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Long-term perspectives: energy, development and the environment*

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The worldwide demand for energy and the need to minimize the environmental impact present a challenge which has been addressed by the International Institute for Applied Systems Analysis (IIASA) and the World Energy Council (WEC). This paper summarizes the findings of a joint two-year IIASA-WEC study to explore the prospects for improving the global availability and quality of energy services, and the wider implications that these improvements may have.

Introduction

The challenge of providing adequate energy services to a growing world population while minimizing environmental impacts at the local, regional and global levels is the focus of the research activities in the energy area at the International Institute for Applied Systems Analysis (IIASA). The ultimate objective is to gain a better understanding of the linkages between energy use, development, and environmental change.

This work started with a detailed assessment of specific technologies that might play a role in reconciling the seemingly conflicting objectives of development and environmental protection. The work led to the development of a framework of long-term energy and emissions scenarios to assess how these new technologies might actually come into widespread use and create substantial benefits. One focus of this work on global and regional scenarios is on policy issues associated with the longer-term implications of developing future energy systems.

At the same time, it is important to look at not only the long-term global features of such scenarios, but also at their near-term local and regional consequences. These consequences most likely will drive policy decisions more forcefully than long-term global perspectives. In examining near-term local and regional consequences, it is particularly valuable to link together research that is often done separately in distinct categories – for example, global warming, acid rain, land use, and water resources. Such linked analysis – cutting across common research fields – is called integrated assessment. The merit of integrated assessment at IIASA is that it combines the experience and richness of developed disciplinary models into one unified scenario formulation approach.[1]

In collaboration with the World Energy Council (WEC), an integrated assessment framework was used to explore the prospects for improving the global availability and quality of energy services, and the wider implications these improvements may have. The study explores a broad range of global energy developments and their consequences, such as the likely financing needs and environmental impacts. This paper summarizes the main features and findings of the joint, two-year IIASA-WEC study, which was presented in *Global energy perspectives to 2050 and beyond*[2] and a number of related publications.[1,3,4,5]

From resource limitations to cleaner energy

The world is not running out of energy, even with the global population expected to double by 2050 and to reach 12 billion by 2100. Indeed, there are enough potential resources, from coal to renewables, so that the world will have choices. It will not be necessary to push every resource to the limit just to keep up with population and economic growth.

Which energy sources and forms will predominate in the future will depend less on resource limits than on which fuels can be most successfully tailored to match consumers' wants. What consumers are looking for are higher levels and improved quality of energy services. In the future, this will result in a continuing, pervasive, and persistent tendency toward more convenient, more flexible, and ever-cleaner structures and forms of energy end use. As incomes increase around the world, people will demand more efficient, cleaner, and less obtrusive energy services.

Understanding long-term energy perspectives is essential for building a future that is more prosperous and more equitable. In the IIASA-WEC study, future

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scenarios were constructed to analyse which policies or investments make the most sense today. Because the future is uncertain, it is important to build a range of scenarios covering many of the possible futures that we can envisage. In the context of the study, scenarios are neither predictions nor forecasts. Rather, each scenario is one alternative image of how the future could unfold. Such a range makes it possible to distinguish features of the future that are likely to be robust in the face of change and those that are likely to be the most sensitive.

IIASA-WEC study on energy perspectives

The IIASA-WEC study explores the prospects for improving the global availability and quality of energy services, and the wider implications these improvements may have. The study centres on three cases of future economic and energy development (cases A, B and C) for eleven world regions (see Table 1). Case A reflects high growth, with high economic and energy growth and rapid technology improvements; case B represents a middle course, with intermediate economic and energy growth and more modest technology improvements; and case C is ecologically driven, incorporating challenging policies to simultaneously protect the environment and to enhance economic equity, which together lead to lower energy use but high overall growth, especially in the South (i.e. developing countries).

