IIASA

An Assessment of Technological Change Across Selected Energy Scenarios

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RR-02-005
May 2002

REPRINT
RESEARCH
REPORT

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Reprinted from a publication by the World Energy Council on behalf of the Study Group on Energy Technologies for the 21st Century, September 2001.

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Published by the World Energy Council, September 2001.

ET21 Task II Foreword

Technology is at the heart of the three goals spelled out in the World Energy Council's Statement, *Energy for Tomorrow's World – Acting Now!* These are access to reliable and affordable modern energy services for all the world's inhabitants, availability of high-quality reliable delivered energy, and energy resources that are accepted as produced and used in harmony with the local, regional and global environment.

With this in mind, the World Energy Council (WEC) at the time of the 1998 Houston Congress, foresaw a need to examine which energy technologies are likely to sustain the world in the 21st century, the steps that need be taken to ensure that these new technologies are available to the marketplace, and what role governments and industry might play. Up to one-half of historical growth in productivity is known to be due to technological change. Accordingly, in 1999 the WEC launched a major study on "Energy Technologies for the 21st Century". The study had two parts. The first was to examine trends in public and private RD&D spending over the past 15 years to see what has been happening by technology area, with regard to the resource base for future development. A report on this part is published as a separate document in parallel with this report.

The second part was to identify both those key technologies that might help achieve the three goals in the WEC statement, and what might be necessary to help bring them to market. This report represents the first phase of that part of the study. The authors, Nebojsa Nakicenovic and Keywan Riahi from the International Institute for Applied Systems Analysis (IIASA) use scenarios done for WEC, those done for the IPCC Special Report on Emissions Scenarios and the IPCC Third Assessment Report, and historical experience with technological learning to identify technologies that appear persistently in a significant class of scenarios and/or within a particular region. They have examined technologies associated with electrical generation, synthetic fuel production, carbon sequestration, transportation technologies and services and energy consumption patterns. As the authors state in this report, technological change is complex, fraught with many uncertainties, and inherently unpredictable. New discoveries, the role of embedded infrastructures, financing, and consumer preferences are impossible to determine *a priori*. By considering a range of possible developments, they identify and prioritize those technologies that appear to be robust, that is they are likely to have widespread dissemination and impact. These are technologies and technology areas worthy of the attention of industry and governments if they are to be deployed and disseminated as part of the process of sustainable economic development. The Study Group and the WEC thank the authors for their thoughtful and timely contribution to this important topic.

WEC proposes to complete the study in the next few years. This next phase will examine other technologies and technological areas and those examined here in greater detail, including end-use and carbon sequestration. It will also examine the strategies of private industries and governments as well as the timing and possible costs of RD&D. The result will be a comprehensive view of strategies and policies on technology development and diffusion that appear most promising in an uncertain future.

Robert Schock, Chairman
Study Group on *Energy Technologies for the 21st Century*
September 2001

An Assessment of Technological Change Across Selected Energy Scenarios

Nebojsa Nakicenovic and Keywan Riahi

July 2001

Introduction

Technological change is a complex process that is associated with many uncertainties. Its future course is inherently unpredictable. The very fact that it is virtually impossible to anticipate specific future technological change is what interests many researchers and innovators. Discovering new possibilities and demonstrating unanticipated possibilities is often what attracts their curiosity. Thus, the risk and opportunity are joint features of technological change rendering the process inherently unpredictable. This is an important reason why studies about future technologies need to consider a range of alternative developments rather than attempting to project a particular direction of change. They need to capture a wide spectrum of developments in order to assess the implications and possibilities of different alternatives. Here we do so on the basis of energy scenarios that contain assumptions about many different technologies, their costs and performance.

A number of economic studies have determined that up to half historical productivity growth is due to technological change and the other half due to all other reasons such as the growth of the labor force, labor productivity, capital stock, etc. The same is true for technological change in scenarios about possible future energy developments. Technological change may be more important in determining the structure of future energy systems and services than some other major driving forces such as population growth and economic development (Nakicenovic *et al.*, 2000a). It should be noted however that technological change in turn is and will continue to be driven by social and economic transformations and human values. This is compounded by great uncertainty as to how far social and economic change, shifting human values and lifestyles, and environmental concerns will drive technological priorities. There is growing evidence in energy scenarios that alternative technological developments resulting from many specific assumptions in energy models can lead to fundamentally different future energy systems structures and services (Alcamo and Nakicenovic, 1998; Nakicenovic, 2000; EIA, 2000; Nakicenovic, Grübler and McDonald, 1998; Morita, Nakicenovic and Robinson, 2000; Riahi and Roehrl, 2000a). For example, scenarios that assume relatively abundant and inexpensive fossil energy and technology availability also tend to have high shares of these options. Scenarios with slow progress of fossil technologies often anticipate high fossil energy costs (internal as well as external) and consequently a degree of decarbonization of future energy systems. These two sets of assumptions are frequently used as devices to accommodate paths of evolution, which are believed to be less, or more, "sustainable" in terms of economic development; and less, or more, compatible with mitigation of the environmental impacts.

Scenarios in the literature offer, in general, a large set of alternative future developments that may be used to assess the ranges and distributions of costs and other characteristics of future energy technologies. These should not, of course, be confused with actual future developments that are unpredictable. Scenarios in the literature may include the actual future development path(s), but this need not necessarily be the case. Surprises and "extreme events" are often situated outside the envelope of future developments encompassed by the scenarios in the literature. Nevertheless, the analysis of the range of future technology characteristics across scenarios in the literature is one of the very few methods available for assessing alternative developments. Another is to conduct "Delphi" studies or other ways of polling the views of experts.

Our approach here is to assess the ranges of deployment and characteristics of future energy technologies on the basis of a number of scenarios developed at IIASA by the MESSAGE energy systems model (Messner and Strubegger, 1995). The reason for choosing one single model for this analysis is simply that detailed information for this model is available and documented in the literature (Riahi and Roehrl, 2000b; IIASA web site; CIESIN web site; Roehrl and Riahi, 2000, etc.). Comparable information is to the best of our knowledge not available at this time for other energy models that contain a high degree of technological resolution (i.e., for other so-called systems-engineering energy models that provide sufficient resolution of the underlying technological detail). Another, completely different reason, for choosing the MESSAGE model is that it was one of the models used to develop both the IIASA-WEC (Nakicenovic, Grübler and McDonald, 1998) and IPCC (Nakicenovic *et al*., 2000a; Riahi and Roehrl 2000a, Morita, Nakicenovic and Robinson, 2000) scenarios.[1] Therefore, it contains a wide range of energy technology developments based on assessments of two large writing teams and expert reviews that were involved in the two scenario development processes with the same basic modeling approach. Presumably, the scenarios thus contain a comprehensive set of alternative but nevertheless comparable technological developments. Here we analyze technological developments across 34 different scenarios from the IIASA-WEC and IPCC studies.

[1] The IIASA-WEC scenarios were developed with six formal models and three databases integrated into the IIASA modeling framework for scenario formulation and analysis (Nakicenovic, Grübler and McDonald, 1998). In addition to MESSAGE, the set includes a model for formulation of main scenario driving forces simply called Scenario Generator, a macroeconomic energy model 11R (Schrattenholzer and Schäfer, 1996), a regional air pollution impacts model RAINS (Alcamo *et al.*, 1990), a model for the assessment of greenhouse gas induced climate change, MAGICC (Wigley *et al.*, 1997) and a basic linked system of national agricultural models, BLS (Fischer *et al.* 1988). The IPCC SRES scenarios were developed by six different integrated models, the IIASA MESSAGE model and the associated IIASA modeling framework constituting one of the six approaches (Nakicenovic *et al.*, 2000a). The Post-SRES scenarios were developed by three additional modeling frameworks resulting in a total of nine integrated models (Morita, Nakicenovic and Robinson, 2000).

Technological Change

There are two basic forms of technological change in energy scenarios. First, technologies change incrementally over the time horizon. This means that from one to another time period in the model some technology characteristics gradually improve or not. Examples of possible improvements are reduction of costs, improvement of efficiency and reduction of emissions per unit activity. The second form is more radical and represents an introduction of completely new technologies at some future points in time. Examples are fusion energy or carbon sequestration from fossil energy sources and storage.

This is quite consistent with the literature on technological change. Schumpeter (1935) was the first student of technology to distinguish these two basic types of change. The main difference of the Schumpetarian approach with respect to energy scenarios is that technological change is usually treated deterministically in any given scenario. The technology is simply assumed to become available by a certain time period with a given cost and performance whereas in reality it is an uncertain evolutionary process. Some technologies become successful while others fail and their costs and performance are functions of many interacting factors. This is the reason for taking a set of scenarios from the literature and assessing the consequences of different directions of technological change across them. As previously mentioned, the basic assumption is that the range will encompass much of the inherent uncertainty through the richness of alternative futures.

Another important feature of technological change is that it is cumulative. Small changes are amplified into fundamental ones as new, successful technologies become adopted and diffuse replacing the older alternatives. For example, new technologies are often more costly and inferior in some ways compared to the older and more "mature" alternatives that dominate the market. However, they often improve as experience is gained by producers (learning-by-doing) and consumers (learning-by-using). Costs and environmental impacts are reduced while other aspects of technology performance are usually also improved. Generally, performance improves. Such gradual and persistent improvements are sometimes correlated with cumulative experience and are referred to collectively as "increasing returns". Empirical relationships between performance improvement or costs reduction with increasing cumulative output or capacity are called "experience" or "learning" curves in the literature. Figure 1 shows such a cost-reduction learning curve for ethanol production from biomass in Brazil.

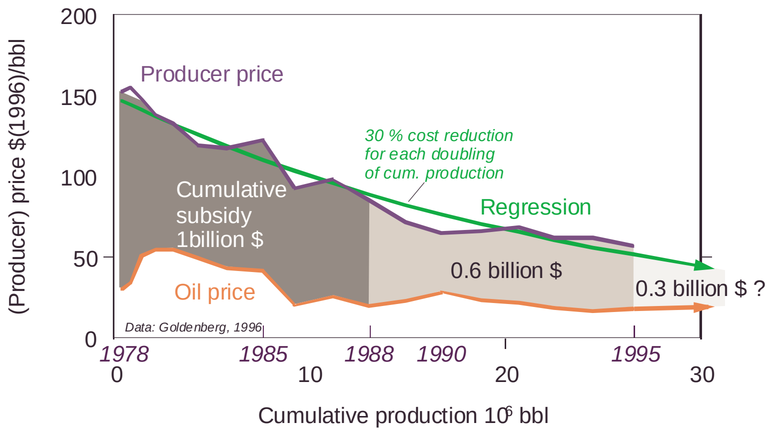

Figure 1. Learning curve for ethanol production in Brazil compared with world oil prices. Source: Grübler, personal communication, based on data from Goldemberg 1996.

Figure 1 shows that the costs of ethanol have declined with increases in cumulative production and are now close to the price levels of crude oil. However, when ethanol was first introduced in the early 1970s after the first oil-price shock, its cost was more than three times that of oil. Through technological improvements and increases in the scale of production, the prices have declined to such an extent that even the relatively low oil prices since 1986 have not been much lower that those of ethanol during the last few years. Figure 1 shows that the future of the process is uncertain and that there is no guarantee that similar rate of improvement can be realized with further expansion of ethanol production. The difference between the ethanol and oil prices gives an indication of the extent to which methanol needed to be "subsidized" to be competitive. These subsidies were borne in some manner by all agents involved, producers, consumers and the government. It remains to be seen whether biomass in the form of liquid fuels will reach competitiveness in the future with oil products, indicating the high degree of uncertainty inherent in any process of technological change and the risk borne by entrepreneurs and the public alike during the early phases of technological diffusion.

Figure 2 shows learning curves of three different energy technologies on logarithmic scale indicating similar rates of learning. The lowest curve shows natural gas turbines that in the early 1960s were more expensive than some other energy technologies at the time. With increases in their application and from learning from aeronautical jet engines for commercial and military aviation, costs declined approximately 20 percent per doubling of cumulative installed capacity. As the result of these developments, the costs have declined so much during the last three decades that today gas turbines offer the cheapest way of generating electricity wherever natural gas is available (i.e., gas grids or LNG terminals exist). The other two electricity generating technologies, windmills and photovoltaics, are not generally competitive due to relatively high capital costs except in some important niche markets. However, they are improving at approximately the same rates as gas turbines did, offering the possibility of becoming cost-competitive assuming further applications and extensive deployment. Windmills are likely to reach this position first, and then photovoltaics, assuming that other competing technologies do not improve sufficiently to maintain their current cost advantage. Clearly, any breakthrough in technologies could of course alter any of these future possibilities. Such considerations also need to take into account the intermittent nature of wind and sunshine, requiring special energy storage devices if capacity to meet base load requirements is to be satisfied. To an extent, these other technology characteristics are also considered in energy models (and not merely the costs) but on a quite coarse scale. For example, the capacity factors and the load curves are presented indicating availability of various technologies in an abstract manner and storage technologies are also included.

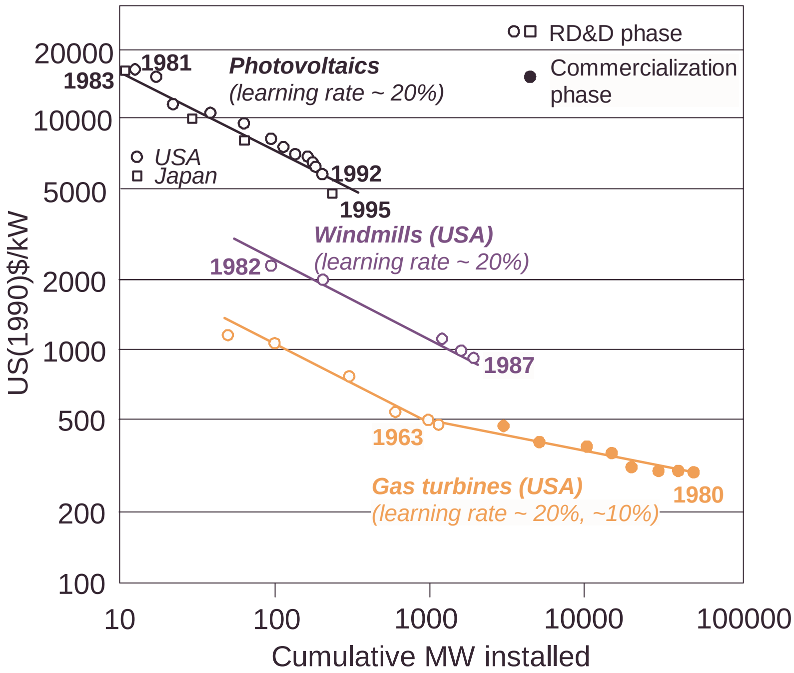

Figure 2. Three learning curves for electricity generation technologies showing historical reduction of costs with increasing scale of installations for gas turbines, windmills and photovoltaics. Source: Nakicenovic, Grübler and McDonald, 1998.

The cost reductions of new technologies through the learning or experience curves are very difficult to capture in standard energy and economic models. Such mathematical problems are "non-convex" meaning that the usual methods of solving energy models do not work. In particular, cost reductions with increases of installed capacity translate into a downward sloping cost curves so that traditional methods do not lead to an equilibrium between supply and demand. This means that the more technology is used the cheaper it becomes while in standard modeling approaches the increasing costs with increasing capacity assure an existence of a stable equilibrium. Consequently, technological learning and other aspects of increasing returns in general are very difficult to capture in standard energy and economic models even though it is an important aspect of technological change in general.- The first attempts to introduce technological learning in energy models have indicated that this invariably either leads to more complex mathematical formulations or to relatively simple and limited applications. MESSAGE model was first to be extended to generate the more complex forms of technological change (e.g. Messner *et al.*, 1996; Messner, 1997; Gritsevskyi and Nakicenovic, 2000). Later, similar extensions were also included in the MARKAL model to account for technological learning (Mattsson, 1997). The IIASA-WEC and IPCC scenarios do not capture explicitly the effects of increasing returns or learning curves due to difficulties in overcoming the mathematical challenges previously mentioned. Instead, these scenarios include capacity, cost and performance "constraints" and assumptions that collectively emulate the effects of increasing returns. This way they include deterministic effects of gradual or incremental technological change once a fundamentally new technology is assumed to have been introduced in a given scenario.

Energy Systems

Energy scenarios are developed by capturing simplified energy systems in models. The 34 scenarios analyzed here encompass all relevant stages of energy conversion, transformation and transport, from energy resources all the way to provision of energy services. Energy imports and exports such as crude oil, oil products or electricity are grouped below "resources" and below "final" category, respectively. Figure 3 illustrates schematically the basic energy system structure as implemented in the scenarios. It shows how individual technologies are connected to each other through their inputs and outputs and across different stages of energy conversion, transformation, transport and end use. Only some selected, representative technologies are shown in this schematic illustration. They nevertheless illustrate all important energy chains. Technologies and connections among them shown in black represent the "1990 technologies" and reference energy system for the base year (1990 in all 34 scenarios). The technologies and their connections marked in red are assumed to become available by 2020. For example, there are many possible primary energy sources (and import possibilities) for electricity generation in 1990 with new technologies becoming available by 2020. Also a number of sources of hydrogen production become available by 2020 such as steam reforming of natural or coal synthesis gases, electrolysis of water through all sources of electricity and finally there is also a possibility of "blending" energy gases into one energy carrier. All technologies in the energy system are associated with a number of characteristics such as energy inputs and outputs, capital and operational costs, facility lifetimes, emissions of various types per unit activity, maximum possible penetration rates and first startup time.

The MESSAGE model is an optimization framework. All of the 34 scenarios assessed here were developed by MESSAGE through minimizing the total systems costs under the constraints imposed on the energy system - such as fossil energy resources, renewable energy potentials, the earliest date new technologies are assumed to be available, the highest rates of market penetration, etc. Given this information and other scenario features such as the demand for energy services, the model configures the evolution of the energy system from the base year to the end of the time horizon (in ten year steps). It provides the installed capacities of technologies, energy outputs and inputs, energy requirements at various stages of the energy systems, costs, emissions, etc.

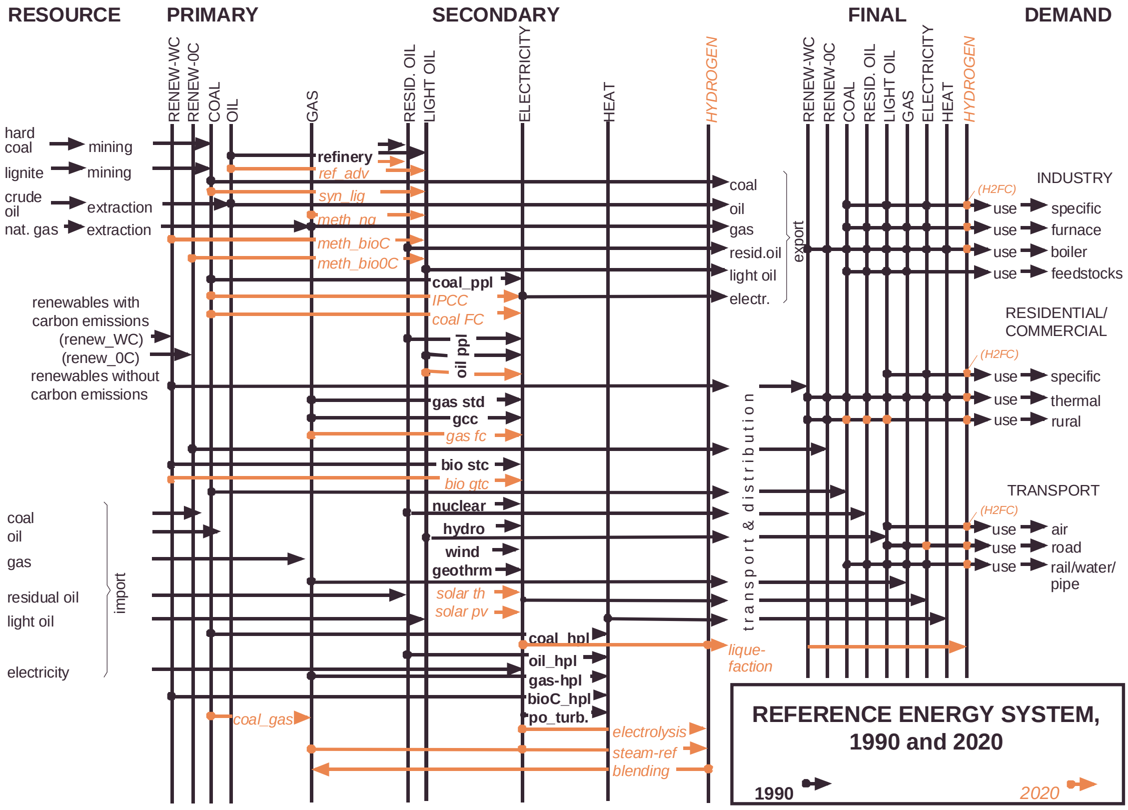

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Figure 3. Schematic diagram of the basic energy system structure in the MESSAGE model.

Further information about the IIASA modeling framework and the MESSAGE model is given in Nakicenovic, Grübler and McDonald, 1998; Riahi and Roehrl, 2000b. The individual models used in the framework include the Scenario Generator (Nakicenovic, Grübler and McDonald, 1998), the MESSAGE (Messner and Strubegger, 1995), the macroeconomic models MACRO (Manne and Richels, 1992; Messner and Schrattenholzer, 2000), the climate model MAGICC (Wigley and Raper, 1997) and several databases, including the CO2DB (Messner and Strubegger, 1991).

Here, we use the set of 34 scenarios to determine which of the technologies play important roles across the range of scenarios in the future, and which are limited to some specific scenario variants. The scenarios are based on very different assumptions about energy demand, future technology characteristics, resource availability, etc. - providing a rich diversity of alternative futures. Thus, technologies that appear to be invariant across this wide range of scenarios can be considered to be robust and resilient with respect to different assumptions. An example of invariant technology is electric transmission lines as they are required in every scenario, and an example of specific technology used only in some scenarios is carbon dioxide storage that is not part of a model solution due to the higher costs unless future carbon emissions are limited in some way. It should be mentioned that carbon removal and storage costs are expected to fall as production capacities and experience with these technologies expands. However, carbon capture and storage are likely to remain to be associated with additional and higher costs than similar energy systems with free release of carbon dioxide into the atmosphere thus making carbon-control technologies a specific feature of mitigation scenarios.

Box 1: Descriptions of technologies and name abbreviations. Note that technology efficiencies improve over time in most of the scenarios, but that plant life and plant factors do not change.

Abbreviation	Technology Description
Coal Std	Aggregation of various types of traditional (single steam cycle) coal power plants. These include plant types without FGD and DENOX, but also other types with FGD up to 90 percent and DENOX up to 50 percent. Some potential for district heat co-generation. Efficiencies for the model base year (1990) range between 38 and 40 percent. Plant life is 30 years and plant factor (availability of utilization) 65 percent.
IGCC	Integrated (coal) gasification combined cycle with 99 percent FGD and DENOX. Some potential for co-generation. Initial efficiency in the base year (1990) is 43 percent plant life is 30 years and plant factor 65 percent.
Oil ppl	Aggregation of various types of oil power plants (includes e.g., Rankine cycle with low NOx emissions and 90 percent DENOX, but also light oil fueled engine plants). Some potential for co-generation. Initial efficiency in the base year (1990) ranges between 40 and 46 percent, plant life is 30 years, plant factor 65 percent.
Gas Std	Standard natural gas power plant (Rankine cycle) with district heat co-generation. Initial efficiency in the base year (1990) is 40 percent, plant life is 30 years and, plant factor 65 percent.
GCC	Natural gas combined cycle power plant including some potential for co-generation. Initial efficiency in the base year (1990) is 50 percent, plant life is 30 years and plant factor 65percent.
GCC 0C	Natural gas combined cycle power plant with zero carbon emissions. CO_2 is assumed to be re-injected in gas or oil fields (e.g., for enhanced recovery). Efficiency loss due to re-injection (compared to GCC) about 1 percent. Plant life is 30 years and plant factor 65 percent.
Coal FC	Coal based high temperature fuel cell. Efficiency is 50 percent, plant life 25 years and plant factor 65 percent. It is assumed in most of the scenarios that this technology will be available commercially after 2010.
Gas FC	High temperature fuel cell powered by natural gas. Rejected heat is available for co-generation. Efficiency is 60 percent, plant life 25 years and plant factor 65 percent. It is assumed in most of the scenarios that this technology will be available commercially after 2010.
Waste	Standard municipal waste power plant (Rankine cycle) with 90 percent FGD and 50 percent DENOX. Initial efficiency in the base year (1990) is 29 percent, plant life is 30 years and plant factor 65 percent.

Bio STC	Biomass power plant (single steam cycle) with some potential for district heat co-generation. Initial efficiency in the base year (1990) is 29 percent, plant life is 30 years and plant factor 65 percent.
Bio GTC	Biomass gasification power plant. Initial efficiency in the base year (1990) is 46 percent, plant life is 25 years and plant factor 65 percent.
Nuc LC	Low-cost conventional nuclear power plant (light and heavy water reactor) . Initial efficiency in the base year (1990) is 30 percent, plant life is 30 years and plant factor 70 percent.
Nuc HC	High-cost conventional nuclear power plant (light and heavy water reactor). Initial efficiency in the base year (1990) is 35 percent, plant life is 30 years and plant factor 75 percent.
Nuc HTR&FBR	Aggregation of various types of advanced nuclear power plants including high temperature and fast breeder reactors with some potential for district heat and hydrogen co-generation. Initial efficiency ranges between 40 and 45 percent. Plant life is 30 years and plant factor 75 percent.
Hydro	Aggregation of various types of hydroelectric power plants. Low and high cost plants are distinguished in all scenarios in order to reflect the influence of different sites and other factors on the plant costs. Plant life is 60 years and plant factor 50 percent.
Solar Th	Solar thermal power plant with storage and some potential for district heat and hydrogen co-generation. Plant life is 25 years and plant factors differ significantly across world regions ranging from 10 to 50 percent.
Solar PV	Aggregation of various types of solar photovoltaic power generation including large-scale power plants and small-scale onsite electricity production. Plant life is 25 years and plant factors differ significantly across world regions ranging from 10 to 50 percent.
Wind	Wind turbine power plant. Plant life is 25 years and plant factor 25 percent.
Geothrm	Geothermal power plant. Plant life is 30 years and plant factor 70 percent.
H2FC	Aggregation of types of hydrogen fuel cells for industrial and residential use with some potential for district heat co-generation. (Note that explicit assumptions for investment costs are not part of the MESSAGE model for all end-use technologies including these types of hydrogen fuel cells. Consequently, it was not possible to include the H2FC fuel cells in the comparison of investment costs.)

Energy and Emissions Scenarios

The set of 34 scenarios includes six developed jointly by IIASA and WEC (Nakicenovic, Grübler and McDonald, 1998), nine developed for the IPCC (the Intergovernmental Panel on Climate Change) Special Report on Emissions Scenarios (Nakicenovic *et al.*, 2000a) and 19 scenarios developed for the IPCC Third Assessment Report (Riahi and Roehrl, 2000a, 2000b; Morita *et al.*, 2001). This third group of 19 scenarios is different as it consists of carbon dioxide emissions mitigation and stabilization scenarios. They include more rapid diffusion of technologies with low and no carbon emissions such as carbon sequestration from fossil energy sources and storage. This is achieved through different policy measures such as cumulative emissions limits. It should be noted that this third group of scenarios represents more than half of the total considered here and thus has an over-proportional bearing on many of features of the whole scenario set.

Global Energy Perspectives

IIASA and WEC earlier undertook a five-year study on "Global Energy Perspectives" (Nakicenovic, Grübler and McDonald, 1998). The study centered on three cases of future social, economic and technological development for 11 world regions. The three cases unfolded into six scenarios of energy systems alternatives. Together, they span a wide range of alternative future developments and scenario driving forces. The three cases are designated as Cases A, B, and C. Case A includes three scenario variants and reflects a high-growth future in terms of vigorous economic development and rapid technology improvement. Case B represents a middle course, with intermediate economic growth and more modest technology improvement. Case C is ecologically driven and achieves sustainable development in the world, incorporating challenging policies to simultaneously protect the environment and enhance interregional and intergenerational equity in two scenario variants (Riahi *et al.* 2001). Both scenarios lead to lower energy use but high overall growth, especially in the South. Table 1 gives an overview of the three cases and their six scenarios of energy systems development.

Table 1: IIASA-WEC Scenarios. The three cases unfold into six scenarios of energy systems alternatives, three Case A scenarios (A1, ample oil and gas; A2, return to coal; and A3, non-fossil future), a single Case B scenario (middle course), and two Case C scenarios (C1, new renewables; and C2, renewables and new nuclear). Source: Nakicenovic, Grübler and McDonald, 1998.

	Population [billion]		**Global Gross Domestic Product (GDP) [trillion (1990)US$]**		**Primary Energy[a] [EJ]**		**Cumulative CO_2 Emissions [GtC]**	**Atmospheric CO_2 Concentration [ppmv]**
	2050	*2100*	*2050*	*2100*	*2050*	*2100*	*1990-2100*	*2100*
WEC-A1	10.1	11.7	100	300	1048	1895	1441	650
WEC-A2	10.1	11.7	100	300	1048	1896	1632	748
WEC-A3	10.1	11.7	100	300	1040	1859	1072	550
WEC-B	10.1	11.7	75	200	837	1464	1139	585
WEC-C1	10.1	11.7	75	220	601	881	635	445
WEC-C2	10.1	11.7	75	220	601	880	622	445

[a] Primary energy is calculated with the substitution equivalent method.
[b] Sulfur emissions include energy related emissions only.
[c] Assuming a climate sensitivity of 2.5°C.

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 favor of more efficient ones, the energy intensity decreases. 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 scenarios, the overall global average energy intensity reductions vary from about 0.8 percent per year to a high figure of 1.4 percent per year during the 21st century. These figures bracket the historical rate experienced by industrialized countries during the last hundred years, of approximately one percent per year, and cumulatively lead to substantial energy intensity decreases across the six scenarios. They also cover most of the range of energy intensity improvements from the scenario database (see Nakicenovic, Grübler and McDonald, 1998). 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.

According to the median demographic projections, the world population is likely to double by the middle of the next century as economic development continues, reaching something less than 12 billion by the year 2100 (Bos and Vu, 1994). This demographic development is representative of most of the central or median population projections (Lutz, 1996; UN, 1998) leading to about 10 billion people in the world by 2100. The IIASA-WEC scenarios combine one such central population projection with other developments that vary across the six scenarios. For example, there is a three to fivefold increase in world economic output by 2050 and a 10 to 15-fold increase by 2100. This also implies that by 2100 the 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. The global primary energy requirements grow less than economic output in all six scenarios, because of improvements in energy intensities. The IIASA-WEC study envisages a 1.5 to 3-fold increase in primary energy use by 2050, and a two to fivefold increase by 2100. The six scenarios are grouped into three different cases of primary energy consumption and economic development covering a wide range of alternative developments.

The scenarios span six different 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 today's levels to emission increases of more than a factor of three. 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. 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-quality 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. 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.[2]

Special Report on Emissions Scenarios

Over three years of work by an international writing team of some 50 scientists and experts culminated in the publication of the Special Report on Emissions Scenarios (SRES) by the Intergovernmental Panel on Climate Change (IPCC). The SRES report (Nakicenovic *et al.*, 2000a) covers what is widely believed to be the full range of demographic, socio-economic and technological driving forces for future emissions of greenhouse gases (GHG) and other radiatively active gases, such as sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen oxides (NO_X), and describes a set of 40 resulting emissions scenarios for the 21st century. The scenarios are based on an extensive literature assessment, six alternative modeling approaches, and an "open process" that solicited worldwide participation and feedback.

The scenarios indicate that the future development of energy systems will play a central role in determining future emissions and suggests that technology is at least as important a driving force as demographic change and economic development, and that all of the driving forces influence not only CO_2 emissions but also the emissions of other GHGs. The scenarios illustrate that similar future GHG emissions can result from very different socio-economic developments, and that similar developments in driving forces can nonetheless result in widely different future emissions. Thus, the SRES reveals many continuing uncertainties that climate research and policy analysis must take into account.

In particular, the report cautions against the use of single "best guess" or "business as usual" scenarios and instead recommends the use of multiple baselines to reflect uncertainty. It also puts technology policy in the forefront of possible response strategies in a warming world, although the uncertainties imply that traditional cost/benefit and cost minimization approaches are no longer appropriate. This is one of the reasons why SRES scenarios can be used to assess the role of energy technologies across alternative future developments. They were purposefully designed to cover a wide range of main driving forces including energy technologies.

[2] These scenarios do not, of course, incorporate all possible "surprises" and contingencies, for the reasons stated in the Introduction. They do, however, encompass a wide range of future possibilities.

The SRES scenarios do not map all possibilities, but indicate general tendencies, with an uncertainty range consistent with the underlying literature. There is no "business-as-usual" scenario because the future is inherently unpredictable. Instead, large uncertainties are associated with future emissions across the scenarios. For instance, carbon dioxide emissions in a low population scenario of seven billion by 2100 range from less than five to almost 40 GtC (giga or billion tons of carbon). Also, as mentioned earlier, alternative combinations of main scenario driving forces can lead to similar levels of GHG emissions.

The SRES team created four different narrative storylines and associated scenario families; each describes a different world evolving through the twenty-first century and each may lead to quite different greenhouse gas emissions trajectories. The storylines and scenario families are:

- A1: a future world of very rapid economic growth, global population that peaks mid-century and declines thereafter, and rapid introduction of new and more efficient technologies. Major underlying themes are economic and cultural convergence and capacity building, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system: fossil intensive (A1FI), non-fossil energy sources (A1T), and a balance across all sources (A1B).
- A2: a differentiated world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, resulting in continuously increasing population. Economic development is primarily regionally orientated and per capita economic growth and technological change more fragmented and slower than other storylines.
- B1: a convergent world with rapid change in economic structures towards a service and information economy, reductions in material intensity and introduction of clean technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improving equity, but without additional climate change policies. Consequently, all scenarios of the B1 family (B1, B1T, B1G) depict alternative directions of technological change striving toward the achievement of sustainable development paths (Riahi *et al.*, 2001).
- B2: a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than for A1 and B1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

The features summarized above were quantified using six different models, resulting in a number of alternative greenhouse gas profiles. In all 40 scenarios were quantified, and 35 included estimates for the full range of gases required for use by climate models. One representative of each scenario family was then selected to provide four “marker” scenarios (A1B, A2, B1 and B2) and another two scenarios were also selected later to illustrate the other two scenario groups (A1FI and A1T), jointly covering 95 percent of the range of the full set of scenarios. These six scenarios are designated as illustrative of the full set of 40 scenarios developed during the process The SRES writing team recommended that at least these six illustrative scenarios be used in scientific and policy assessments to reflect uncertainty ranges.

Compared to the IPCC IS92 scenarios (Leggett *et al.*, 1992), the recent global population projections are generally lower and this is reflected in SRES scenarios. Table 2 summarizes the main features of the nine IIASA scenarios developed for SRES.

A1 and B1 scenario families share a low population projection that leads to an initial increase to some nine billion people by the middle of the century and declines to seven billion by 2100. B2 family is based on a median population projection of about ten billion people by 2100, slightly lower than the single global population projections shared by the six IIASA-WEC scenarios (leading to about 12 billion by 2100). Finally, A2 family of scenarios is based on a high population projection of 15 billion people by 2100.

Table 2: IIASA SRES Scenarios. The four SRES scenario families include nine greenhouse gas emissions scenarios developed by the IIASA modeling framework. The four A1 scenarios (A1B, balanced technology; A1C and A1G, fossil intensive; and A1T, rapid technological change), a single A2 scenario (coal intensive), a single B2 scenario (dynamics as usual), and three B1 scenarios (B1, balanced technology; B1G, fossil intensive; and B1T, rapid technological change). The full SRES set consists of 40 scenarios developed with six different modeling frameworks. Source: Nakicenovic *et al.* 2000.

	Population [billion]		**Global Gross Domestic Product (GDP) [trillion (1990)US$]**		**Primary Energy[a] [EJ]**		**Cumulative CO_2 Emissions [GtC]**	**Atmospheric CO_2 Concentration [ppmv]**
	2050	*2100*	*2050*	*2100*	*2050*	*2100*	*1990-2100*	*2100*
SRES-A1B	8.7	7.1	187	550	1422	2681	1562	724
SRES-A1C	8.7	7.1	187	550	1377	2325	2046	950
SRES-A1G	8.7	7.1	187	550	1495	2737	2092	891
SRES-A1T	8.7	7.1	187	550	1213	2021	1122	560
SRES-B1	8.7	7.1	136	328	837	755	842	486
SRES-B1G	8.7	7.1	166	350	911	1157	902	509
SRES-B1T	8.7	7.1	136	328	819	714	776	464
SRES-B2	9.4	10.4	110	235	869	1357	1143	603
SRES-A2	11.3	15.1	82	243	1014	1921	1662	783

[a] Primary energy is calculated with the direct equivalent method.
[b] Sulfur emissions include also non-energy related emissions.
[c] Assuming a climate sensitivity of 2.5^{o}C.

The SRES scenarios cover a wider range of driving forces and in particular of energy and land-use structures. All SRES scenarios describe futures that are more affluent than today, and a narrowing of relative income differences among world regions is assumed in many of the scenarios. Global economic output increases from more than three times in the lowest scenarios to more than 20 times in the highest cases. Convergence of regional per capita incomes can lead to either high or low GHG emissions.

Compared to the previous IPCC scenarios (the IS92 set, Leggett *et al.*, 1992) GHG and SO_2 emissions in the SRES scenarios are generally lower and cover a wider range of driving forces and emissions consistent with the underlying literature. Again it needs to be stressed that the SRES scenarios do not seek to encompass all “surprises” and contingencies, and there is a huge future research agenda for how far future societal and environmental priorities could influence individual values and lifestyles, political platforms and policies. But the SRES scenarios are more in line with the ranges of IIASA-WEC scenarios. Global CO_2 emissions from energy range from 3.3 to 37 GtC by 2100 compared to 6 GtC in 1990 and from land-use changes from a sink of 2.5 GtC to a source of about 1.5 GtC by 2100 compared to a source of about 1 GtC estimated for 1990 (which is associated with a high degree of scientific uncertainty). Some of the energy and many of the land-use emissions paths show trend reversals where initially emissions increase, peak, and then gradually decline. Like CO_2, the anthropogenic emissions of CH_4 and N_2O span a very wide range by 2100. SO_2 emissions peak within the net few decades and decrease until 2100 when they range from 11 to 83 MtS compared to some 76 MtS in 1990. These developments in the SRES scenarios lead to generally higher levels of radiative forcing compared with the IS92 scenarios. Initial calculations of future climate change by IPCC Third Assessment Report indicate that the SRES scenarios would result in projected increases in global mean surface temperature of about 1.4 to 5.8 degrees Centigrade by 2100 in contrast to the previous IPCC assessment (Second Assessment Report) of 1 to 3.5 degrees Centigrade. These higher projections are primarily the result of the lower projections of SO_2 emissions, which tend to cool the climate, thus offsetting the warming effect of GHG emissions. They are also due to higher radiative forcing of GHGs in the climate models. About half of the uncertainty of the calculated climate change range is due to the alternative trajectories of future emissions resulting from SRES scenarios and the other half is due to the uncertainty of a given emissions trajectory across a range of climate models used by IPCC.

Here we consider only nine scenarios developed by the MESSAGE model from the whole set of 40 scenarios developed by six different modeling frameworks. The reasons are that MESSAGE has also been used to develop the IIASA-WEC scenarios. This means that the assumptions and other relevant scenario features are comparable across the two studies. The more important reason is that MESSAGE is the only systems-engineering model of the six used in SRES. Other models do not include the detail on technologies needed for this analysis and comparison of the role of new and advanced technologies across scenarios. Even the MESSAGE model, however, relies principally on an energy supply technologies’ database, whereas technologies relating to end-uses and greater efficiency are likely to be at least as important for future developments.[3]

[3] Note that the modeling of technological changes in the end-use sector is particularly difficult, since it is not exclusively economic thinking that drives the customers' choice for end-use devices. End users are willing to pay more for more convenient and flexible energy forms, in contrast to companies in the supply sectors, which usually follow the premise of profit maximization. Such real world imperfections are difficult to deal with in cost-optimization models such as MESSAGE. Therefore, in MESSAGE the end-use technologies are included in a more stylized and generic way considering so-called inconvenience costs (i.e., cost premiums in addition to the real costs of end-use technologies expressing the willingness to pay for favored technologies)

Post-SRES Scenarios

The third set of scenarios considered here was also developed for the IPCC Third Assessment Report (Morita, Nakicenovic and Robinson, 2000). They are based on the SRES scenarios as baselines for the assessment of possible emissions mitigation strategies, hence the name Post-SRES. In particular, the scenarios were developed to understand better the nature and extent of mitigation measures and policies needed across the four SRES scenarios families to achieve stabilization of atmospheric GHG concentrations in the 22nd century. Four alternative stabilization levels of atmospheric concentrations of CO_2 (equivalent) were considered, 450 ppmv (parts per million volume), 550 ppmv, 650 ppmv and 750 ppmv. This compares the current atmospheric concentrations of about 368 ppmv and the pre-industrial concentrations of some 280 ppmv two centuries ago.

The Post-SRES scenarios are harmonized with their four SRES baselines with respect to three key driving forces of future emissions: population development, economic growth and final energy use. Other salient features of the four SRES scenario families were also adopted for the Post-SRES mitigation scenarios.

The Post-SRES scenarios were developed by nine different modeling teams including the six from the SRES scenarios. Most of the modeling teams analyzed more than two SRES baseline scenarios, and half of them analyzed more than one stabilization case for at least one of these baselines. In total, 50 Post-SRES scenarios were analyzed by the nine different integrated modeling frameworks. The IIASA modeling framework that includes the MESSAGE model was one of the nine used to develop Post-SRES scenarios. In total, 19 out of the 50 Post-SRES scenarios were developed by the MESSAGE model. The main characteristics for the 19 Post-SRES scenarios developed by the MESSAGE model are summarized in Table 3.

In order to reduce CO_2 and other GHG emissions, each modeling team assumed specific technology policy measures for their scenario quantification. These ranged from emissions taxes and limits to introduction of zero-carbon energy options and carbon sequestration through scrubbing, removal and storage. In the case of the MESSAGE model, the CO_2 mitigation measures included concentration limitations for the four ceilings of 450, 550, 650 and 750 ppmv (Riahi and Roehrl, 2000). This resulted in an endogenous choice of appropriate mitigation measures by the model from the above portfolio of technologies.

Table 3: IIASA Post-SRES Scenarios. The nine SRES scenario developed by the IIASA modeling framework served as baselines for 19 stabilization scenarios. They include four A1B (balanced technology) scenarios, five A1C (coal intensive), four A1G (gas and oil intensive), two A1T (rapid technological change), three A2 scenarios (dynamics as usual), and one B2 (sustainable development) scenario. Four different atmospheric CO_2 concentrations' stabilization of 450, 550, 650 and 750 ppmv (CO_2 equivalent) are indicated next to the scenario's name. Source: Riahi and Roehrl, 2000a.

	Population [billion]		**Global Gross Domestic Product (GDP) [trillion (1990)US$]**		**Primary Energy [EJ]**		**Cumulative CO_2 Emissions [GtC]**	**Atmospheric CO_2 Concentration [ppmv]**
	2050	*2100*	*2050*	*2100*	*2050*	*2100*	*1990-2100*	*2100*
A1B-450	8.7	7.1	187	550	1447	2707	701	450
A1B-550 (1)	8.7	7.1	187	550	1403	2691	1065	553
A1B-550 (2)	8.7	7.1	186	547	1339	2505	1052	550
A1B-650	8.7	7.1	187	550	1413	2681	1350	647
A1C-450	8.7	7.1	187	550	1429	2884	668	451
A1C-550 (1)	8.7	7.1	187	550	1346	2413	1005	548
A1C-550 (2)	8.7	7.1	185	541	1269	2188	1050	550
A1C-650	8.7	7.1	187	550	1331	2396	1312	639
A1C-750	8.7	7.1	187	550	1279	2258	1283	752
A1G-450	8.7	7.1	187	550	1562	2815	694	447
A1G-550	8.7	7.1	187	550	1485	2787	1060	551
A1G-650	8.7	7.1	187	550	1483	2787	1359	644
A1G-750	8.7	7.1	187	550	1486	2786	1658	752
A1T-450	8.7	7.1	187	550	1204	2077	703	455
A1T-550	8.7	7.1	187	550	1210	2020	1056	553
A2-550	11.3	15.1	81	236	959	1571	1077	550
A2-650	11.3	15.1	82	243	996	1810	1444	650
A2-750	11.3	15.1	81	238	992	1610	1396	750
B2-550	9.4	10.4	109	231	881	1227	949	550

[a] Assuming a climate sensitivity of 2.5°C.

An important result from these stabilization scenarios across all nine modeling approaches is that the reductions from the four alternative scenarios families (different worlds labeled A1, A2, B1 and B2) required different technology measures. Stabilization from baselines with high emissions such as A2, but relatively low rates of economic growth, is more difficult - especially for low concentrations ceilings - compared to baselines with high rates of economic growth and low emissions such as B2 and some variants of A1 (A1T). This again illustrates the important role of technology (or the choices made among technology options) in determining the salient features of future energy systems. Future worlds with high rates of economic growth and technological innovations are better placed to reduce emissions in these stabilization scenarios and can generally achieve these goals at lower costs. In addition, the choice of a particular stabilization level from any given baseline significantly affects the technologies needed for achieving the necessary emissions mitigation. For example, a wider range of technological measures and their widespread diffusion is required for stabilizing at 450 ppmv compared with higher levels.

It is also apparent from these scenarios that no single measure will be sufficient to achieve stabilization at any given level. This means that the CO_2 and other GHG emissions cannot be reduced from baseline scenarios by any single technology. There is no "silver bullet". Instead, a portfolio of technologies needs to be developed and adopted in addition to other social, behavioral and structural changes. Furthermore, the rates of technological change required for achieving a given stabilization level are significantly affected by the choice of development path over the 21st century. This is an important finding. The nature of the development path itself has an important bearing on the direction of technological change in the scenarios. For example, scenarios with lower rates of technological change are more likely to rely heavily on coal while scenarios with low energy demands coupled with high economic growth are more likely to rely more heavily on renewable sources of energy. Several robust technology options emerge in the case of the 19 Post-SRES stabilization scenarios developed by the MESSAGE model. In particular, the electricity sector is not dominated by any single technology; however, hydrogen, fuel cells and carbon sequestration are the most robust in stabilization cases from all alternative baselines.

Scenario Comparisons

The 34 scenarios analyzed in this assessment encompass a wide range of future energy use in the world and thus test the possible role of future energy technologies under different circumstances. On one side of this range are scenarios with very high energy use of up to six times current levels, and on the other scenarios with a high degree of energy savings and conservation that cap future energy needs at less than twice the current use. Clearly, scenarios with high energy use imply different energy technology portfolios compared with scenarios that put emphasis on end-use energy savings and enhanced performance of energy services.

Figure 4 shows the range of future primary energy use across the 34 scenarios. The highest scenarios approach primary energy levels of 3,000 EJ while the lowest stay below 800 EJ by 2100. The six IIASA-WEC scenarios (labeled in black) share three levels of primary energy use. The scenario range includes nine SRES and 19 Post-SRES scenarios. The 28 IPCC SRES and Post-SRES scenarios overlap with the IIASA-WEC ones over the lower range, but extend the upper part of the distribution considerably. This is primarily due to the high rates of economic development in some of them. The Post-SRES stabilization scenarios use SRES scenarios as baselines so that the primary energy use levels are basically the same for each pair of the scenarios.

