional oil (from 43% in 1990 to 23% by 2050, from where it declines asymptotically towards zero at the end of the 21st century). The progressive depletion of oil resources in the scenario reflects the current view as to the finiteness of conventional oil resources, a picture also confirmed by other quantifications of the storyline. However, the decline in oil market share should not be interpreted as a physical “running out”, but rather as a gradual replacement process via price competition with synfuels and other alternatives as oil prices rise, along with the need to access ever more remote and expensive petroleum deposits. Once oil becomes increasingly expensive a substantial proportion of coal is converted into synthetic liquid fuels. Nuclear and renewable energy sources gradually increase in importance from 1990 to 2100, while the share of natural gas remains almost constant.

As in the A2 marker scenario, and with the exception of A2-IMAGE, coal becomes a major fuel by 2100 (45-50% of primary energy) in all the scenarios, followed by renewable sources (19-31%) and natural gas (9-18%). A higher share of renewable energy and a lower share of nuclear energy is the major difference between the scenarios.

B1 scenarios

The B1 marker scenario describes a structural transition in energy systems towards increasing shares of non-fossil energy. This long-term transition features a temporary reliance on fossil fuels, in particular with natural gas as the preferred transitional fuel. Structural changes in energy supply are comparatively fast because of both the dynamic viewpoint on energy-efficiency improvements and structural change, and the “dematerialisation” of economic activities, which is characteristic for the B1 world. A lasting long-term trend of B1 is also the continuously declining share of coal in the global primary energy mix, caused by local and regional environmental considerations. Until 2050, the global energy system remains fossil fuel dominated (with an important shift away from coal to gas use within fossil fuels). By 2020, fossils still account for some 79% of global primary energy (23% coal, 54% oil and

gas combined). By 2100, however, the transition away from fossil fuels is well underway, they only account for some 47% of primary energy use, mostly natural gas. Generally, even this scenario of significant structural change illustrates the long lead times needed for a “systematic” transition away from the current dominance of fossil fuels. Energy efficiency and “dematerialisation” of the economy are central parts of this transition in the B1 scenario. Whenever nuclear, renewable, and biomass costs are low, the share of coal declines and that of other resources increases. How the changes occur is model specific. Drastic shifts are not expected before 2050.

B2 scenarios

The B2 marker scenario first follows a trend towards increasing shares of gas, followed by renewable energy sources, and finally, as oil and gas start to become insufficient, increasingly returns to coal. The global diversification results from heterogeneous trends at the regional level and is largely a function of the more modest assumptions concerning technology improvements and oil and gas resource availability that are characteristic for the B2 world. Countries with low income and high resource availability continue to rely on fossil fuels up to the end of the 21st century, such as China, Former Soviet Union and the Middle East. Regions with low resource availability, such as Africa and South America, rely on renewable and nuclear energy. The decreasing share of coal and oil in the primary energy structure of the OECD countries is substituted by the growing share of renewable energy, gas, and nuclear energy. A major characteristic of the B2 scenario is the increasing importance of synthetic liquid fuels in the second half of the 21st century, because of a continuous phase out of conventional oil in all regions.

Common to all B2 scenarios is their gradual transition away from conventional oil and gas. However, alternative scenarios depict very different trends in structural change, ranging from increased reliance on coal and coal-derived synfuels (B2-ASF, B2High-MiniCAM) to more biomass- and nuclear-intensive scenarios (B2-AIM, B2-MARIA, and B2-IMAGE). Generally, this reflects the considerable uncertainty as to direction and pace of technological change in the technologically more fragmented world described in the B2 scenario storyline.

Carbon Dioxide

CO₂ is the largest contributor to anthropogenic **radiative forcing** of the atmosphere. The main sources of anthropogenic CO₂ emissions are fossil fuel combustion and the net release of carbon from changes in the terrestrial ecosystem, commonly referred to as land-use changes. Fossil fuels are generally named **hydrocarbons** and hydrocarbons occurrences are the largest storage of carbon. SRES 40 scenarios of CO₂ emission can be seen in figure ## and cumulative CO₂ emissions in figure ##. The atmospheric concentration of CO₂ prior to the industrialisation was around 228ppm (parts per million), a concentration that has been rising with time, in 1990 it reached 353ppm and in 1998 it was 365ppm. **Reference Kyoto booklet** and United Nations Framework Convention on Climate Change (UNFCCC), <http://www.unfccc.int>)

Multiple baselines and overlapping emissions ranges have important implications for making policy analysis, e.g., similar policies might have different impacts in different

scenarios. Combination of policies might shape the future development in the direction of certain scenarios.