The three cases were further differentiated into six scenarios of energy systems alternatives: three case A scenarios (A1, A2 and A3), a single case B scenario, and two case C scenarios (C1 and C2)

- Scenario A1 – ample oil and gas
- Scenario A2 – return to coal
- Scenario A3 – fossils phase-out
- Scenario B – middle course
- Scenario C1 – new renewables with nuclear phase-out
- Scenario C2 – renewables and new nuclear.

Energy intensities will improve

In all scenarios, economic development outpaces the increase in energy, leading to substantial reductions of energy intensities. As individual technologies progress, and as inefficient technologies are retired in favour of more efficient ones, the amount of primary energy needed per unit of gross domestic product (GDP) – the energy intensity – decreases. With all other factors being equal, the faster the economic growth, the higher the turnover of capital, and the greater the energy intensity improvements.

In the six scenarios, improvements in individual technologies were varied across a range derived from historical trends and current literature about future technology characteristics. Combined with the economic growth patterns of the different scenarios, the overall global average energy intensity reductions vary from about 0·8% per year, in line with the historical experience, to a high figure of 1·4% per year. These figures bracket the historical rate experienced by more industrialized countries during the last 100 years, which was approximately 1% per year as the long-term average, and cumulatively lead to substantial energy intensity decreases across all scenarios. Efficiency improvements are significantly higher in some regions, especially over shorter periods of time.

In addition to the energy intensity improvements, the rates of technological change and availability of energy resources also vary in a consistent manner across the scenarios. For example, the high rates of economic growth are associated with rapid technological advance, ample resource availability, and high rates of energy intensity improvement. Conversely, low rates of economic growth result in a more limited expansion of energy resources, lower rates of technological innovation in general, and lower rates of reduction in energy intensities.

Global energy needs will increase

World population is likely to double by the middle of the twenty-first century as economic development continues, reaching 12 billion by 2100 (Fig. 1). The likely result, according to the scenarios, is a three- to fivefold increase in world economic output by 2050, and a ten- to fifteenfold increase by 2100. By 2100, per capita incomes in most of the currently developing countries will have reached levels characteristic of the developed countries today, making current distinctions between the two groups of countries obsolete. Nonetheless, in many parts of the world local difficulties

Table 1. Overview of the main characteristics of the scenarios in the IIASA-WEC study

	Case A	Case B	Case C
Economic growth	High	Medium	Low (North) High (South)
Energy intensity improvements	Medium	Low	High
Technology/resource availability	High	Medium	Low (fossil) High (non-fossil)
Number of scenarios	3	1	2

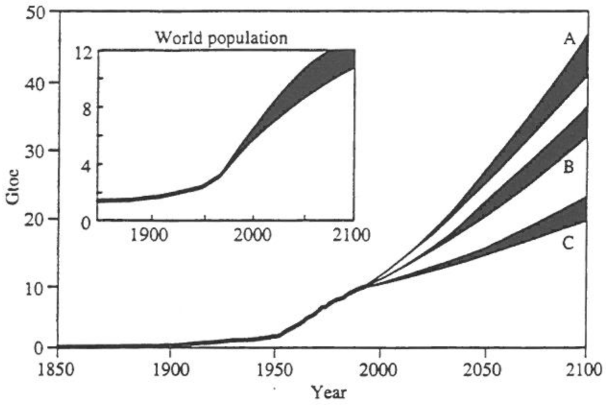

Fig. 1. Global primary energy use, 1850 to present, and in three cases to 2100 (Gtoe). The inset shows global population growth, 1850 to present, and projection to 2100 (from Reference 6) in billions of people