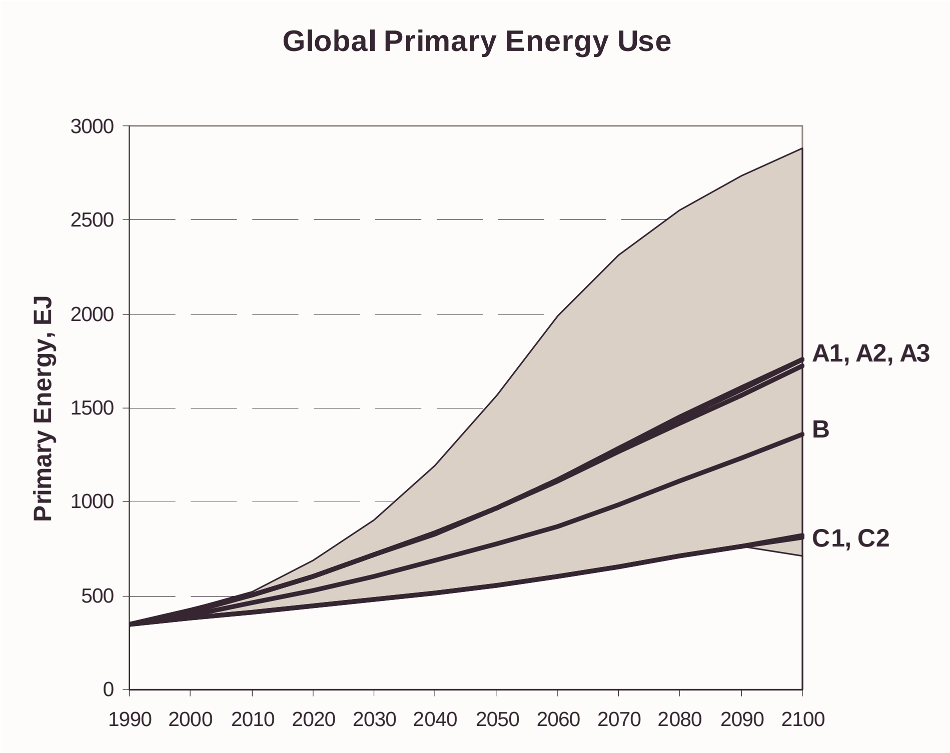

Figure 4. Global primary energy use. The three cases of energy use are shown for the six IIASA-WEC scenarios (labeled in black) and the range for the IPCC SRES scenarios developed by IIASA. The Post-SRES stabilization scenarios use SRES scenarios as baselines so that the primary energy requirements are basically the same for each pair of the scenarios. The range includes nine SRES and 19 Post-SRES.

Different technological portfolios are used across these 34 scenarios for provision of the required energy services. Thus, the structures of the energy systems are quite different in general and even for scenarios that share similar energy requirements. Figure 5 illustrates this indirectly by showing CO_2 emissions. The six IIASA-WEC scenarios are shown individually. The ranges are given for the IPCC SRES scenarios and the Post-SRES stabilization scenarios developed by IIASA. The Post-SRES emissions stabilization scenarios use SRES scenarios as baselines. SRES range includes nine and post SRES 19 IIASA scenarios. Three ranges are shown, SRES, overlap of SRES and Post-SRES and Post-SRES.

The six IIASA-WEC scenarios span a wide range of emissions, from more than three times current emission to less than half. The three A scenarios (A1, A2 and A3) that share the high primary energy trajectory differ fundamentally in their CO_2 emissions. The main reason is different structures of the energy system as the result of alternative technological developments. The highest emissions are associated with the A2 scenario, which is coal intensive and represents a development path of relatively modest development of alternative technologies. Consequently, there is a pervasive “return” to coal as conventional oil and gas tend to be exhausted and because renewables continue to be costly and difficult. In contrast, the A3 scenario leads to a pervasive diffusion of new energy technologies including both clean fossil fuels (particularly natural gas) as well as renewables and nuclear. Thus, the emissions return to current levels by 2100 after peaking during the mid-century. Scenario A1 is a “balanced” scenario with respect to the development of new technologies and the continuing role of the old ones. Scenario B is characterized by a quite similar energy system structure, but a lower, median economic growth path. The emissions trajectory of scenario A3 is consistent with atmospheric stabilization at 550 ppmv, indicating that technological change can lead to significant emissions reductions without explicit mitigation measures and consequently also at “no additional” cost. Finally, the two C scenarios that represent “ecologically driven” futures lead to a fundamental shift away from fossil fuels in the energy system and radical reduction of primary energy use in delivering needed energy services through conservation and energy saving. In contrast, these two scenarios include carbon and energy taxes that facilitate the shift away from fossil fuels and a reduction of energy requirements. As a result, the CO_2 emissions are impressively low and constant with a stabilization at below 450 ppmv. Thus, together, the six scenarios cover most of the possibilities of future technology mixes in the energy system, from coal-intensive to renewable systems.

The nine IIASA SRES scenarios cover the lower range of IIASA-WEC scenarios but extend the upper bound well above 30 GtC. The reasons for this wide range are similar to those for the IIASA-WEC scenarios. The SRES A1 scenarios branch out into three different paths of technological development, from coal-intensive futures to those with a rapid shift toward non-fossil fuel and high efficiency technologies. These differences in the technology base of the SRES A1 scenarios span the full range of future emissions, from more than five times current ones (30 GtC) to less than half. Very high rates of economic development and energy requirements (see Figure 4) are the main reason why the SRES A1 scenarios greatly exceed the upper bound of the IIASA-WEC scenarios. Other SRES scenarios are situated within the range of the A1 family. The differences between their emissions trajectories are due in part to varying diffusion rates of new technologies and in part due to different levels of economic and population growth.

As already mentioned, the IIASA Post-SRES scenarios use SRES cases as baselines. For example, energy use is quite similar for each pair as well as other important driving forces. As mentioned, the main difference is that Post-SRES scenarios limit the future atmospheric GHG concentrations at four levels varying between 650 and 450 ppmv (CO_2 equivalent). This affects the structure of the energy system in comparison to the baseline. The change is greater the higher the need to mitigate emissions either because the baseline emissions are high or because the stabilization level is low. Generally, mitigation measures favor more efficient technologies, a shift toward decarbonization either through higher shares of natural gas or introduction of carbon sequestration through scrubbing, removal and storage, and a shift toward renewables and nuclear energy. The diffusion of

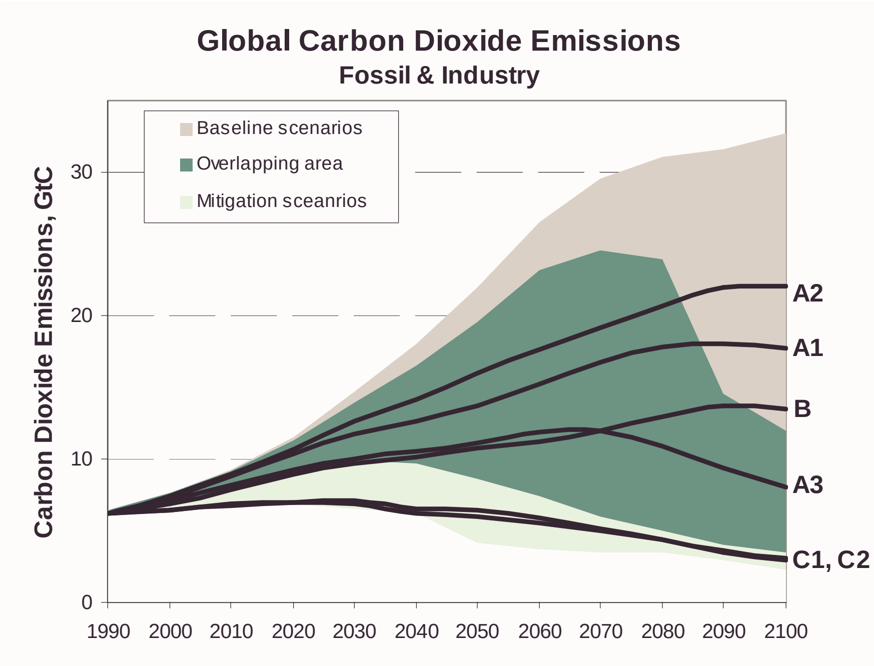

Figure 5. Global carbon dioxide (CO_2) emissions. The six IIASA-WEC scenarios (labeled in black) are shown individually. The ranges are given for the IPCC SRES scenarios and the Post-SRES stabilization scenarios developed by IIASA. The Post-SRES emissions stabilization scenarios use SRES scenarios as baselines. The SRES range includes nine and Post-SRES 19 scenarios. Three ranges are shown, SRES range, overlap of SRES and Post-SRES and Post-SRES range.

carbon scrubbing, removal and storage technologies is one of the greatest differences between Post-SRES scenarios and their SRES baselines. Carbon scrubbing and removal are significant in most of Post-SRES scenarios. Some marginal deployment of these technologies occurs both in IIASA-WEC A3 as well as in some SRES A1 scenarios. This is not related to emissions mitigation but rather some use of these technologies become economic because captured CO_2 has a commercial value in these scenarios for enhanced oil recovery. In contrast, Post-SRES scenarios lead to a wide diffusion of carbon scrubbing and removal technologies.

Fossil Reserves and Resources Across the Scenarios

The perceptions about global energy resources have changed during the last decades. On one side there is the traditional view that conventional energy reserves of oil and natural gas are limited, say to some four to six decades at current consumption levels. However, this is a static view of energy resources. A more dynamic view is that the future availability of energy is to a large degree a function of energy technologies and economic conditions. Historically, this has certainly been the case. Improvements in energy technologies have reduced the adverse environmental impacts of energy at all scales and, at the same time, have also increased the estimates and availability of energy sources. In a way, the quantity of global fossil energy resources available to future generations can be considered to be a growing endowment. However, resources are not an end in themselves and their attractiveness must be seen in context with the energy service needs of our societies, the technologies which convert different resources into energy services, and the economics associated with their use, including environmental impacts. As technologies improve, it becomes possible to economically assess and extract deeper, lower quality and more remote deposits. In addition, the more speculative occurrences of fossil energy, especially unconventional deposits of natural gas in form of hydrates, are truly vast and, if ever exploited, could supply any conceivable future energy demands for centuries to come.

Table 4 shows fossil energy reserves, resources and additional occurrences relative to cumulative historical consumption and their use in 1988. It gives fossil energy deposits divided into reserves, resources, the resource base and additional occurrences. Oil and gas are divided into conventional and unconventional deposits. Reserves are known and are recoverable with present technologies at prevailing market conditions. Resources are occurrences in addition to reserves, with less certain geological assurance, or lacking present economic feasibility, or both. Changing market conditions, innovation diffusion, and advances in science can transform resources into reserves. Thus, the growth of reserves can occur even without new resource discoveries. The resource base is the sum of reserves and resources. It includes all potentially recoverable coal, conventional oil and natural gas, unconventional oil resources (such as gas in shale, tar sands, and heavy crude), and unconventional natural gas resources (such as gas in Devonian shale, tight sand formations, geopressured aquifers, and coal seams). Additional occurrences are all other hydrocarbon deposits that are known to exist but are associated with great uncertainty about their extent, technology and economics of recovery. Methane hydrates are an example of a clean and potentially enormous energy resource. Recent estimates indicate that there might be three times more natural gas deposited in hydrates than in all other hydrocarbon occurrences.

Table 4: Global hydrocarbon reserves, resources, and occurrences, in ZJ (10^{21}J). Data sources: Nakicenovic *et al*, 1996; Nakicenovic, Grübler and McDonald, 1998, WEC, 1998, Masters *et al.*, 1994; and Rogner *et al.*, 2000.

	Consumption		Reserves	Resources	Resource	Additional
	1860–1998	1998			Base	Occurrences
Oil						
Conventional	4.85	0.13	6	6	12	
Unconventional	0.29	0.01	6	16	22	60
Gas						
Conventional	2.35	0.08	6	11	17	
Unconventional	0.03	--	9	26	35	800
Coal	5.99	0.09	21	179	200	140
Total	13.51	0.31	48	238	286	1000

Table 4 summarizes recent estimates from a number of literature sources and gives the occurrences of oil, natural gas and coal derived from the literature (Nakiceonivic *et al.*, 1996; Nakicenovic, Grübler and McDonald, 1998, WEC, 1998, Masters *et al.*, 1994; and Rogner *et al.*, 2000). The estimates were chosen so as to correspond to the highest plausible values from the literature. They indicate that severe resource constraints can be avoided even over time scales of centuries provided that the appropriate technological development actually takes place to render vast resources into economically exploitable reserves. Given current oil and gas reserve-to-production ratios of some four decades, it is obvious that the currently estimated reserves will be depleted long before the fossil energy era is likely to come to an end. Thus, without the appropriate technological development that leads to continuous transfer and reclassification of some resources into reserves, the availability of oil and natural gas sources might indeed become limited during 21st century.

Driven by economics, technological and scientific advances, and policy decisions, the hydrocarbon resource base has expanded over time, and reserves have been continuously replenished from resources and from new discoveries (Masters *et al.*, 1994; Nakicenovic, Grübler and McDonald, 1998; Rogner *et al.*, 2000). Thus, it can be expected that the hydrocarbon resource base is likely to expand and exceed the current estimates shown in Table 4. Some deposits currently classified as occurrences will enter the resource base and eventually become reserves. The argument then becomes more one of cost and development of extraction, treatment and environmental mitigation technologies rather than of ultimately available reserves (Gregory and Rogner, 1998).

Currently identified global fossil energy reserves are estimated at more than 48 ZJ (48,000 EJ or about 1,160 Gtoe). This quantity is theoretically large enough to last more than 150 years at the current level of global fossil energy consumption (310 EJ or 8.5 Gtoe in 1998), or is three and a half times larger than the total cumulative fossil energy extraction since 1860. Coal accounts for more than half of all fossil energy reserves. Nevertheless, even oil and gas reserves would last for about 120 years at current global consumption levels.

Current estimates of fossil resources and additional occurrences are much larger but more uncertain than reserves. The global resource base (reserves and resources) is estimated at some 286 ZJ (6,900 Gtoe), with additional occurrences of more than 1000 ZJ (24,000 Gtoe), mostly in the form of methane hydrates. Thus, hydrocarbon energy sources are abundantly available in the world and the known deposits are likely to last more than a century, and with technological and scientific progress in energy extraction, many centuries.

What is limited is conventional oil, currently the fuel of choice for most end uses, especially transportation. Much of the abundant occurrences of hydrocarbons consist of coal and unconventional oil and gas. Use of these sources of energy is associated with adverse environmental impacts. As more difficult, lower quality and more remote deposits are exploited, it can be expected that environmental impacts will increase unless vigorous mitigation measures are enacted. In other words, what is limited are “clean and easy” hydrocarbon deposits. Thus, improvements in efficiency and environmental compatibility of energy technologies are important prerequisites for utilizing more difficult hydrocarbon deposits.

This more dynamic view of energy resources is reflected both in the IIASA-WEC and SRES scenarios where the availability of fossil energy sources is assumed to be a function of other relevant scenario characteristics such as the rates of technological change and energy investments. Table 5 summarizes oil and gas reserves and resources available across the scenarios. Coal is not shown in Table 5 as it is assumed to be abundant and the future cumulative consumption levels do not come even close to the quantities shown in Table 4. The main issue across the scenarios is which portion of the oil and gas resources shown in Table 4 could be extrapolated in the future with close to conventional methods and current prices and which portion would require the availability of advanced and new technologies at competitive costs. As technologies improve and market conditions change, some resources are in any case transferred (reclassified) into what we consider to be the reserves. Another important development is that some of the so-called unconventional sources of oil and gas are becoming competitive, such as the extraction of methane from coal beds.

Table 5. Eight categories of conventional and unconventional oil and gas reserves, resources and additional occurrences used in the 34 scenarios, in ZJ (10^{21}J). Table shows which of the categories are deployed in each scenario and compares cumulative use from 1990 to 2100 with historical consumption from 1860 to 1988.

	Conventional reserves and resources	**Unconventional**			**Unconventional and additional occurrences**				
		Enhanced recovery	**Recoverable**					**Historical Consumption 1860-1998**	
Category	**I,II,III**	**IV**	**V**	**VI**	**VII**	**VIII**	**Total**		
Oil	12.4	5.8	1.9	14.1	24.6	35.2	94	5.1	
Gas	16.5	2.3	5.8	10.8	16.2	800	852	2.4	
		Scenario assumptions						**Consumption 1990-2100**	
Scenario/ Category	**I,II,III**	**IV**	**V**	**VI**	**VII**	**VIII**		**Oil**	**Gas**
SRES									
A1B	gas/oil	gas/oil	gas/oil	gas/oil	gas	---		25.5	31.8
A1T	gas/oil	gas/oil	gas/oil	gas/oil	gas	---		20.8	24.9
A1O&G	gas/oil	gas/oil	gas/oil	gas/oil	gas/oil	gas		34.4	49.1
A1C	gas/oil	gas/oil	gas/oil	---	---	---		18.5	20.5
A2	gas/oil	gas/oil	gas/oil	gas	---	---		19.6	24.5
B1	gas/oil	gas/oil	gas	gas	---	---		17.2	23.9
B2	gas/oil	gas/oil	gas/oil	gas	---	---		19.4	26.9
WEC									
A1	gas/oil	gas/oil	gas/oil	gas/oil	gas/oil	gas/oil		34.0	28.9
A2	gas/oil	gas/oil	gas/oil	---	---	---		18.7	21.2
A3	gas/oil	gas/oil	gas	gas	gas	---		17.4	36.1
B	gas/oil	gas/oil	gas/oil	---	---	---		17.8	19.6
C1	gas/oil	---	---	---	---	---		12.4	14.9
C2	gas/oil	---	---	---	---	---		12.4	14.2

Table 5 gives eight categories of oil and gas availability across all 34 scenarios and shows which of the categories are actually used in the IIASA-WEC and SRES scenarios. Figures 6a and 6b show the cumulative use of oil and gas, respectively, within each of the eight categories across the 34 scenarios. Each "error bar" shows the range across for IIASA, SRES and Post-SRES scenarios for a given category from the upper to the lower bound and for the median. The IIASA-WEC scenarios are highlighted separately through dashed bars, which also show the upper and lower bound as well as the median. Figures 6a and 6b also show in how many scenarios each of the eight categories is available, in percent on the right hand side. The first three categories in Table 5 and Figures 6a and 6b constitute conventional oil and gas as given in Table 4. They are deployed in all scenarios. The following three categories constitute unconventional oil and gas, divided into what might be available in form of enhanced oil and gas recovery and unconventional reserves and resources. The last two categories represent additional occurrences. In case of oil only one scenario extends into the eight category but the cumulative use is comparatively small with less than 0.5 ZJ as shown in Figure 6a. The natural gas story is more complicated. Most of the occurrences in the seventh category constitute more difficult unconventional gas resources while the eight category is enormous constituting of vast quantities of methane hydrates. The challenge is to understand the conditions and technologies that would make some of these quantities available economically during the 21st century. The actual use of methane hydrates (category eight) is more modest with about 25 ZJ in the most extreme scenario and with more than 20 ZJ in the median case. However, 20 percent of all scenarios tap into methane hydrates. Most of them are Post-SRES mitigation cases indicating that this energy source might become more attractive due to its low carbon intensity in low emissions futures.

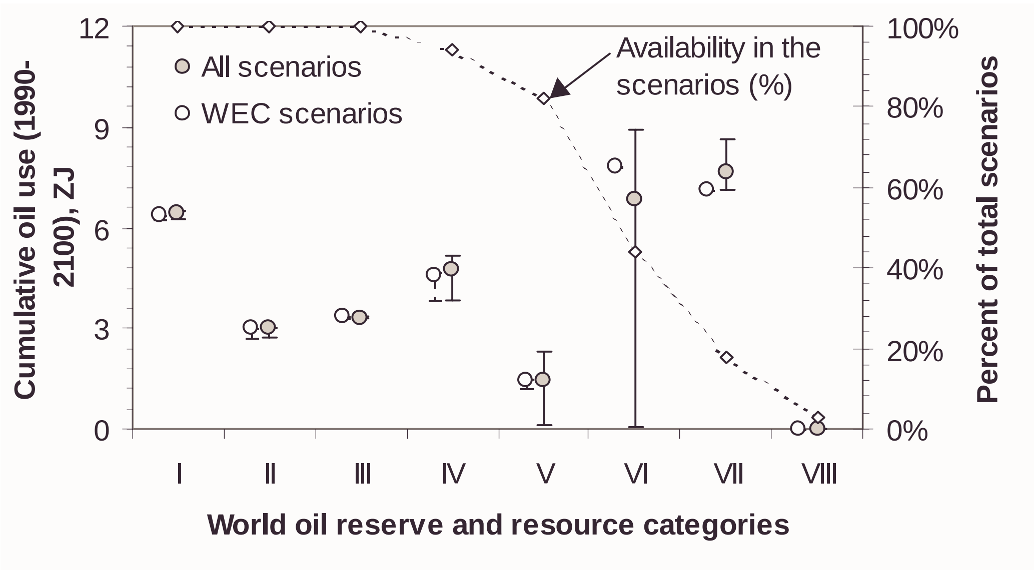

Figure 6a**.** Cumulative oil use from 1990 to 2100 across 34 scenarios, in ZJ (10^{21}J), for the eight categories of conventional and unconventional oil reserves, resources and additional occurrences used in the 34 scenarios. Each bar shows the range across IIASA SRES and Post-SRES scenarios for a given technology from upper to lower bound and for the median. The IIASA-WEC scenarios are highlighted separately through dashed bars, showing the upper and lower bound as well as the median. Also shown on the right hand side is in how many scenarios each of the eight categories is available, in percent.

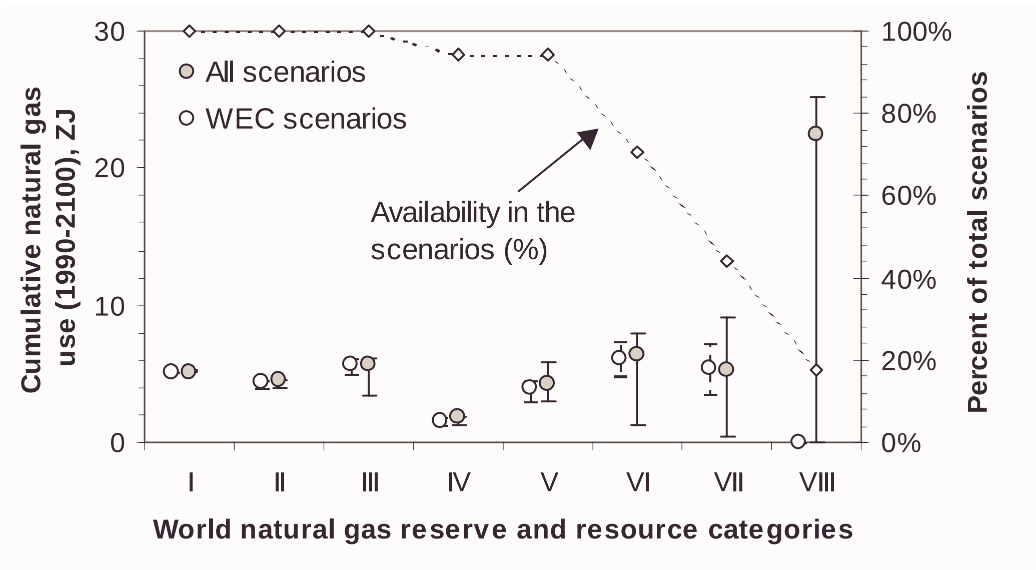

Figure 6b. Cumulative gas use from 1990 to 2100 across 34 scenarios, in ZJ (10^{21}J), for the eight categories of conventional and unconventional gas reserves, resources and additional occurrences used in the 34 scenarios. Each bar shows the range across IIASA SRES and Post-SRES scenarios for a given technology from upper to lower bound and for the median. The IIASA-WEC scenarios are highlighted separately through dashed bars, showing the upper and lower bound as well as the median. Also shown on the right hand side is in how many scenarios each of the eight categories is available, in percent.

Generally, the first five categories are available in most scenarios. The main exceptions are the two IIASA-WEC C scenarios that are limited to conventional oil and gas categories. The last two categories of additional occurrences and more difficult unconventional gas resources are available only in some scenarios with very rapid growth such as more oil and gas intensive cases of SRES and Post-SRES A1 scenario family and IIASA-WEC A1 and A3 scenarios. As the result the cumulative fossil energy use varies over a wide range across the scenarios depending on the assumed availability of oil and gas resources as well as other relevant scenario characteristics such as the rates of technological change. Another important determinant of fossil energy deployment and technology choice across the scenarios is the cost. As mentioned, MESSAGE is an optimizing framework for determining the cost optimal structure of future energy systems. Consequently, costs of fossil energy sources are crucial in determining energy systems structures. Figures 7a and 7b show the evolution of shadow prices of oil and gas, respectively, in the nine SRES scenarios. Shadow prices represent marginal costs, in this case of oil and gas extraction. Scenarios with rapid rates of technological change expand the access to oil and gas at relatively low marginal costs keeping the energy supply options wide open while other scenarios with higher marginal costs of oil and gas evolve toward a stronger reliance on coal and non-fossil energy sources.

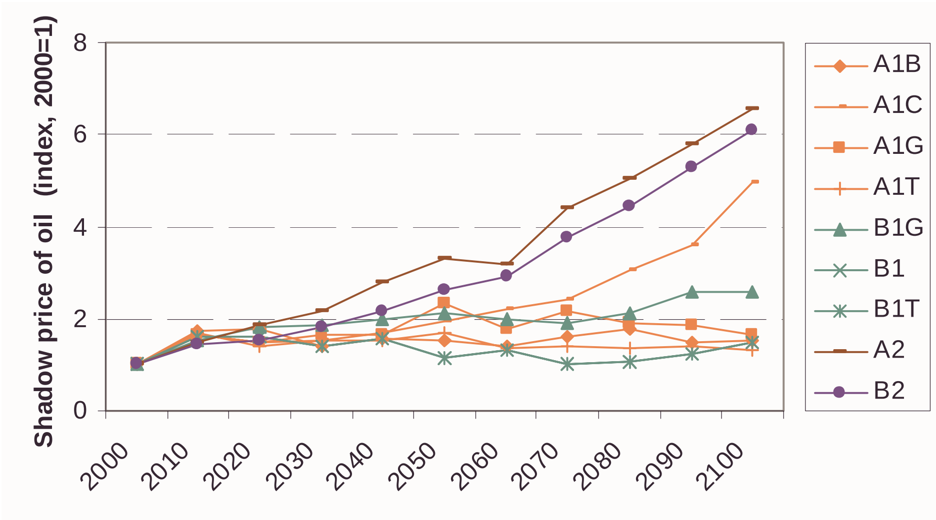

Figure 7a. Shadow price of oil in nine SRES scenarios, as index 2000=1.

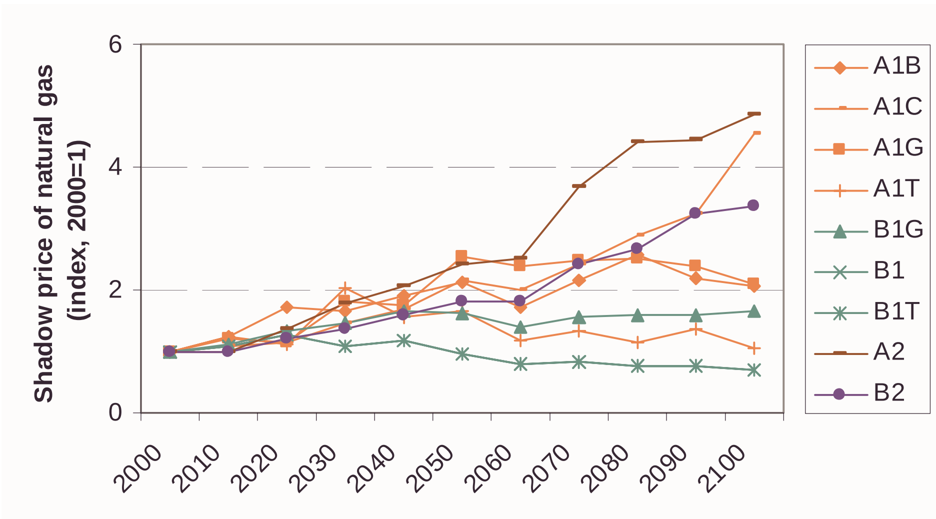

Figure 7b. Shadow price of natural gas in nine SRES scenarios, as index 2000=1.

The differences in fossil energy requirements across the scenarios increase over the time horizon leading to considerable divergence across the scenarios by the end of the century. Table 6 summarizes these differences for oil and gas by showing consumption levels and the reserves to production ratio in 2100. The oil and gas intensive scenarios are characterized both through high consumption levels and high reserves to production ratios. This indicates the dynamic nature of resources across the scenarios and their timely transfer into reserves as time unfolds and technological and economic conditions change. Table 5 shows variations in the cumulative use of oil and gas from 1990 to 2100 across the scenarios. The highest use of oil gas is in SRES A1C&G case with 34.4 ZJ of oil and 49.1 ZJ of gas while the lowest is in IIASA-WEC C2 scenario with 12.4 ZJ of oil and 14.2 ZJ of gas. Even the highest oil and gas use is well below the resource base given in Table 5 meaning that in all scenarios much of the oil and gas will be left in the ground by the end of the 21st century.

Table 6. Oil and gas consumption, in EJ, and reserves-to-production ration, in years, in 2100 across the 34 scenarios.

	Natural gas		Oil	
	Consumption (EJ/yr)	**R/P ratio (years)**	**Consumption (EJ/yr)**	**R/P ratio (years)**
SRES scenario estimates for 2100				
A1B	350	49	138	65
B1H	244	40	53	44
B1	215	49	45	55
B1T	166	81	48	54
A1G	1241	629	391	59
A1C	118	24	56	37
A1T	196	127	77	178
B2	337	38	52	38
A2	289	92	47	330
WEC scenario estimates for 2100				
A1	452	1785	354	226
A2	130	23	73	31
A3	430	35	53	30
B	204	23	111	28
C1	89	14	44	11
C2	96	20	46	9
1990 estimates	*72*	*58*	*139*	*43*

The evolution of fossil energy resources utilization across scenarios can be easily illustrated in the context of total energy requirements. Figure 8 shows fossil energy requirements across 34 scenarios against total final energy requirements. The 45 degree line indicates a hypothetical situation where each increment in final energy requirements is met through a proportional amount of fossil energy conversion into final energy. In other words, the structure of primary energy consumption would remain unchanged and any final energy demand increase would be divided equally across fossil and non-fossil primary sources. It is noteworthy that the trajectories of most of the 34 scenarios are situated below the 45 degree line. This means that considerable decarbonization takes place in most of the scenarios. There is a noticeable divergence among the trajectories as final energy requirements increase with the passage of time. The differences are especially pronounced for scenarios that surpass 1 ZJ total annual final energy demand. Some of them pass through a maximum level reaching peak fossil energy requirements and than proceed toward faster rates of decarbonization. Three of the IIASA-WEC scenarios indicate similar degrees of decarbonization even at lower levels of final energy demand between 0.5 and 1 ZJ per year. Figure 8 indicates most explicitly that the scenario dynamics are not driven by fossil energy scarcities but rather by other scenario driving forces, such as the rates of technological change, that shape both the availability of fossil and other energy sources to future generations.

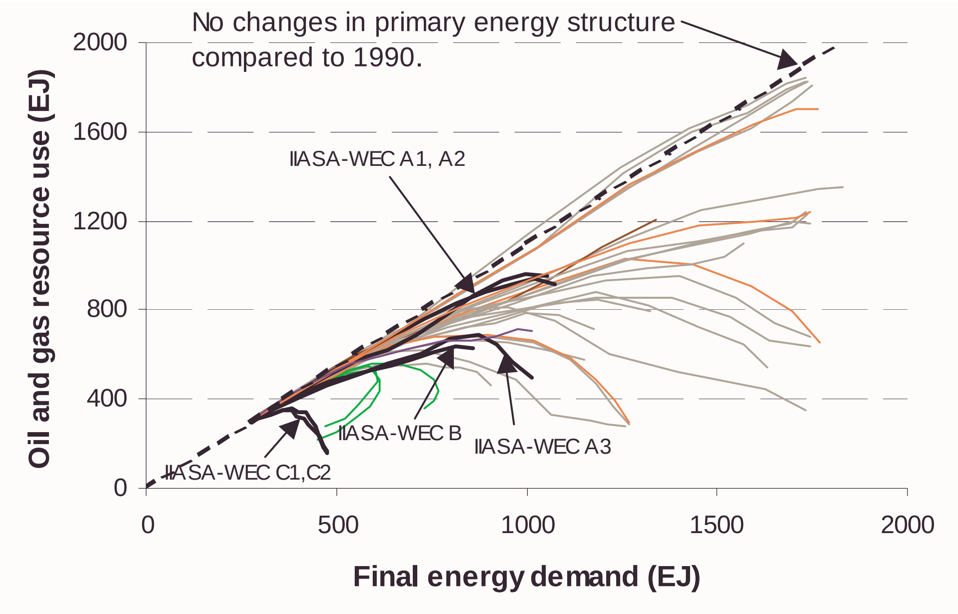

Figure 8. Fossil energy requirements and final energy demand across 34 scenarios, in EJ per year. The dashed line indicates a hypothetical situation where additional final energy demand is fulfilled in the same proportion from fossil and non-fossil primary energy sources.

Production of Synthetic Fuels Across the Scenarios

Figure 9 shows the ranges of synfuels production by deployed technology across scenarios. Figure 9a shows the ranges for 2020, Figure 9b for 2050 and Figure 9c for 2100. The first four technologies from left to the right produce synthetic liquids from coal, biomass and natural gas, while the next eight technologies produce synthetic gases from coal, biomass, solar, nuclear and various sources of electricity. Each “error bar” shows the range across IIASA, SRES and Post-SRES scenarios for a given technology from the upper to the lower bound and for the median. The IIASA-WEC scenarios are highlighted separately through dashed bars, which also show the upper and lower bound as well as the median. The main reason for substantially lower ranges for the six IIASA-WEC scenarios is that they have a lower span of energy use, especially when compared to some of the high demand (e.g. SRES A1 family) scenarios. In addition, more than half of the 34 scenarios are mitigation and stabilization cases which *ceteris paribus* would lead to higher deployment of low and zero-carbon energy carriers such as electricity and hydrogen. This is indeed reflected by a trend toward higher production of hydrogen initially from natural gas and increasingly from renewables and nuclear.

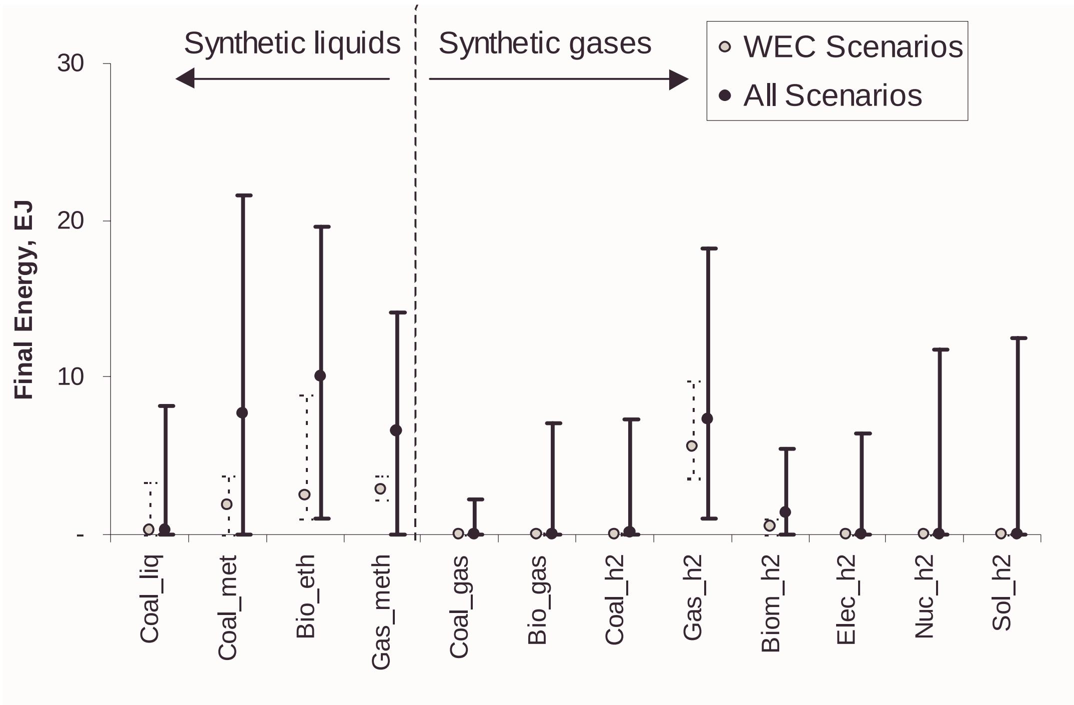

Figure 9a. Ranges of synthetic liquids and gases production across scenarios EJ per year for 2020. Each bar shows the range across IIASA SRES and Post-SRES scenarios for a given technology from upper to lower bound and for the median. The IIASA-WEC scenarios are highlighted separately through dashed bars, showing the upper and lower bound as well as the median.

Initially hydrogen is produced from natural gas and to a lesser degree by zero-carbon energy sources, nuclear and solar. The production is substantial by 2020 (Figure 8a) in some scenarios reaching up to 20 EJ per year of hydrogen produced by natural gas and up to more than 10 EJ per year by nuclear and solar each. Average production across all scenarios is quite low. Only the median of hydrogen from natural gas reaches significant levels of almost 10 EJ per year. By 2050 (Figure 8b) hydrogen production from natural gas increases five-fold in the highest scenarios with the median in the region of some 25 EJ per year. Solar hydrogen increases even more rapidly in the highest scenarios with more than 150 EJ per year but the median is very low and comparable to the medians of other sources of hydrogen. Nuclear and solar become the dominant sources of hydrogen by the end of the century reaching very high levels in the highest scenarios of some 450 and 1100 EJ per year (Figure 8c). Even the medians are high, especially for solar hydrogen with some 100 EJ per year. Some of the coal-intensive carbon mitigation scenarios shift from methanol to hydrogen production with carbon capture and storage. Natural gas is the most robust source of hydrogen across a wide range of scenarios through 2020 and 2050. By the end of the century solar followed by nuclear hydrogen become more robust options across a wide range of scenarios.

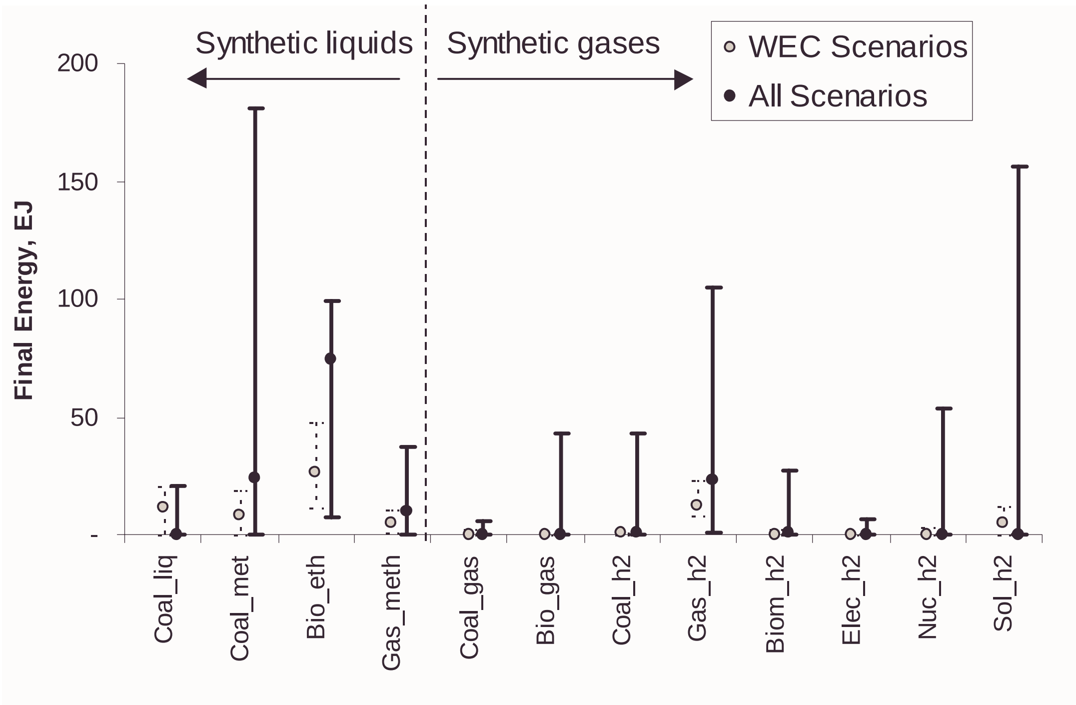

Figure 9b. Ranges of synthetic liquids and gases production across scenarios EJ per year for 2050. Each bar shows the range across IIASA SRES and Post-SRES scenarios for a given technology from upper to lower bound and for the median. The IIASA-WEC scenarios are highlighted separately through dashed bars, showing the upper and lower bound as well as the median.

Production of synthetic liquids in 2020 is shared almost equally by coal and natural gas methanol and biomass ethanol both in the highest scenarios that reach between 15 and 20 EJ per year for the three sources of synliquids and in terms of the medians that are in the range of some 10 EJ per year. By 2050 coal becomes the dominant source of liquids in the highest (coal-intensive) scenarios, but the median remains relatively low with about 25 EJ per year. In contrast, the median of biomass ethanol increases rapidly to some 75 EJ per year while the highest scenarios have only marginally higher ethanol production. The situation does not change drastically by the end of the century except that the production levels of synthetic liquids increase somewhat.

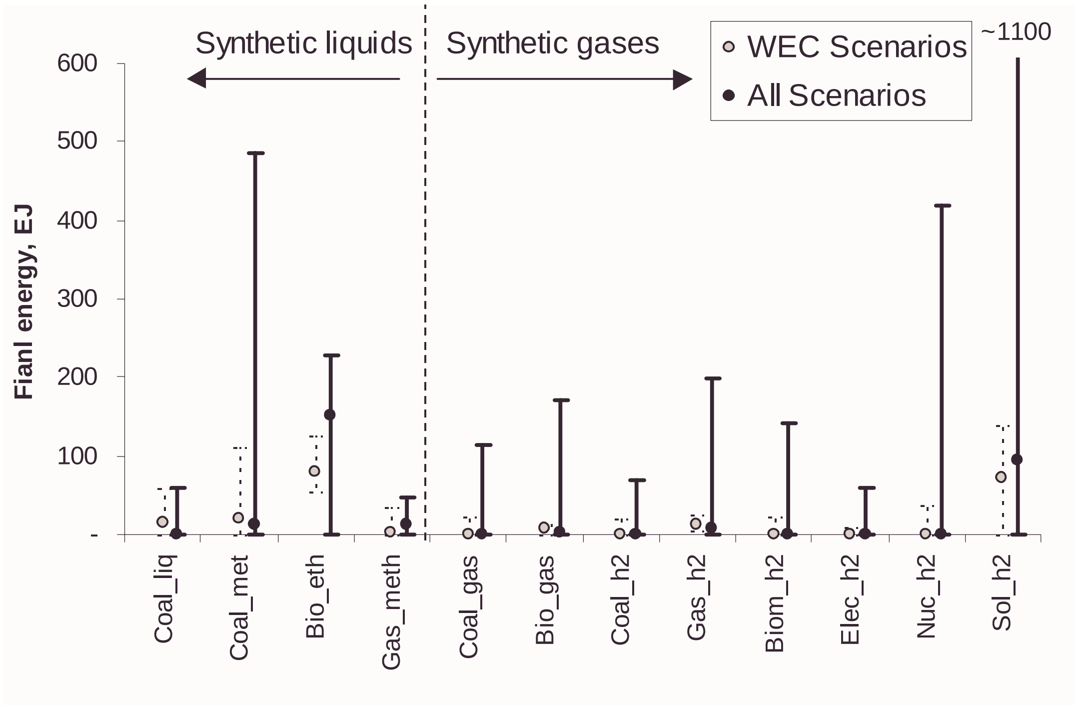

Figure 9c. Ranges of synthetic liquids and gases production across scenarios EJ per year for 2100. Each bar shows the range across IIASA SRES and Post-SRES scenarios for a given technology from upper to lower bound and for the median. The IIASA-WEC scenarios are highlighted separately through dashed bars, showing the upper and lower bound as well as the median.

Electricity Generation Across the Scenarios

Figure 10 shows the ranges of electricity generation by deployed technology across scenarios. Figure 10a shows the ranges for 2020, Figure 10b for 2050 and Figure 10C for 2100. Each "error bar" shows the range across for IIASA, SRES and Post-SRES scenarios for a given technology from the upper to the lower bound and for the median. The IIASA-WEC scenarios are highlighted separately through dashed bars, which also show the upper and lower bound as well as the median. The main reason for substantially lower ranges for the six IIASA-WEC scenarios is that they have a lower span of energy use, especially when compared to some of the high demand (e.g. SRES A1 family) scenarios. In addition, more than half of the 34 scenarios are mitigation and stabilization cases which *ceteris paribus* would lead to higher deployment of low and zero-carbon electricity generation technologies as was the case with production of synthetic fuels. The relative roles of traditional electricity technologies such as coal power plants decrease consistently across all scenarios while the role of advanced technologies such as fuel cells, combined cycles with carbon removal, solar and nuclear power become more important as time progresses in the scenarios.

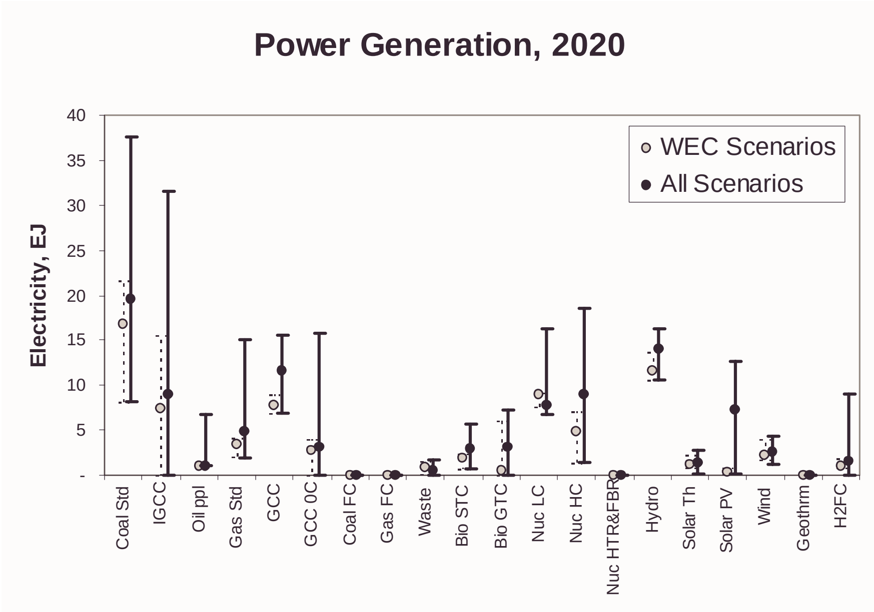

Figure 10a. Ranges of electricity generation across scenarios EJ per year for 2020. Each bar shows the range across IIASA SRES and Post-SRES scenarios for a given technology from upper to lower bound and for the median. The IIASA-WEC scenarios are highlighted separately through dashed bars, showing the upper and lower bound as well as the median.

The medians and the upper bounds indicate that the structure of electricity generation does not change radically compared with the current situation by 2020 (Figure 10a). The rigidities of the energy system are too large as much of the current generating capacity will survive through 2020. The dominant technologies continue to be standard coal (coal std), advanced coal (IGCC), standard natural gas and natural gas combined cycle (gas std and GCC) and conventional “low-cost” nuclear systems (nuc lc) and hydropower (hydro). The highest deployment across advanced technologies takes place for natural gas combined cycle with carbon scrubbing (only in stabilization scenarios), and “high-cost” nuclear (nuc hc) and photovoltaics systems (solar pv). Windmills (wind) and hydrogen fuel cells (h2fc) are also among the technologies that diffuse rapidly, but they have lower installed capacities compared with the large-scale power systems such as coal or nuclear power plants.

Changes are much more significant by 2050 (Figure 10b). Half a century is long enough for the replacement of most of the current energy system by new technologies. This is well illustrated by a significant shift from conventional (standard) coal (coal std), gas (gas std) and nuclear (nuc lc) to advanced systems such as combined cycle technology (GCC, IGCC) and high temperature reactors (nuc htr&fbr)[4]. The use of conventional (standard) technologies virtually ceases across the scenarios by the 2050s. Fuel cells, hydrogen technologies and carbon scrubbing (in stabilization scenarios) also expand dramatically.

[4] The major advantage of high temperature reactors compared to conventional heavy or light water reactors is their high degree of safety, and their high operation temperature, which enables the efficient co-generation of hydrogen via steam reforming of natural-gas. Note, however, that particularly the hydrogen production via the electrolysis of water (from Nuc HTR) plays a key role in decarbonizing the energy system in some carbon mitigation scenarios.

At the same time, the variability in the technologies across scenarios increases as well, characterized by a comparatively larger difference between the upper bound and the median (the long "upper tail" of the distribution).