Emissions from fossil fuels and industry

In 1990 fossil fuels were the main source of anthropogenic CO₂ emissions. It is expected that future CO₂ emission levels will depend primarily on the total energy consumption and the structure of energy supply. The total energy consumption is driven by population size, level of affluence, technological development, environmental concerns, and other factors. The composition of energy supply is determined by estimated reserves of fossil fuel and the availability, relative efficiency, and cost of supply technologies. Emissions from gas flaring¹¹ and industrial emissions are much lower in comparison with energy related emissions.

Up to about the 2040s and the 2050s, emissions tend to rise in all scenarios, but at different rates. Across scenarios this reflects changes in the underlying driving forces, such as population, economic output, energy demand, and the share of fossil fuels in energy supply. By 2050, the emissions range covered by the 40 SRES scenarios is from about 9 to 27GtC, with the mean and median values equal to about 15GtC. The range between the 25th and 75th percentiles of emissions extends from 12 to 18GtC (i.e. from twice to thrice that in 1990). A fair number of scenarios (eight out of 40) also indicate the possibility of much higher emissions. Another eight SRES scenarios have 2050 emissions below the 25th percentile. The range of emissions across the 40 SRES scenarios is between 3 and 37GtC, which reflects either a decrease to half the 1990 levels or an increase by a factor of six. Similar emission levels can arise from different combinations of driving-force variables that are embedded in the SRES scenario families and groups.

A1 scenario family

Rapid economic growth in the A1 family scenario leads to high energy demand and therefore to a steep increase in CO₂ emissions in the first decades of the 21st century. Structural changes in the energy supply become effective only in the longer term.

In the A1 marker scenario, the global average per capita final energy demand grows. In the meantime, the final energy carbon intensity declines relatively slowly, which results in a steep increase in CO₂ emissions in the first decades of the 21st century. After 2050, when structural changes in the energy sector take effect, carbon intensity declines rapidly. The resultant CO₂ emissions range for the scenario family is so wide that most of the remaining SRES scenarios fall within its bandwidth. The highest cumulative CO₂ emission reached in the A1 scenario family is larger than 2500GtC by 2100.

A2 scenario family

In the A2 scenario family, alternative energy technologies develop relatively slowly and fossil fuels maintain their dominant position in the energy supply mix. Global CO₂ emissions in the A2 marker scenario increase by more than fourfold over their 1990 level. Unlike the rest of the A2 family scenarios, the A2-IMAGE scenario yields

¹¹ Burning of gas that cannot be of use or e.g. cannot be transported from the oilrig.

constant emissions after 2050. The differences are explained by the combination of a lower energy demand and by a larger share of natural gas in the energy supply mix. Total cumulative carbon emissions from the marker scenario range between 1710 and 1860GtC by 2100.

B1 scenario family

In the B1 marker scenario the rapid technological change toward resource saving and ecologically sound solutions is assumed to spread very quickly, facilitated by high turnover rates in capital stock in currently less developed regions. As a result, energy requirements increase slowly and a shift away from fossil fuels eventually breaks the already slow upward trend in carbon emissions. Emissions peak around 2040, twice the level of 1990, and by 2100 the emissions fall below the base-year level.

The B1 family also includes one scenario in which energy-related emissions continue to increase throughout the modelling period, B1-MiniCAM. In this scenario the final energy demand is assumed to rise more rapidly with increasing income than the rest of the B1 scenarios. The total cumulative CO₂ emissions in the B1 scenario group range between 770 and 1390GtC by 2100.

B2 scenario family

The B2 marker scenario has a steady increase of CO₂ emissions. Differences in emissions are largest around 2050, which reflects the different patterns of structural change in the energy systems in anticipation of depletion of conventional oil and gas. Total cumulative CO₂ emissions in the scenario group range between 1164 and 1686GtC by 2100.