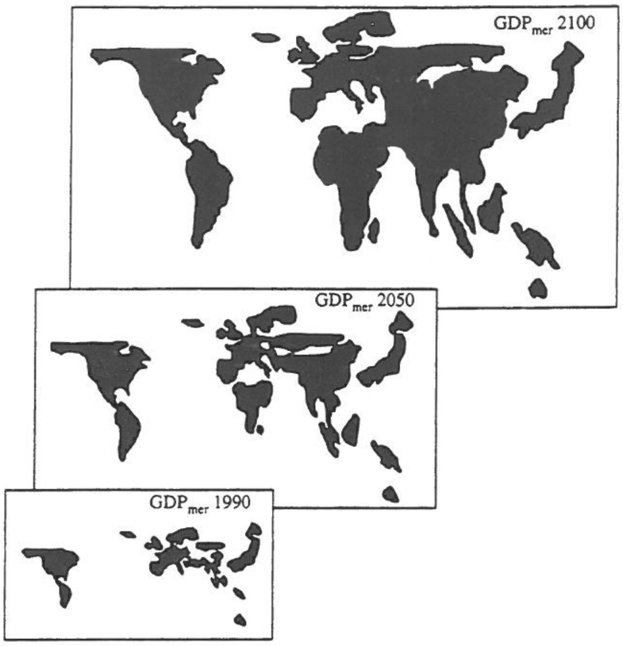

Fig. 2. The changing geography of economic wealth, case B, in 1990, 2050 and 2100. The areas of world regions are proportional to their respective 1990 levels of GDP, expressed at market exchange rates

will persist, and despite rapid economic development adequate energy services may not be available to every citizen, even in 100 years time.

Global demand for energy services will grow by as much as an order of magnitude by 2050. Primary energy requirements will grow less, because of improvements in energy intensities; the study envisages a 1·5 to threefold increase in primary energy use by 2050, and a two- to fivefold increase by 2100. The six scenarios are grouped into three different levels of primary energy consumption covering this wide range of alternative developments (as shown in Fig. 1).

The economic growth trajectories are illustrated in a novel way in Fig. 2. In this figure, the sizes of different world regions analysed in the study are proportional to their current GDP (expressed as market exchange rates). In 1990 the economic map of the world, which also approximates to energy-use patterns, looks odd, reflecting current disparities among regions. Most developing regions are barely discernible compared with Japan, Western Europe and North America. Compare, for example, the size of Japan in 1990 with that of China and the Indian subcontinent.

For 2050 and 2100, the figures correspond to the median case B scenario (case B is shown because it has the lowest rates of growth). The top map in Fig. 2 shows world continents according to economic activities as they appear in 2100. In terms of economic development as well as access to energy, the world map for 2100 looks less odd; not only are the regions larger, reflecting their economic and energy use growth, but disparities among the regions are smaller, bringing the maps much closer to the geographic maps with which we are familiar.

These maps give a positive view of the future by illustrating a case of successful global development. The world is affluent and the difference between the poor and the rich as we know it today disappears. In most regions of the world the standards of living approach those currently found in Western Europe. This change is possible with slower growth in energy requirements due to impressive improvements in energy efficiency and conservation that lead to a reduction in energy intensities.

Energy forms and services will improve

The scenarios cover a wide range of energy supply possibilities, from a tremendous expansion of coal production to strict limits on it, from a phase-out of nuclear energy to a substantial increase in its use, from carbon emissions in 2100 that are only one-third of present levels to emission increases of more than a factor of 3. Yet, for all the variations explored in the alternative scenarios, all manage to match the likely continuing push by consumers for more flexible, more convenient, and cleaner forms of energy (Fig. 3). This means that all energy is increasingly transformed and converted into quality carriers such as electricity, liquids, and energy gases. For example, the direct use of solids by final consumers disappears by 2050.

Alternative structures of future energy systems are capable of meeting these stringent demands for higher energy end-use and services. Despite all the variations, the scenarios look quite similar through 2020, and all still rely on fossil fuels. However, after 2020 the scenarios start to diverge.