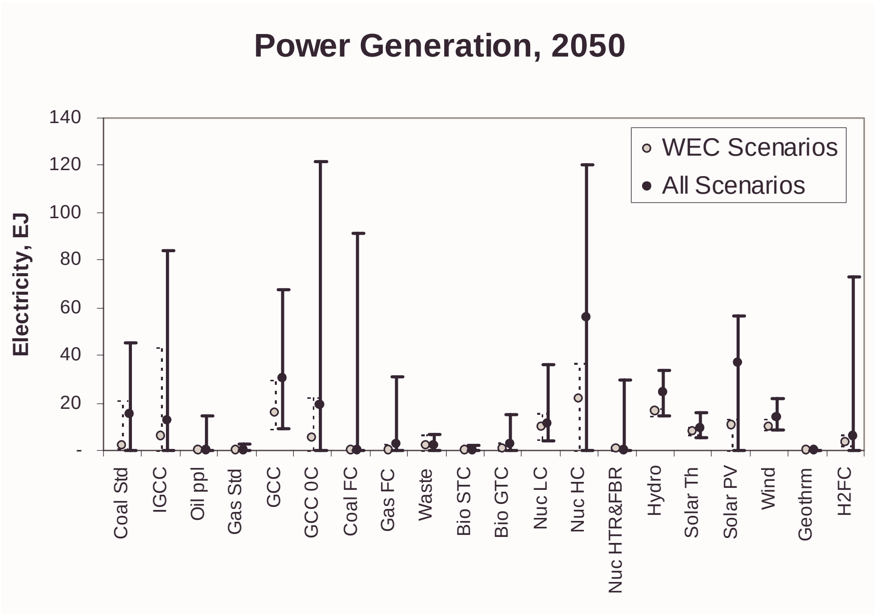

Figure 10b. Ranges of electricity generation across scenarios EJ per year for 2050. Each bar shows the range across IIASA, SRES and Post-SRES scenarios for a given technology from upper to lower bound and for the median. The IIASA-WEC scenarios are highlighted separately through dashed bars, showing the upper and lower bound as well as the median.

Figure 10b indicates that technological variability becomes greater as scenarios drift away from each other in terms of the energy systems structure and technological emphasis. Clearly, scenarios with much higher deployment of given technologies lead to better performance and comparatively lower cost, indicating increasing "path dependency" in energy development. This tendency is amplified significantly by 2100 (Figure 10c). Energy systems will be fundamentally different in hundred years compared to today irrespective of which direction technologies change. Also the "tails" of the distribution become more elongated. The differences between alternative energy development trajectories accumulate through technology replacements resulting in a wide divergence of scenarios form each other.

Figure 11 summarizes the deployment of different electricity generating technologies across the IIASA and SRES scenarios. It shows that conventional (standard) coal, oil and gas power plants are phased out of the scenarios after the 2020s. The natural-gas combined-cycle technology increases in importance and replaces the phased-out conventional capacity. This development is accompanied by coal gasification in conjunction with combined cycle. Furthermore, advanced natural-gas combined-cycle technology with carbon scrubbing and storage is introduced in the scenarios with emissions mitigation measures (and to a more limited extent in scenarios without mitigation measures as a source of CO_2 for enhanced oil recovery). Last, but not least, the fuel cells diffuse widely after the 2020s predominately powered by natural gas and later also by hydrogen.

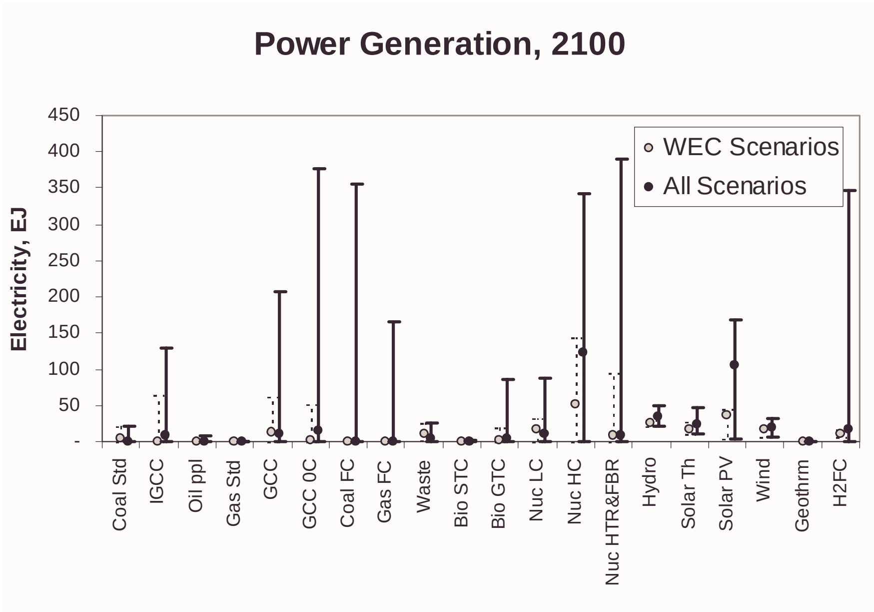

Figure 10c. Ranges of electricity generation across scenarios EJ per year for 2100. Each bar shows the range across IIASA, SRES and Post-SRES scenarios for a given technology from upper to lower bound and for the median. The IIASA-WEC scenarios are highlighted separately through dashed bars, showing the upper and lower bound as well as the median.

Generally, the scale of technology deployment increases over the time horizon significantly. The range is up to 40 EJ by 2020 (see Figure 10a) increasing to 130 EJ by 2050 (Figure 10b) and to some 400 EJ by 2100, which is comparable to total current global energy use. This illustrates the significant increase in the scale of electricity generation across the scenarios. Consequently, sizeable improvements in technology performance and reduction of costs can be expected as the result of accumulated experience and increased scale of operations worldwide.

The wide and diverging scale of electricity generating technology deployment across scenarios is reflected in a changing pattern of investment cost distribution. The greater the diffusion of a given technology, the lower the investment costs are likely to become with experience gained through technology learning.

Figure 12 illustrates the patterns of (capital) investment cost changes across all scenarios for ten selected technologies. The changing costs are shown for the same technologies as the scale of application in Figure 10. Figure 12a shows the investment costs distribution for 2020, Figure 12b for 2050 and Figure 12c for 2100.

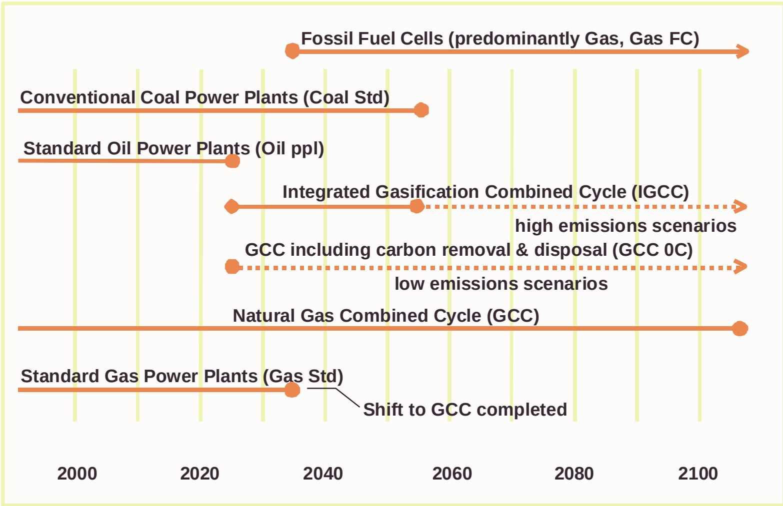

Figure 11. Deployment of fossil electricity generation technologies during the 21st century across IIASA SRES scenarios. Orange lines indicate the duration of technology deployment across scenarios. Source: Nakicenovic, *et al*. 2000b.

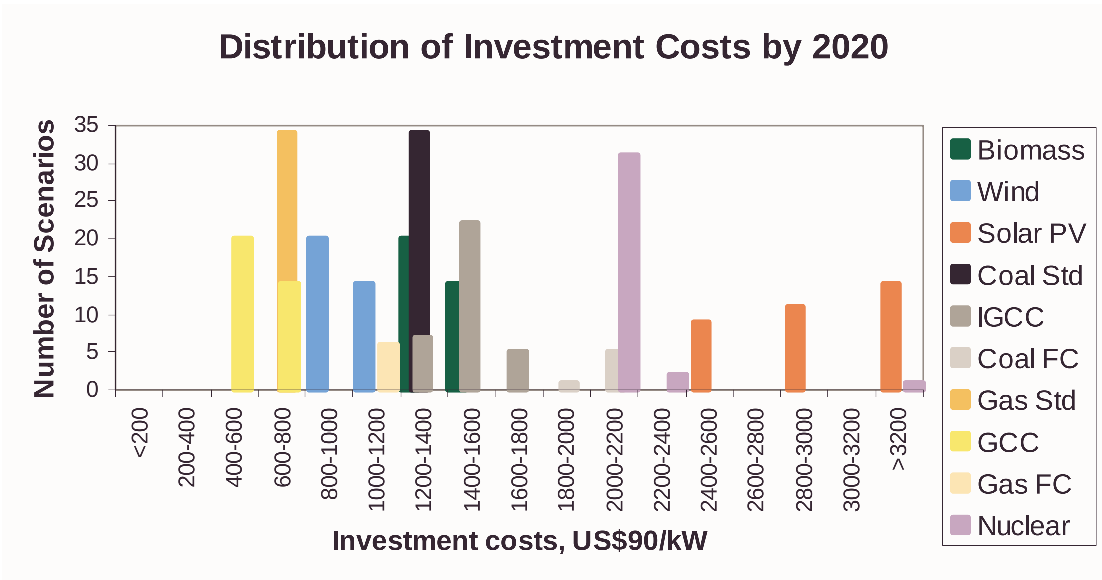

Figure 12a. Distribution of investment costs for electricity generation across scenarios in 2020. The colored bars show the distribution of costs for selected technology groups for 34 scenarios including IIASA SRES, Post-SRES, and IIASA-WEC scenarios. Some have multiple peaks indicating that the given distribution has more than one mode, e.g., see distribution for photovoltaics, labeled as solar pv. Mode peaks include between five and 34 scenarios.

* Note that the biomass category shows average costs for the Bio STC and Bio Std technologies, the costs for Coal Std includes FGD (90 percent) and DENOX (50 percent), the GCC category does not include costs for CO_2 removal and storage, and that the nuclear category shows average costs for the Nuc LC and Nuc HC technologies. Hydropower is not included in the figure because the costs are assumed to be identical across all scenarios and are distinguished only for two categories, small and large hydro, that do not change over time. For a description of the technology abbreviations see Box 1.

Clearly, the investment costs are only one of the components of technology costs that include for instance also fuel expenses, operating and maintenance costs, discount rates and so on. The so-called annualized or levelized costs give an annual aggregate figure for all of these cost components but have the decided disadvantage that the obtained values depend a lot on the choice of future discount rates and fuel taxation levels. Only the investment costs component is compared here in order to avoid the potential pitfalls of comparing annualized costs that are more a function of the above assumptions than actual differences in technology characteristics. It should also be noted that costs in general and especially the investment costs alone do not offer sufficient information to assess alternative technology options and form policy decisions about these options.

The distribution of investment costs of electricity generation technologies in 2020 is not all that different from the current situation. This is again due to the fact that much of the current generating capacity is still likely to be in operation two decades because of the long-life times of the equipment and other rigidities of the energy system. Many of the scenarios (20) rank natural gas combined cycle to have the lowest investment costs. The second cheapest option across all scenarios (34) is conventional gas, which means that natural gas ranks the lowest in terms of investment costs of all electricity technologies by 2020. The same share of scenarios (about 20) gives wind power generation as ranked next in rising cost terms, followed by biomass, standard coal and IGCC technologies. Solar photovoltaics and conventional nuclear (nuc lc & nuc hc) are the most expensive in 2020. All the technologies except solar photovoltaics have single modes by 2020. The distribution of photovoltaics costs portrays three modes indicating the complexity (and uncertainty) of some of these distributions

This pattern of cost distributions illustrates generally why natural-gas combined-cycle is the technology of choice across most of the scenarios in literature. Its contribution to future electricity generation is mostly limited by resources and market penetration constraints rather than through competitive pressure from other technologies.

The cost distributions change somewhat by 2050 (Figure 12b). The main difference is a “compression” of distributions in the lower costs ranges. The most impressive reduction in investment costs occurs for the photovoltaics. From clearly the most expensive technology in 2020, their distribution spreads from very low costs (in the range of natural-gas combined cycles) to the level of nuclear power plants. Conventional natural gas (gas std) and conventional coal (coal std) maintain both the high distribution peaks and their relative positions. The distributions of other technologies bunch more, with relatively little effect on their relative positions, with natural-gas combined cycle maintaining the position of lowest costs.

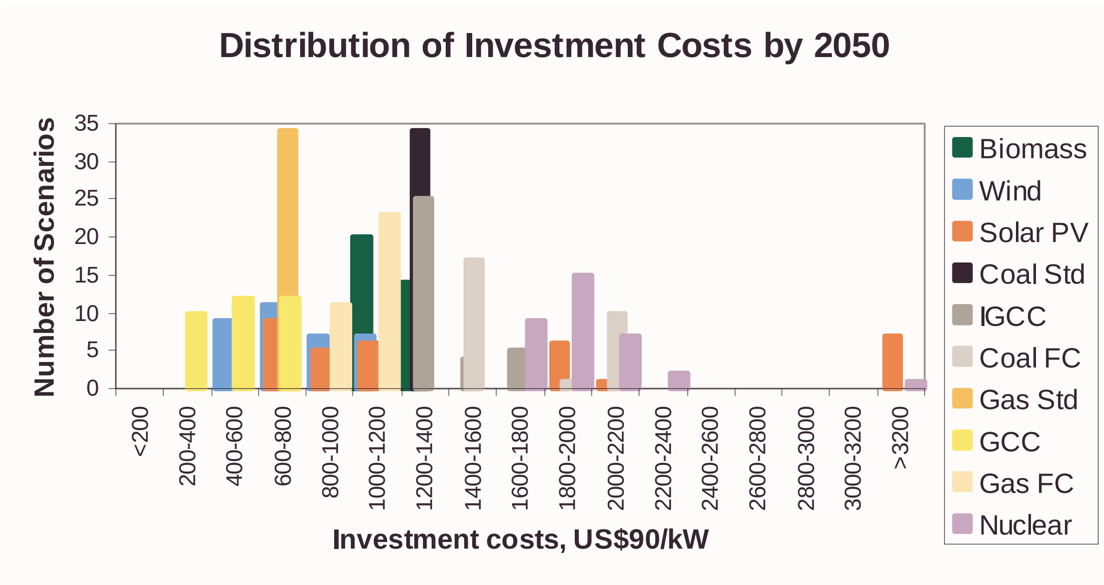

Figure 12b. Distribution of investment costs for electricity generation across scenarios in 2050. The colored bars show the distribution of costs for selected technology groups for 34 scenarios including IIASA SRES, Post-SRES, and IIASA-WEC scenarios. Some have multiple peaks indicating that the given distribution has more than one mode, e.g., see distribution for photovoltaics, labeled as solar pv. Mode peaks include between five and 34 scenarios.

* Note that the biomass category shows average costs for the Bio STC and Bio Std technologies, the costs for Coal Std includes FGD (90 percent) and DENOX (50 percent), the GCC category does not include costs for CO_2 removal and storage, and that the nuclear category shows average costs for the Nuc LC and Nuc HC technologies. Hydropower is not included in the figure because the costs are assumed to be identical across all scenarios and are distinguished only for two categories, small and large hydro, that do not change over time. For a description of the technology abbreviations see Box 1.

The compression of the costs distribution continues through 2100 as shown in Figure 12c. Again, conventional natural gas and coal (gas std and coal std) maintain their relative positions with high peaks. The distribution of photovoltaics continues to spread and now virtually covers the whole interval between the lowest and the highest costs. There are a few scenarios that rank photovoltaics in each cost category. With the exception of coal fuel cells, all other technologies also develop multiple modes. This all shows that the investment costs (with the notable exception of conventional natural gas and coal) vary quite a lot across scenarios as time progresses. Scenarios generally diverge from each other also in this respect. The notion of path dependency is thus also reflected in the investment costs distributions. Increasing scale of application of a technology leads to costs reductions and improvement of performance. The scenarios illustrate in this way the effect of learning by doing. Also the opposite is true. Technologies remain costly if they are not applied.

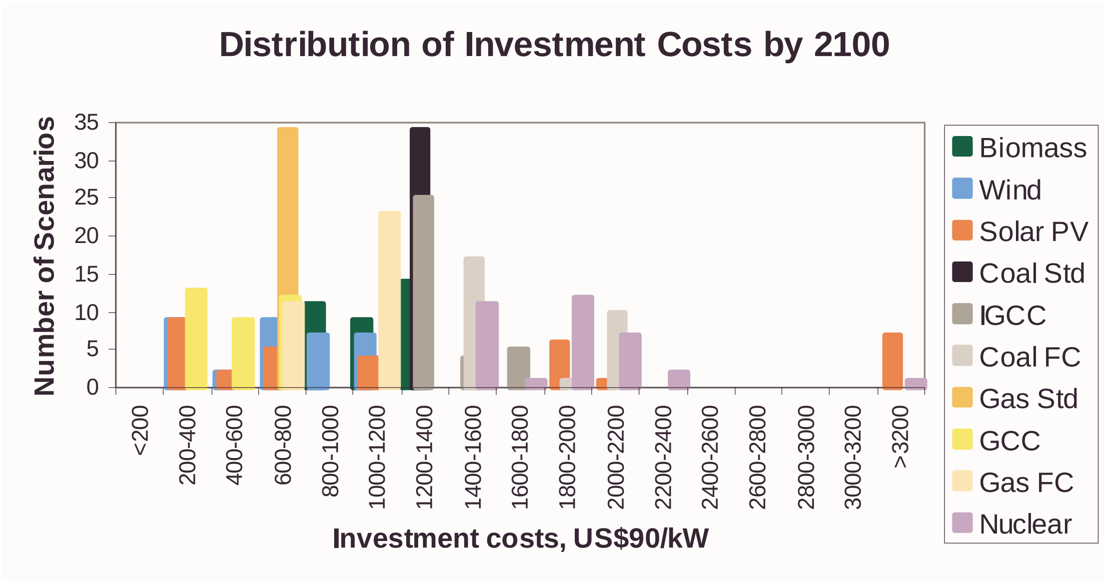

Figure 12c. Distribution of investment costs for electricity generation across scenarios in 2100. The colored bars show the distribution of costs for selected technology groups for 34 scenarios including IIASA SRES, Post-SRES, and IIASA-WEC scenarios. Some have multiple peaks indicating that the given distribution has more than one mode, e.g., see distribution for photovoltaics, labeled as solar pv. Mode peaks include between five and 34 scenarios.

* Note that the biomass category shows average costs for the Bio STC and Bio Std technologies, the costs for Coal Std includes FGD (90 percent) and DENOX (50 percent), the GCC category does not include costs for CO_2 removal and storage, and that the nuclear category shows average costs for the Nuc LC and Nuc HC technologies. Hydropower is not included in the figure because the costs are assumed to be identical across all scenarios and are distinguished only for two categories, small and large hydro, that do not change over time. For a description of the technology abbreviations see Box 1.

The degree of technological learning across scenarios is illustrated in Table 4 for different electricity technologies. The first column shows the range of average learning rates for each technology across all 34 scenarios between 1990 and 2100. The second column gives the same information for the six IIASA-WEC scenarios. The third column compares these rates with the range from the literature and the fourth gives the respective literature source. It should be noted, however, that technology learning has been calculated *ex post* for these scenarios. None of them included the possibility of endogenous technological learning. Instead, the “learning rates” given in the first two columns illustrate how investment costs decline across scenarios as the respective installed capacity of the technology expands. In the model itself, the costs declines in time are exogenous while the scale of capacity expansion is endogenous. Thus, the derived “learning rate” is a mixture of scenario inputs and outputs. One implication of thehigher learning rates indicated is that major RD&D efforts, and perhaps major new concepts, are required if some of the technologies are realistically going to play a major role in meeting future energy needs.

Table 7: Learning rates (percent per year) across 28 IIASA SRES and Post-SRES scenarios, six IIASA-WEC scenarios, and from the literature sources.

	Scenario Estimates (1990-2100)		***Literature Range***	
	All Scenarios	IIASA-WEC Scenarios	Learning Rate	Literature Source
Coal Std	0% - 0%	0% - 0%	1% - 8.4%; OECD: 7.6%	1,2
IGCC	0% - 7%	0% - 3%	USA: 3%	2,3
Coal FC	-1% - 8%	0% - 0%		
Gas Std	0% - 0%	0% - 0%		
GCC	1% - 8%	1% - 8%	-11% - 34%; EU: 4%	1,3,4
Gas FC	0% - 13%	0% - 3%		
Solar PV	0% - 28%	0% - 13%	18% - 35%	3, 9, 10
Nuclear	0% - 10%	0% - 5%	OECD: 5.8%	1
Wind	2% - 12%	2% - 7%	4% - 32%; OECD: 17%	1, 5, 6, 7, 8
Biomass	0% - 13%	3% - 7%		

Literature sources: 1: Kouvaritis *et al.* (2000), 2: Joskow and Rose (1985), 3: IEA (2000), 4: Claeson (1999), 5: CEC (1997), 6: Loiter and Bohm (1999), 7: Durstewitz (1999), 8: Neij (1999), 9: Harmon (2000), 10: Maycock and Wakefield (1975).

* The table depicts learning rates for the same technology groups as shown in Figures 8a,b,c.

Furthermore, learning and diffusion are not only required for energy supply technologies. They will be required for end-use technologies and energy saving also. This is a needed area for further research and reporting.

Fuel Requirements for Transportation Across the Scenarios

Changes in the patterns of electricity end use are an important driver of structural transformation of the whole electricity sector. Similarly, changing patterns of mobility and goods transport across the scenarios drive the transformations in the structure of final energy carriers. Today, most of the energy for transport is provided by oil and liquid final energy forms derived from oil such as diesel and gasoline. The relative roles of these traditional motor fuels decreases consistently across all scenarios while the role of synthetic fuels such as methanol, ethanol and hydrogen become more important as time progresses in the scenarios.

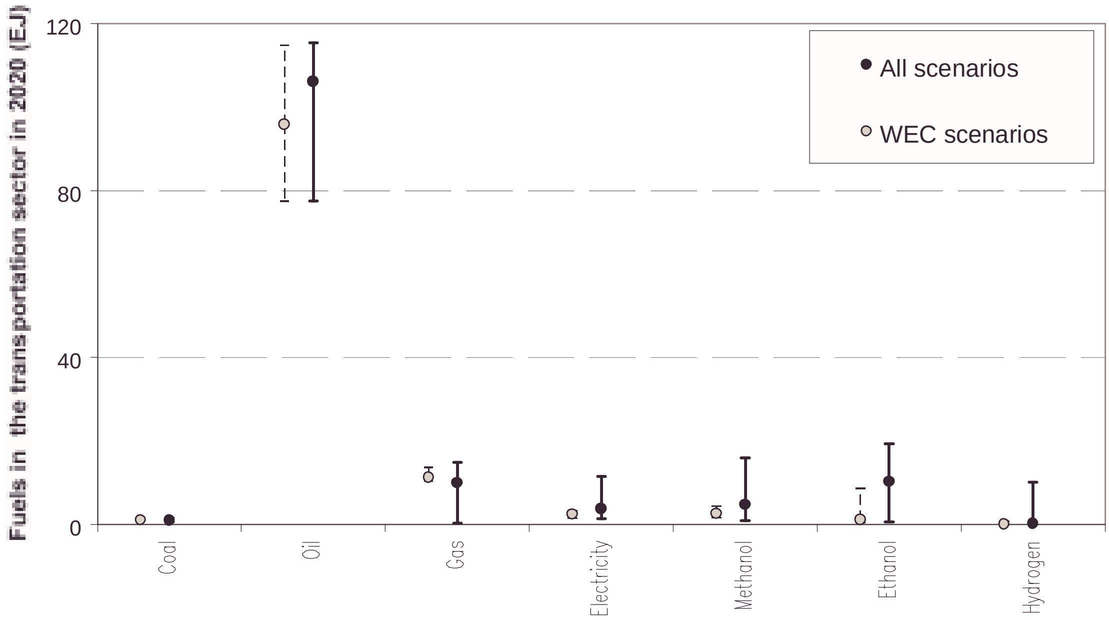

Figure 13a. Ranges of fuel requirements for transportation across scenarios EJ per year for 2020. Each bar shows the range across IIASA SRES and Post-SRES scenarios for a given technology from upper to lower bound and for the median. The IIASA-WEC scenarios are highlighted separately through dashed bars, showing the upper and lower bound as well as the median.

Figure 13 shows the ranges of final energy requirements for transportation by fuel across scenarios in EJ per year while Figure 14 shows the same requirements in terms of shares. Figure 13a shows the ranges of final energy requirements for 2020, Figure 13b for 2050 and Figure 13c for 2100. Figure 14a shows the ranges of final energy shares for 2020, Figure 13b for 2050 and Figure 13c for 2100. Each “error bar” shows the range across for IIASA, SRES and Post-SRES scenarios for a given final energy form from the upper to the lower bound and for the median. The IIASA-WEC scenarios are highlighted separately through dashed bars, which also show the upper and lower bound as well as the median. As mentioned, the main reason for substantially lower ranges for the six IIASA-WEC scenarios is that they have a lower span of energy use, especially when compared to some of the high demand (e.g. SRES A1 family) scenarios. In addition, more than half of the 34 scenarios are mitigation and stabilization cases which *ceteris paribus* would lead to higher deployment of low and zero-carbon fuels in transportation such as electricity and synthetic liquid and gaseous fuels.

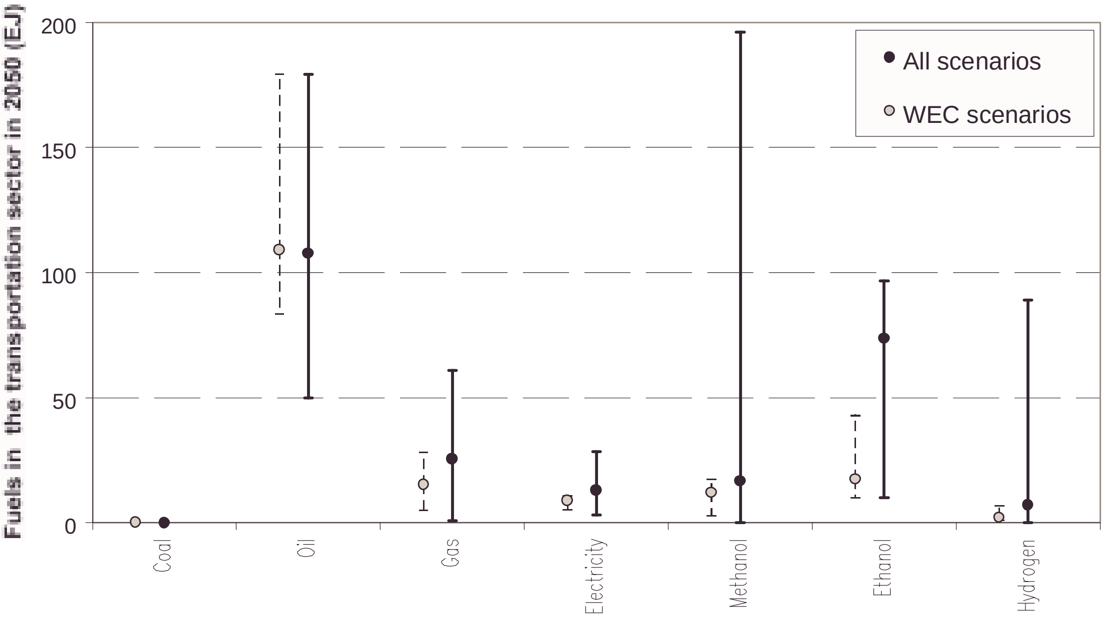

Figure 13b. Ranges of fuel requirements for transportation across scenarios EJ per year for 2050. Each bar shows the range across IIASA SRES and Post-SRES scenarios for a given technology from upper to lower bound and for the median. The IIASA-WEC scenarios are highlighted separately through dashed bars, showing the upper and lower bound as well as the median.

Figures 13a and 14a clearly show that this heavy dependence on oil for transportation continues across the scenarios through 2020. Between 80 and almost 120 EJ of oil-derived motor fuels are required in 2020 across the scenarios with medians in the regions of about 100 EJ per year. This is so because mobility and goods transport continue to increase across all scenarios even in the most developed regions of the world during the next decades. Synthetic fuels derived from other primary energy sources such as gas, coal and biomass play a comparatively small role by 2020 indicating again large inertia inherent in energy systems. It takes decades to develop new infrastructures for alternative fuels such as methanol or hydrogen produced from other energy sources. Their contributions reach some 20 EJ per year by 2020 in the highest of the scenarios. This translates into market shares of less than 15 percent with medians in the range of about ten percent compared with a market share of 60 to 90 percent with a median of about 80 percent for oil products (see Figure 14a).

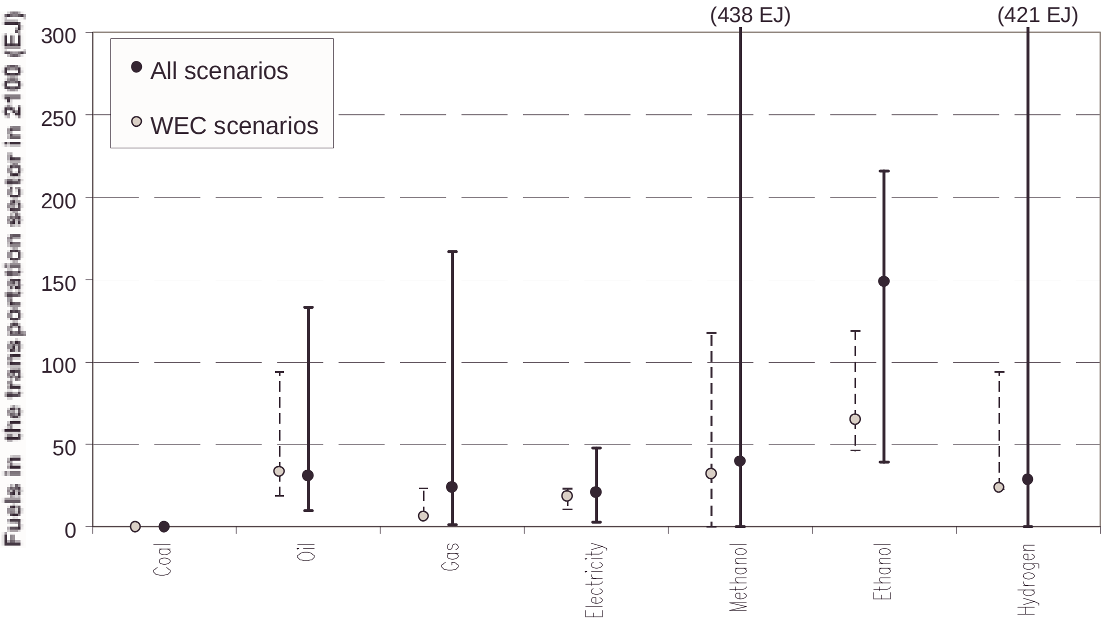

Figure 13c. Ranges of fuel requirements for transportation across scenarios EJ per year for 2100. Each bar shows the range across IIASA SRES and Post-SRES scenarios for a given technology from upper to lower bound and for the median. The IIASA-WEC scenarios are highlighted separately through dashed bars, showing the upper and lower bound as well as the median.

Figures 13b and c and Figures 14b and c illustrate how this dependence on oil for transport changes across the scenarios toward a more balanced portfolio of energy carriers for transportation by 2050. Initially, the heavy dependence on oil shifts toward methanol in high-growth scenarios with high shares of coal such as SRES A1C. Much of the coal is converted into methanol for transport reaching up to 200 EJ per year by 2050 well in excess of the highest contribution of oil products of some 180 EJ per year. However, this is so only in the most extreme scenarios, the median contribution of methanol is still relatively modest with about 20 EJ per year or less than ten percent market share (see Figure 14b). In fact, natural gas and biomass in the form of ethanol are more important in terms of their median contributions by 2050.

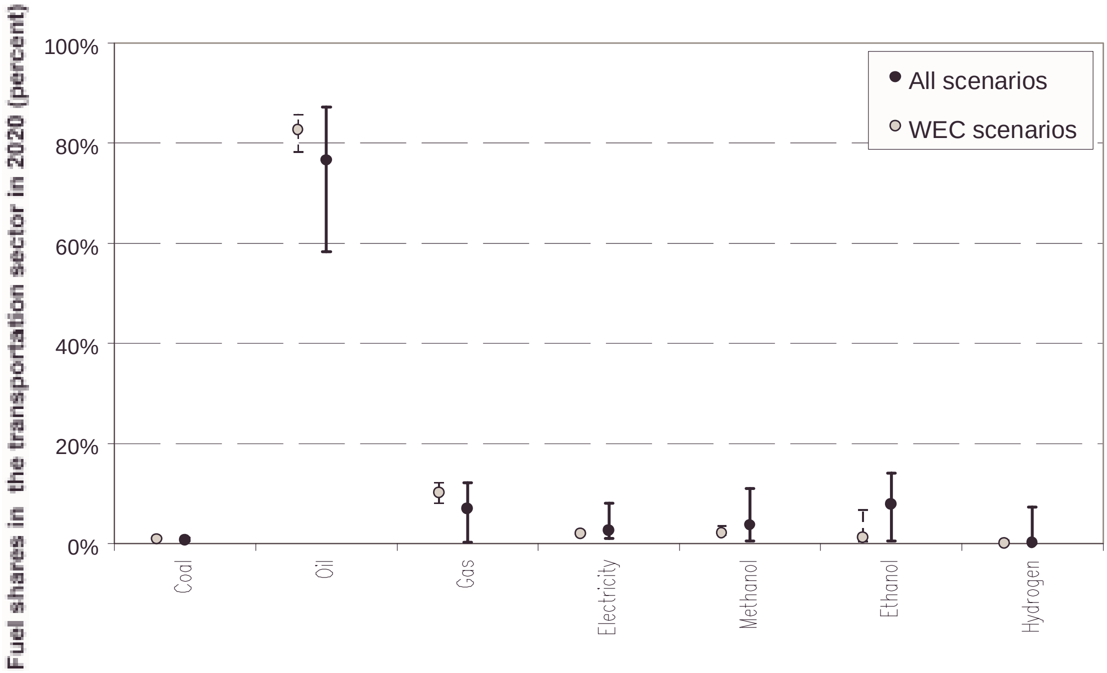

Figure 14a. Ranges of fuel market shares in transportation across scenarios in percent for 2020. Each bar shows the range across IIASA SRES and Post-SRES scenarios for a given technology from upper to lower bound and for the median. The IIASA-WEC scenarios are highlighted separately through dashed bars, showing the upper and lower bound as well as the median.

Transportation fuels derived from natural gas and biomass are also crucial for reducing carbon emissions from the transportation sector in the mitigation scenarios (Post-SRES). Biomass median is second highest after crude oil reaching some 75 EJ per year by 2050 indicating that ethanol production from biomass is not only a robust technology in itself but also an important fuel for transportation both as a replacement of oil and as a carbon emissions mitigation option. The growing role of hydrogen has to be seen also in this context. The mitigation versions of coal-intensive future such as the SRES A1C scenario shift from methanol production to hydrogen with carbon capture and storage. This explains the low median for hydrogen production and the “long tail” of the distribution towards the high contribution levels is some mitigation scenarios.

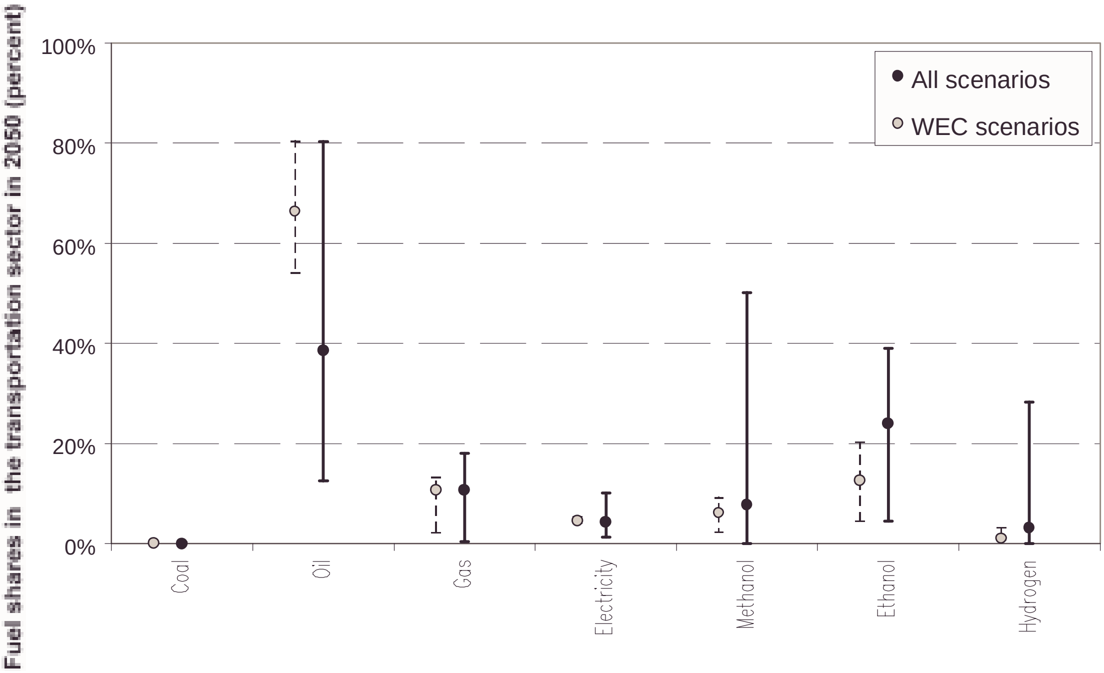

Figure 14b. Ranges of fuel market shares in transportation across scenarios in percent for 2050. Each bar shows the range across IIASA SRES and Post-SRES scenarios for a given technology from upper to lower bound and for the median. The IIASA-WEC scenarios are highlighted separately through dashed bars, showing the upper and lower bound as well as the median.

The importance of synthetic fuels derived from low or zero-carbon energy sources increases dramatically toward the end of the century especially in the mitigation scenarios. Crude oil decreases from being the most important source of transportation fuels in 2020 to being the fifth down the line by 2100 (see Figures 13a and c and 14a and c), behind hydrogen, ethanol, methanol and gas both in terms of medians and highest scenarios. Biomass is the most dominant source of transportation fuels across all scenarios with a median of 150 EJ in 2100 and a median market share of more than 30 percent. Methanol and hydrogen dominate in the highest scenarios with 440 and 420 EJ in 2100, respectively. As mentioned, these are coal-intensive futures (SRES A1C) where coal is converted into methanol or hydrogen with carbon capture. Thus, the heavy dependence on oil for transportation that still persists through 2020 shifts toward increasing contributions of methanol and ethanol towards the 2050s and then also hydrogen by the end of the century. Ethanol for biomass becomes the most robust fuel in the transport sector but the overall structure of supply is much more balanced and diversified toward the second half of the century than today.

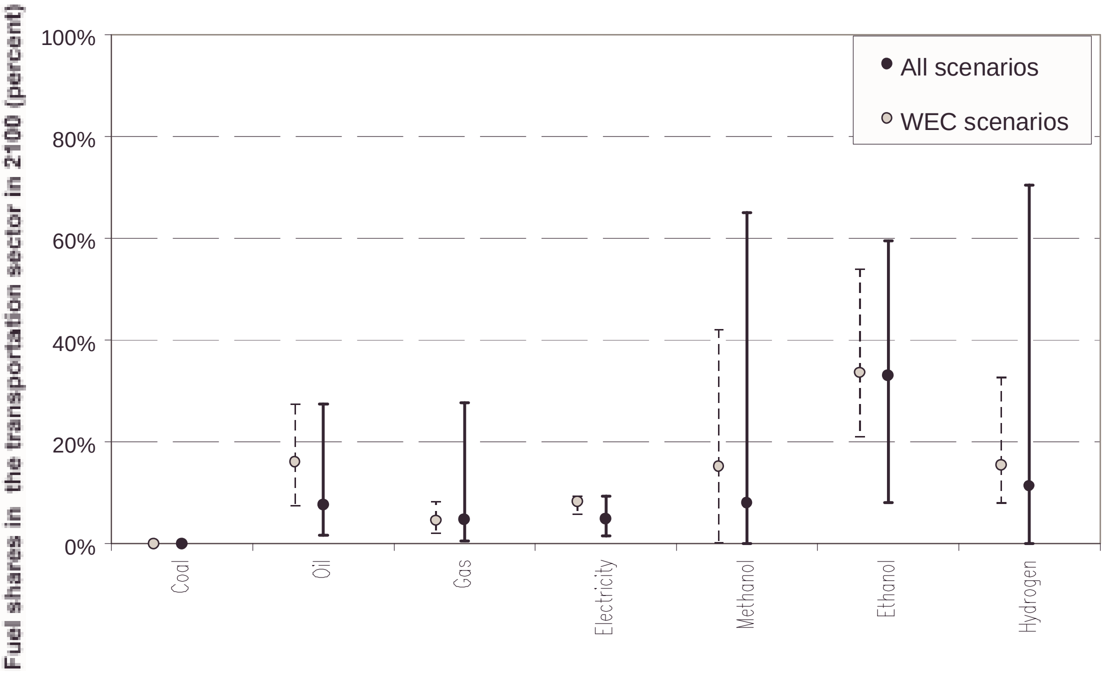

Figure 14c. Ranges of fuel market shares in transportation across scenarios in percent for 2100. Each bar shows the range across IIASA SRES and Post-SRES scenarios for a given technology from upper to lower bound and for the median. The IIASA-WEC scenarios are highlighted separately through dashed bars, showing the upper and lower bound as well as the median.

Conclusions

The main objective of this assessment was to consider a range of alternative developments of future energy technologies rather than to attempt to project any one particular direction of technological change. This is important because the future is inherently unpredictable and any one single projection is therefore inappropriate as the assessment tool. Technological change is a complex process that is associated with many uncertainties. Consequently, our approach was to capture a wide spectrum of developments in order to assess the implications and possibilities of the materialization of different alternatives. Scenarios in the literature offer, in general, a large set of alternative future developments that could be used to assess the ranges and distributions of costs and other characteristics of future energy technologies. These should of course not be confused with actual future developments that are unpredictable. Instead, collectively the scenarios in the literature outline a range of possible developments that presumably also includes the relevant future development path.

The adopted method was to assess the ranges of deployment and characteristics of future energy technologies on the basis of a number of scenarios, developed at IIASA by the MESSAGE energy systems model, that contain assumptions about many different technologies, their costs and performance. The reason for choosing one single model for this analysis was simply that detailed information for this model is available and is documented in the literature. Another, completely different reason, for choosing the MESSAGE model was that it was one of the models used to develop both the IIASA-WEC and IPCC scenarios. Therefore, it contains a wide range of energy technology developments based on assessments of large writing teams and expert reviews that were involved in the two scenario development processes with the same basic modeling approach. Presumably, the scenarios thus contain a comprehensive set of alternative but nevertheless comparable technological developments. Here we analyzed technological developments across 34 different scenarios.

One of the main conclusions of the assessment (which has also been reached elsewhere) is that technology may be more important in determining the structure of future energy systems and services than key driving forces such as availability of resources, population growth or economic development. The choice of technology options is, however, a product of changing social and economic priorities, behavioral changes, and environmental considerations. There is growing evidence in energy scenarios that alternative technological developments that result from many specific assumptions in energy models can lead to fundamentally different future energy systems structures and services. For example, scenarios that assume relatively abundant and inexpensive fossil energy and technology availability also tend in general to have high shares of these options. On the other hand, scenarios with slow progress of fossil technologies also often anticipate high fossil energy costs and consequently a modest degree of decarbonization of future energy systems. However, the pace and scale of technological change in scenarios are heavily dependent upon learning rates, which are a mixture of scenario inputs and outputs. They may, nevertheless, suggest areas where RD&D efforts are best focussed.

The five main findings of the assessment are that:

- different development paths favor certain technologies and thus affect the direction of the overall technological change in a fundamental way;

- research, development and deployment portfolios with different technologies are the only hedge against the uncertainties described by the ranges of the scenarios;

- widespread and rapid diffusion of technologies implies improvements in technical performance, reduction of costs and emissions and that this is a cumulative process; and

- “robust” generic energy sector technologies (across the wide range of scenarios) include efficiency improvements, decarbonization, clean energy carriers such as electricity, synfuels and hydrogen and in the long run also zero-carbon energy sources such as renewables and nuclear; and finally

- the most “robust” single technologies across all variation in the 34 scenarios include combined-cycle in the medium term (during the first half of the century) and fuel cells, photovoltaics and nuclear energy in the long term (during the second half of the century)..

These five main findings of the assessment summarize what the 34 scenarios, encompassing many alternative future development paths tell us now about the likely future technologies that need to be developed and deployed during the next few decades:

Contribution of Conventional Nuclear Power to Electricity Generation

Histograms of frequency distribution of the role of conventional nuclear power in electricity generation across scenarios, number of scenarios (from a total of 34) and generation in EJ per year. Figure A shows the nuclear contribution in 2020, Figure B in 2050 and Figure C in 2100. Two technologies, Nuc LC and Nuc HC (see Box 1) constitute the aggregate nuclear contribution. The relative positions of IIASA-WEC scenarios are indicated in the histograms. After clustering during the first decades within the region of up to 40 EJ per year, the scenarios bifurcate up to 2050 into two groups, those with less than 60 EJ per year and those between 80 and 140 EJ per year. The IIASA-WEC scenarios fall all within the first group, while mitigation scenarios with low stabilization levels tend on average to promote the role of nuclear energy. The spread of scenarios is quite wide by the end of the century. It is interesting that some of the mitigation scenarios fall in the groups with high nuclear contribution while other do not. A possible reason is that after a century of development of new technologies, some scenarios with low emissions can shift toward higher roles of decarbonization and renewables. Thus, nuclear energy is quite a robust technology option in the long run.

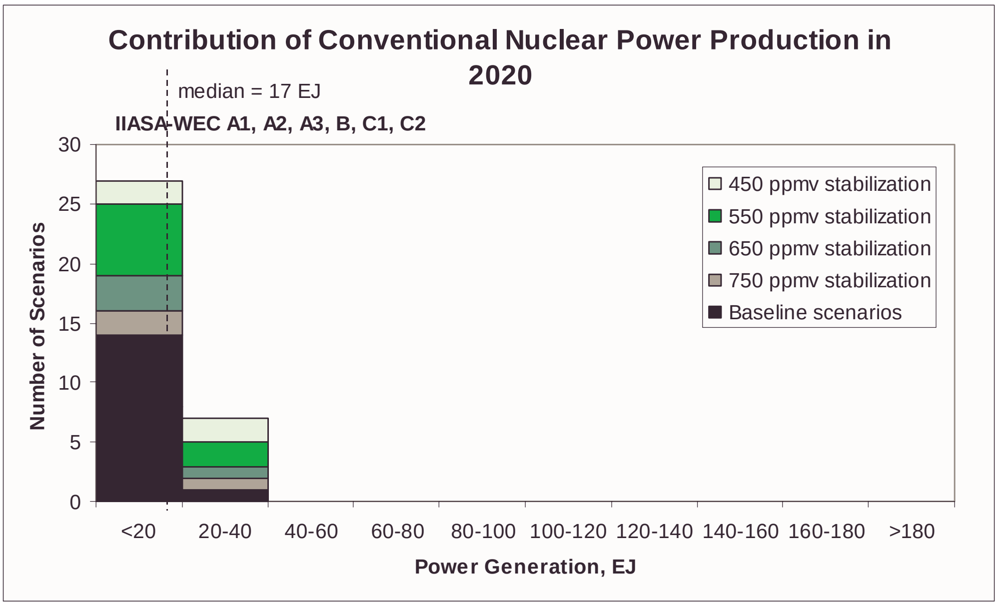

Figure A. Histogram of conventional nuclear power contribution to electricity generation across scenarios in 2020. Nuclear contribution is an aggregate of two technologies, Nuc LC and Nuc HC (see Box 1).

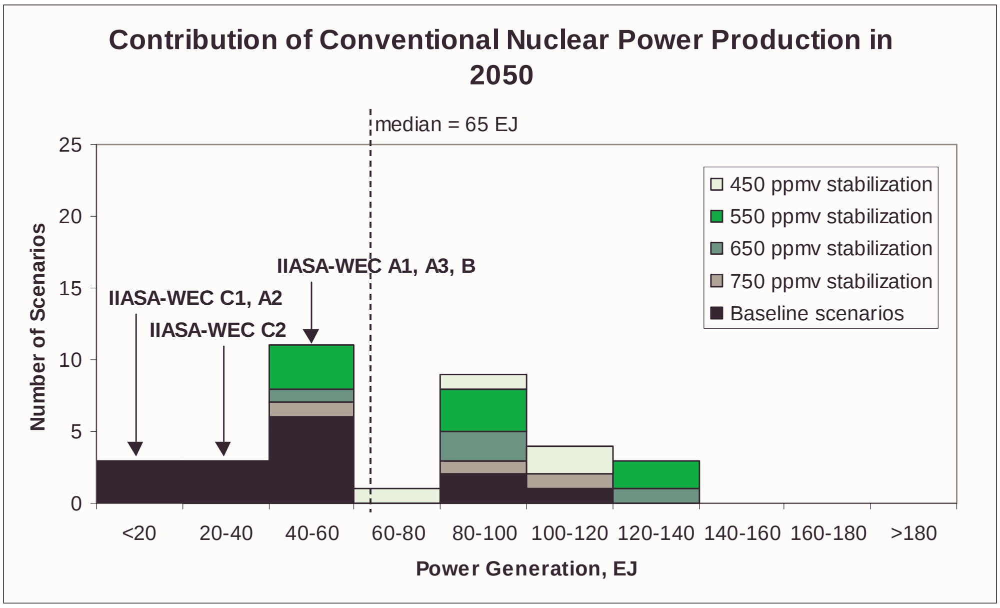

Figure B. Histogram of conventional nuclear power contribution to electricity generation across scenarios in 2050. Nuclear contribution is an aggregate of two technologies, Nuc LC and Nuc HC (see Box 1).