Comparison with IPCC's 40 Scenarios of World Anthropogenic CO₂ Emission

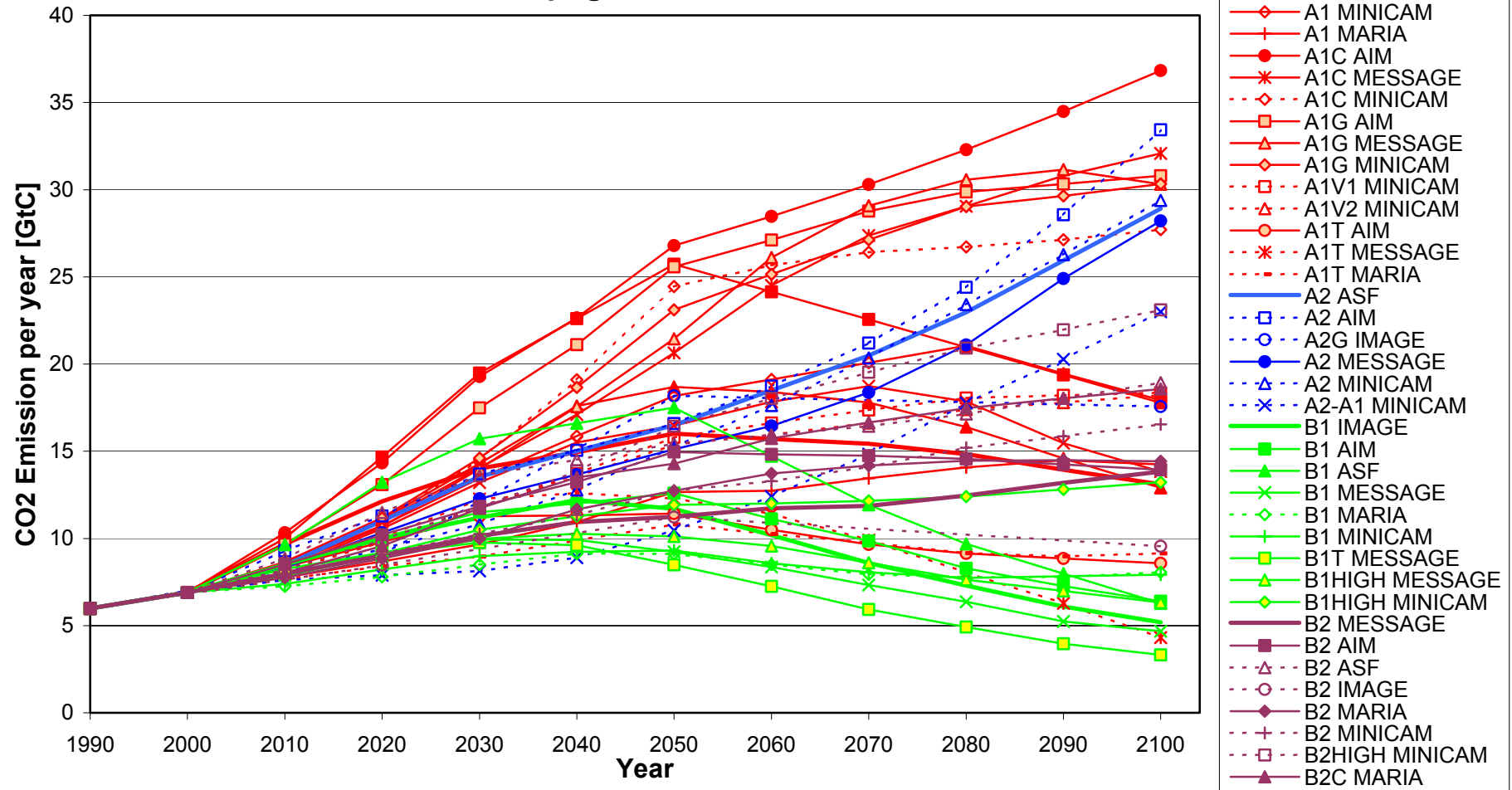


Figure ##. IPCC's 40 scenarios on anthropogenic CO₂ emission 1990-2100.