The roles of different primary energy sources vary across the six scenarios, contributing to divergence. Some continue to be fossil fuel intensive, others envisage stronger shifts toward alternative sources of energy

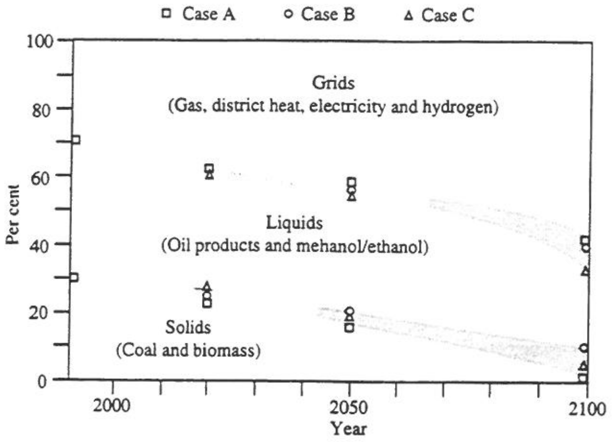

Fig. 3. World supply of final energy by form: solids (coal and biomass), liquids (oil products and methanol/ethanol), and grids (gas, district heat, electricity and hydrogen). Overlapping shaded areas indicate variations across cases A, B and C

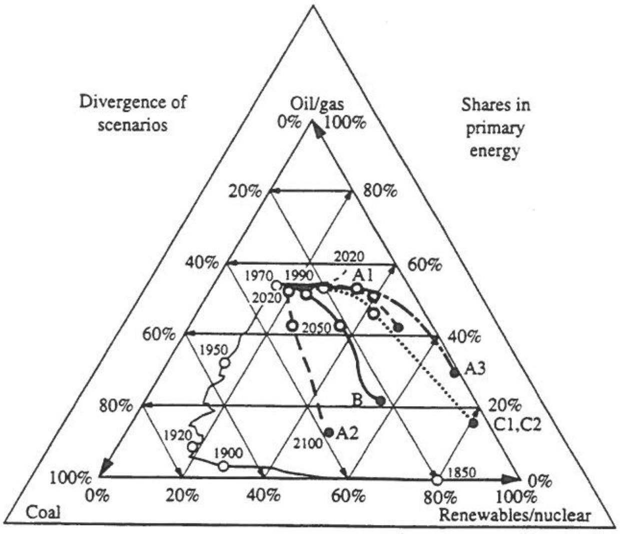

Fig. 4. Divergence in the structures of energy systems. Contribution from oil and gas, coal, and nuclear and renewable energies (percentages)

such as renewables or nuclear power. The geophysical availability of energy resources is not a major constraint in itself. Instead, the availability of energy resources and the rates at which they are converted into reserves are a function of the nature of the envisaged development strategies themselves. Part of the divergence in the structures of energy systems depends on policy choices and development strategies. For example, two case C scenarios that assume aggressive international cooperation focused on environmental protection and international economic equity, use much less fossil fuel than the other scenarios. Fig. 4 illustrates this long-term divergence in the structures of energy systems across the scenarios.

Each corner of the triangle in this figure represents a hypothetical situation in which all primary energy is supplied by a single energy source: oil and gas on the top, coal on the lower left, and renewables and nuclear energy on the lower right. Nuclear energy and new renewables are grouped together because they are the principal non-fossil energy alternatives available in the longer term. The illustration shows the historical development of the global energy system starting in the 1850s, when most primary energy needs were met by traditional (usually non-renewable) sources of energy such as wood and animal power, as well as the development trajectory to 1990.

Scenarios branch out during the post-2020 period. Some become coal intensive, like the high growth scenario A2, others are more renewable and nuclear intensive, like scenario A3 and the two ecologically-driven scenarios (C1 and C2). All of them eventually lead to a partial shift from fossil fuels to other sources of energy; however, they follow alternative development paths. As the paths spread out, they form diverging future developments. To some extent they are mutually exclusive. Most of the post-2020 divergences will depend on technological developments and industrial strategies implemented between now and then. Which energy sources in 2020 will most closely match the more flexible, more convenient, and cleaner forms of energy desired by consumers? Which will have made the investments in research and development that will give them a technological edge? And which will have successfully refocused their businesses away from merely providing tonnes of coal, or kilowatt-hours of electricity, toward providing increasingly flexible, convenient, and clean energy services to consumers?