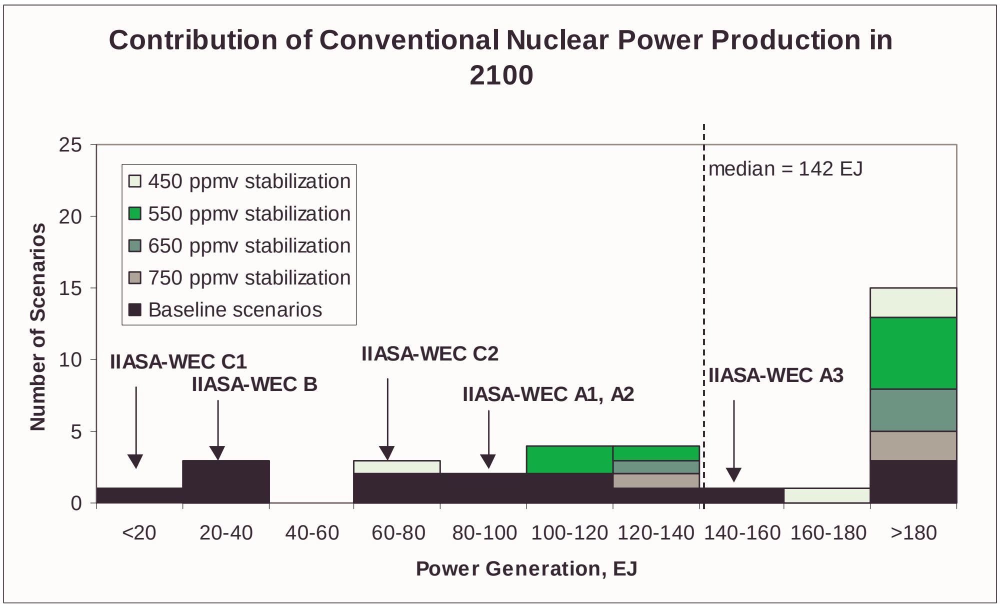

Figure C. Histogram of conventional nuclear power contribution to electricity generation across scenarios in 2100. Nuclear contribution is an aggregate of two technologies, Nuc LC and Nuc HC (see Box 1).

Contribution of Hydrocarbon Fuel Cells to Electricity Generation

Histograms of frequency distribution of the role of hydrocarbon fuel cells in electricity generation across scenarios, number of scenarios (from a total of 34) and generation in EJ per year. Figure A shows the fuel cells contribution in 2020, Figure B in 2050 and Figure C in 2100. Two technologies, Gas FC and Coal FC technologies (see Box 1), constitute the aggregate fuel cells contribution. The relative positions of IIASA-WEC scenarios are indicated in the histograms. After clustering during the first decades within the region of up to 20 EJ per year, some scenarios lead to very substantial contribution of fuels cells by 2050 of up to 120 EJ per year. The distribution is very skewed in 2050. Virtually all scenarios that fall above the mean are mitigation cases. All other scenarios fall within the interval up to 40 EJ per year. The spread of scenarios is quite wide by the end of the century. Mitigation cases are mixed with other scenarios without any obvious pattern as was the case 50 years earlier. Thus, fuel cells are a robust technology option in the long run.

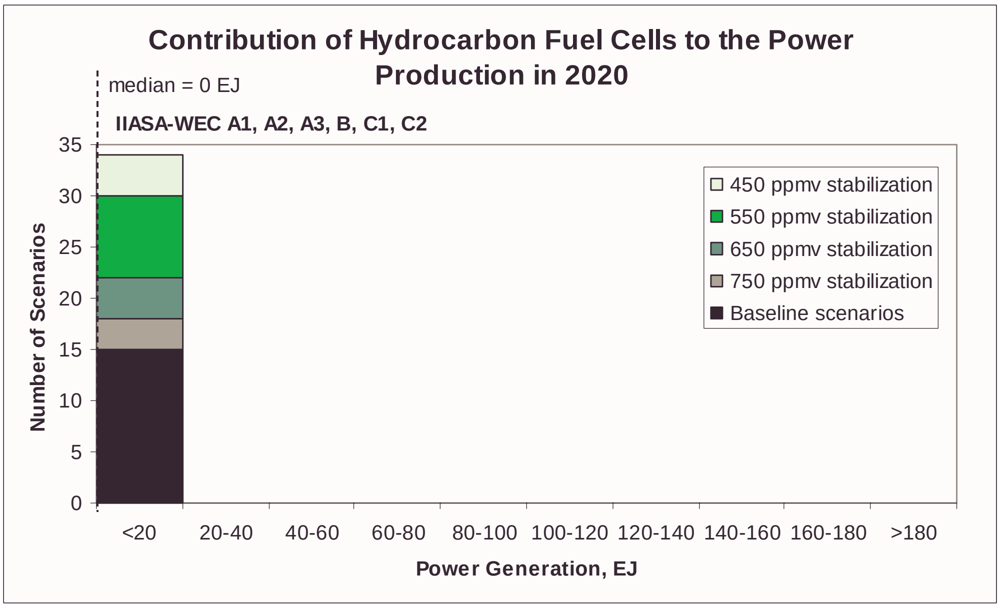

Figure A. Histogram of the hydrocarbon fuel cells contribution to electricity generation across scenarios in 2020. Fuel cells contribution is an aggregate of two technologies, Gas FC and Coal FC (see Box 1).

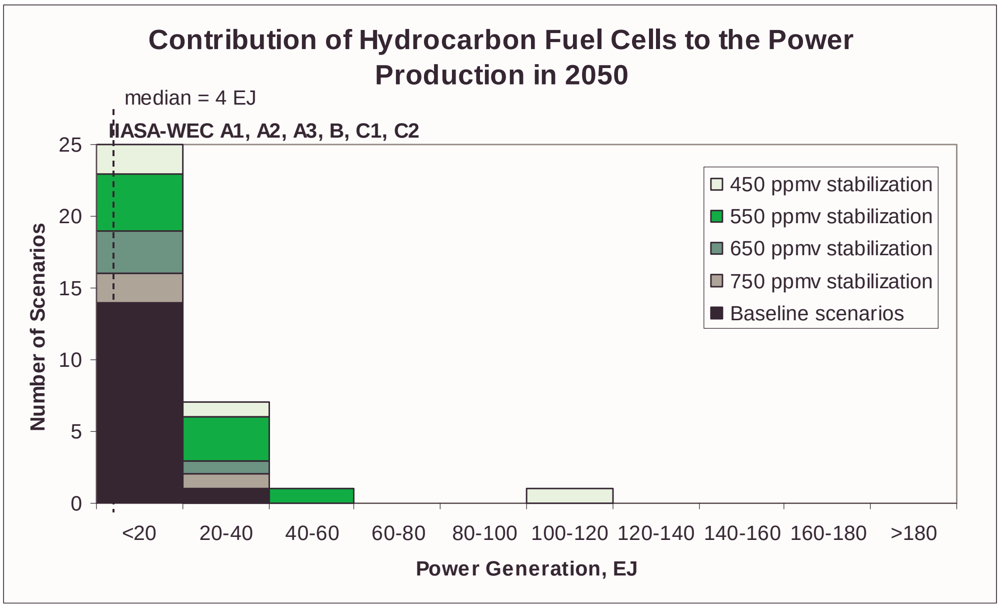

Figure B. Histogram of the hydrocarbon fuel cells contribution to electricity generation across scenarios in 2050. Fuel cells contribution is an aggregate of two technologies, Gas FC and Coal FC (see Box 1).

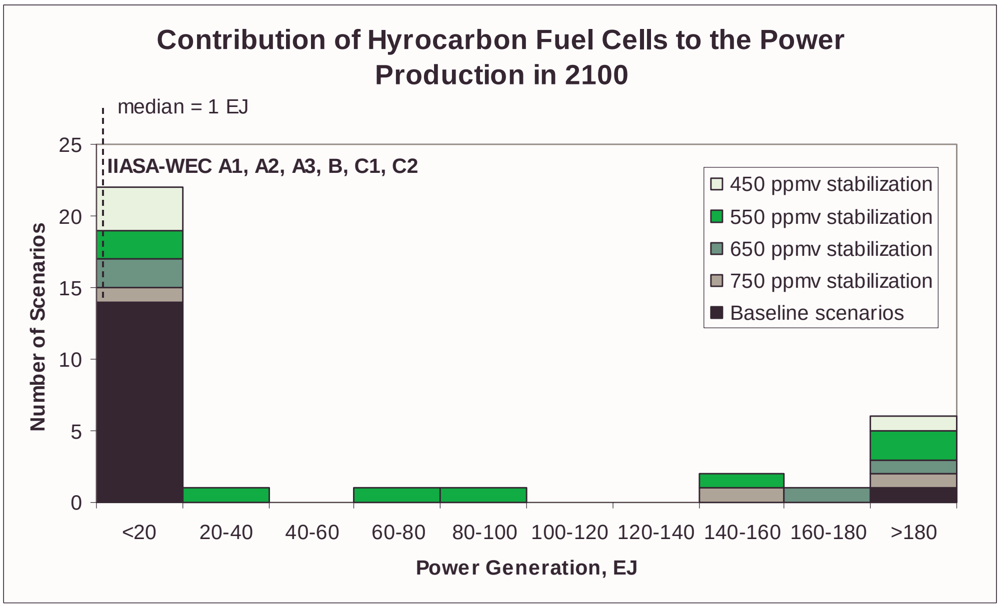

Figure C. Histogram of the hydrocarbon fuel cells contribution to electricity generation across scenarios in 2100. Fuel cells contribution is an aggregate of two technologies, Gas FC and Coal FC (see Box 1).

Contribution of Hydrogen Fuel Cells to Electricity Generation

Histograms of frequency distribution of the role of hydrogen fuel cells (H2FC, Box 1) in electricity generation across scenarios, number of scenarios (from a total of 34) and generation in EJ per year. Figure A shows the fuel cells contribution in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. After clustering during the first decades within the region of up to 20 EJ per year in much the same way as hydrocarbon fuel cells (see above), some scenarios lead to a substantial contribution of fuels cells by 2050 of up to 80 EJ per year. The distribution is very skewed in 2050. A few scenarios that fall between 20 and 40 EJ per year are mitigation cases. Mitigation and baseline scenarios are otherwise well mixed with respect to the contribution of hydrogen fuel cells below and above these levels. The spread of scenarios is quite wide by the end of the century. Again, mitigation and baseline scenarios jointly presented in most of the categories. . Thus, the hydrogen fuel cells penetration in the long run is quite independent on the need to control carbon emissions. The hydrogen fuel cells are apparently favored and a robust technology choice across the scenarios despite the thigher complexity of the respective energy chains.

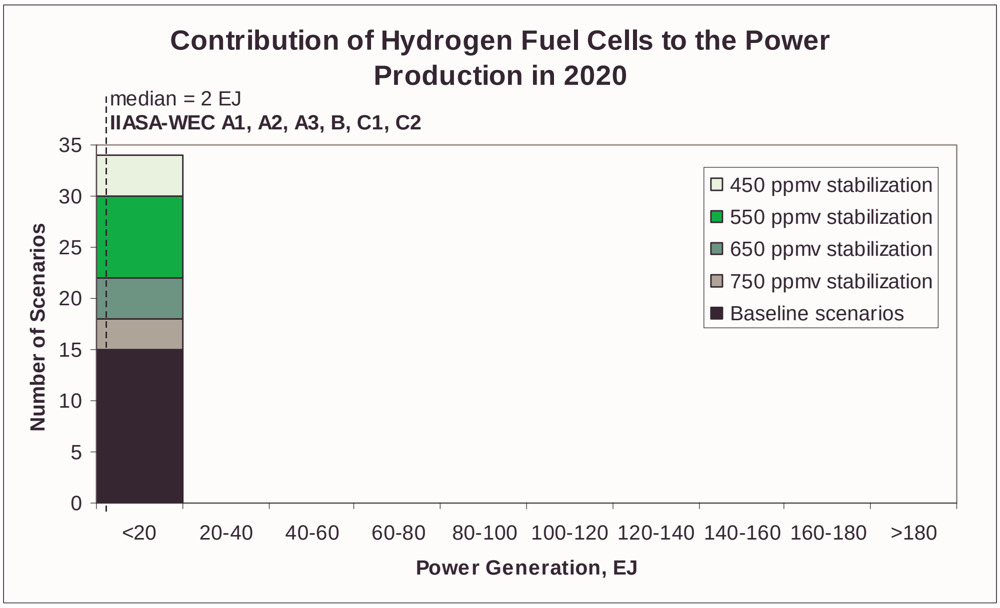

Figure A. Histogram of the hydrogen fuel cells (H2FC) contribution to electricity generation across scenarios in 2020.

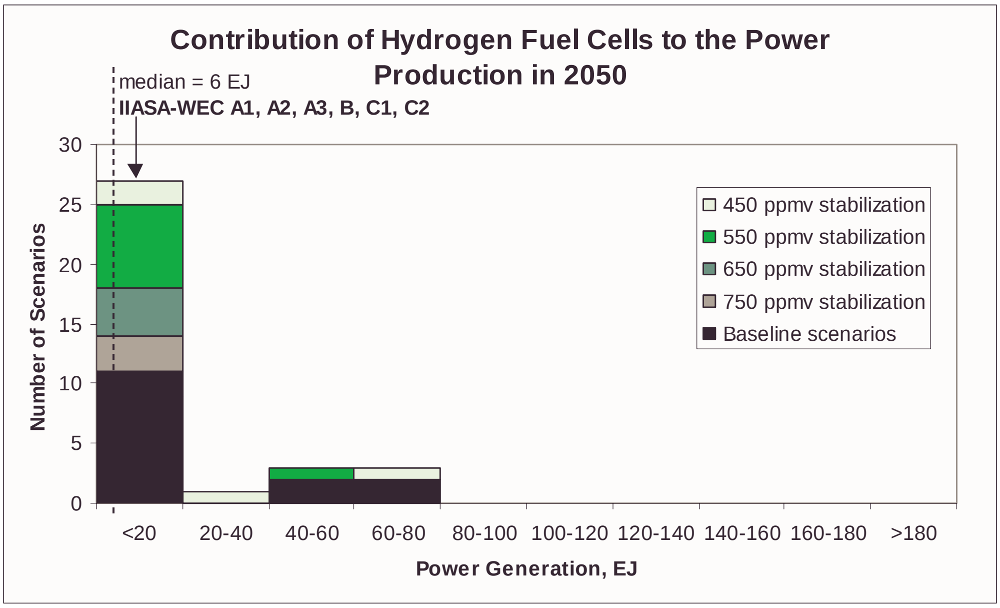

Figure B. Histogram of the hydrogen fuel cells (H2FC) contribution to electricity generation across scenarios in 2050.

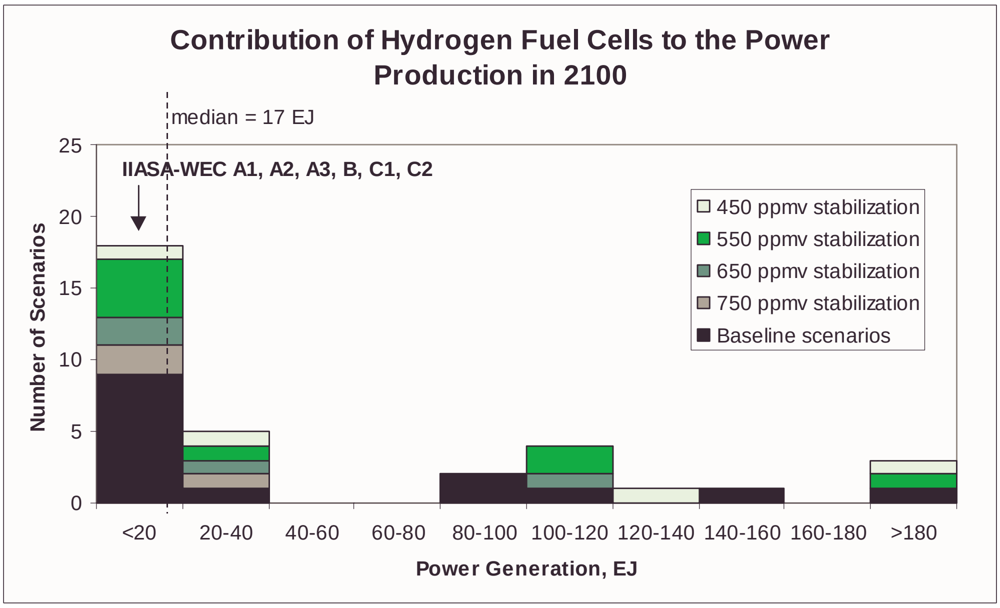

Figure C. Histogram of the hydrogen fuel cells (H2FC) contribution to electricity generation across scenarios in 2100.

Contribution of the Conventional Coal Power Plants to Electricity Generation

Histograms of frequency distribution of the role of conventional coal power plants (Coal Std) in electricity generation across scenarios, number of scenarios (from a total of 34) and generation in EJ per year. Figure A shows the contribution in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. This is one of the technologies that is not favored in the long run across all scenarios. The reasons are the relatively high capital costs associated with lower efficiencies compared to advanced coal technologies and other options. The maximal contribution of about 40 EJ per year in 2020 is marginally extended by 2050 only to decline again to this level by 2100. For obvious reasons, the contribution is lower in the mitigation cases, all of them cluster within the interval up to 20 EJ per year by 2100. However, advance technologies such as IGCC become the main source of electricity from coal as is indicated in Figure 1b and c. Advanced coal technologies are favored in the long run across all scenarios due to the lower costs (improvement with increasing scale of application) of the whole energy chain and substantially lower emissions of carbon dioxide and other pollutants.

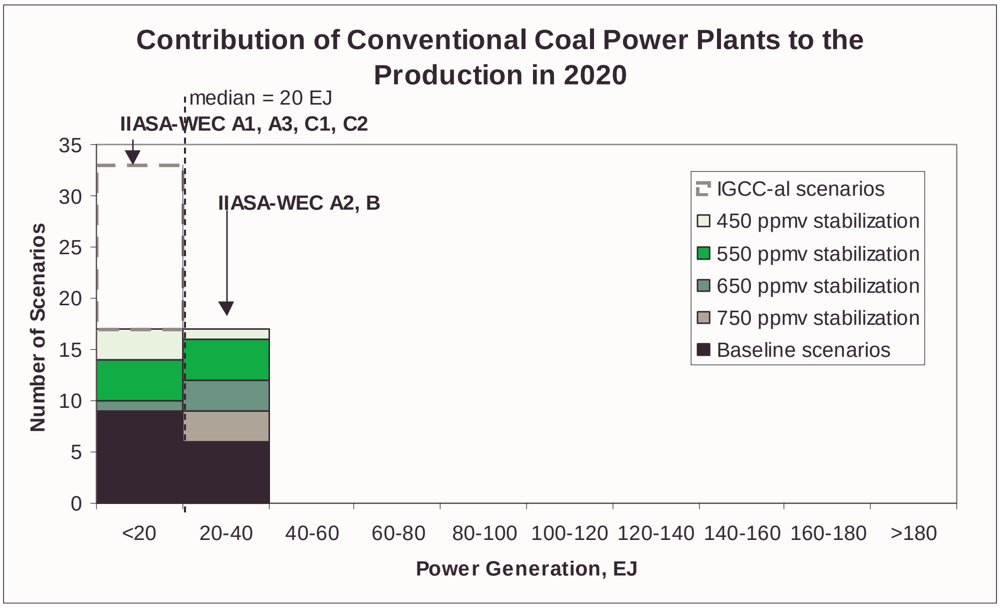

Figure A. Histogram of the conventional coal power plants (Coal Std) contribution to electricity generation across scenarios in 2020 compared to the contribution of IGCC power plants (gray, dashed lines).

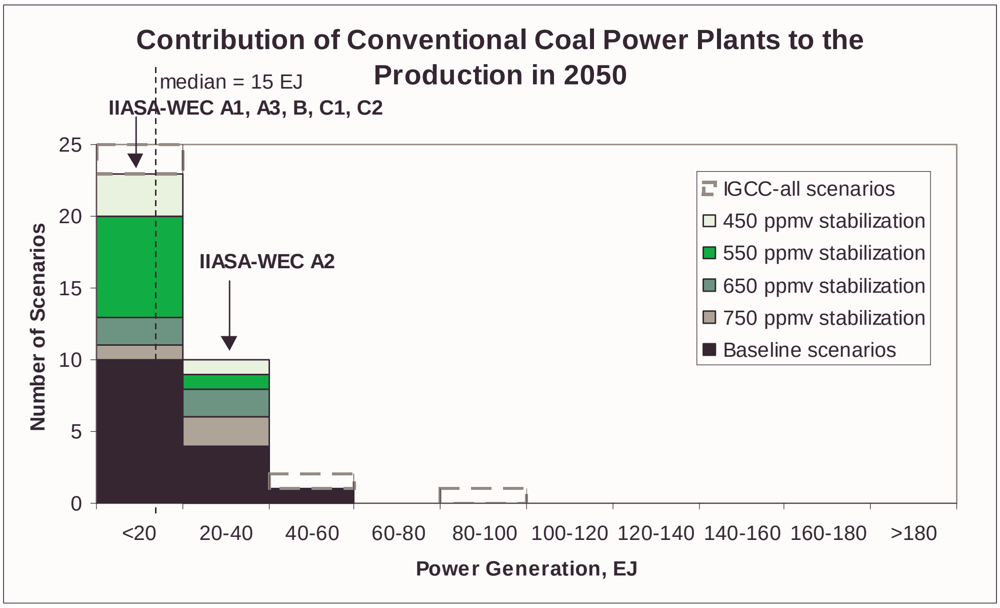

Figure B. Histogram of the conventional coal power plants (Coal Std) contribution to electricity generation across scenarios in 2050 compared to the contribution of IGCC power plants (gray, dashed lines).

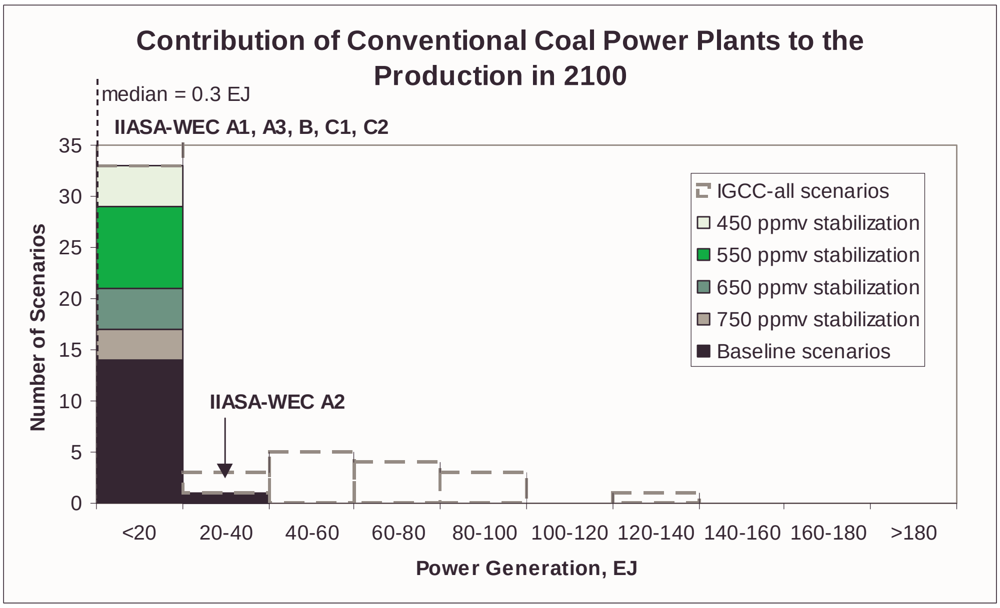

Figure C. Histogram of the conventional coal power plants (Coal Std) contribution to electricity generation across scenarios in 2100 compared to the contribution of IGCC power plants (gray, dashed lines).

Contribution of Solar Photovoltaics Cells to Electricity Generation

Histograms of frequency distribution of the role of solar-photovoltaics electricity generation across scenarios, number of scenarios (from a total of 34) and generation in EJ per year. Figure A shows the photovoltaics contribution in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. After clustering during the first decades within the region of up to 20 EJ per year in much the same way as hydrocarbon fuel cells, some scenarios lead to a substantial contribution of photovoltaics cells by 2050 of up to 60 EJ per year. The distribution is quite symmetrical in 2050 especially for scenarios without any mitigation measures. The spread of scenarios is quite wide by the end of the century and it bifurcates in to two groups, one under 80 EJ per year and one from 100 to 180 EJ per year. All of the IIASA-WEC scenarios fall in the first cluster below the mean. All mitigation cases with very low stabilization levels of 450 ppmv fall in the second cluster. Thus, the photovoltaics electricity is a very robust technology option across all scenarios in the long run with and without mitigation measures. However, very stringent mitigation clearly favors very high contribution of photovoltaics in the very long run.

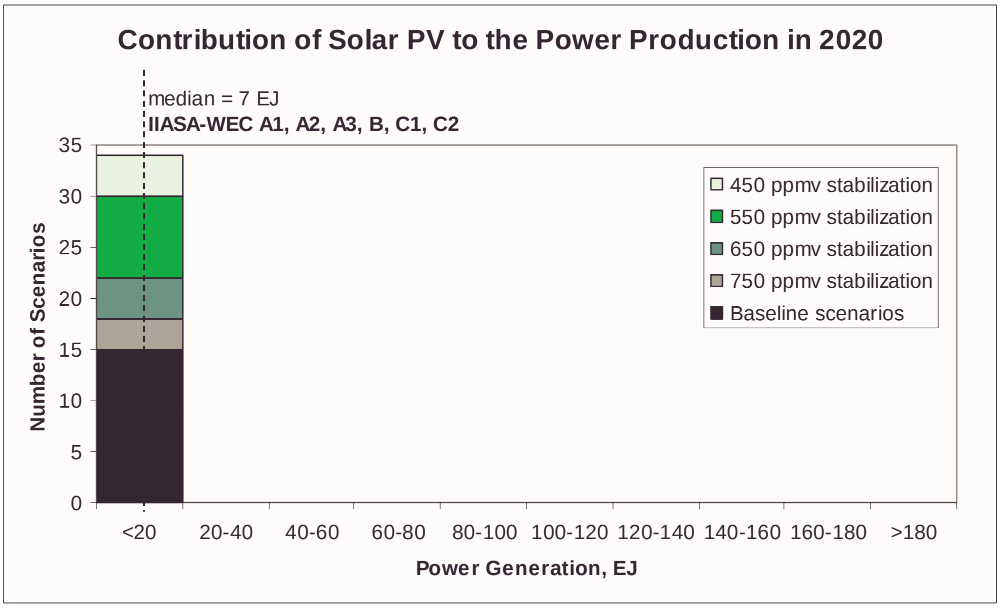

Figure A. Histogram of solar photovoltaics contribution to electricity generation across scenarios in 2020.

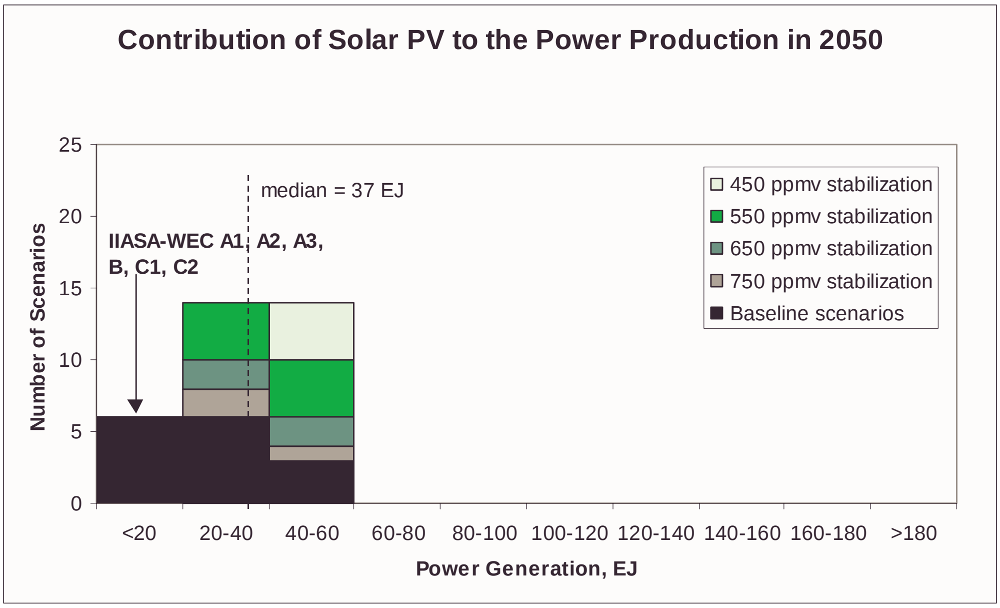

Figure B. Histogram of solar photovoltaics contribution to electricity generation across scenarios in 2050.

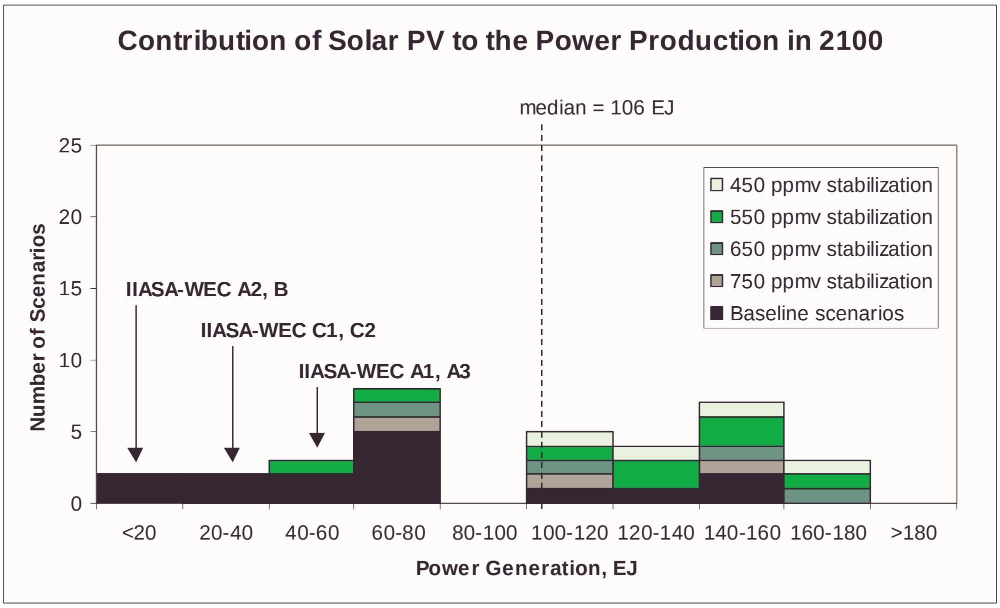

Figure C. Histogram of solar photovoltaics contribution to electricity generation across scenarios in 2100.

Contribution of Natural-Gas Technologies to Electricity Generation

Histograms of frequency distribution of the role of all natural gas power plants (see Box 1) in electricity generation across scenarios, number of scenarios (from a total of 34) and generation in EJ per year. Figure A shows the natural gas contribution to electricity in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. After clustering during the first decades within the region of up to 20 EJ per year, electricity from natural gas expands very rapidly across the scenarios reaching up to 160 EJ per year by 2050 and 180 EJ per year by 2100. Scenarios are almost equally distributed across the ranges with a pronounced peak between 20 and 60 EJ per year in 2050. IIASA-WEC scenarios fall generally below the mean mostly because of their relatively low energy demands compared with the SRES range. Natural gas proves to be a very robust source of electricity across all scenarios, it is important across all scenarios, with and without mitigation measures, and during the whole century.

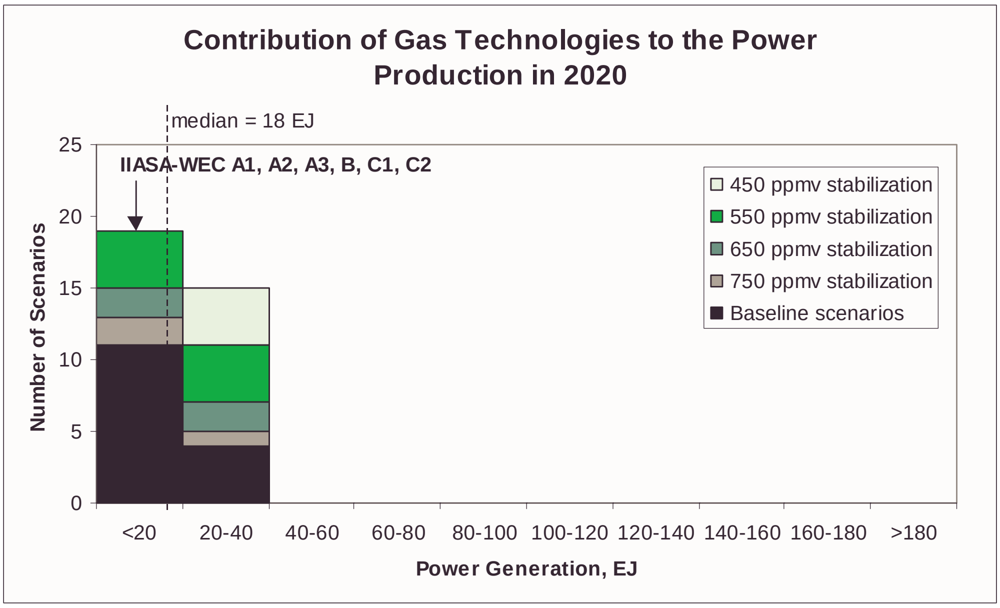

Figure A. Histogram of gas technologies contribution to electricity generation across scenarios in 2020. The contribution of natural gas is an aggregate of four technologies, Gas Std, GCC, GCC 0C, and Gas FC technologies (see Box 1).

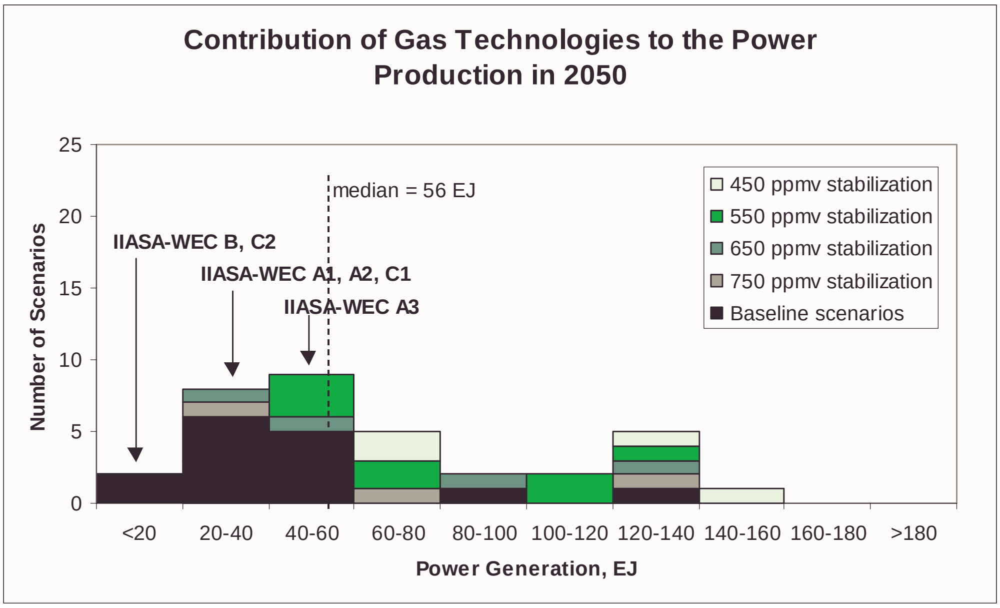

Figure B. Histogram of gas technologies contribution to electricity generation across scenarios in 2050. The contribution of natural gas is an aggregate of four technologies, Gas Std, GCC, GCC 0C, and Gas FC technologies (see Box 1).

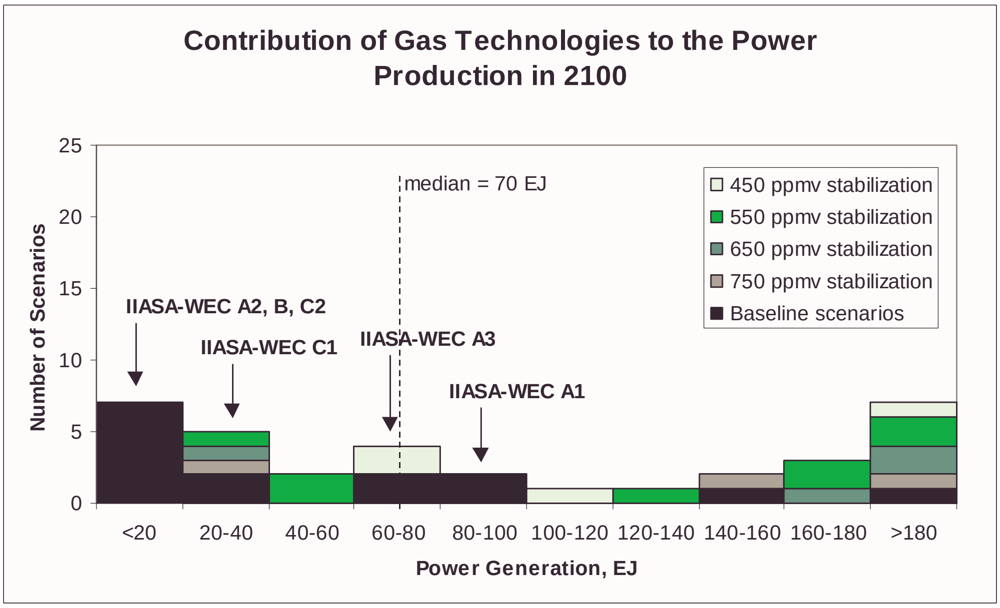

Figure C. Histogram of gas technologies contribution to electricity generation across scenarios in 2100. The contribution of natural gas is an aggregate of four technologies, Gas Std, GCC, GCC 0C, and Gas FC technologies (see Box 1).

Contribution of All Natural-Gas Combined-Cycle Power Plants to Electricity Generation

Histograms of frequency distribution of the role of all natural gas combined cycle power plants in electricity generation across scenarios, number of scenarios (from a total of 34) and generation in EJ per year. Some of the mitigation scenarios include carbon scrubbing and storage. Figure A shows the gas combined cycle contribution to electricity in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. After clustering during the first decades within the region of up to 40 EJ per year, electricity from natural gas expands very rapidly across the scenarios reaching up to 160 EJ per year by 2050 and 180 EJ per year by 2100. Scenarios are almost equally distributed across the ranges with a very pronounced peak between 20 and 60 EJ per year in 2050. IIASA-WEC scenarios fall generally below the mean mostly because of their relatively low energy demands compared with the SRES range. However, two of them portray very high contributions by 2100 in the range from 60 to 100 EJ per year. There is a certain degree of bifurcation among the scenarios by 2100 with more than half of them falling in the lowest and the highest categories. The scenarios in the highest category are mostly mitigation cases that deploy a lot of carbon combined cycle with carbon scrubbing and storage rendering natural gas in to a "zero-carbon" electricity option. Nevertheless, just like all natural gas technologies the combined-cycle natural gas proves to be a very robust source of electricity across all scenarios, with and without mitigation measures, and during the whole century.

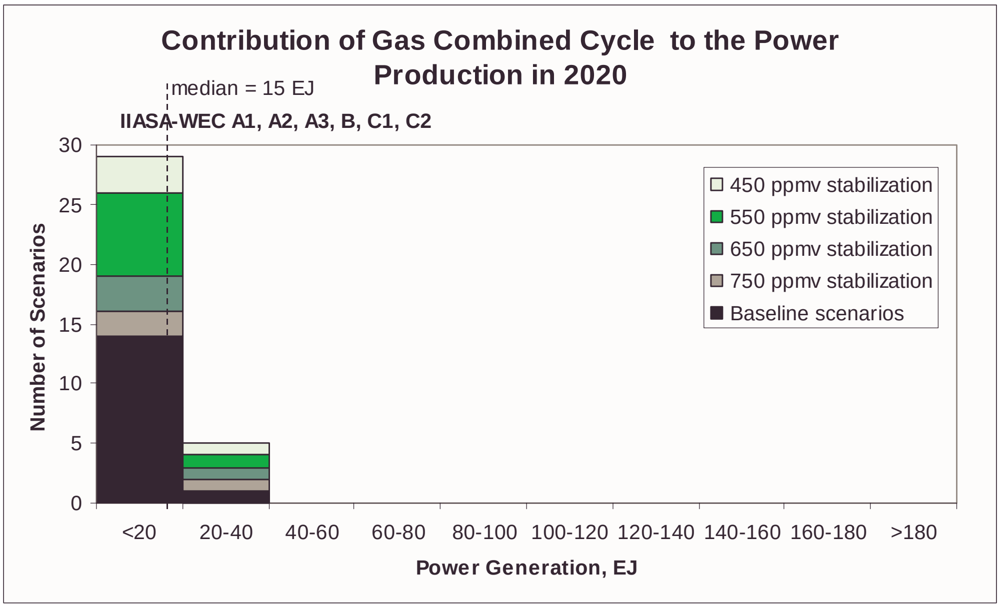

Figure A. Histogram of all natural-gas combined cycle contribution to electricity generation across scenarios in 2020. The contribution of natural gas combined cycle power plants is an aggregate of two technologies, GCC and GCC 0C. technologies (see Box 1).

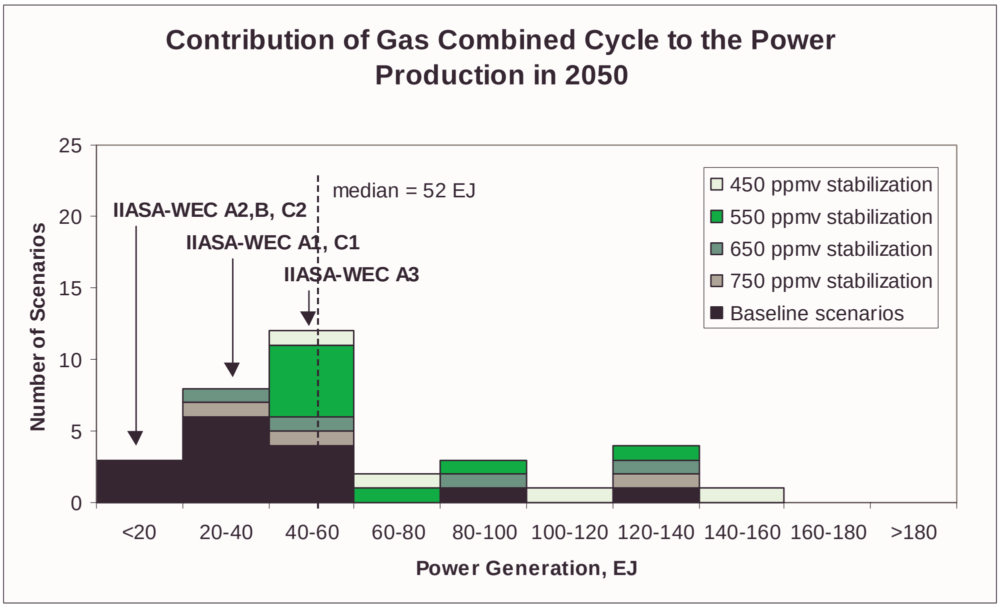

Figure B. Histogram of all natural-gas combined cycle contribution to electricity generation across scenarios in 2050. The contribution of natural gas combined cycle power plants is an aggregate of two technologies, GCC and GCC 0C. technologies (see Box 1).

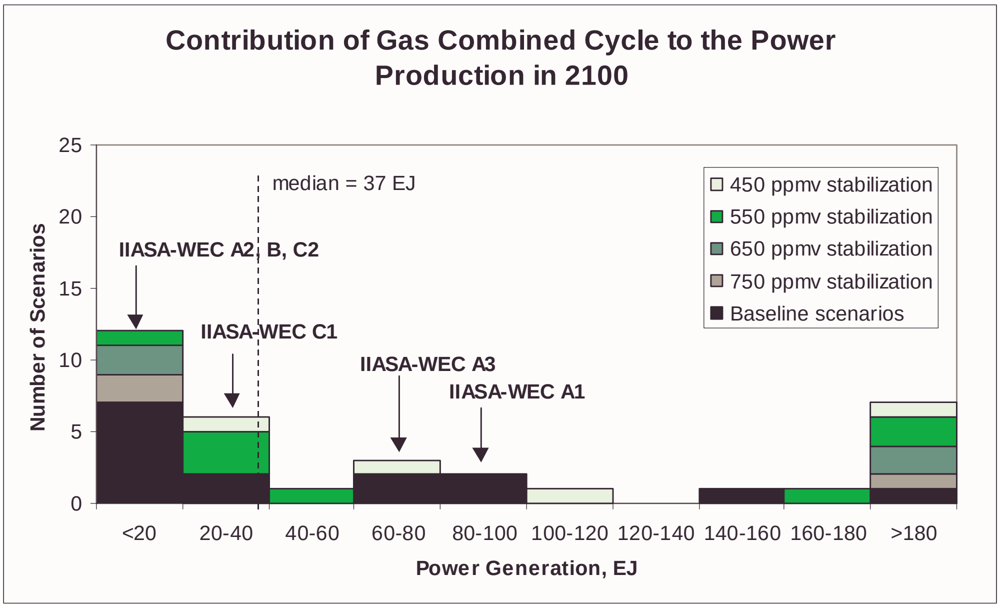

Figure C. Histogram of all natural-gas combined cycle contribution to electricity generation across scenarios in 2100. The contribution of natural gas combined cycle power plants is an aggregate of two technologies, GCC and GCC 0C. technologies (see Box 1).

Contribution of Natural-Gas Combined Cycle Power Plants without Carbon Scrubbing and Storage to Electricity Generation

Histograms of frequency distribution of the role of natural gas combined cycle power plants (GCC, without carbon scrubbing and storage) in electricity generation across scenarios, number of scenarios (from a total of 34) and generation in EJ per year. Figure A shows the natural gas contribution to electricity in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. After clustering during the first decades within the region of up to 20 EJ per year, electricity from natural gas expands across the scenarios reaching up to 80 EJ per year by 2050 and 180 EJ per year by 2100. Scenarios portray a very strong peak between 20 and 40 EJ per year in 2050 and between 0 and 20 EJ per year by 2100. Nevertheless, just like all natural gas technologies the combined-cycle natural gas proves to be a very robust source of electricity across all scenarios, it is important across all scenarios, but less so without carbon scrubbing and removal.

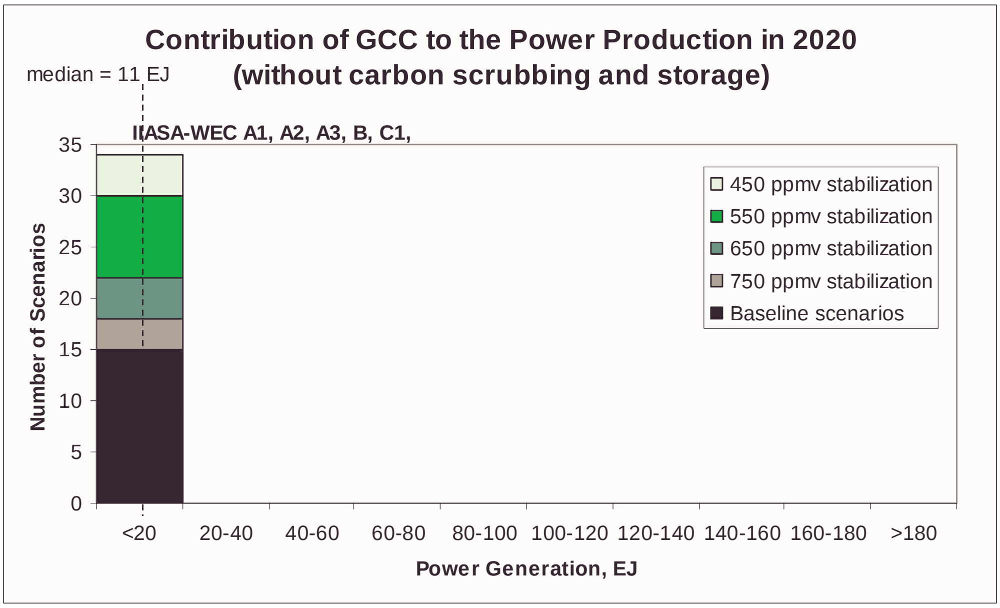

Figure A. Histogram of natural-gas combined cycle power plants (GCC, without carbon scrubbing and storage) contribution to electricity generation across scenarios in 2020.

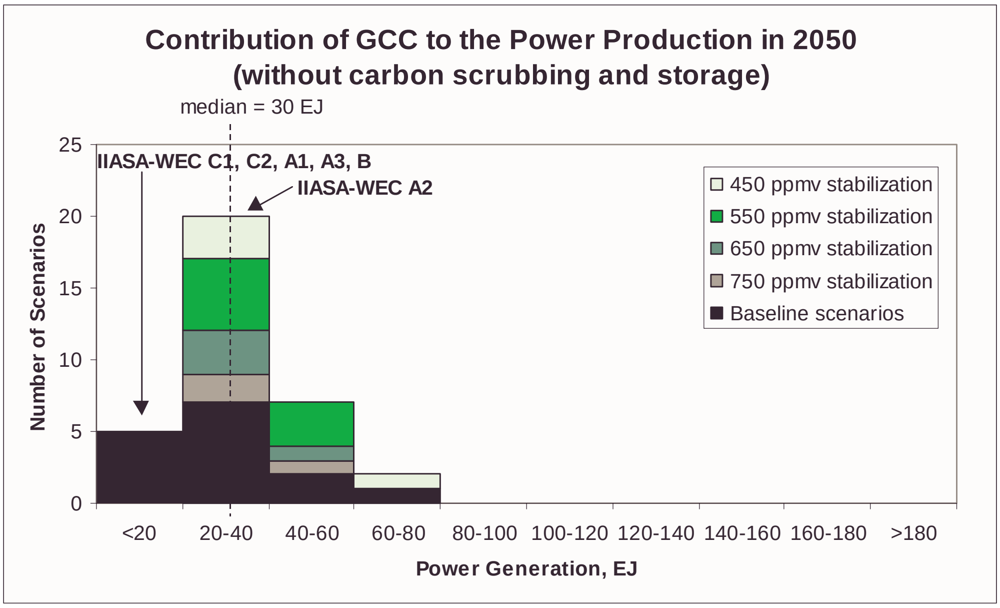

Figure B. Histogram of natural-gas combined cycle power plants (GCC, without carbon scrubbing and storage) contribution to electricity generation across scenarios in 2050.

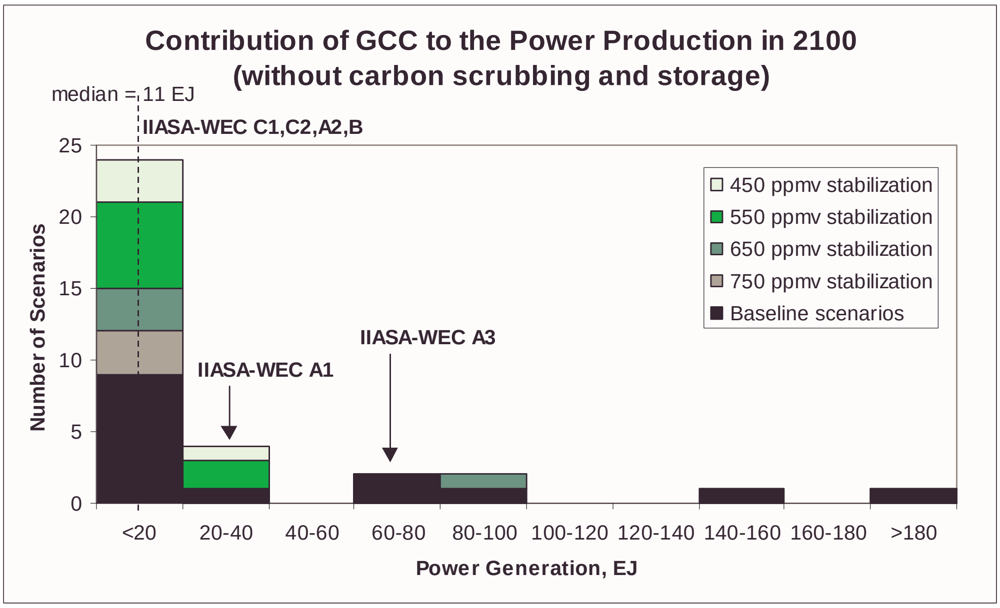

Figure C. Histogram of natural-gas combined cycle power plants (GCC, without carbon scrubbing and storage) contribution to electricity generation across scenarios in 2100.

Contribution of Biomass Power Plants to Electricity Generation

Histograms of frequency distribution of the role of biomass power plants in electricity generation across scenarios, number of scenarios (from a total of 34) and generation in EJ per year. Figure A shows the biomass contribution in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. After clustering through 2050 within the region of up to 20 EJ per year in much the same way as for hydrocarbon fuel cells and solar pv, some scenarios lead to a much more substantial contribution of biomass to electricity generation by 2100 of up to 100 EJ per year. Actually, the distribution is quite asymmetrical in 2100 for all scenarios. Most of the scenarios are still clustered within the region of up to 20 EJ per year and include both mitigation and baseline scenarios. A few of the mitigation scenarios, however, extend to the region between 80 and 100 EJ per year. This results in the bifurcation by end of the century into two groups, one under 60 EJ per year and one from 80 to 100 EJ per year. All of the IIASA-WEC scenarios fall in the first cluster. Notable is the fact that the mean contribution of biomass across all scenarios falls over the time from 8 EJ per year in 2020 to 3.3 EJ per year in 2050 increasing slightly to 5 EJ per year by 2100. Thus, the biomass for electricity generation is not employed much across many scenarios indicating that it is not a very robust technology option in the long run with and without mitigation measures. However, is does play a very important role in some of the scenarios also in the very long run.

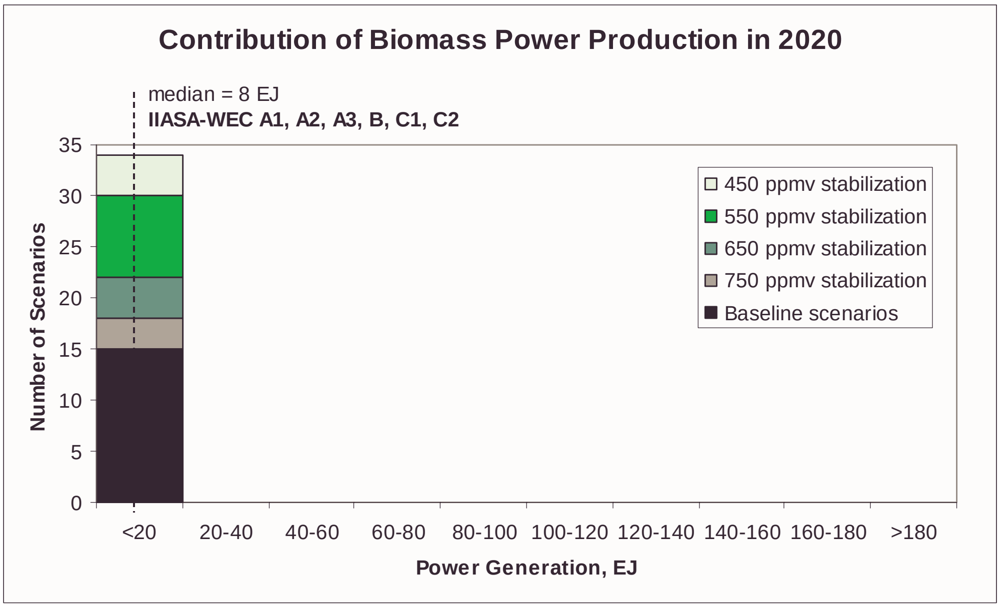

Figure A. Histogram of biomass contribution to electricity generation across scenarios in 2020. Biomass contribution is an aggregate of two technologies, Bio STC and Bio GTC (see Box 1).

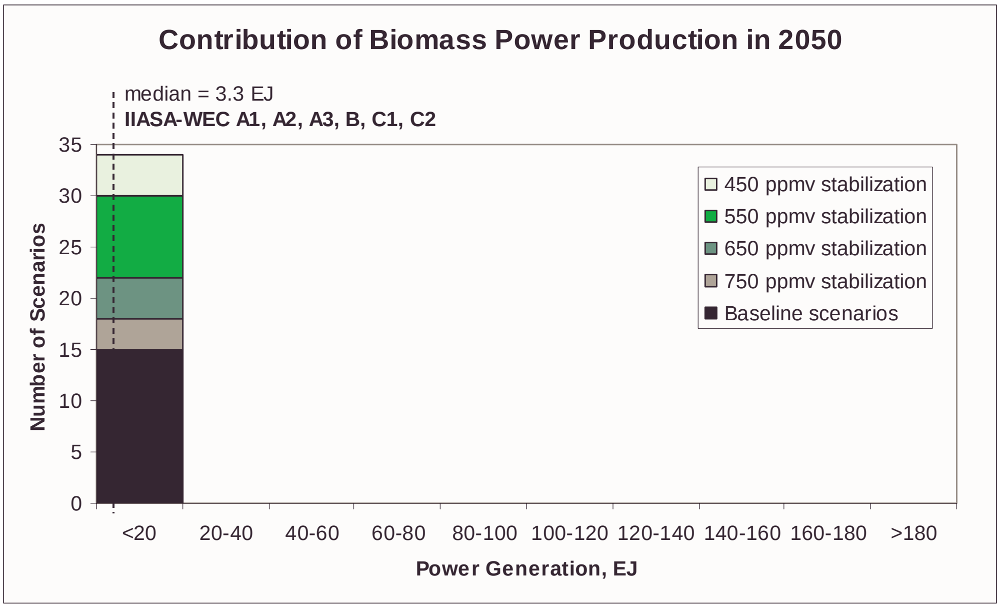

Figure B. Histogram of biomass contribution to electricity generation across scenarios in 2050. Biomass contribution is an aggregate of two technologies, Bio STC and Bio GTC (see Box 1).

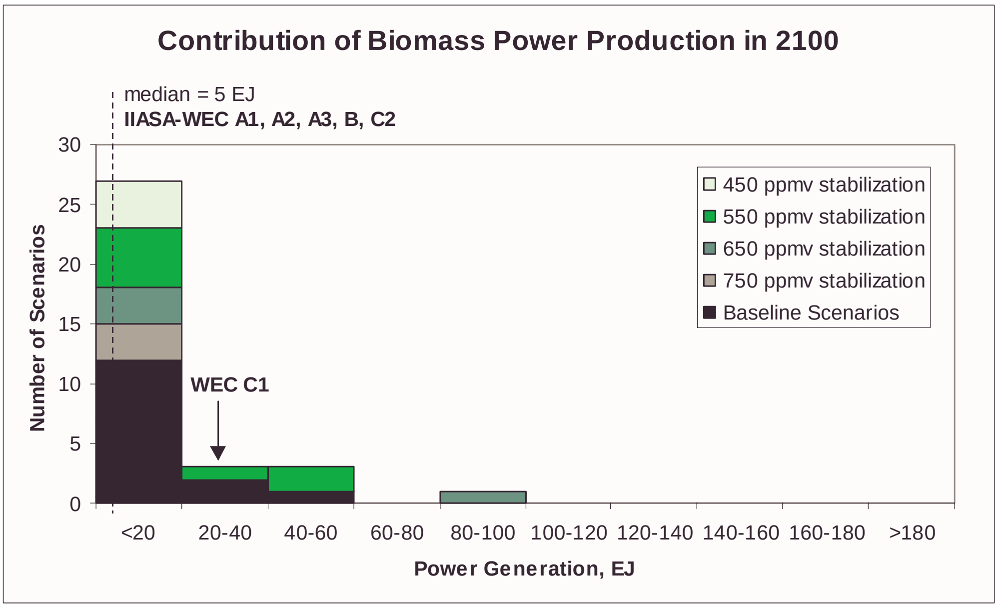

Figure C. Histogram of biomass contribution to electricity generation across scenarios in 2100. Biomass contribution is an aggregate of two technologies, Bio STC and Bio GTC (see Box 1).

Contribution of Wind Plants to Electricity Generation

Histograms of frequency distribution of the role of wind power plants in electricity generation across scenarios, number of scenarios (from a total of 34) and generation in EJ per year. Figure A shows the wind power contribution in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. After clustering through 2020 within the region of up to 20 EJ per year in much the same way as hydrocarbon fuel cells and solar pv, some scenarios lead to a more substantial contribution of wind power to electricity generation by 2050 continuing through 2100 of up to 40 EJ per year. Thus, the distribution is quite narrow over the whole time horizon. Most of the scenarios cluster within the region of up to 20 EJ per year and include both mitigation and baseline scenarios. All of the IIASA-WEC scenarios fall within the same range of up to 20 EJ per year with the exception of A3 scenario. The mean contribution of wind power across all scenarios increases over the time from 3 EJ per year in 2020 to 18 EJ per year by 2100. This is a substantial mean increase over time considering the fact that wind is an intermittent source of electricity so that high shares of electricity generation need to be enhanced by dedicated storage. Such storage facilities are not required as the share of wind stays below the critical thresholds in the scenarios. Basically, the sheer size of the grid offers the necessary buffering capacity that offsets the intermittent nature of wind power. Thus, wind power plays a very important role across the scenarios also in the very long run. It can be characterized to be a robust technology option even without the deployment of costly dedicated storage facilities.

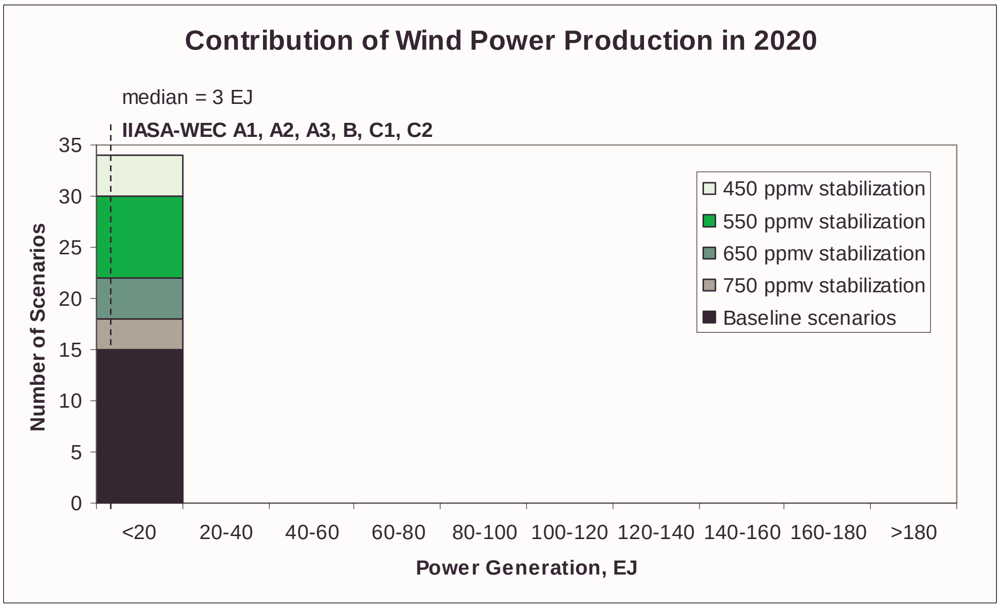

Figure A. Histogram of wind contribution to electricity generation across scenarios in 2020.

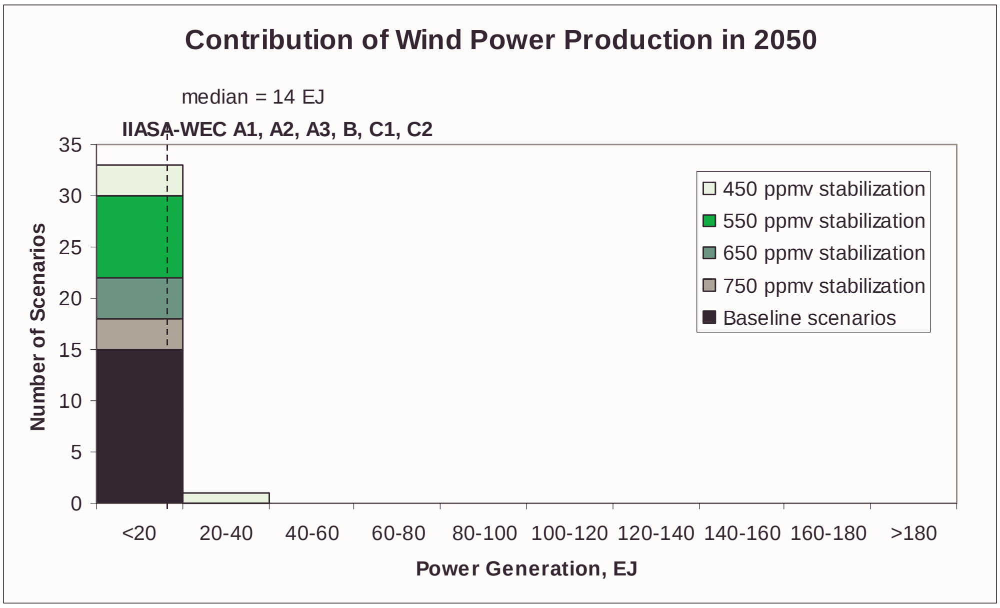

Figure B. Histogram of wind contribution to electricity generation across scenarios in 2050.

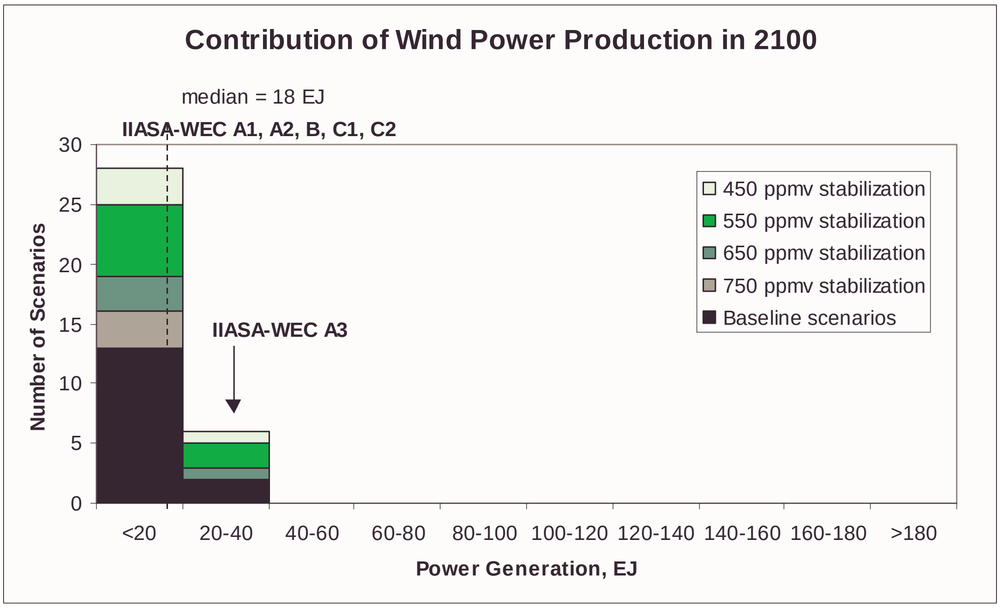

Figure C. Histogram of wind contribution to electricity generation across scenarios in 2100.

Contribution of Coal Gasification to Hydrogen Production

Histograms of frequency distribution of hydrogen production through coal gasification across scenarios, number of scenarios (from a total of 34) and production in EJ per year. Figure A shows the hydrogen production in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. After clustering through 2020 within the region of up to 20 EJ per year, some mitigation scenarios lead to a much more substantial hydrogen production of up to 60 EJ per year by 2050. However, most of the scenarios are still below 20 EJ per year including all baseline scenarios (without mitigation measures). This implies that production of hydrogen from coal becomes economical only if decarbonization is a high priority as is the case in mitigation scenarios. In fact, the high levels of hydrogen production of between 40 to 60 EJ per year occur only in the case of most stringent mitigation measures required to achieve atmospheric carbon dioxide concentrations stabilization at 450 ppm. The distribution does not change much by 2100. The only exception is that some of the 450 ppm stabilization scenarios shift into the higher category of 60 to 80 EJ per year. The distribution is quite asymmetrical for all three time periods and all scenarios because most of the scenarios are clustered within the region of up to 20 EJ per year and include some mitigation and all baseline scenarios. All of the IIASA-WEC scenarios fall in the first cluster with less than 20 EJ per year. Notable is the fact that the median is very low with 1 EJ per year and that it does not change much throughout the century. Thus, the hydrogen from coal is not a very robust technology option in the long run and is deployed only in the most stringent mitigation measures.

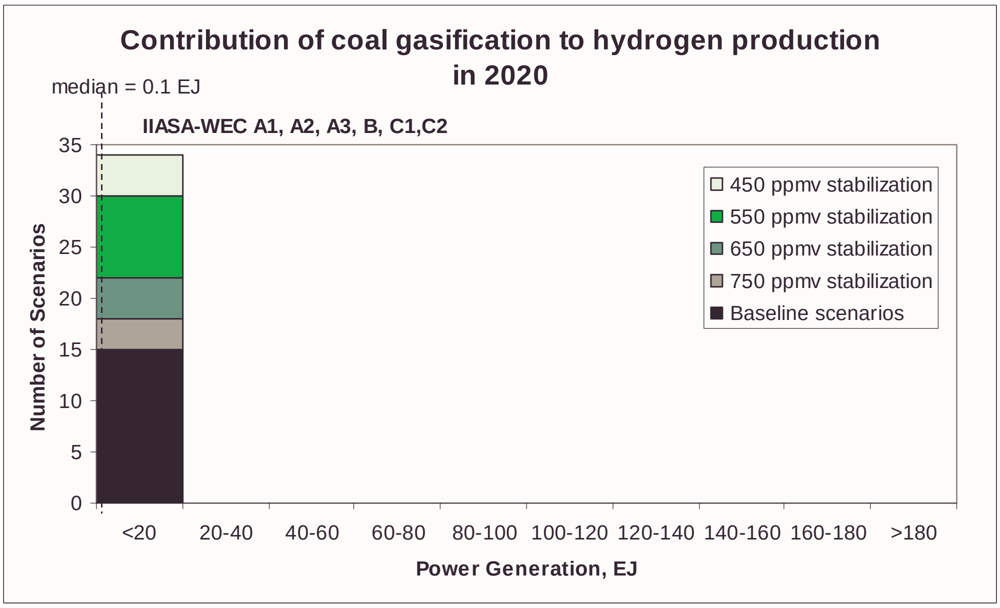

Figure A. Histogram of hydrogen production from coal gasification across scenarios in 2020.

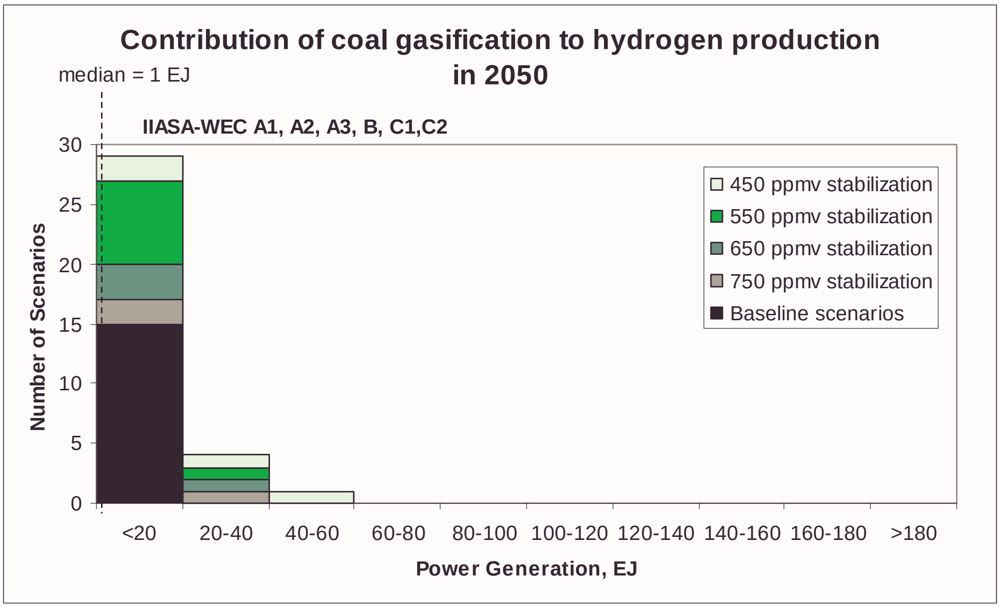

Figure B. Histogram of hydrogen production from coal gasification across scenarios in 2050.

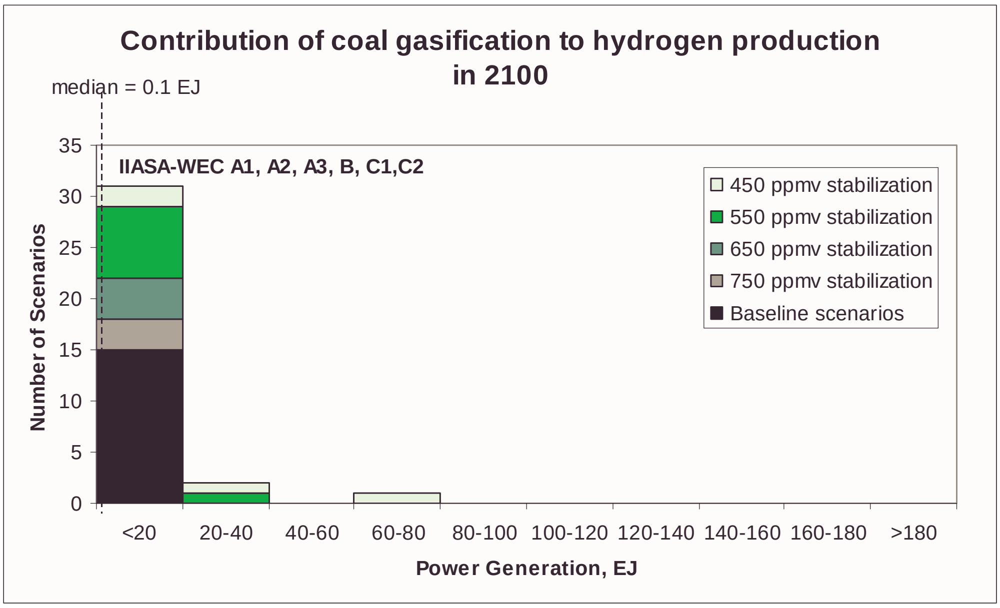

Figure C. Histogram of hydrogen production from coal gasification across scenarios in 2100.

Contribution of Coal to Liquids Production

Histograms of frequency distribution of coal liquefaction and light-oil synthesis across scenarios, number of scenarios (from a total of 34) and production in EJ per year. Figure A shows the liquids production in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. After clustering through 2020 within the region of up to 20 EJ per year, some baseline scenarios lead to a more substantial liquids production of up to 40 EJ per year by 2050. However, most of the scenarios are still below 20 EJ per year including all mitigation scenarios This is different from the situation of hydrogen production from coal where higher levels occurred only in the mitigation scenarios. Apparently coal liquefaction is not attractive in mitigation cases because of the carbon-intensity of the produced liquids. This trend is strengthened toward the end of the century although the distribution does not change fundamentally. In fact, it is identical to the case of hydrogen production by 2100. Most of the scenarios cluster within the first interval of up to 20 EJ per year, a few extend to 40 EJ per year, the interval between 40 and 60 EJ per year is empty and there are again a few scenarios in the interval of up to 80 EJ per year. All mitigation scenarios remain in the lowest category. Thus, coal liquefaction is not a robust strategy especially should mitigation of carbon emissions become widespread. The distribution is quite asymmetrical for all three time periods and all scenarios. All of the IIASA-WEC scenarios fall in the first cluster with less than 20 EJ per year. Notable is the fact that the median is very low with less than 1 EJ per year and that it does not change much throughout the century. Thus, the transformation of coal to liquids is not a very robust technology option in the long run and is deployed only in the scenarios without mitigation measures.

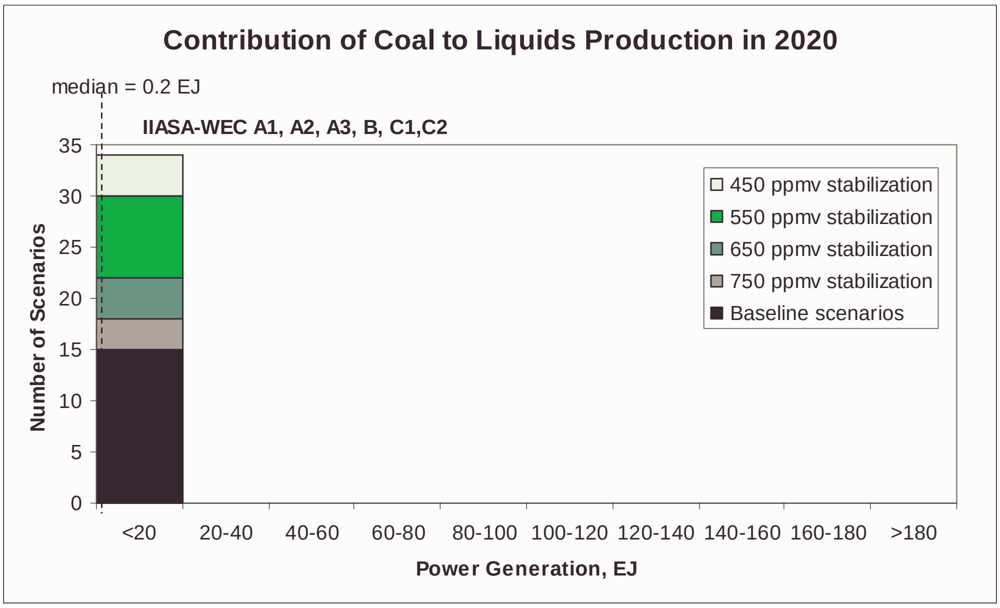

Figure A. Histogram of liquids production from coal across scenarios in 2020.

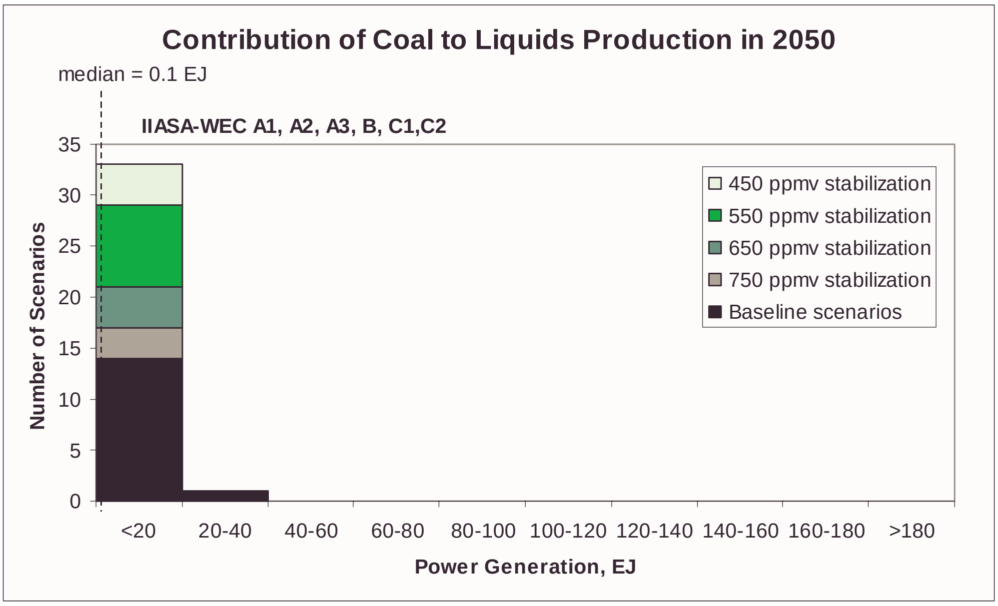

Figure B. Histogram of liquids production from coal across scenarios in 2050.

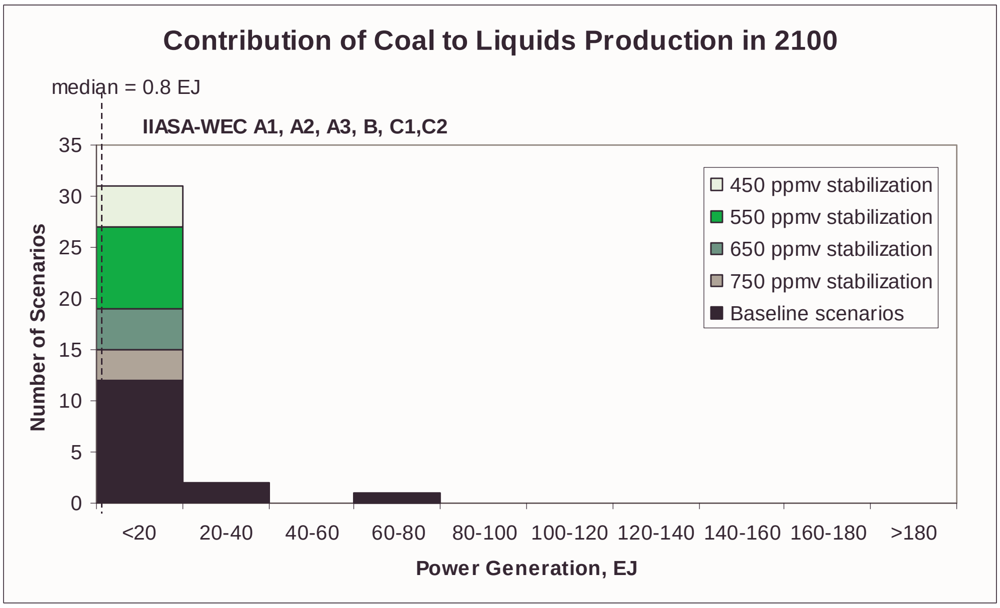

Figure C. Histogram of liquids production from coal across scenarios in 2100.

Contribution of Coal to Methanol Production

Histograms of frequency distribution of methanol production from coal across scenarios, number of scenarios (from a total of 34) and production in EJ per year. Figure A shows the methanol production in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. After clustering through 2020 mostly within the range of up to 20 EJ per year with only a few scenarios extending up to 40 EJ per year, some baseline scenarios lead to a much more substantial methanol production by 2050. Majority of scenarios falls within the region of up to 60 EJ per year but many extend well beyond into the region of between 140 and more than 180 EJ per year. The space in-between is vacant. Thus, the distribution is very asymmetrical in 2050 portraying strong bifurcation into two distinct clusters of scenarios. Most of the scenarios that fall in the higher cluster are mitigation cases. The spread of scenarios is quite wide by the end of the century. Mitigation cases are mixed with other scenarios without any obvious pattern. Thus, methanol production from coal is a robust technology option in the long run. Most of the methanol is used in the transportation sector and for hydrocarbon fuel cells in the electricity sector thus leading to very high conversion efficiencies and comparatively low emissions. It is therefore not accidental that the distributions of hydrocarbon fuel cells and methanol production from coal are very similar in all three time periods. Two of the six IIASA-WEC scenarios also portray high levels of methanol production by 2100 falling into the ranges of 60 to 80 EJ and 100 to 120 EJ per year, respectively. Notable is the fact that the medians are quite low especially in 2050 and 2100 with values of 25 and 13 EJ per year, respectively, given how widespread are the distributions of the scenarios.

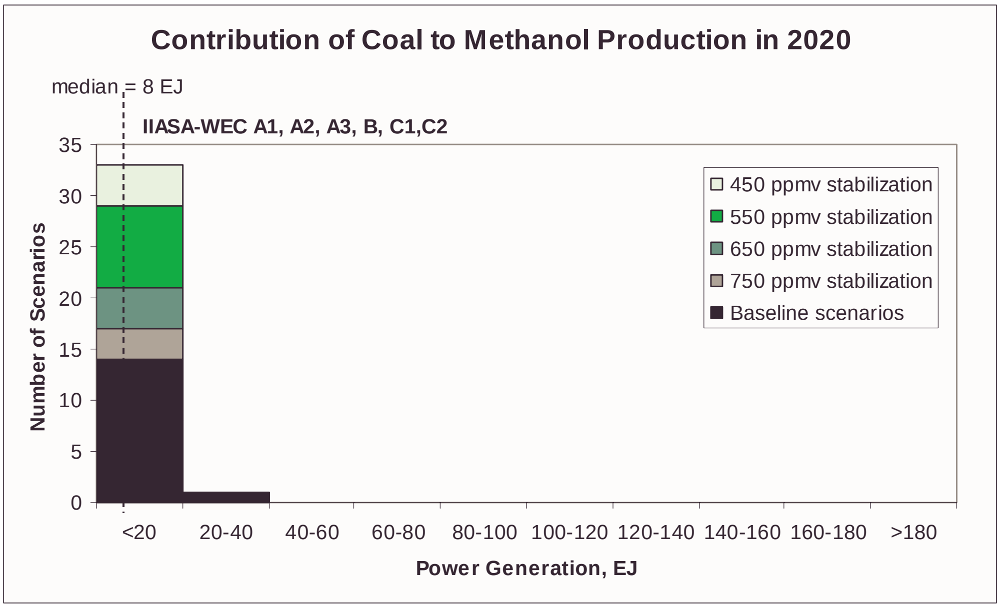

Figure A. Histogram of methanol production from coal across scenarios in 2020.

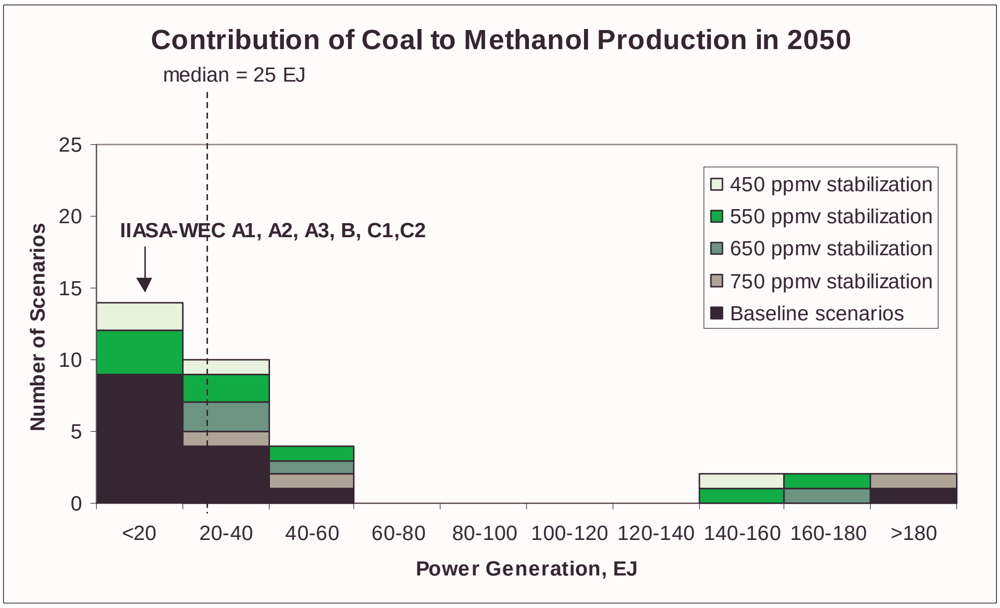

Figure B. Histogram of methanol production from coal across scenarios in 2050.

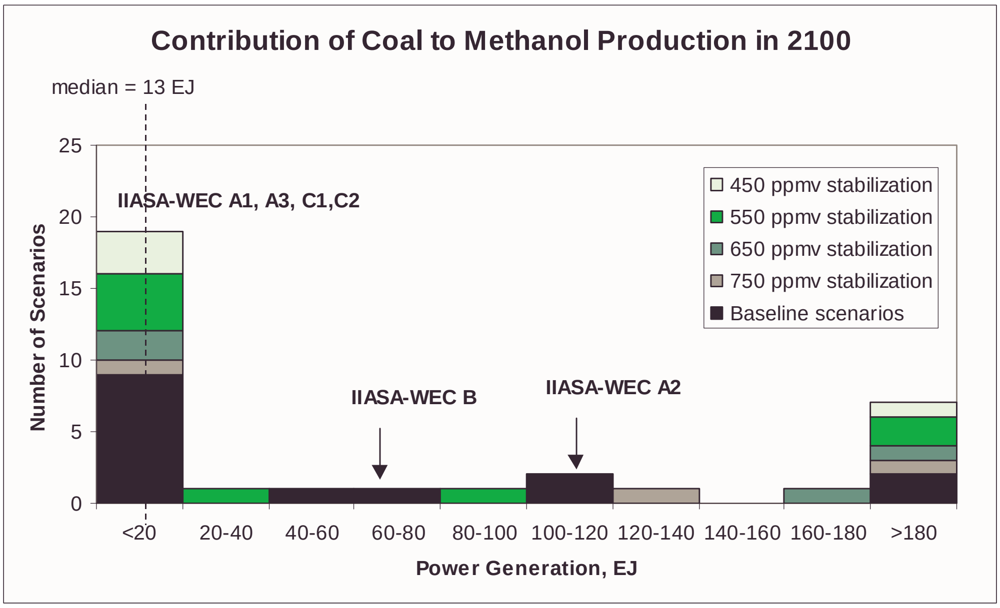

Figure C. Histogram of methanol production from coal across scenarios in 2100.

Contribution of Biomass to Ethanol Production

Histograms of frequency distribution of methanol production from coal across scenarios, number of scenarios (from a total of 34) and production in EJ per year. Figure A shows the methanol production in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. After clustering through 2020 within the region of up to 20 EJ per year, the scenarios cover a wide range of up to 100 EJ per year by 2050. All mitigation scenarios fall within a high interval of 60 to 100 EJ per year. This indicates the importance of biomass as a mitigation option. However, the baseline scenarios also extend into this interval indicating that over the next decades biomass is also a very robust energy source across a wide range of scenarios. The IIASA-WEC scenarios are distributed over the interval up to 60 EJ per year. The IPCC baseline scenarios are quite evenly distributed over the whole range up to 100 EJ per year. The median is quite high with 25 EJ per year because mitigation cases all cluster toward the high end of the range. Consequently, the distribution is very skewed by 2050. All scenarios are distributed more evenly by the end of the century covering all intervals except the contributions between 20 and 40 EJ per year and slightly higher clustering within the last interval of more than 180 EJ per year. This results in a very high median contribution of 151 EJ per year. Thus, ethanol production from biomass is a very robust energy technology across a very wide range of scenarios.

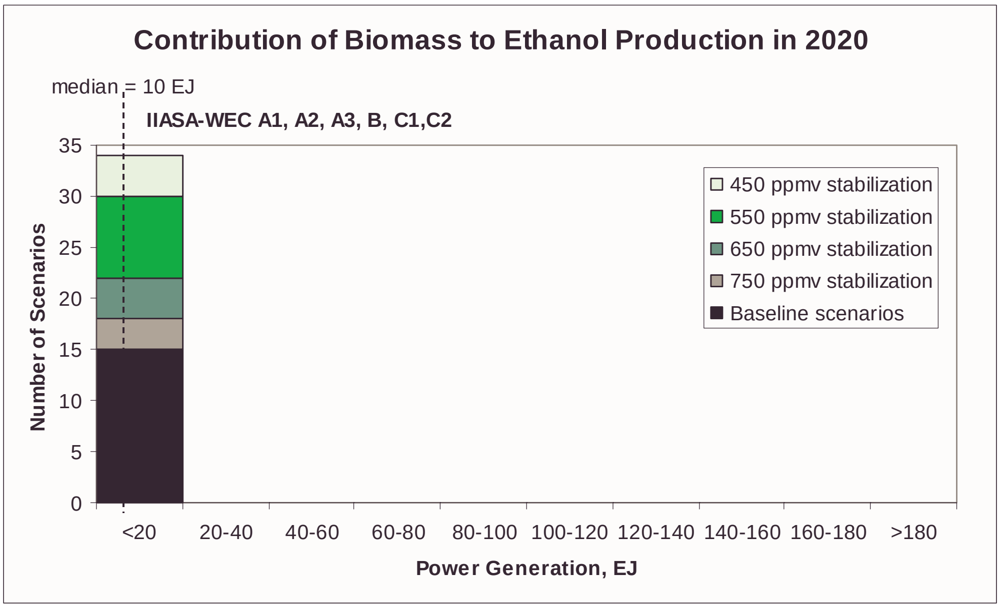

Figure A. Histogram of ethanol production from biomass across scenarios in 2020.

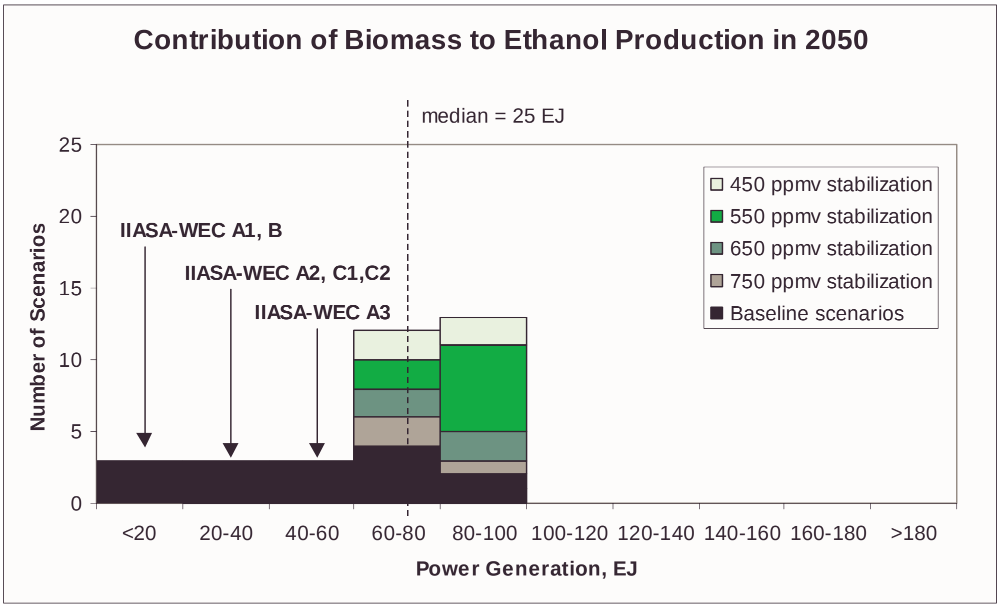

Figure B. Histogram of ethanol production from biomass across scenarios in 2050.

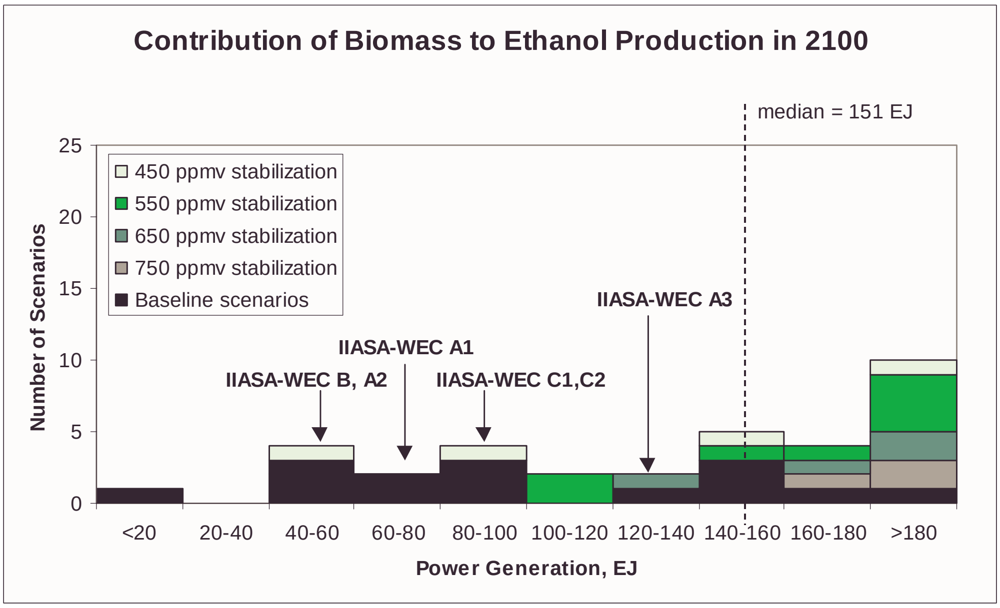

Figure C. Histogram of ethanol production from biomass across scenarios in 2100.