The answers to these questions will be determined between now and 2020. Near-term investment decisions and efforts in technology research and development will determine which of the alternative development paths will become dominant in the post-2020 period. Because of the long lifetimes of power plants, refineries, and other energy investments, there is not a sufficient turnover of such facilities to reveal large differences in the scenarios prior to 2020, but the seeds of the post-2020 world will have been widely sown by then.

Nuclear will contribute to the post-fossil age

All three cases reflect substantial growth for all energy industries through to at least 2020. This growth is based on the assumption incorporated in all cases of increasingly open markets, in which subsidies favouring established industries are removed and a more 'level playing field' becomes reality.

This change will create substantial reshuffling within and among energy sectors. The result will likely be characterized by one or more of the following labels:

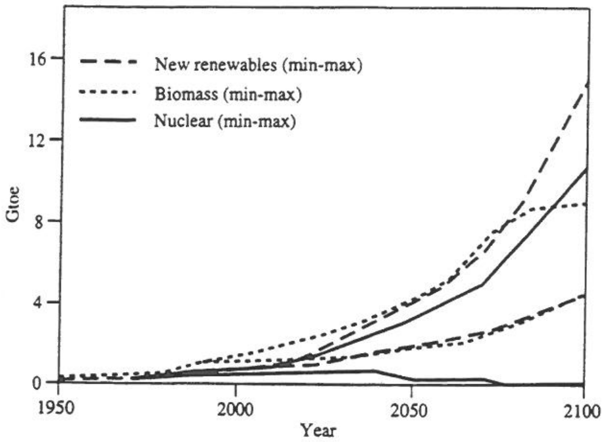

Fig. 5. Minimum and maximum annual renewable and nuclear energy production across the six scenarios, 1950–2100 (Gtoe), primary energy equivalent

intersector integration, energy cascading, organizational flattening, service orientation, global competition, common carrier or third-party transport, and integrated resource planning. These factors will have a large impact on the production profiles summarized above (see Fig. 4). New business opportunities will emerge, centred primarily on the conversion of non-oil sources to liquid end-use fuels and, in the distant future, to hydrogen. Coal, natural gas, biomass, nuclear power and solar energy may all find new markets in synfuel, methanol, and hydrogen production. In the longer run, the present separation into coal, oil and natural gas, and nuclear and emerging renewable industries, will probably be less distinct.

Although the next two to three decades offer ample opportunities for all present energy sectors to do extremely well, the scenarios show diverging prospects after 2020, when different energy industries embark on often mutually exclusive development paths. For nuclear energy, the range of possibilities is extremely broad. Fig. 5 compares nuclear energy's maximum and minimum development paths across the six scenarios with those of biomass and new renewables (such as wind, solar and hydropower) grouped together. The range for nuclear energy extends from more than a fivefold increase by 2050 in cases A and B, through scenario C2's new generation of small-scale nuclear technologies, to scenario C1's phase-out of nuclear power altogether in the second half of the twenty-first century.

How nuclear energy actually develops will depend on when and how proliferation, waste, and safety concerns are resolved, and whether the climate change issue will add additional weight to nuclear energy's characteristic as a zero-carbon option. For example, scenarios with the highest nuclear contributions (A1, A3 and B) translate into annual grid connections of up to 70 GWe per year by 2050. Although this increase is enormous compared with current construction rates, additions of some 30 GWe per year were realized in the mid 1980s.