Contribution of Natural Gas to Methanol Production

Histograms of frequency distribution of methanol production from natural gas across scenarios, number of scenarios (from a total of 34) and production in EJ per year. Figure A shows the methanol production in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. After clustering through 2020 within the region of up to 20 EJ per year in much the same way as methanol production from coal, some scenarios lead to a more substantial contribution of natural gas to methanol production by 2050 of up to 40 EJ per year extending up to 60 EJ per year by 2100. Thus, the distribution is quite narrow over the whole time horizon. All scenarios cluster within this narrow range and include both mitigation and baseline scenarios. All of the IIASA-WEC scenarios fall within the range of up to 20 EJ per year with the exception of A1 scenario. The median contribution across all scenarios increases over the time from 7 EJ per year in 2020 to 11 EJ per year by 2100. Thus, natural gas plays quite an important role across the scenarios also as the source of methanol in addition to its important role in electricity generation.

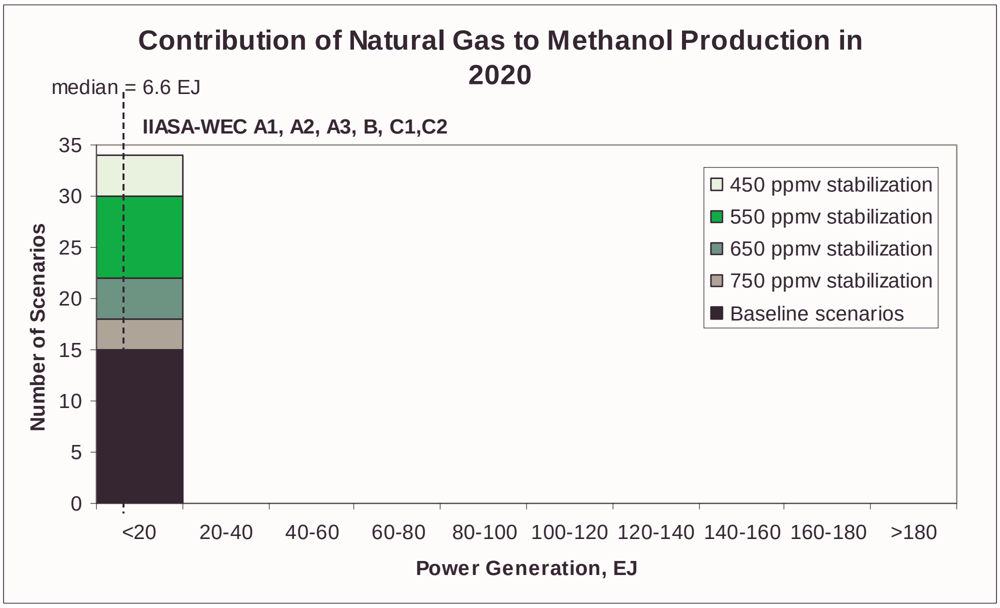

Figure A. Histogram of methanol production from natural gas across scenarios in 2020.

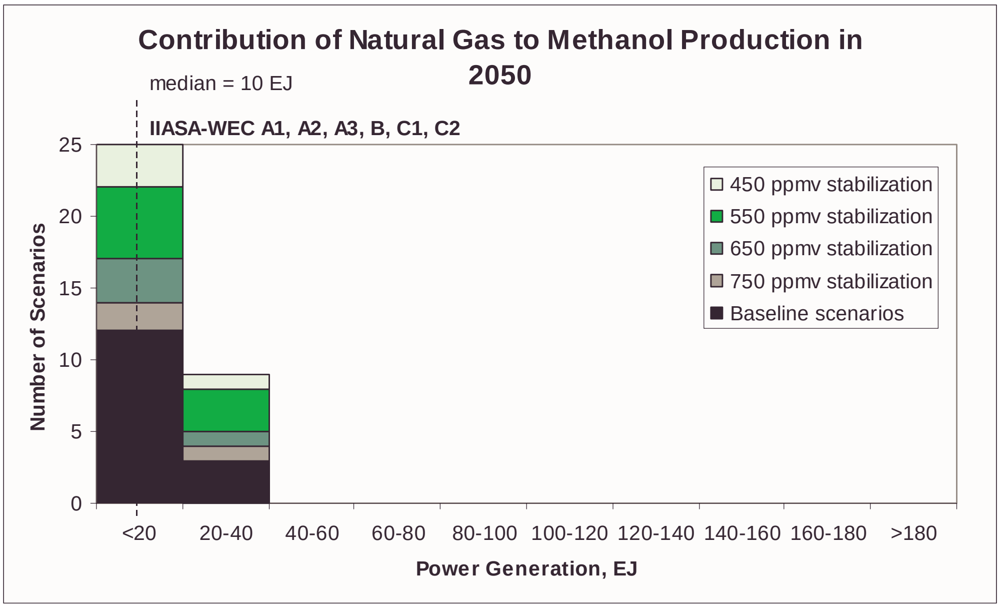

Figure B. Histogram of methanol production from coal across scenarios in 2050.

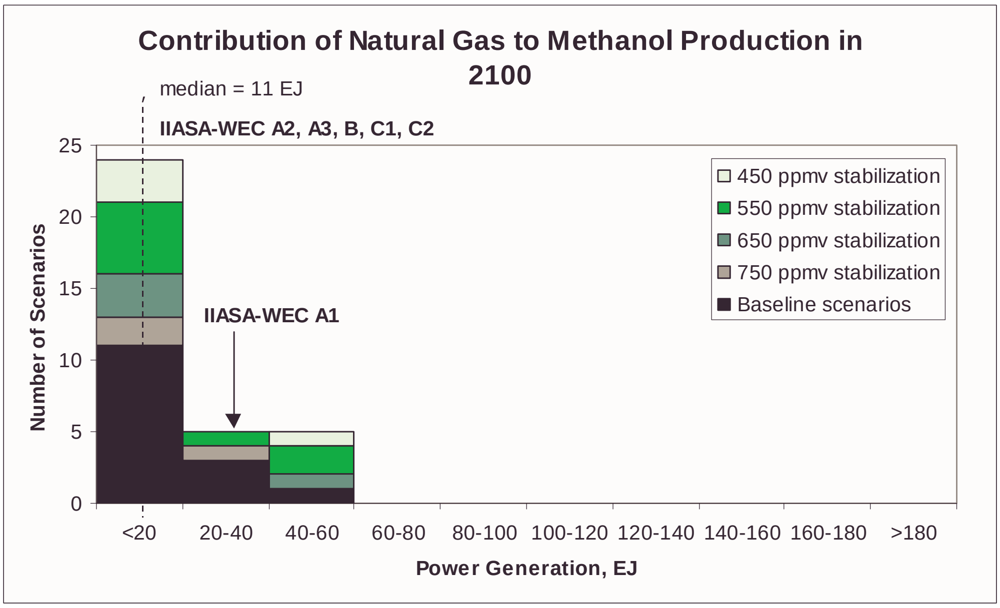

Figure C. Histogram of methanol production from coal across scenarios in 2100.

Contribution of Coal to Syngas Production

Histograms of frequency distribution of syngas production from coal gasification across scenarios, number of scenarios (from a total of 34) and production in EJ per year. Figure A shows the syngas production in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. After clustering within the narrow range of up to 20 EJ per year through 2050, some scenarios lead to very substantial contribution of syngas production from coal by 2100 of up to 120 EJ per year. The distribution is very skewed in 2100 and portrays an unoccupied gap between 80 and 100 EJ per year. All of the IIASA-WEC scenarios fall within the narrow range of up to 20 EJ per year over the whole time period with the exception of the A2 scenario. Altogether, coal plays a modest role in syngas production across the scenarios with a similar distribution as coal liquefaction. Notable is the fact that the median is very low with much less than 1 EJ per year and that it does not change much throughout the century. Thus, the gasification of coal for syngas production is not a very robust technology option in the long run.

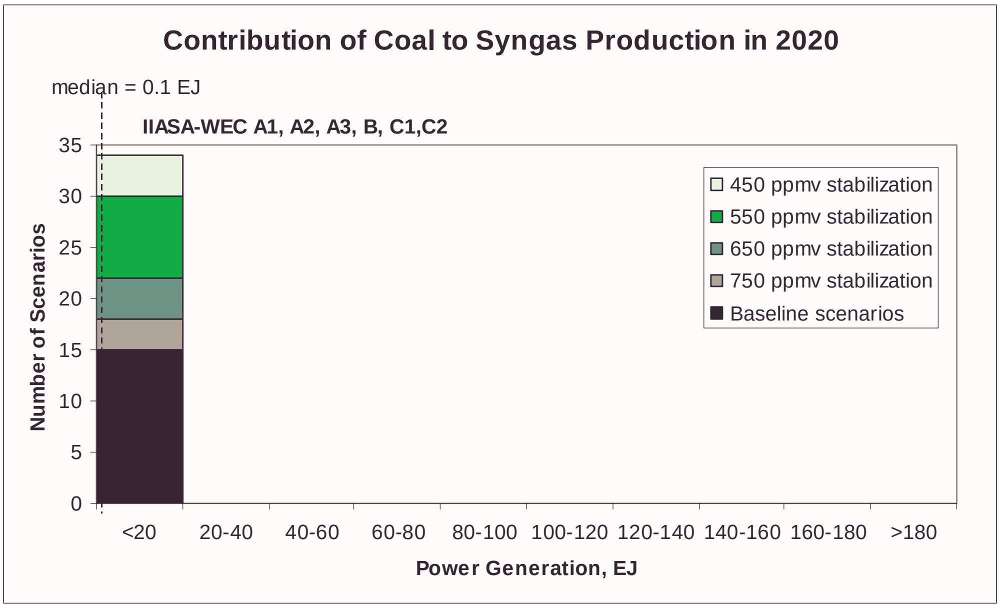

Figure A. Histogram of syngas production from coal across scenarios in 2020.

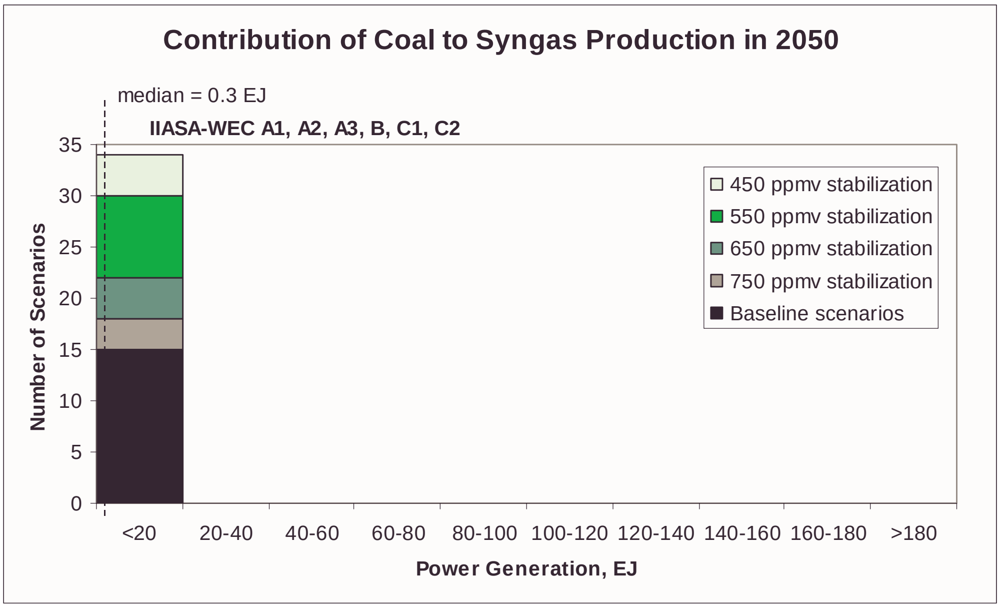

Figure B. Histogram of syngas production from coal across scenarios in 2050.

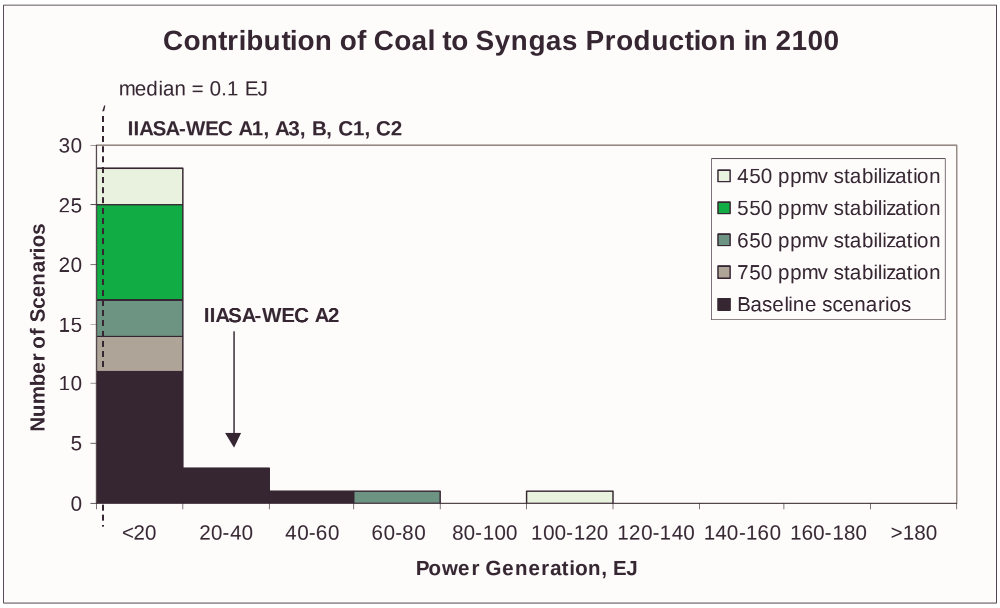

Figure C. Histogram of syngas production from coal across scenarios in 2100.

Contribution of Biomass to Syngas Production

Histograms of frequency distribution of syngas production from biomass gasification across scenarios, number of scenarios (from a total of 34) and production in EJ per year. Figure A shows the syngas production in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. After clustering within the narrow range of up to 20 EJ per year through 2020, a few mitigation scenarios lead to a more substantial contribution of syngas production from biomass by 2050 of up to 60 EJ per year. The clustering of the scenarios continues throughout the century, but a few more of the mitigation scenarios spread forming a very long distribution tail extending all the way to 180 EJ per year. However, the tail is very thin and is interrupted by three unoccupied intervals. Thus, the distribution is very skewed both in 2050 and 2100. All of the IIASA-WEC and IPCC baseline scenarios fall within the narrow range of up to 20 EJ per year as well as majority of the mitigation cases. This means that syngas production from biomass becomes more widespread if decarbonization becomes a more important priority. Altogether, biomass plays a modest role in syngas production across the scenarios with a similar distribution as syngas production from coal and coal liquefaction. Notable is the fact that the median is very low with much less than 1 EJ per year and that it does not change much throughout the century increasing modestly to 1.6 EJ per year by 2100. Thus, the gasification of bomass for syngas production is not a very robust technology option in the long run.

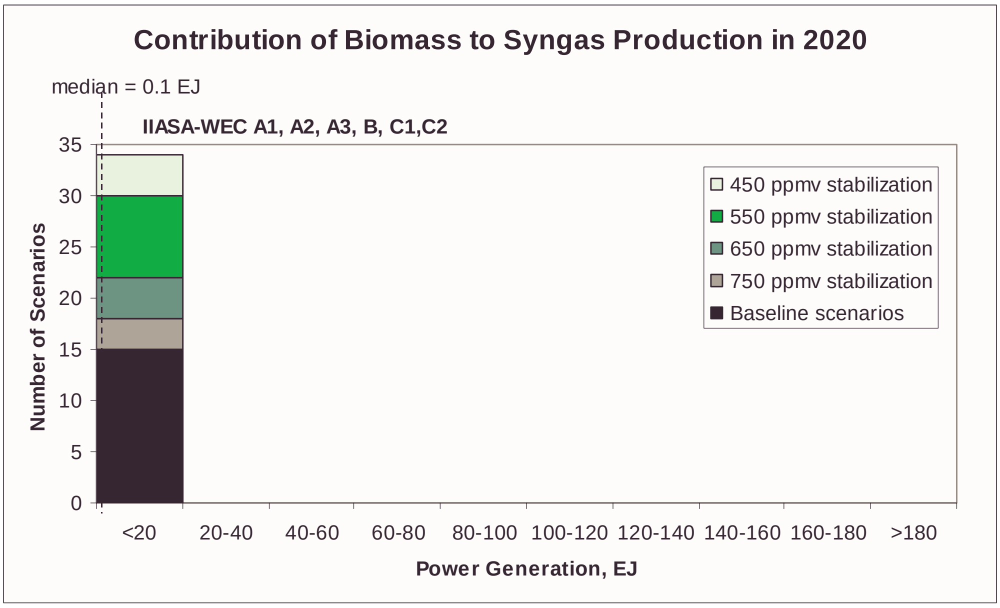

Figure A. Histogram of syngas production from biomass across scenarios in 2020.

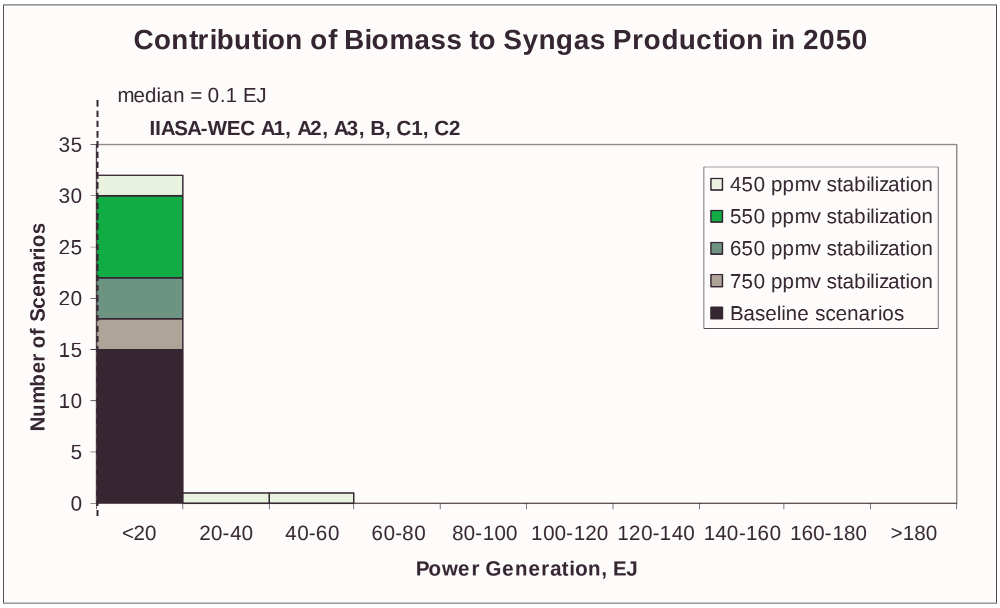

Figure B. Histogram of syngas production from biomass across scenarios in 2050.

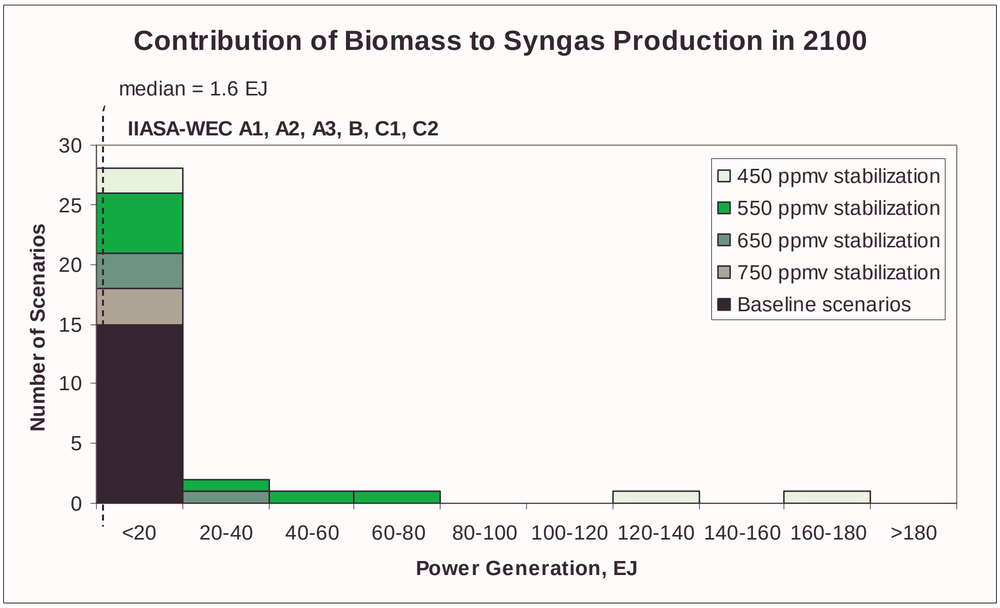

Figure C. Histogram of syngas production from biomass across scenarios in 2100.

Contribution of Natural Gas Steam Reforming to Hydrogen Production

Histograms of frequency distribution of hydrogen production from steam-reforming of natural gas across scenarios, number of scenarios (from a total of 34) and production in EJ per year. Figure A shows the hydrogen production in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. After clustering through 2020 within the range of up to 20 EJ per year, the distribution extends considerably by 2050. Majority of scenarios still falls within the range of up to 40 EJ per year but some extend well beyond into the region of 120 EJ per year. Thus, the distribution is very skewed in 2050, but the median increases considerably from 7.3 EJ per year in 2020 to 23 EJ per year by 2050 because most of the scenarios are situated in the region of up to 40 EJ per year. Most of the scenarios re-cluster in the narrow range up to 20 EJ per year by 2100. However, the distribution also becomes even more skewed with a very thin tail extending beyond 180 EJ per year by 2100. This tail of the distribution is interrupted by three unoccupied intervals. Six from the ten scenarios that extend beyond 20 EJ per year occupy the interval of 100 to 120 EJ per year. Consequently, the median also falls back to 7.7 EJ per year. Thus, hydrogen production from natural gas is more important through 2050 than beyond that period.

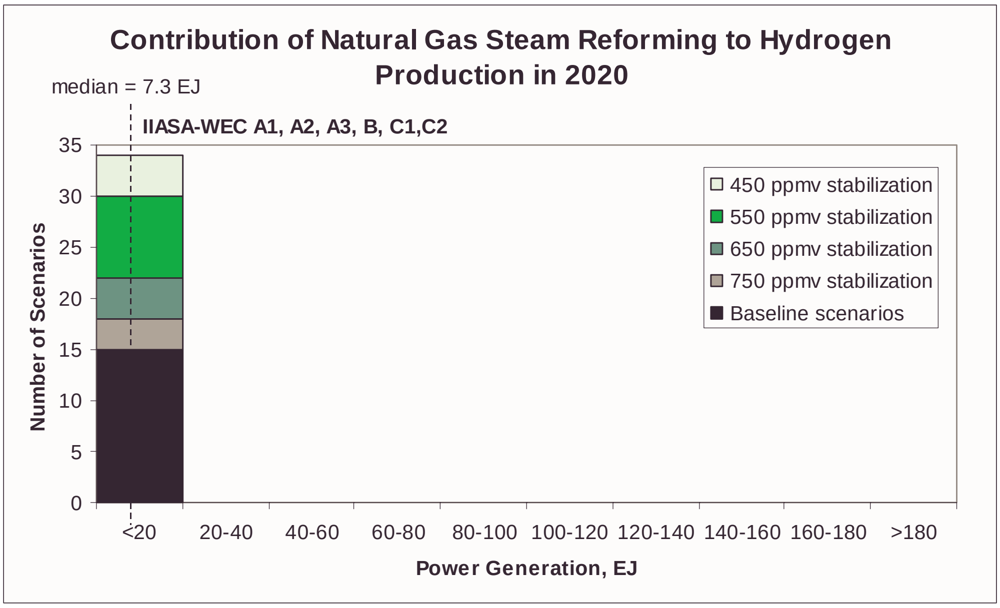

Figure A. Histogram of hydrogen production from natural gas across scenarios in 2020.

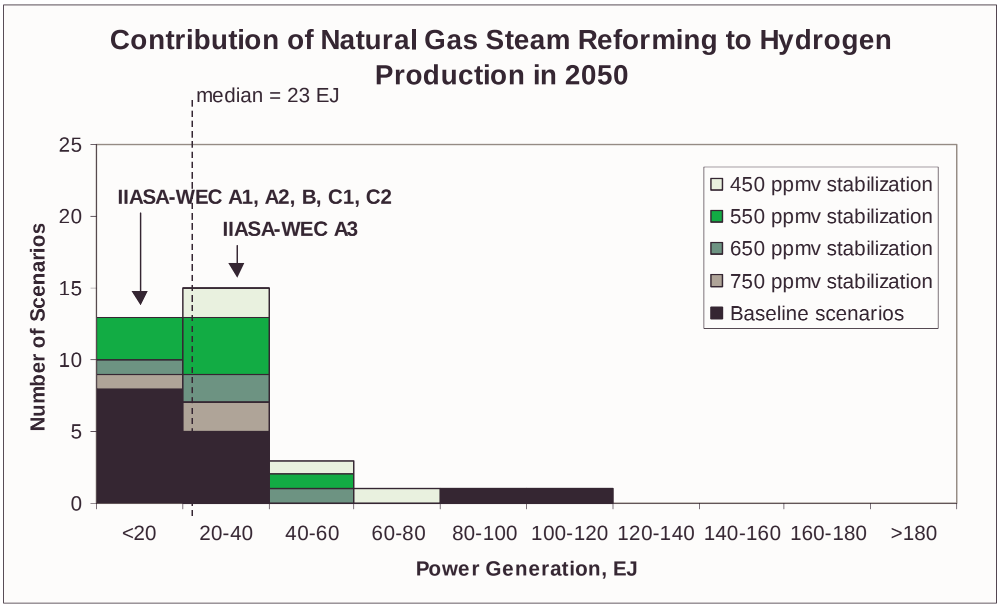

Figure B. Histogram of hydrogen l production from natural gas l across scenarios in 2050.

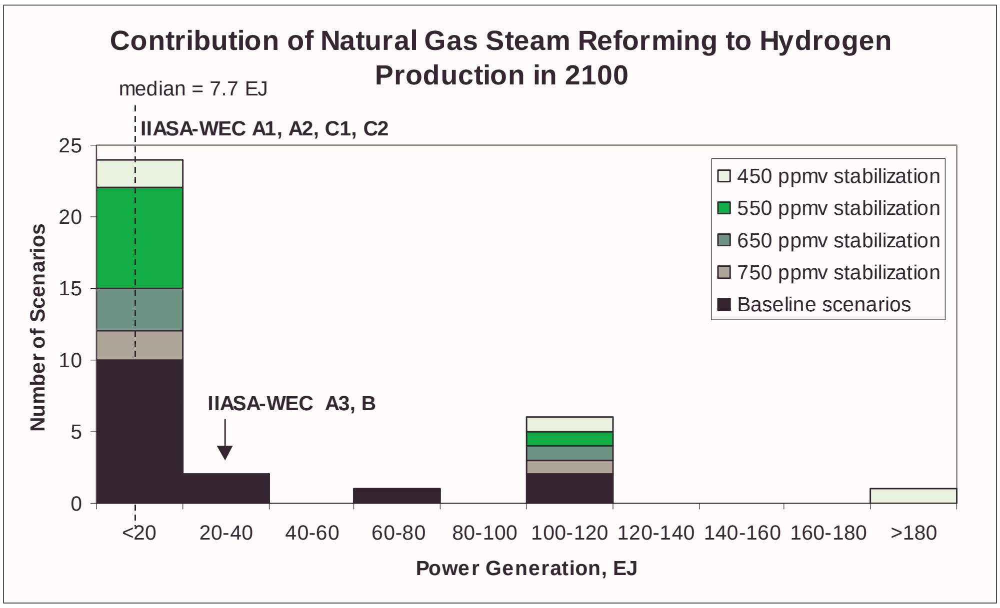

Figure C. Histogram of hydrogen production from natural gas across scenarios in 2100.

Contribution of Biomass to Hydrogen Production

Histograms of frequency distribution of hydrogen production from biomass gasification across scenarios, number of scenarios (from a total of 34) and production in EJ per year. Figure A shows the hydrogen production in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. After clustering within the narrow range of up to 20 EJ per year through 2020, two IPCC baseline scenarios lead to a more substantial contribution of hydrogen production from biomass by 2050 of up to 40 EJ per year. The clustering of the scenarios continues throughout the century, but a few more of the mitigation scenarios spread forming a very long distribution tail extending all the way to 160 EJ per year. However, the tail is very thin consisting of only three scenarios so that it is interrupted by two unoccupied intervals. Thus, the distribution is very skewed both in 2050 and 2100. All of the mitigation scenarios and IIASA-WEC fall within the narrow range of up to 20 EJ per year with the exception of A2. This means that hydrogen production from biomass plays a modest role in hydrogen production across the scenarios with a similar distribution as syngas production from coal and biomass. Notable is the fact that the median is very low and decreases from 1.3 EJ per year in 2020 to 0.1 EJ per year by 2100 Thus, the gasification of biomass for hydrogen production is not a very robust technology option in the long run.

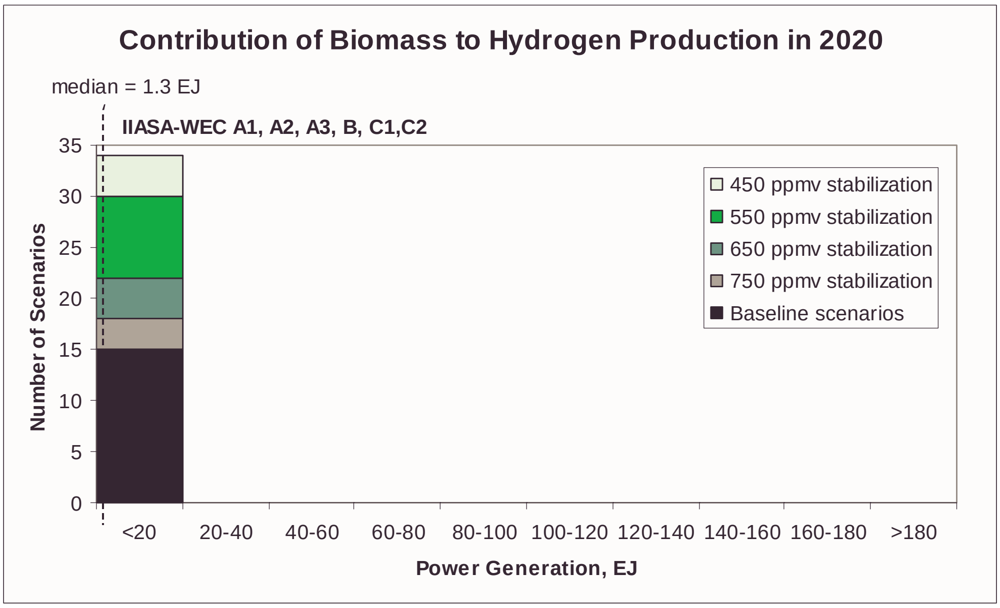

Figure A. Histogram of hydrogen production from biomass across scenarios in 2020.

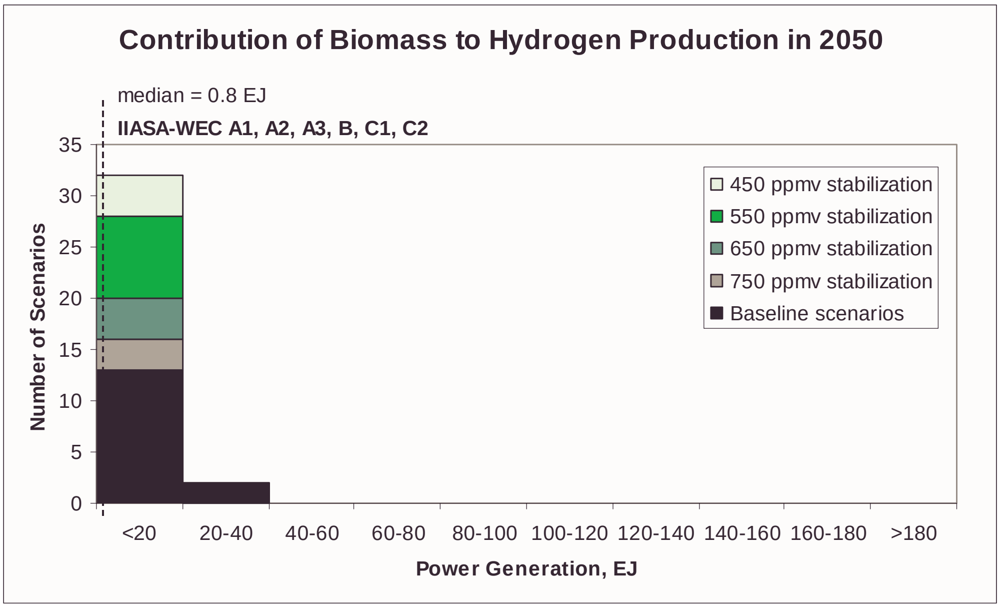

Figure B. Histogram of hydrogen production from biomass across scenarios in 2050.

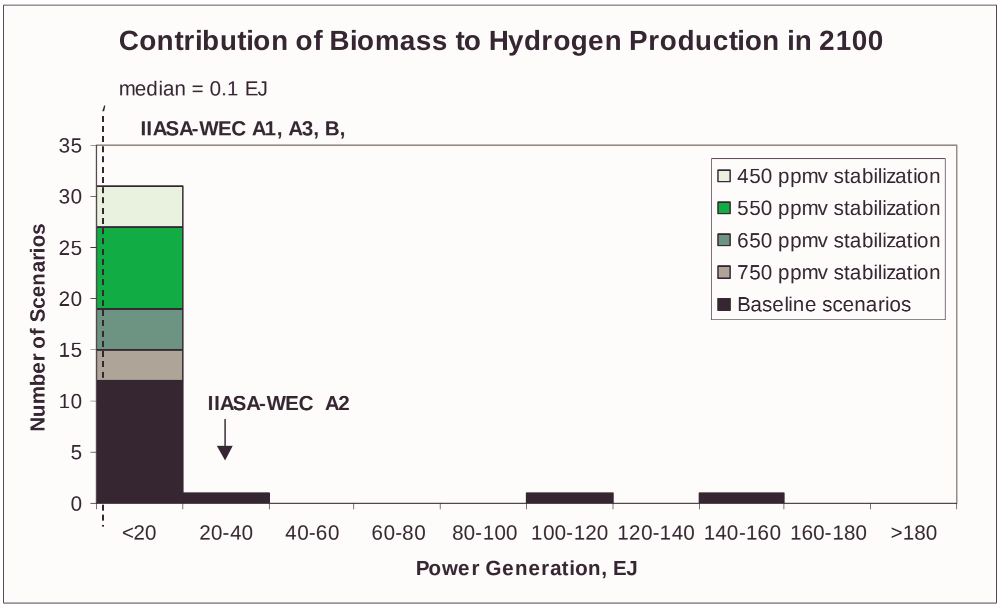

Figure C. Histogram of hydrogen production from biomass across scenarios in 2100.

Contribution of Electricity to Hydrogen Production

Histograms of frequency distribution of hydrogen production through electrolysis across scenarios, number of scenarios (from a total of 34) and production in EJ per year. Figure A shows the hydrogen production in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. All scenarios cluster within the narrow range of up to 20 EJ per year throughout the century with the exception of two mitigation scenarios with the low ceiling of atmospheric carbon dioxide concentrations of 450 ppmv that are in the range of 40 to 60 EJ per year by 2100. In fact, electrolysis does not play any significant role in the majority of scenarios**.** This is illustrated by the median of zero throughout the whole century, which indicates that in more than fifty percent of the scenarios electrolysis does not enter the market at all. Therefore, electrolysis does not constitute an important option for hydrogen production.

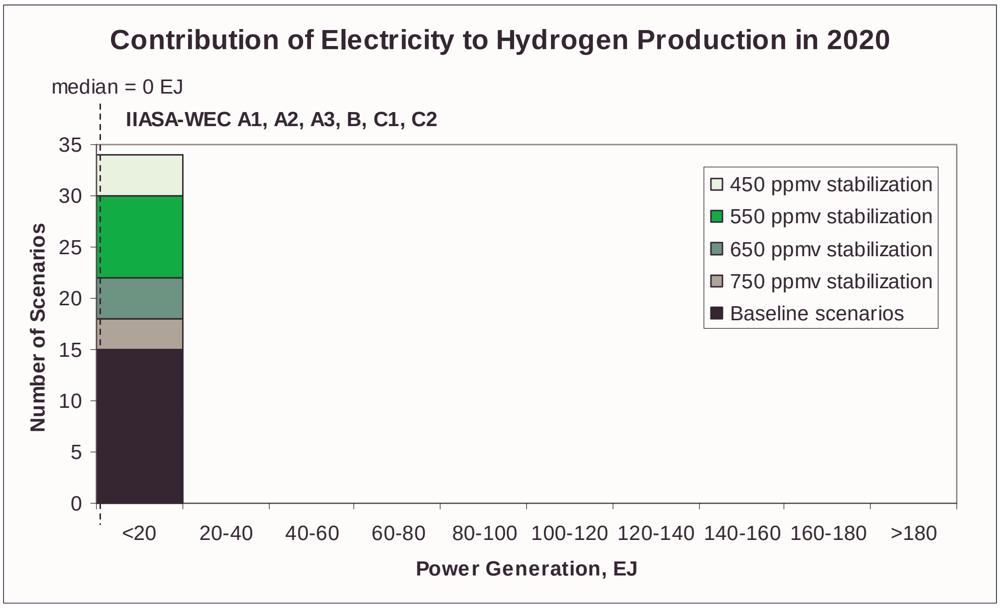

Figure A. Histogram of hydrogen production from electricity across scenarios in 2020.

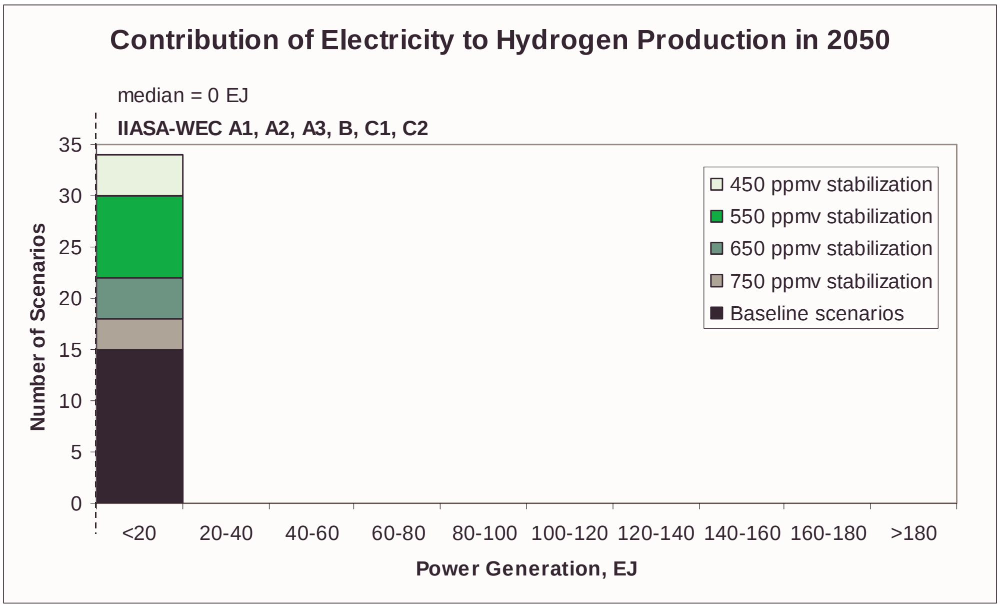

Figure B. Histogram of hydrogen production from electricity across scenarios in 2050.

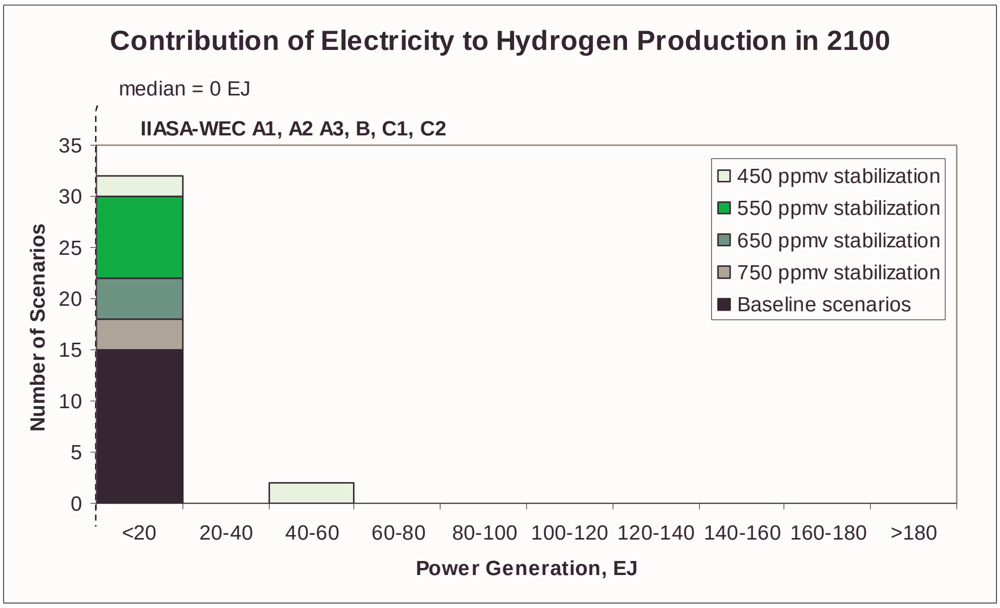

Figure C. Histogram of hydrogen production from electricity across scenarios in 2100.

Contribution of Nuclear Energy to Hydrogen Production

Histograms of frequency distribution of hydrogen production from high-temperature nuclear reactors across scenarios, number of scenarios (from a total of 34) and production in EJ per year. Figure A shows the hydrogen production in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. After clustering within the narrow range of up to 20 EJ per year through 2020, four scenarios lead to a more substantial contribution of syngas production from biomass by 2050 of up to 60 EJ per year. The clustering of the scenarios continues throughout the century, but a few more scenarios spread forming a very long distribution tail extending all the way beyond 180 EJ per year. However, the tail is very thin and is interrupted by three unoccupied intervals. Thus, the distribution is very skewed both in 2050 and 2100. All of the IIASA-WEC with the exception of A1 in 2100 fall within the narrow range of up to 20 EJ per year. This means that hydrogen production from nuclear energy becomes slightly more widespread but continues to play a modest role in hydrogen production across the scenarios with a similar distribution as syngas production from coal and bomass liquefaction. Notable is the fact that the median is zero EJ per year, which indicates that in more than fifty percent of the scenarios electrolysis does not enter the market at all. Thus, the production of hydrogen through high-temperature nuclear reactors is not a very robust technology option in the long run.

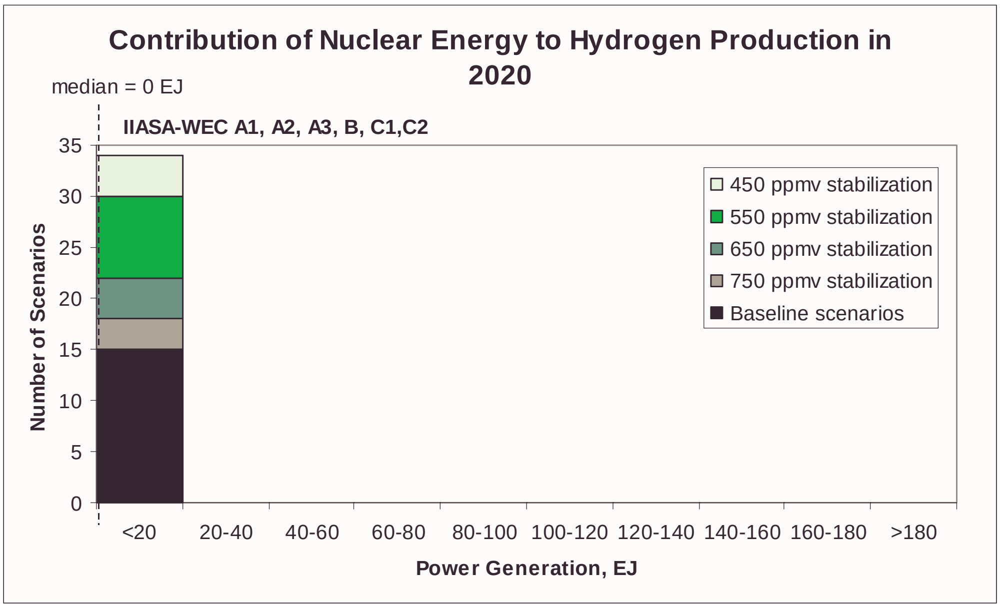

Figure A. Histogram of hydrogen production from nuclear energy across scenarios in 2020.

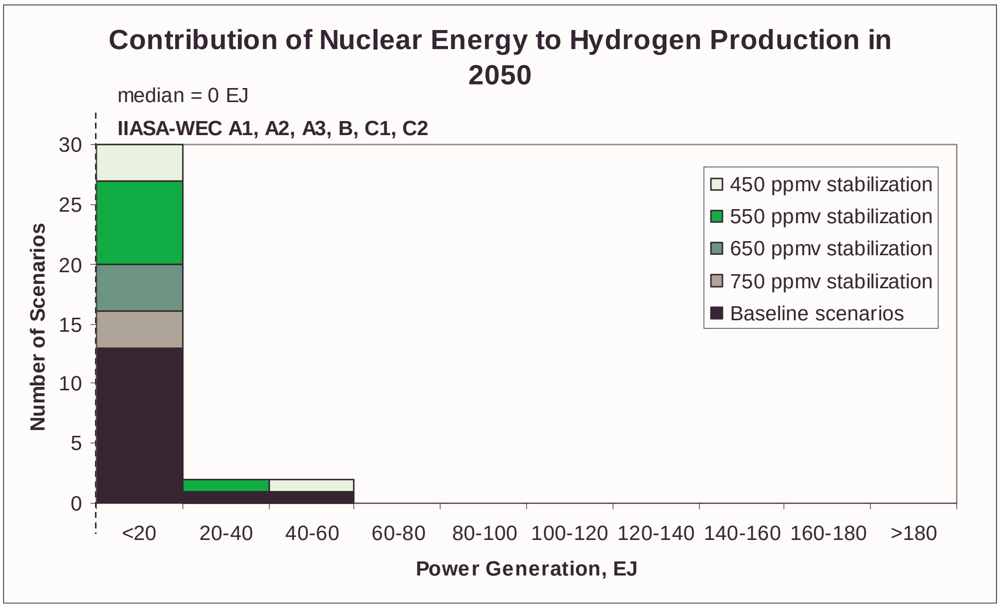

Figure B. Histogram of hydrogen production from nuclear energy across scenarios in 2050.

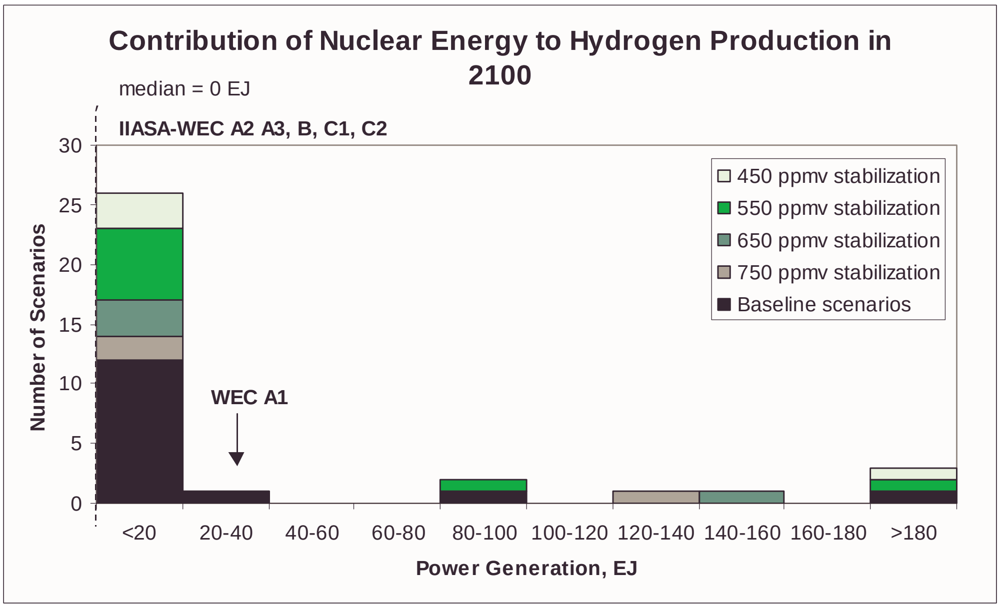

Figure C. Histogram of hydrogen production from nuclear energy across scenarios in 2100.

Contribution of Solar Thermal to Hydrogen Production

Histograms of frequency distribution of hydrogen production from solar thermal power plants across scenarios, number of scenarios (from a total of 34) and production in EJ per year. Figure A shows the hydrogen production in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. After clustering through 2020 within the range of up to 20 EJ per year, the distribution extends considerably by 2050. Majority of scenarios still falls within the range of up to 20 EJ per year including all IIASA-WEC scenarios, but some scenarios extend well beyond into the region of 160 EJ per year. This long tail of the distribution is interrupted by two unoccupied intervals. Thus, the distribution is very skewed in 2050, and most of the scenarios are situated in the region of up to 20 EJ per year. This clustering in the narrow range up to 20 EJ per year is still pronounced by 2100. However, the distribution bifurcates with equal number of scenarios forming a second pronounced cluster within the interval of 180 EJ and beyond. These two modes of the distribution are connected by a very thin tail extending with a gap in the range of 140 to 180 EJ per year in 2100. Consequently, the median increases considerably from zero in 2050 to 95 EJ per year by 2100. Thus, hydrogen production from solar thermal becomes an important source of hydrogen by 2050 and even more so beyond that period.

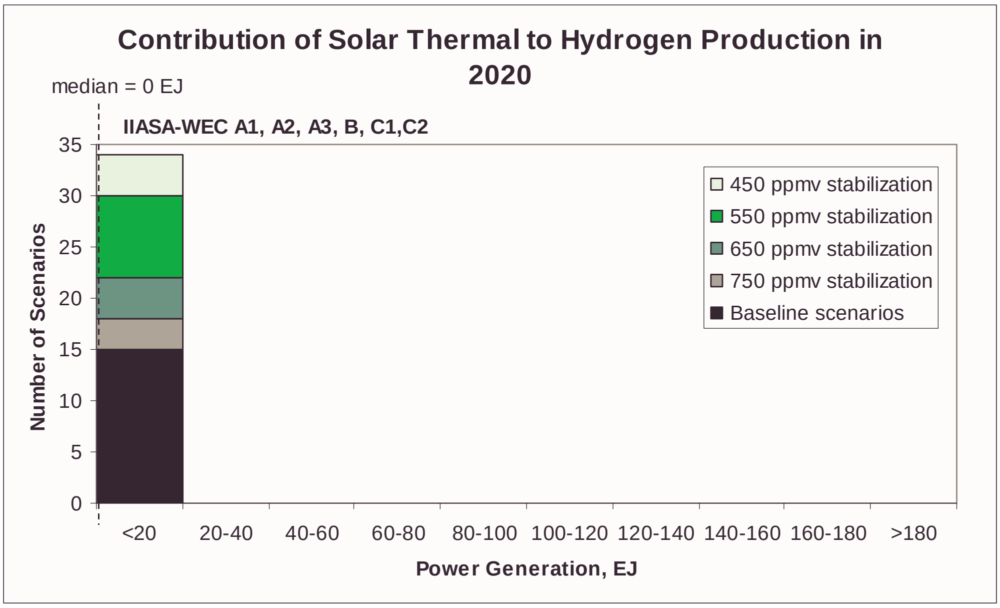

Figure A. Histogram of hydrogen production from solar thermal across scenarios in 2020.

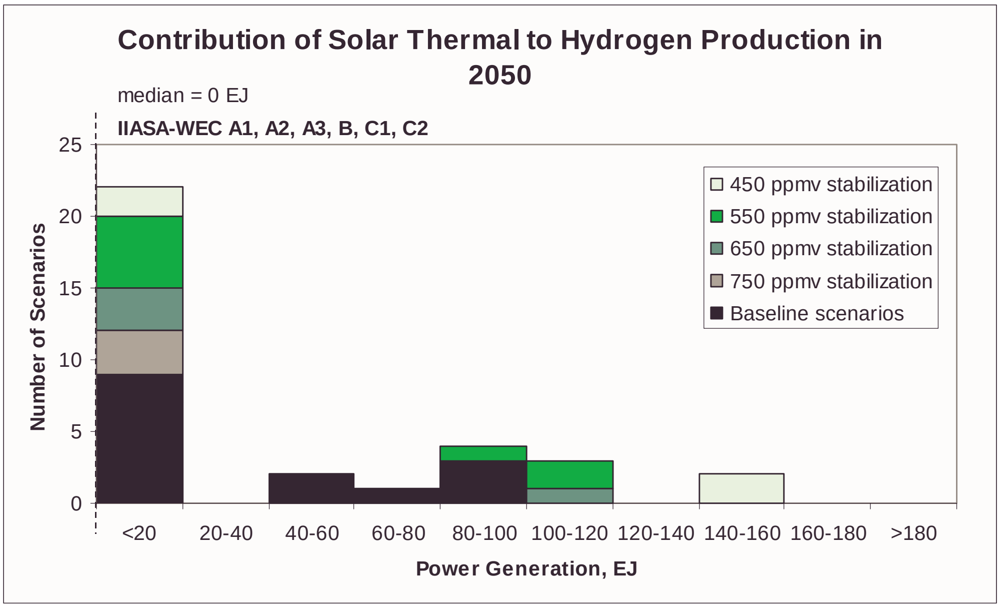

Figure B. Histogram of hydrogen production from solar thermal across scenarios in 2050.

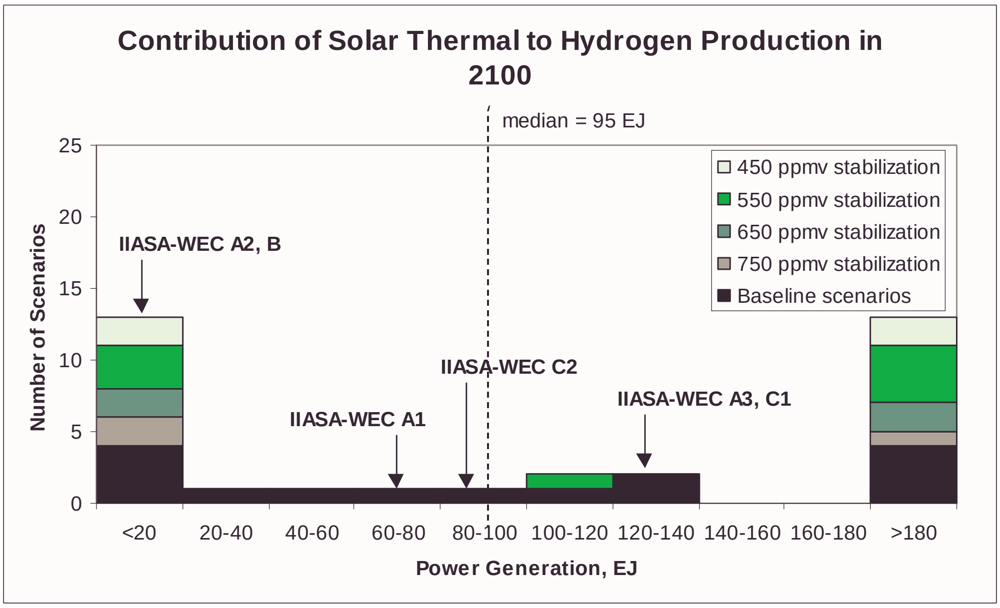

Figure C. Histogram of hydrogen production from solar thermal across scenarios in 2100.

Investment Costs for Conventional Nuclear Power Plants

Histograms of frequency distribution of the investment costs of conventional nuclear power plants across scenarios, number of scenarios (from a total of 34) and 1990 dollars per kW installed electric capacity. Figure A shows the average investment costs for two nuclear technologies, Nuc LC and Nuc HC (see Box 1) in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. After clustering during the first decades within the region of more than $1800 per kW installed electric capacity, some of the investments in 2050 in new capacity become lower extending down to $1600 per kW installed and start bifurcating into two categories with costs between $1400 to 1600 and $1800 and more per kW installed by 2100. The main exception is the IIASA-WEC A3 scenario that has substantial nuclear shares by 2100 and investment costs in between the two distribution peaks. All of the other nuclear investment costs for the IIASA-WEC scenarios fall in the upper category partially because the scale of application is not as high as in IPCC scenarios and partially because more advanced and thus costlier facilities are assumed for the latter periods.

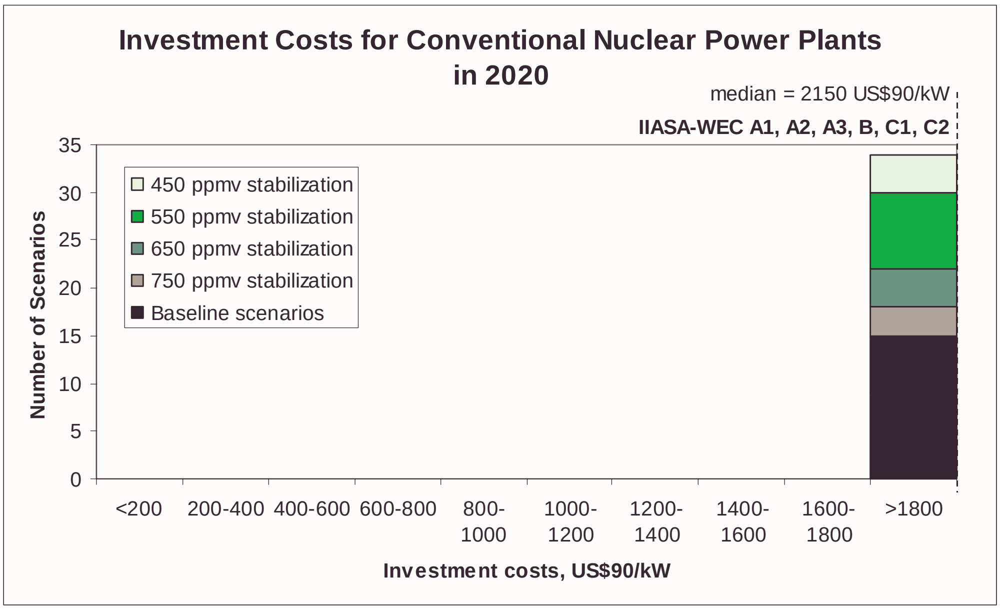

Figure A. Histogram of investment costs for conventional nuclear power plants across scenarios in 2020. Average costs for two nuclear technologies, Nuc LC and Nuc HC (see Box 1)

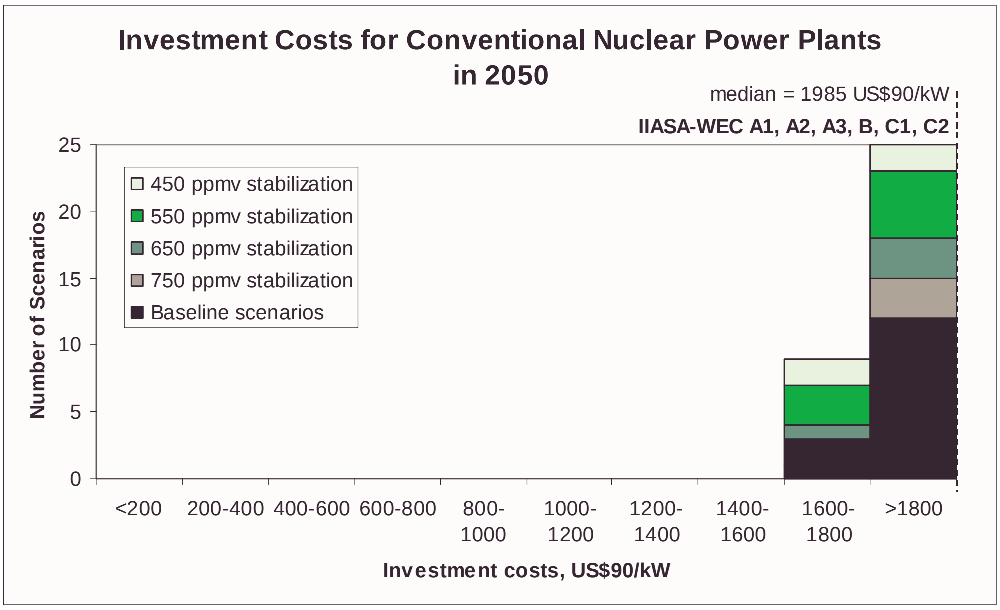

Figure B. Histogram of investment costs for conventional nuclear power plants across scenarios in 2050. Average costs for two nuclear technologies, Nuc LC and Nuc HC (see Box 1)

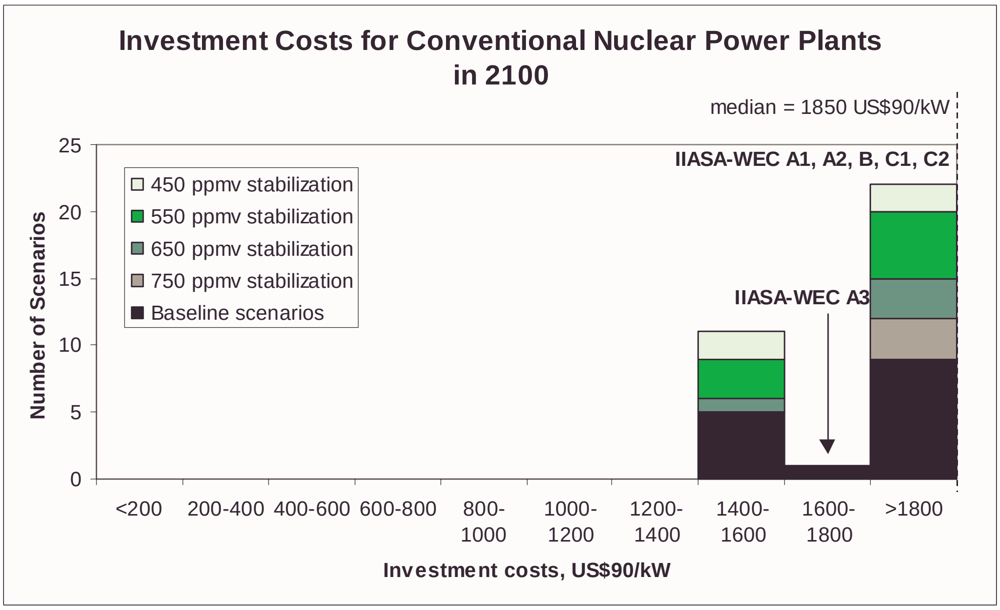

Figure C. Histogram of investment costs for conventional nuclear power plants across scenarios in 2100. Average costs for two nuclear technologies, Nuc LC and Nuc HC (see Box 1)

Investment Costs for Coal Fuel Cells

Histograms of frequency distribution of the investment costs of coal fuel cells across scenarios, number of scenarios (from a total of 34) and 1990 dollars per kW installed electric capacity. Figure A shows the investment costs in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. After clustering during the first decades within the region of more than $1800 per kW installed electric capacity, the investment costs bifurcate into two categories, one with costs between $1400 to 1600 and the other with $1800 and more per kW installed during the period from 2050 to 2100. Most of the mitigation scenarios fall within the lower cost category interval primarily because the scale of application of these technologies is higher in these scenarios leading to higher assumed rates of costs reductions.

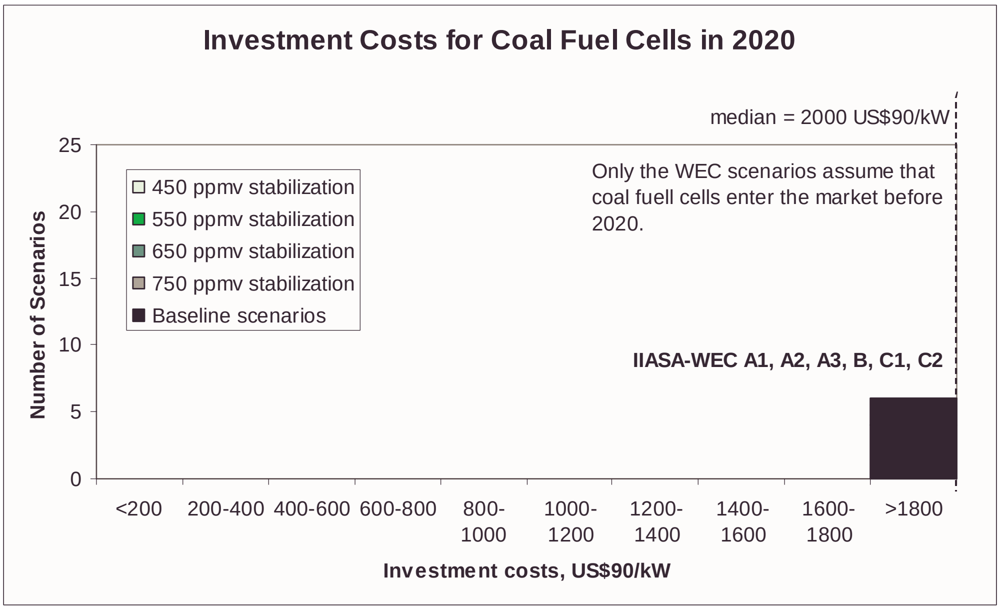

Figure A. Histogram of investment costs for coal fuel cells (Coal FC) across scenarios in 2020.

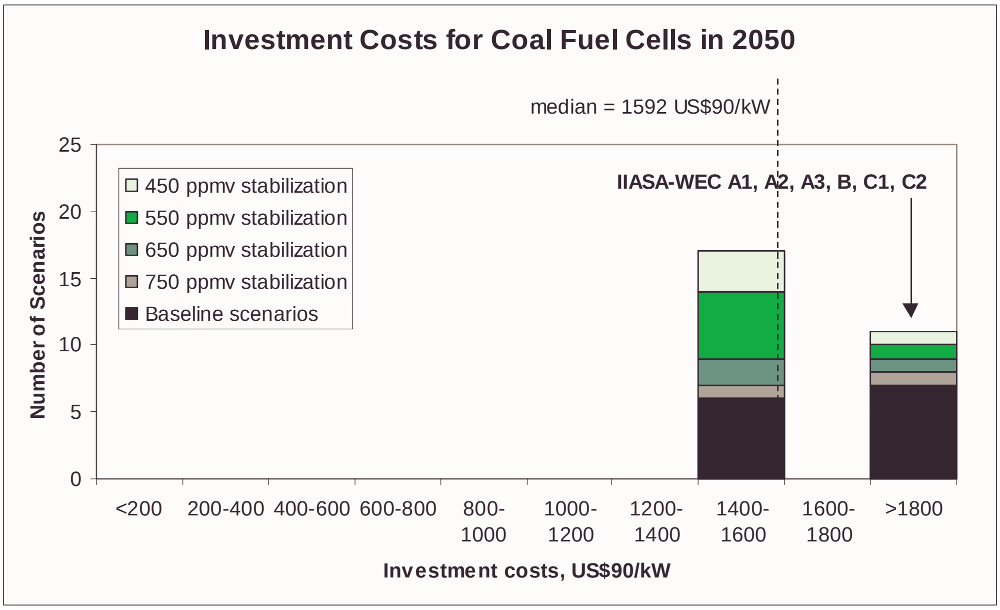

Figure B. Histogram of investment costs for coal fuel cells (Coal FC) across scenarios in 2050.

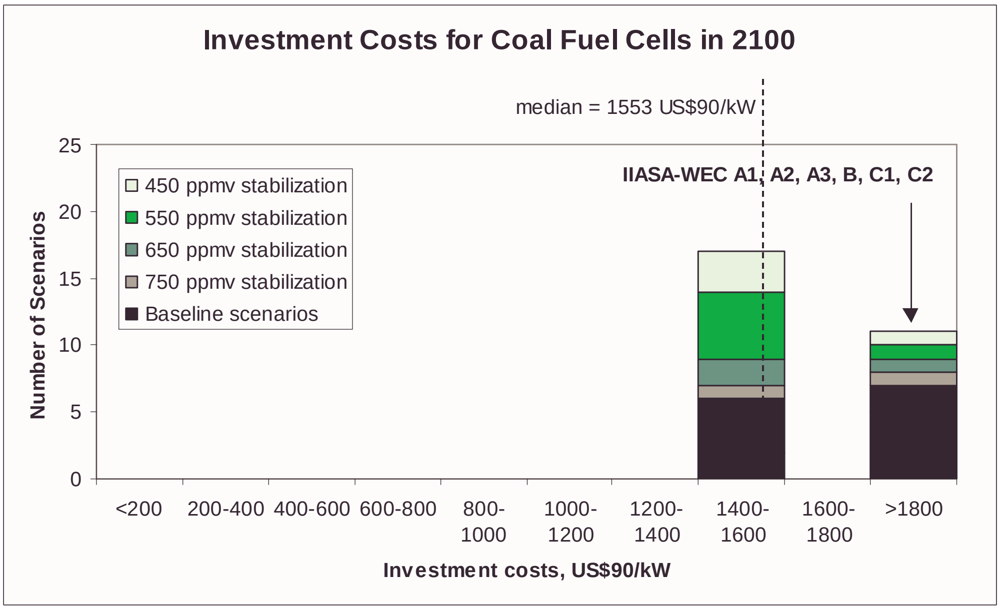

Figure C. Histogram of investment costs for coal fuel cells (Coal FC) across scenarios in 2100.

Investment Costs for Natural-Gas Fuel Cells

Histograms of frequency distribution of the investment costs of natural gas fuel cells across scenarios, number of scenarios (from a total of 34) and 1990 dollars per kW installed electric capacity. Figure A shows the investment costs in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. After clustering during the first decades within the region of between $1000 and 1200 per kW installed electric capacity, some of the investments in 2050 in new capacity become lower extending down to $800 per kW installed and start bifurcating into two categories with costs between $600 to 800 and between $1000 and 1200 per kW installed by 2100. Most of the mitigation scenarios fall within the lower cost category interval primarily because the scale of application of these technologies is higher in these scenarios leading to higher assumed rates of costs reductions. The IIASA-WEC scenarios fall in the upper category primarily because the scale of application is not as high as in IPCC scenarios.

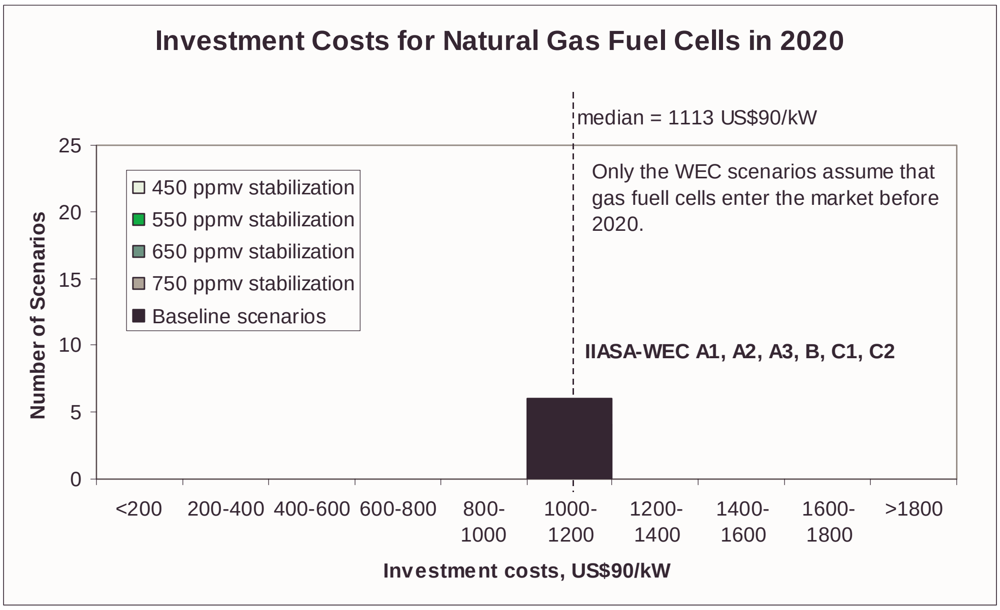

Figure A. Histogram of investment costs for natural-gas fuel cells (Gas FC) across scenarios in 2020.

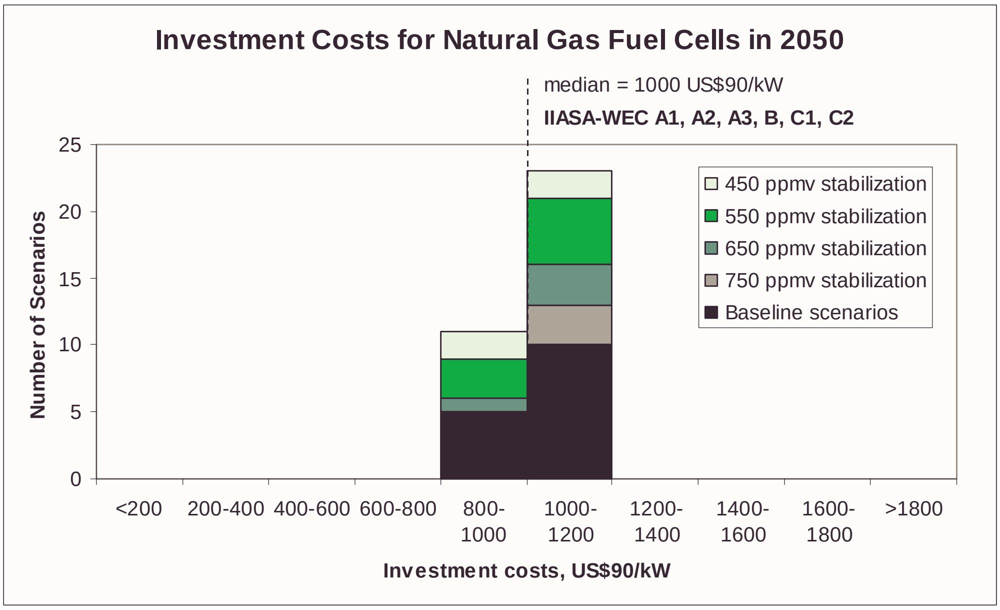

Figure B. Histogram of investment costs for natural-gas fuel cells (Gas FC) across scenarios in 2050.

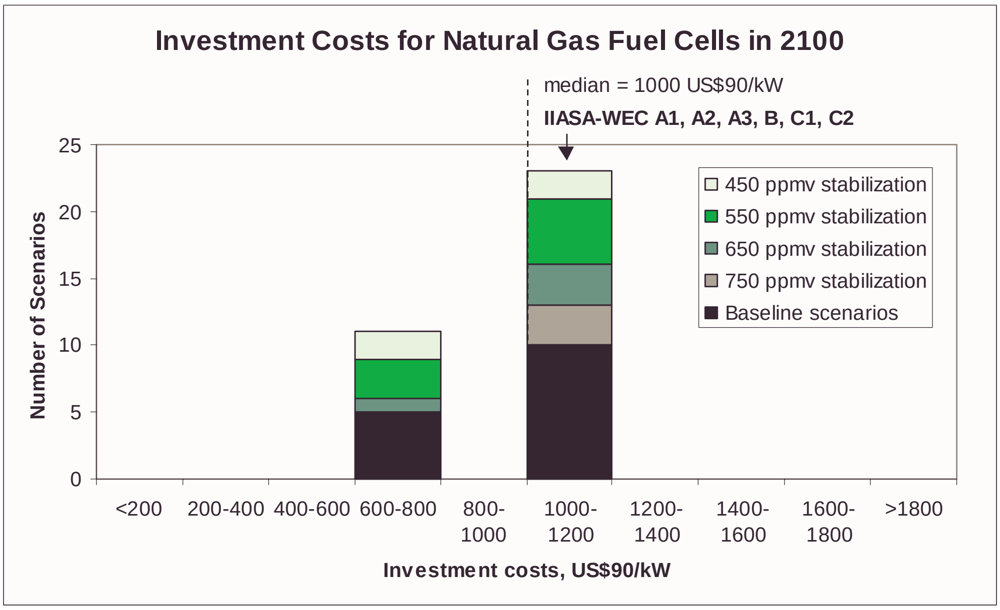

Figure C. Histogram of investment costs for natural-gas fuel cells (Gas FC) across scenarios in 2100.

Investment Costs for Conventional Coal Power Plants

Histograms of frequency distribution of the investment costs of conventional (steam cycle) coal power plants across scenarios, number of scenarios (from a total of 34) and 1990 dollars per kW installed electric capacity. Figure A shows the investment costs in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. Investment costs cluster during the whole time horizon within the region of between $1200 and 1400 per kW installed electric capacity. After 2020 the conventional steam-cycle power plants are gradually phased out in all scenarios because advanced, more efficient and cleaner, technologies become more competitive. Therefore, the installed capacities decline across the scenarios, more rapidly in the mitigation scenarios, leading to little improvement in investment costs.

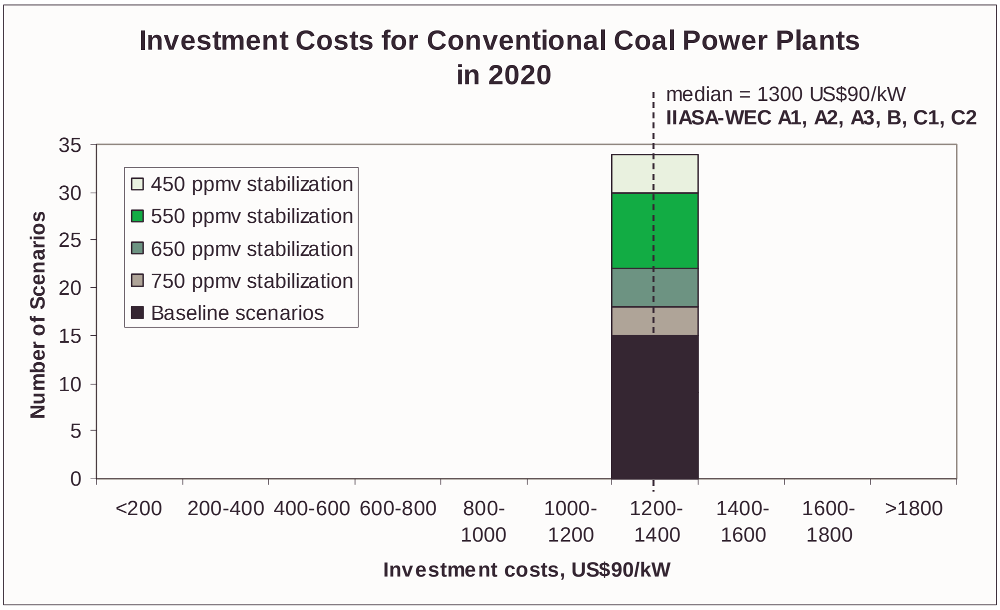

Figure A. Histogram of investment costs for conventional coal power plants (Coal Std with 90 percent FGD and 50 percent DENOX) across scenarios in 2020.

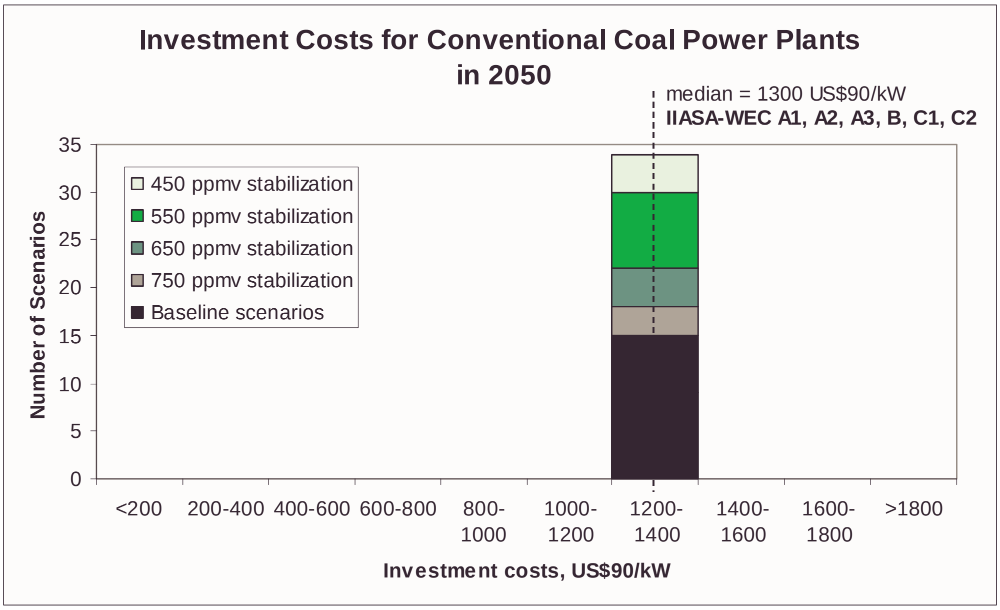

Figure B. Histogram of investment costs for conventional coal power plants (Coal Std with 90 percent FGD and 50 percent DENOX) across scenarios in 2050.

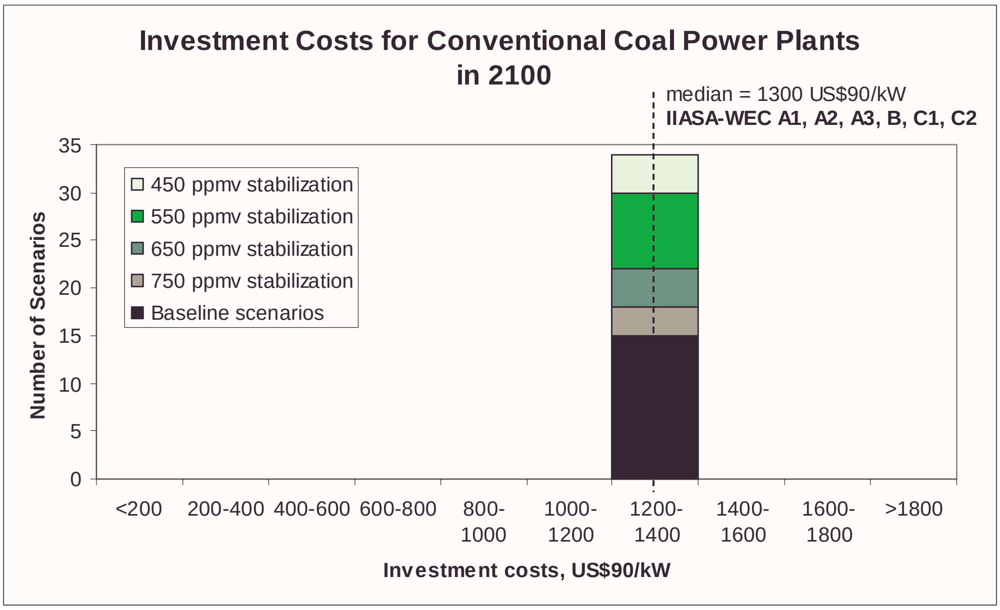

Figure C. Histogram of investment costs for conventional coal power plants (Coal Std with 90 percent FGD and 50 percent DENOX) across scenarios in 2100.

Investment Costs for Conventional Natural-Gas Power Plants

Histograms of frequency distribution of the investment costs of conventional (steam cycle) natural gas power plants across scenarios, number of scenarios (from a total of 34) and 1990 dollars per kW installed electric capacity. Figure A shows the investment costs in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. Investment costs cluster during the whole time horizon within the region of between $600 and 800 per kW installed electric capacity. After 2020 the conventional steam-cycle power plants are gradually phased out in all scenarios because advanced, more efficient and cleaner, technologies become more competitive. Therefore, the installed capacities decline across the scenarios, more rapidly in the mitigation scenarios, leading to little improvement in investment costs.

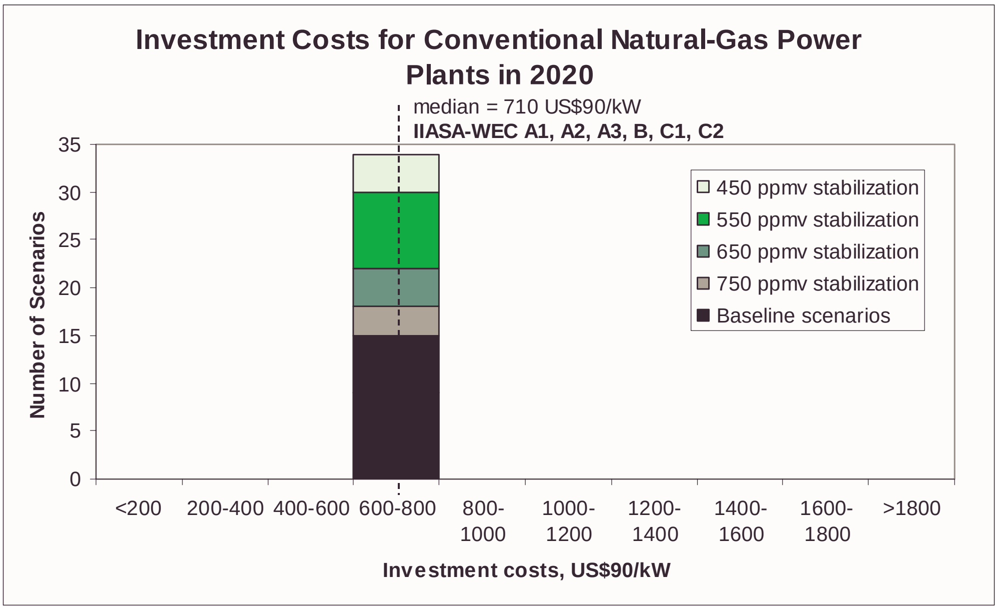

Figure A. Histogram of investment costs for conventional natural-gas power plants (Gas Std) across scenarios in 2020.

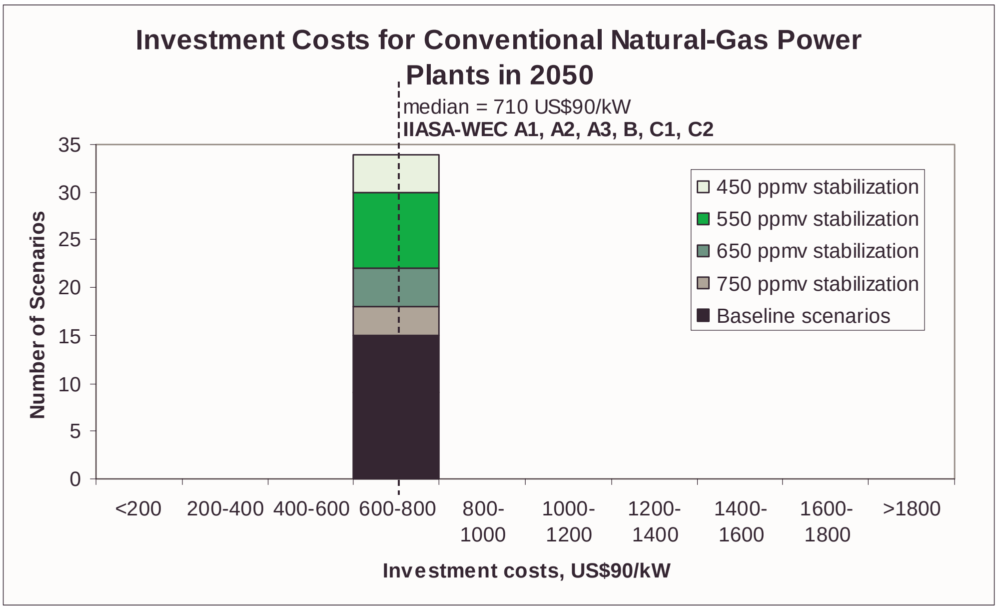

Figure B. Histogram of investment costs for conventional natural-gas power plants (Gas Std) across scenarios in 2050.

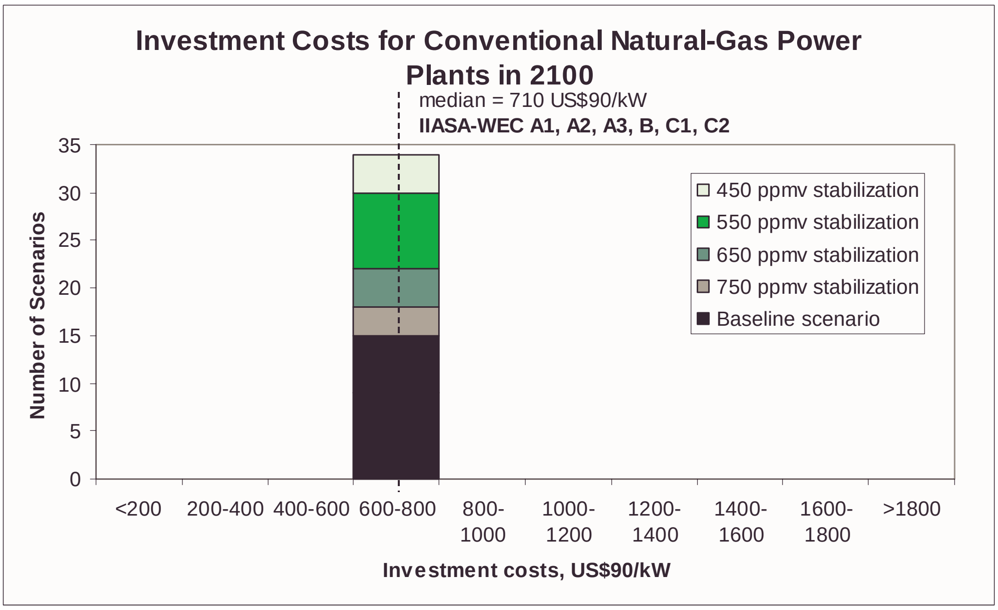

Figure C. Histogram of investment costs for conventional natural-gas power plants (Gas Std) across scenarios in 2100.

Investment Costs for Solar Photovoltaics Power Plants

Histograms of frequency distribution of the investment costs of solar photovoltaics electric generating capacity across scenarios, number of scenarios (from a total of 34) and 1990 dollars per kW installed electric capacity. Figure A shows the investment costs in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. Investment costs cluster during the whole time horizon within the category of more than $1800 per kW installed electric capacity. In fact, the median capacity costs in 2020 are substantially higher with about $2800 per kW installed. Thereafter, the costs decline in many scenarios spreading virtually across the whole range from $200 to more than $1800 per kW installed by 2100. Generally the investment costs per unit capacity decline more rapidly in the mitigation scenarios because of much higher scale of deployment. This illustrates very clearly at the scenario level the effects of increasing returns. Most of the IIASA-WEC scenarios are situated close to the median unit investment costs of about $1000 per kW installed for the period after 2050. The main exceptions are the B and A2 scenarios that are much more intensive in conventional technologies such as coal and nuclear power. Therefore, the installed capacities increase only gradually in these two scenarios, leading to little improvement in investment costs that continue to be situated in the category of $1800 and more per kW installed.

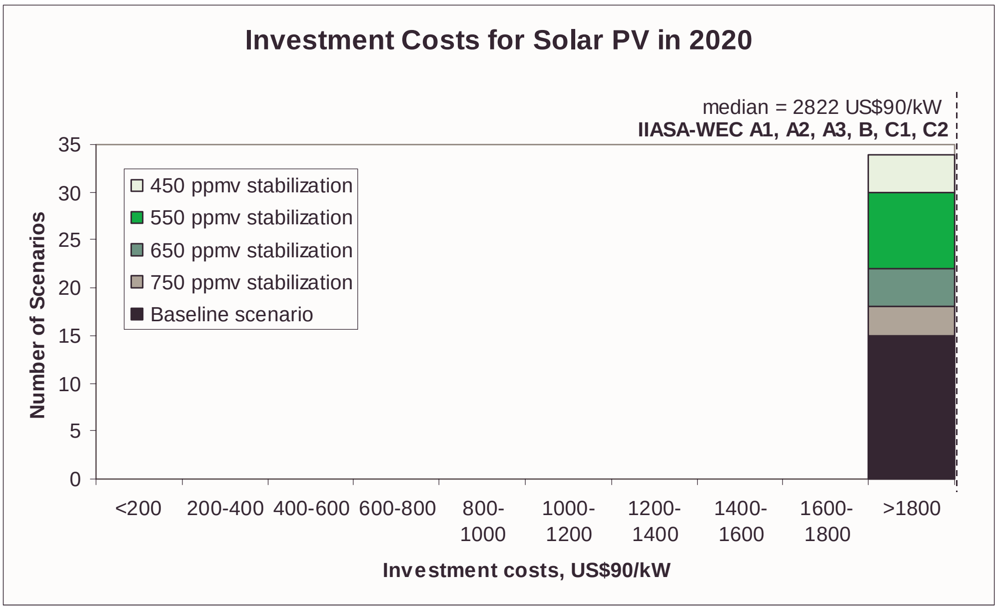

Figure A. Histogram of investment costs for solar photovoltaics power plants across scenarios in 2020.

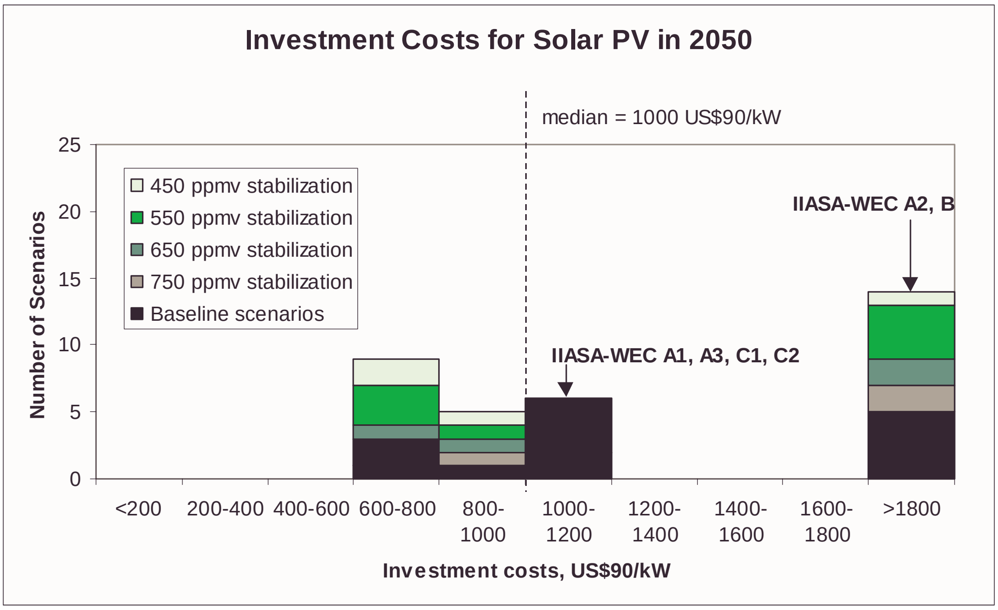

Figure B. Histogram of investment costs for solar photovoltaics power plants across scenarios in 2050.

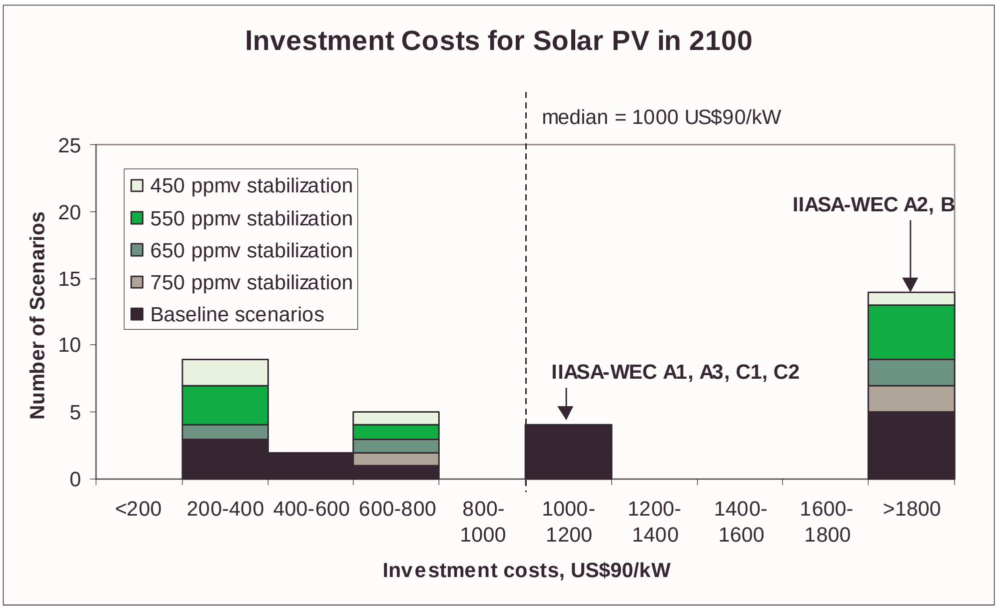

Figure C. Histogram of investment costs for solar photovoltaics power plants across scenarios in 2100.