The realization of such construction rates requires a fundamental change in the public's perception of nuclear power. The nuclear industry must develop and demonstrate not only new, convincingly safe, possibly smaller-scale reactor designs that incorporate 'inherently safe' and 'walk-away' features, but also efficient and 'robust' fuel cycles and waste disposal solutions. These objectives are crucial, especially because a substantial share of the new capacities (even in the low nuclear scenarios) would be located in developing countries. Extensive technology transfer and education of local human resources in the developing countries are essential prerequisites. Also required are substantial reductions in capital costs, initially through shorter construction times and ultimately through standardization and series-type production. Policy-makers are called upon to design, implement, and enforce global non-proliferation mechanisms.

The range of different nuclear futures explored in the six scenarios is wide indeed, reflecting the current uncertainty surrounding its use. This uncertainty is unlikely to disappear in the near future. One conclusion, therefore, is that a precautionary nuclear strategy advances a wide range of possible technology developments, ranging between small-scale decentralized technologies and large, integrated technologies with the full fuel cycle. This strategy would assure the preservation of the necessary know-how and engineering capability, should a new nuclear age emerge. It would also be compatible with less ambitious prospects, because it would not 'lock up' enormous resources and infrastructure investment in current technologies.

Capital requirements will present challenges

A conclusion that is consistent across all six scenarios is that the capital requirements of the energy sector will be extremely large, but not infeasible. Over the next three decades, capital requirements across the scenarios are estimated to range between US\$13 to 20 trillion (10^{12}) at 1990 prices (see Fig. 6). The latter amount equals the total 1990 global economic output.

The good news is that investment requirements are likely to expand at a slower pace than overall economic growth. But there are two pieces of bad news. First, the energy sector will have to raise an increasing portion of its capital from the private sector, where it will face stiffer competition and return on investment criteria. Second, most of the investments that must be made are in the developing countries, where currently both international development capital and private investment capital are scarce.

The situations in the reforming economies of Central and Eastern Europe are equally serious: required

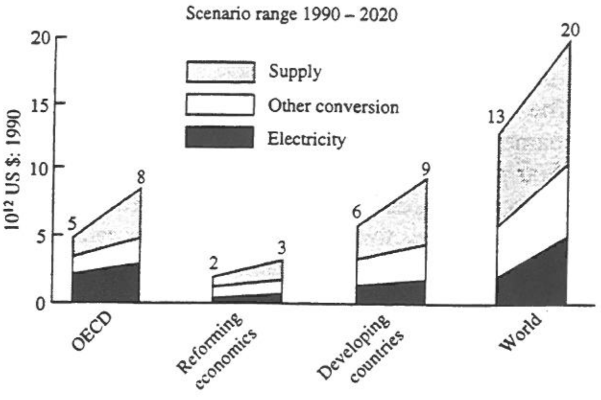

Fig. 6. Range of cumulative energy sector investments for OECD, reforming economies, developing countries, and world total, 1990–2020 (US$ trillions, 10^{12})

energy sector investments could amount to up to 10% of GDP, or to some US$3000 billion over the next three decades (Fig. 6). These high investment needs are a legacy of the high energy intensity of the former centrally planned economies and recent declines in investments that went along with economic recession. The result is a substantial need for reconstruction and upgrading of energy infrastructures.

Local environmental impacts will be vital issue

In rural developing areas worldwide, the demand for cleaner energy end-uses includes a shift away from cooking with wood in inefficient traditional open fireplaces. This change will reduce indoor pollution levels, currently estimated to be 20 times higher than in industrialized countries.

In the booming cities of China and south-east Asia, high levels of air pollution must be addressed with both cleaner fuels and active abatement measures. A high dependence on coal with no abatement measures would result in significant regional acidification and cause key agricultural crops in the region to suffer acid deposition that is ten times the sustainable level before 2020. People worldwide already suffer from local and regional air pollution, and both governments and individuals are taking steps to improve the situation. These actions are part of the drive toward higher efficiencies and cleaner fuels. They also have the positive spin-off effect of reducing carbon emissions and possible global warming, although that is not their principal motivation.

Decarbonization will improve the environment

The continuing shift toward higher quality fuels means continued decarbonization of the energy system. Decarbonization means lower adverse environmental impacts per unit of energy consumed, independent of any active policies specifically designed to protect the environment. At the global level, decarbonization translates into lower carbon dioxide (CO_2) emissions and a lower risk of global warming.

However, decarbonization may not be enough to offset future increases in greenhouse gas emissions and concentrations, especially in cases where fossil fuel use continues to be the primary source of world energy. Like the future structures of the energy systems, the CO_2 emissions paths for the six scenarios also diverge (Fig. 7). They range from very high emission levels for the coal-intensive high growth scenario A2, to emission reductions in the ecologically-driven case C scenarios sufficient to lead to atmospheric concentrations of about 430 ppmv after 2100 (Fig. 8).

This latter result is consistent with the lowest concentration levels analysed during the Intergovernmental Panel on Climate Change Carbon Dioxide Concentrations Exercise. An important feature of this result is that very low CO_2 emissions trajectories are not achieved by constraints, but rather by high levels of economic, technological and social development. Environmental awareness increases, and results in environmental protection on all scales: local, regional, and global.

Thus, the decarbonization of energy is not sufficient to reduce future emissions of greenhouse gases, given the expanding energy needs of a growing world economy. Additional active policies are required. In some cases, they are mutually reinforcing: policies to reduce global CO_2 emisisons, for example, also reduce acidification risks. In other cases, they work at cross purposes: restrictions on nuclear power, for example, may mean a greater dependence on fossil fuels.

In all cases, however, faster technological improvement means quicker progress toward the clean fuels desired by consumers, and cleaner fuels mean a cleaner environment. Thus, near-term investment decisions and efforts in technology research, development and

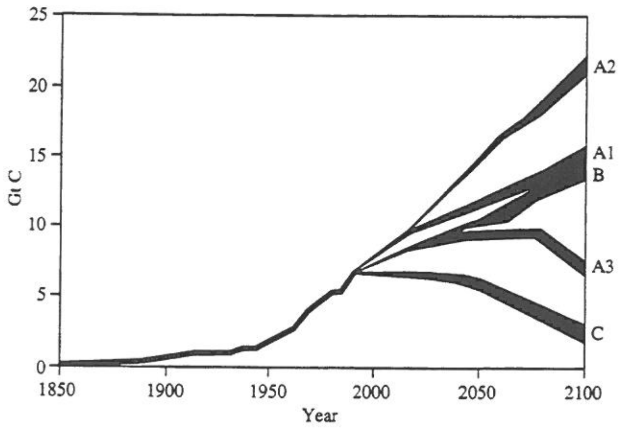

Fig. 7. Global energy-related carbon emissions, 1850–1990, and for three scenarios families to 2100 (GtC)

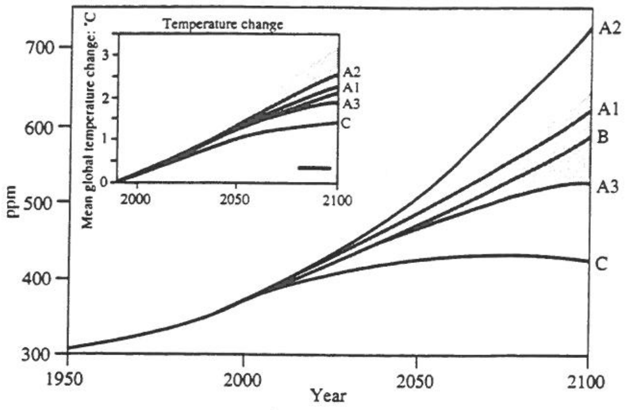

Fig. 8. CO_2 concentration (ppmv), 1950–2100, and global mean temperature change (°C), 1990–2100. The (substantial) model uncertainties are indicated for case B

demonstration will determine which of the alternative development paths analysed in the IIASA-WEC study might become dominant in the post-2020 period. The choices may be wide open now. They will be a lot narrower by then.

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