Investment Costs for Natural-Gas Combined-Cycle Power Plants

Histograms of frequency distribution of the investment costs of natural gas combined-cycle power plants across scenarios[5], number of scenarios (from a total of 34) and 1990 dollars per kW installed electric capacity. Figure A shows the investment costs in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. Investment costs cluster during the whole time horizon. They fall between $400 and 800 per kW installed capacity in 2020. Later with substantial expansion in installed capacities across all scenarios, in some of them costs decline down to $200 per kW installed. The distribution of scenarios is fairly even across the cost categories (initially two and latter three) with IIASA-WEC scenarios also being distributed in same manner.

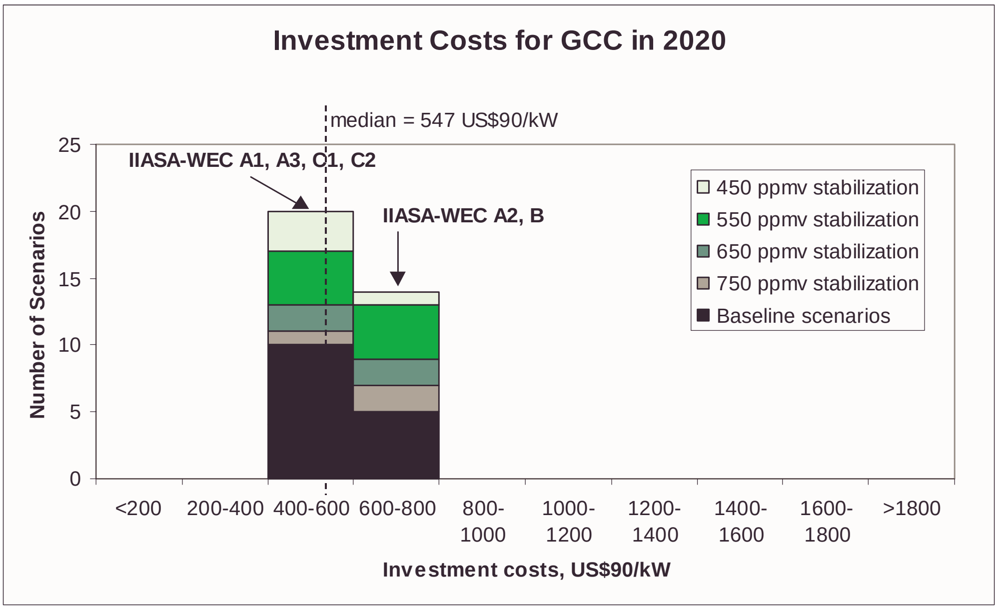

Figure A. Histogram of investment costs for natural-gas combined-cycle power plants (GCC, without carbon removal and storge) across scenarios in 2020

[5] Note that the histograms, presented in this section, do not include carbon removal or storage investment costs for natural gas combined cycle (GCC) power plants. The combined-cycle power plants with carbon removal and storage in the mitigation scenarios are assumed to have higher costs of about 20 percent.

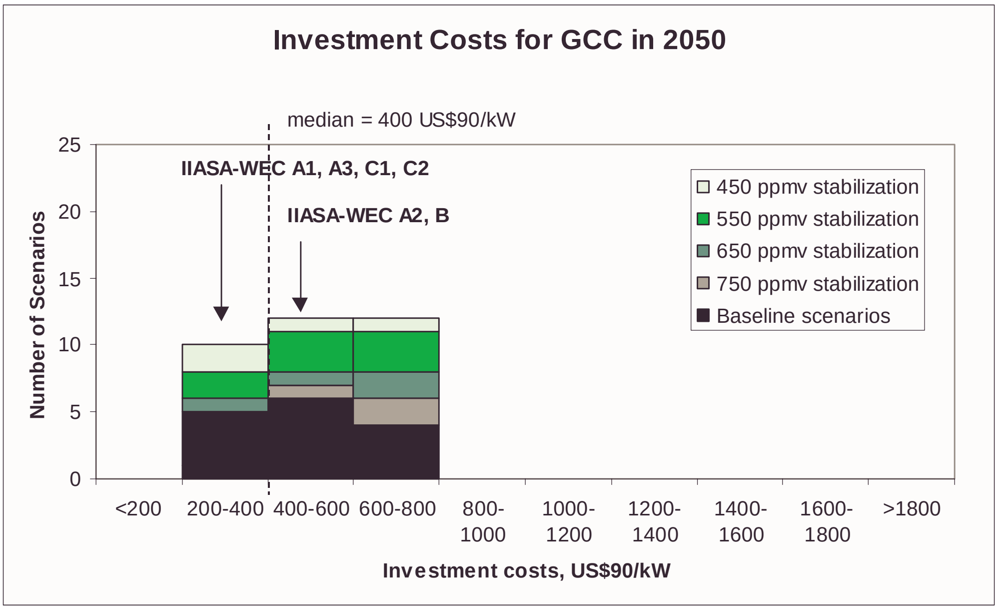

Figure B. Histogram of investment costs for natural-gas combined-cycle power plants (GCC, without carbon removal and storage) across scenarios in 2050

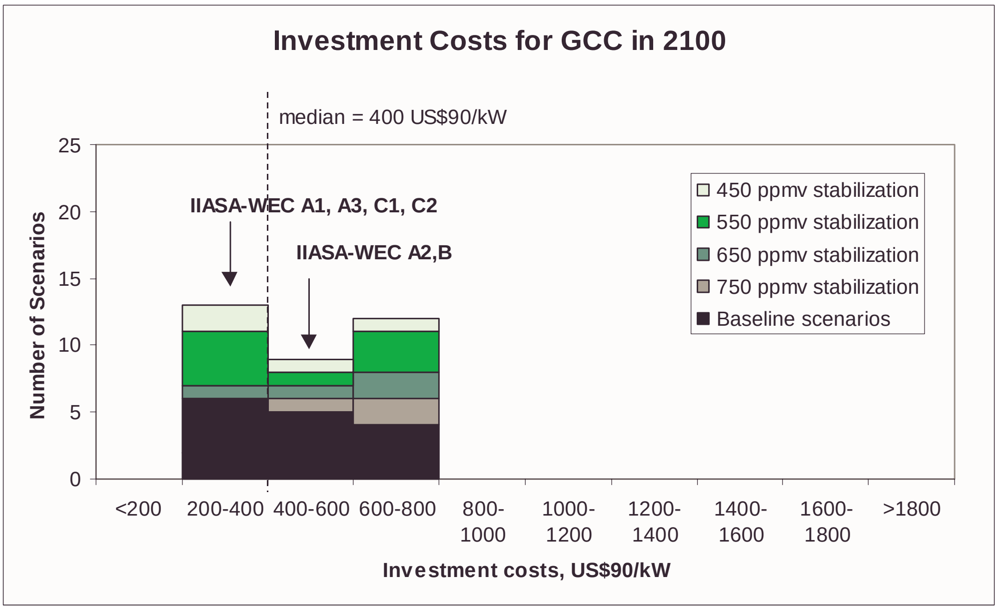

Figure C. Histogram of investment costs for natural-gas combined-cycle power plants (costs for carbon removal and storage are not included).across scenarios in 2100.

Investment Costs for Biomass Power Plants

Histograms of frequency distribution of the investment costs of biomass power plants across scenarios, number of scenarios (from a total of 34) and 1990 dollars per kW installed electric capacity. Figure A shows the investment costs in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. Investment costs cluster during the whole time horizon. They are between $1200 and 1600 per kW installed capacity in 2020 falling slightly to between $1000 and 1400 per kW installed capacity in 2050. However, the distribution remains essentially the same over this period. Later with substantial expansion in installed capacities across all scenarios, in some of them costs decline down to $800 per kW installed. The distribution of scenarios is fairly even across the cost categories (initially two and latter three) with IIASA-WEC scenarios also being distributed in same manner but with a higher mean.

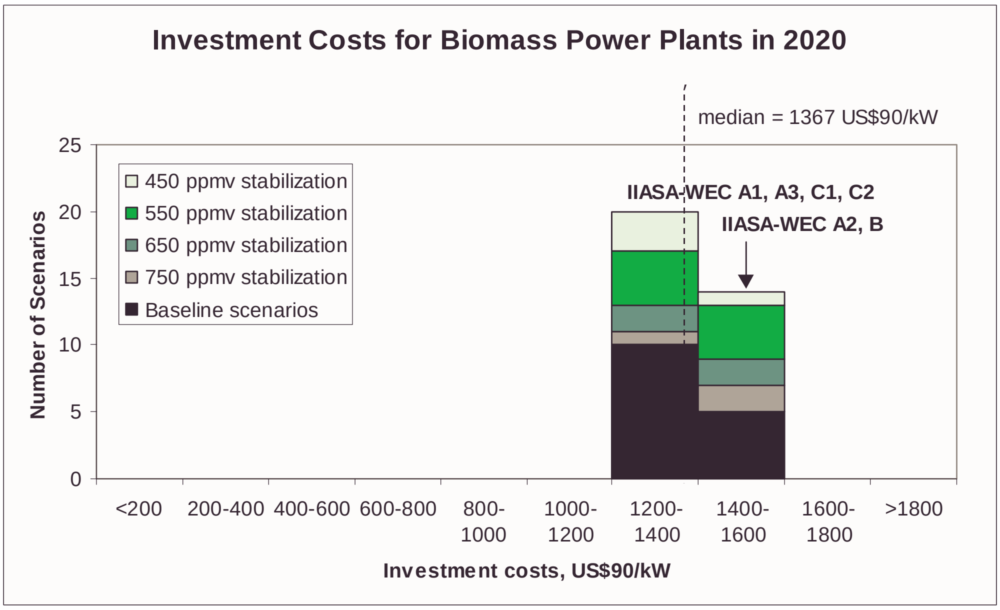

Figure A. Histogram of investment costs for biomass power plants across scenarios in 2020. Average costs for two biomass technologies, Bio STC and Bio GTC technologies (see Box 1).

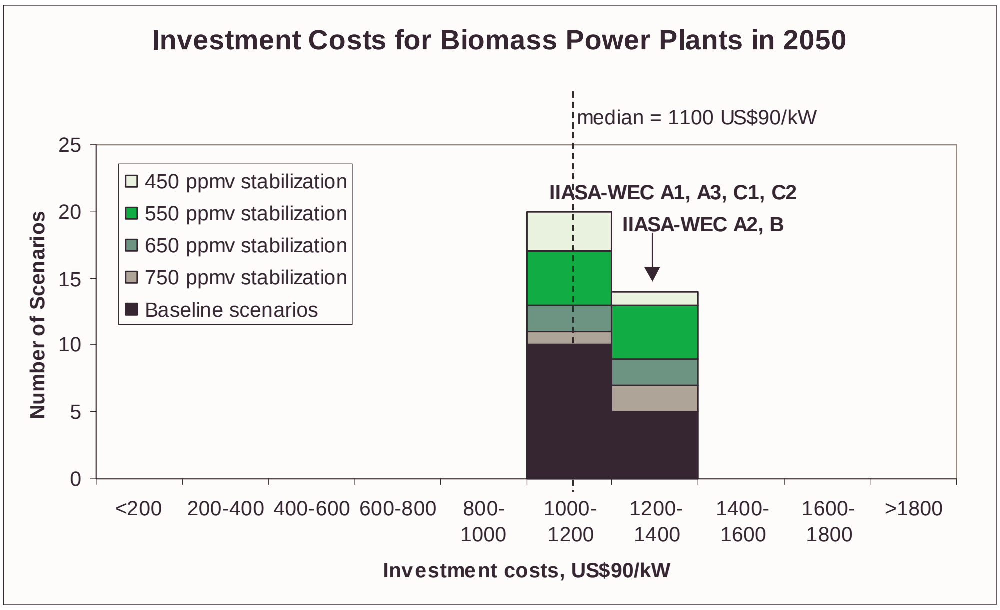

Figure B. Histogram of investment costs for biomass power plants across scenarios in 2050. Average costs for two biomass technologies, Bio STC and Bio GTC technologies (see Box 1).

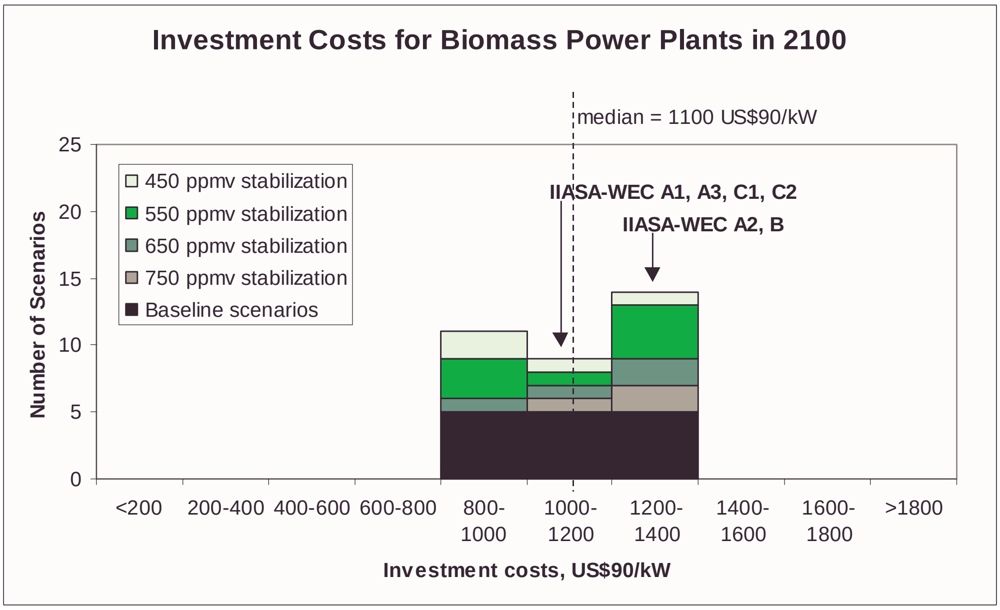

Figure C. Histogram of investment costs for biomass power plants across scenarios in 2100. Average costs for two biomass technologies, Bio STC and Bio GTC technologies (see Box 1).

Investment Costs for Wind Power Plants

Histograms of frequency distribution of the investment costs of wind power plants across scenarios, number of scenarios (from a total of 34) and 1990 dollars per kW installed electric capacity. Figure A shows the investment costs in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. Investment costs cluster during the period through 2020 between $800 and 1200 per kW installed capacity. Thereafter, the costs generally fall but the most expensive facilities still extend up to $1200 per kW installed. The scenarios also spread out extending down to $400 per kW installed by 2050 and further down to $200 per kW installed. The distribution of scenarios is fairly even across the cost categories (initially two, three by 2050 and five by 2100) with IIASA-WEC scenarios also being distributed in same manner. The distribution of mitigation and baseline scenarios is also quite even across all cost categories.

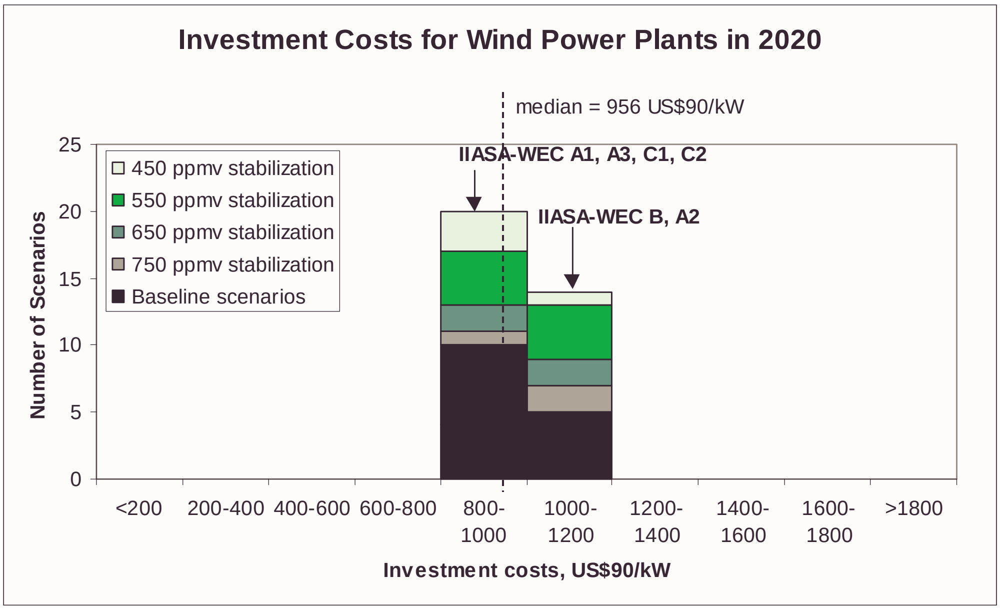

Figure A. Histogram of investment costs for wind power plants across scenarios in 2020.

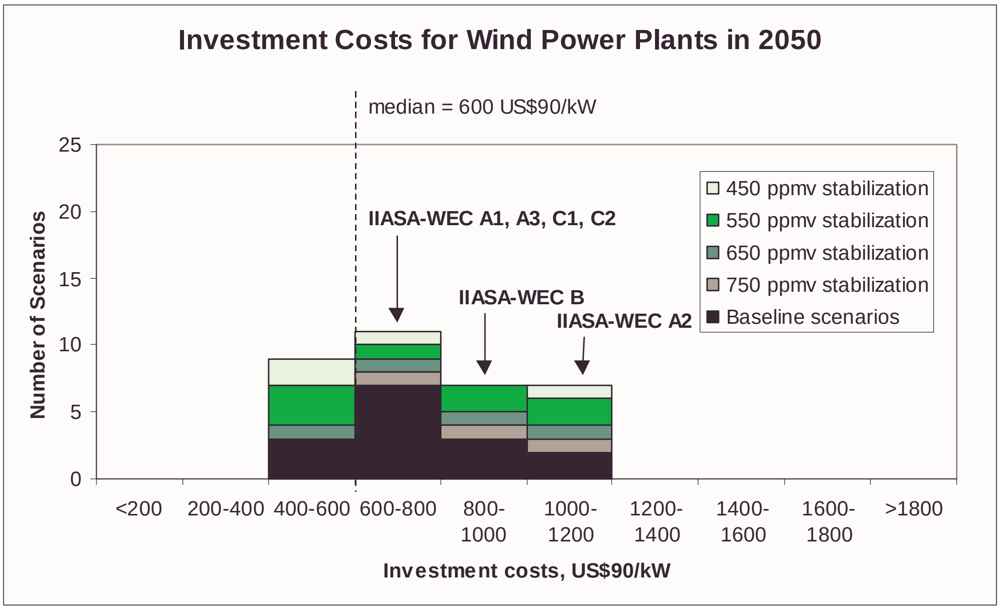

Figure B. Histogram of investment costs for wind power plants across scenarios in 2050.

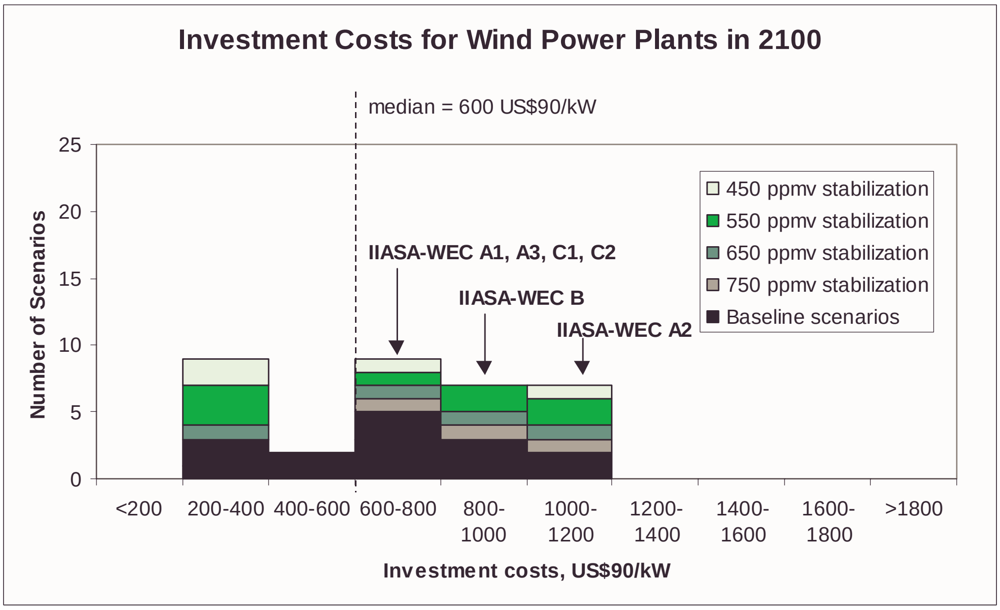

Figure C. Histogram of investment costs for wind power plants across scenarios in 2100.

Investment Cost for Hydrogen Production through Coal Gasification

Histograms of frequency distribution of the investment costs for hydrogen production through coal gasification across scenarios, number of scenarios (from a total of 34) and 1990 dollars per kW production capacity. Figure A shows the investment costs in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. Investment costs are distributed asymmetrically during the whole time horizon. They are between $800 and 1400 per kW production capacity in 2020 falling slightly to between $600 and 1400 per kW in 2050 and 2100. However, the distribution remains essentially the same over this period. There are basically three groups of scenarios, the largest is with costs in the lower ranges with the other two groups covering the higher investment cost ranges. Essentially, the two lower groups shift by one category downward leaving the interval of $1000 to 1200 per kW unoccupied. The distribution of scenarios is fairly even across the cost categories (initially two and latter three) with IIASA-WEC scenarios also being distributed in same manner. The median investment cost decline marginally from $990 per kW in 2020 to $780 per kW by 2050 and beyond. The cost reductions are quite modest because of relatively low hydrogen prediction levels from this technology over the whole time period.

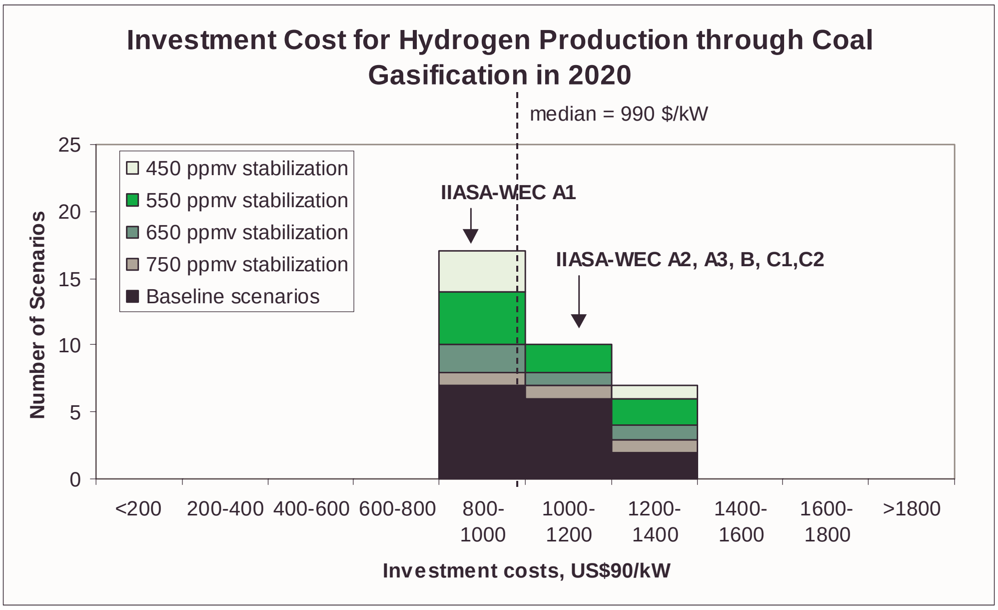

Figure A. Histogram of investment costs for hydrogen production through coal gasification across scenarios in 2020.

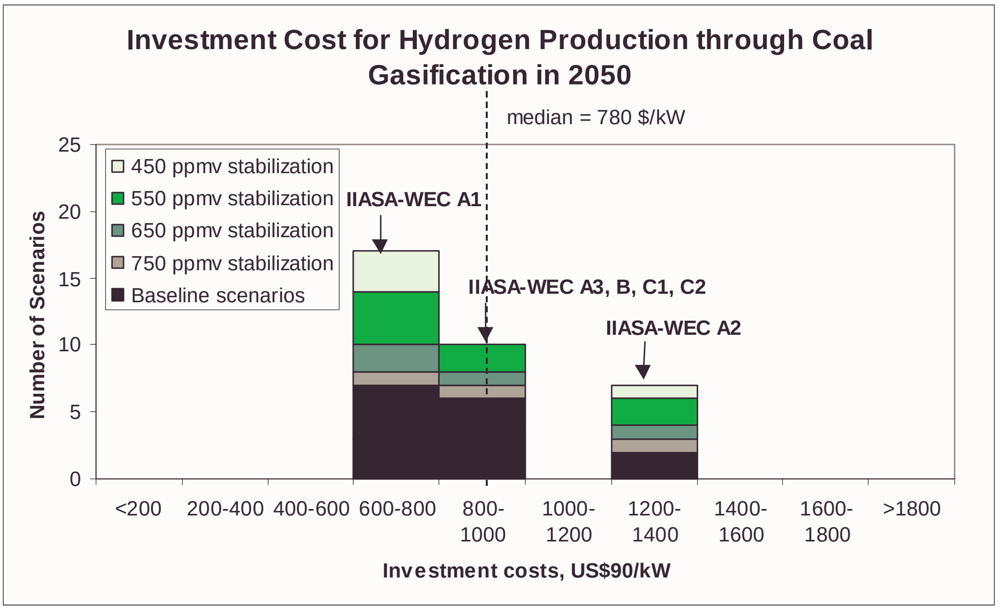

Figure B. Histogram of investment costs for hydrogen production through coal gasification across scenarios in 2050.

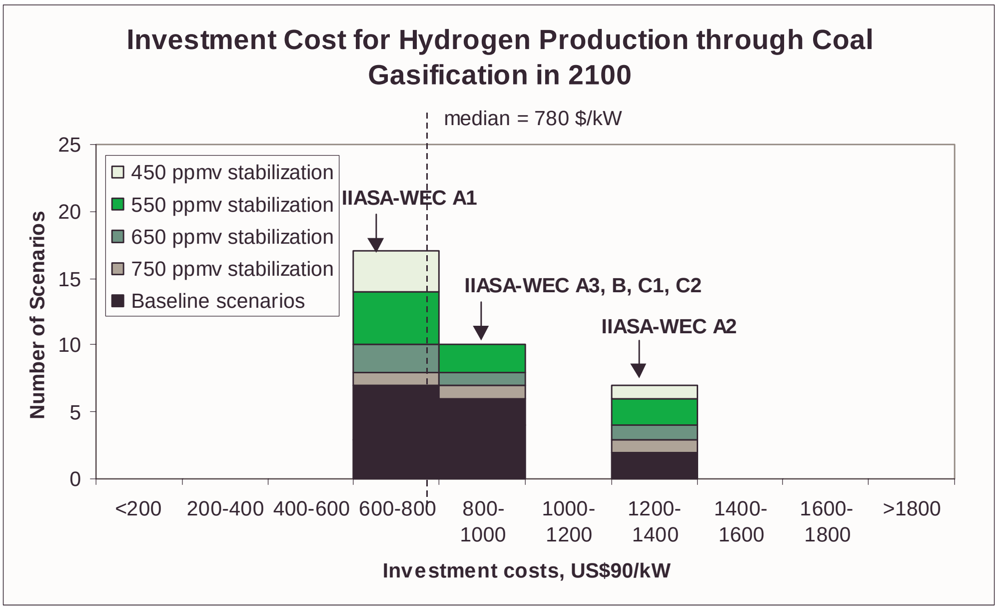

Figure C. Histogram of investment costs for hydrogen production through coal gasification across scenarios in 2100.

Investment Cost for Liquids Production from Coal

Histograms of frequency distribution of the investment costs for coal liquefaction across scenarios, number of scenarios (from a total of 34) and 1990 dollars per kW production capacity. Figure A shows the investment costs in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. Investment costs are distributed asymmetrically during the whole time horizon. They are between $1200 and 1600 per kW production capacity in 2020 falling slightly to between $1000 and 1600 per kW in 2050 and 2100. However, the distribution remains essentially the same over this period. Initially there are three groups of scenarios with majority of costs clustering between the $1200 and 1400 per kW interval. A bit more than half of these scenarios shift to the lower costs category in the subsequent periods. There are basically three groups of scenarios, the largest is with costs in the lower ranges with the other two groups covering the higher investment cost ranges. The IIASA-WEC scenarios are distributed evenly over the initial two and subsequent three groups. The median investment cost decline marginally from $1222 per kW in 2020 to $1205 per kW by 2050 and beyond. The cost reductions are quite modest because of relatively low coal liquefaction prediction levels over the whole time period.

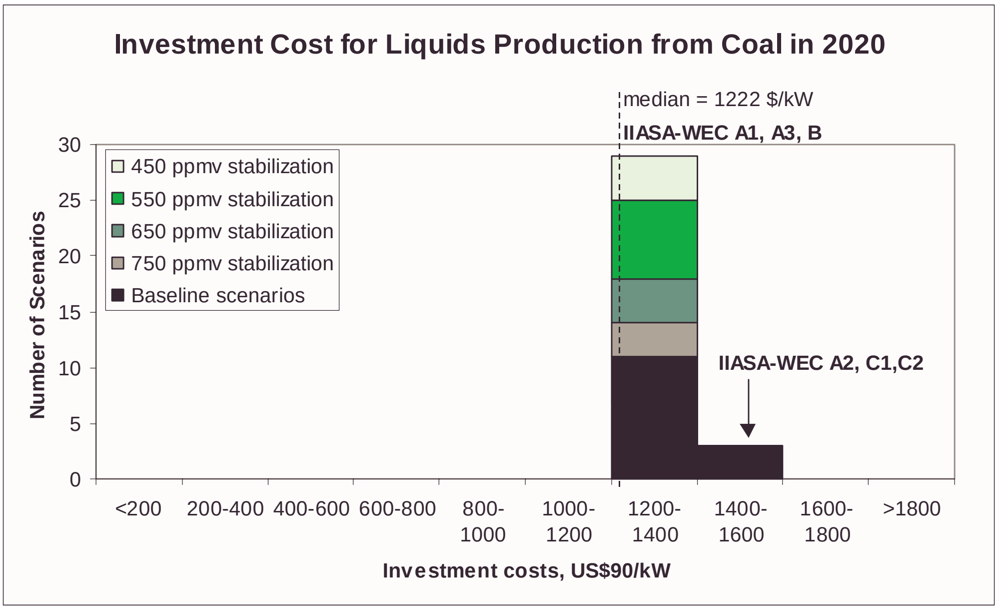

Figure A. Histogram of investment costs for coal liquefaction across scenarios in 2020.

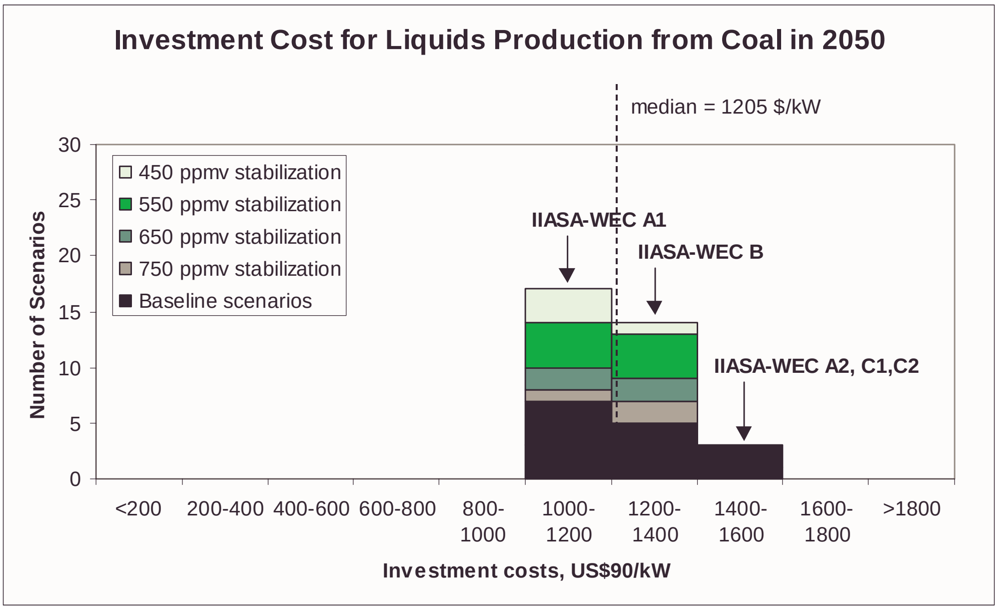

Figure B. Histogram of investment costs for coal liquefaction across scenarios in 2050.

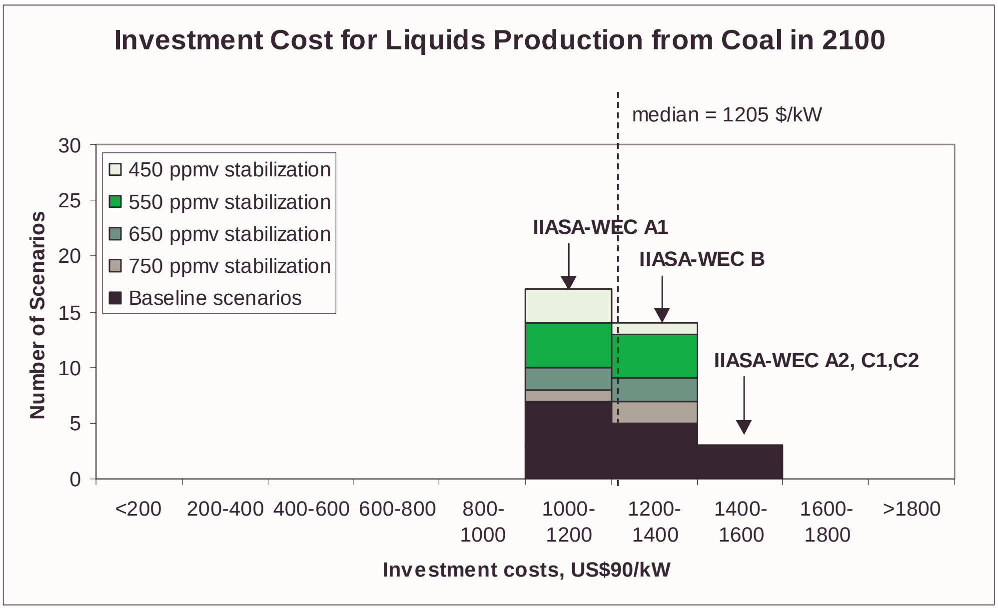

Figure C. Histogram of investment costs for coal liquefaction across scenarios in 2100.

Investment Costs for Methanol Production from Coal

Histograms of frequency distribution of the investment costs for methanol production from coal across scenarios number of scenarios (from a total of 34) and 1990 dollars per kW production capacity. Figure A shows the investment costs in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. Investment costs cluster during the whole time horizon. They are grouped within the interval of $1000 and 1400 per kW in 2020. Later with substantial expansion in production capacities across all scenarios, in some of them costs decline down to $800 per kW leaving the upper end of the distribution essentially unchanged. The distribution of scenarios is fairly even across the cost categories (initially two and later three) with IIASA-WEC scenarios also being distributed in same manner.

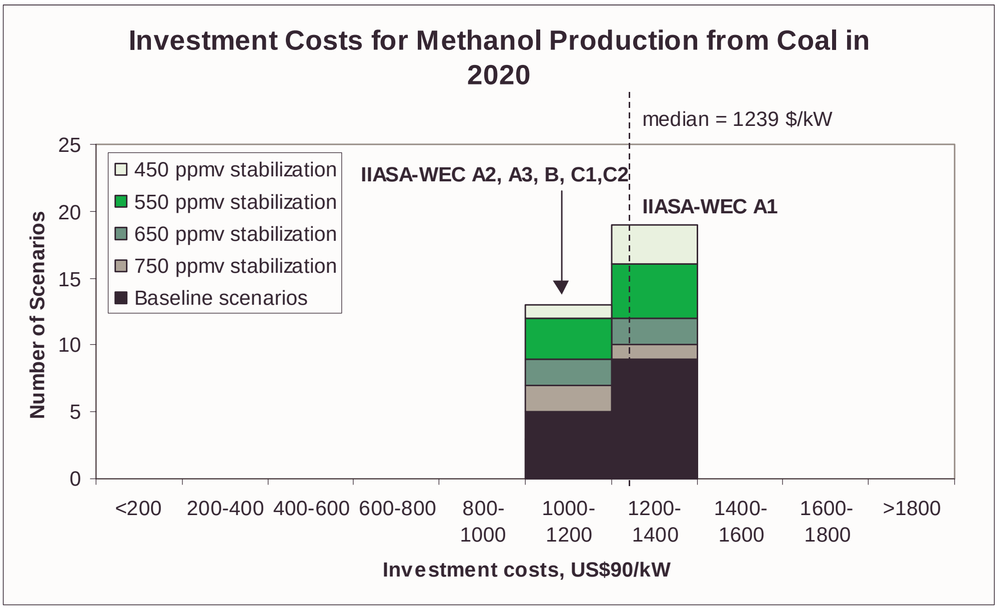

Figure A. Histogram of investment costs for methanol production from coal across scenarios in 2020.

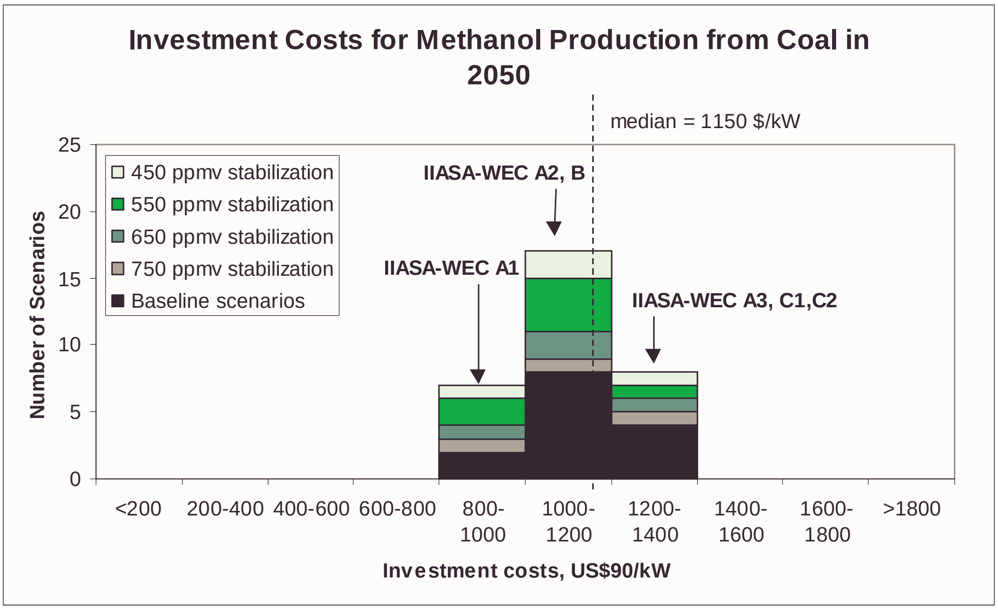

Figure B. Histogram of investment costs for methanol production from coal across scenarios in 2050.

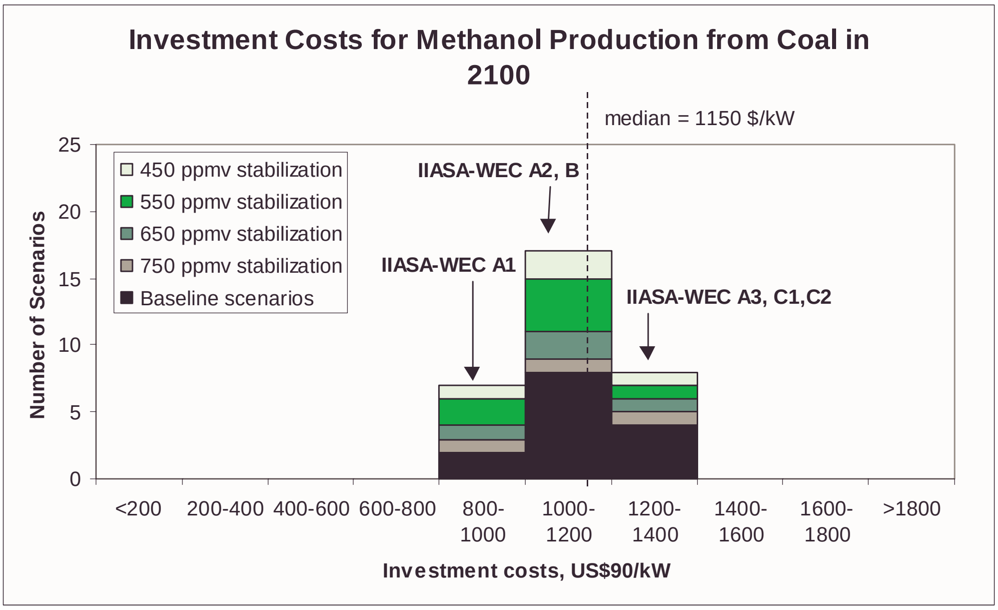

Figure C. Histogram of investment costs for methanol production from coal across scenarios in 2100.

Investment Costs for Ethanol Production from Biomass

Histograms of frequency distribution of the investment costs for ethanol production from biomass across scenarios number of scenarios (from a total of 34) and 1990 dollars per kW production capacity. Figure A shows the investment costs in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. Initially, the investment costs cluster within three cost categories ranging from $800 to 1400 per kW. They are grouped within the interval of $1000 and 1400 per kW production capacity in 2020. Thereafter, costs decline as the production of ethanol expands across the scenarios. The range also increases from $400 to 1200 per kW by 2050 and is characterized by two pronounced distribution modes. Later with substantial expansion in ethanol production, in some scenarios costs decline down to $400 per kW leaving the upper end of the distribution essentially unchanged. The distribution bifurcates by 2100 into two distinct and disconnected modes. The distribution of baseline and mitigation scenarios is fairly even across the cost categories with IIASA-WEC scenarios also being distributed in same manner. The median costs decline from more than $1200 per kW in 2020 to $1150 per kW by 2050 and beyond.

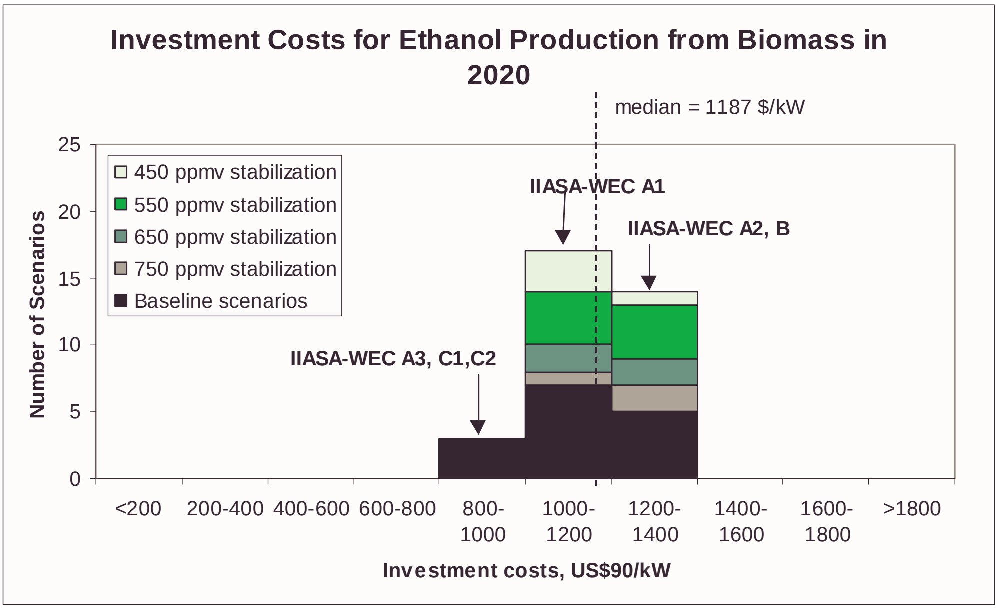

Figure A. Histogram of investment costs for ethanol production from biomass across scenarios in 2020.

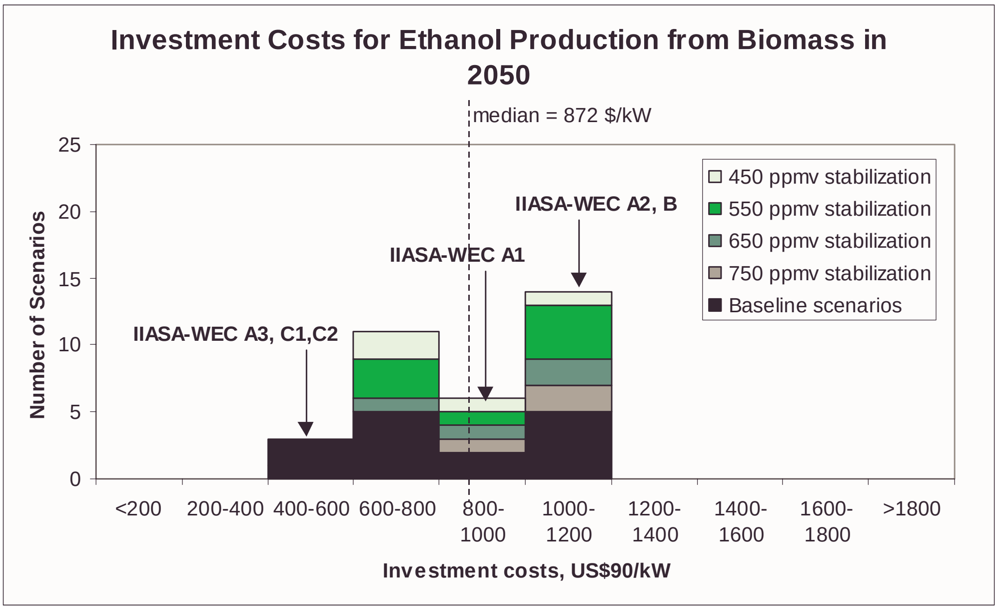

Figure B. Histogram of investment costs for ethanol production from biomass across scenarios in 2050.

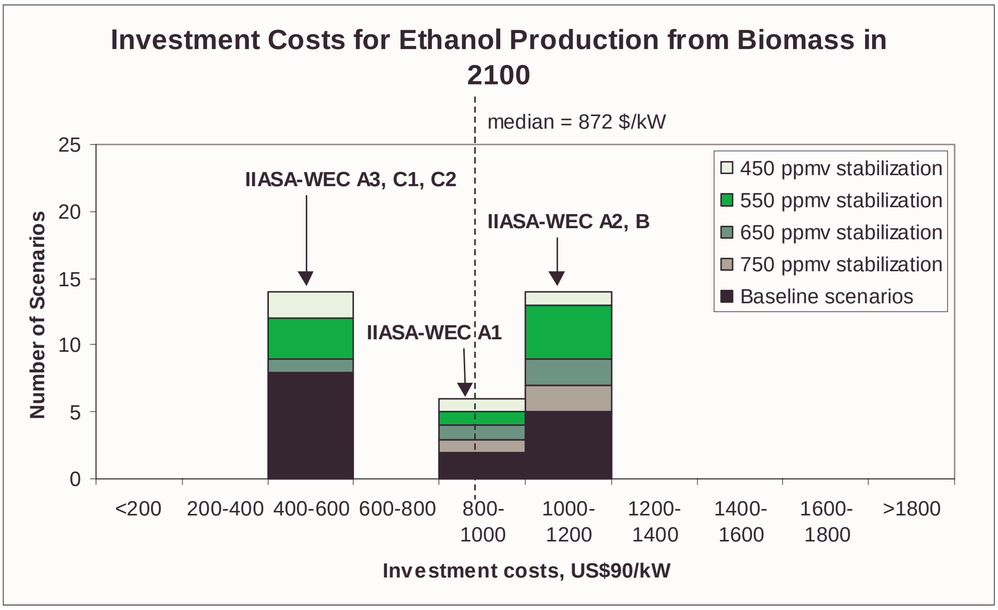

Figure C. Histogram of investment costs for ethanol production from biomass l across scenarios in 2100.

Investment Costs for Methanol Production from Natural Gas

Histograms of frequency distribution of the investment costs for methanol production from natural gas across scenarios number of scenarios (from a total of 34) and 1990 dollars per kW production capacity. Figure A shows the investment costs in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. Investment costs cluster during the whole time horizon. They are grouped within the interval of $400 and 800 per kW production capacity in 2020. Later with the expansion in production capacities across all scenarios, in two of them costs decline down to $200 per kW leaving the upper end of the distribution essentially unchanged. The distribution of scenarios is skewed with a pronounced mode in the cost interval of $400 to 600 per kW, but is fairly even across the cost categories (initially two and later three) with IIASA-WEC scenarios clustering in the cost interval of $400 to 600 per kW. The median declines from $578 per kW in 2020 to $480 per kW by 2050 and beyond.

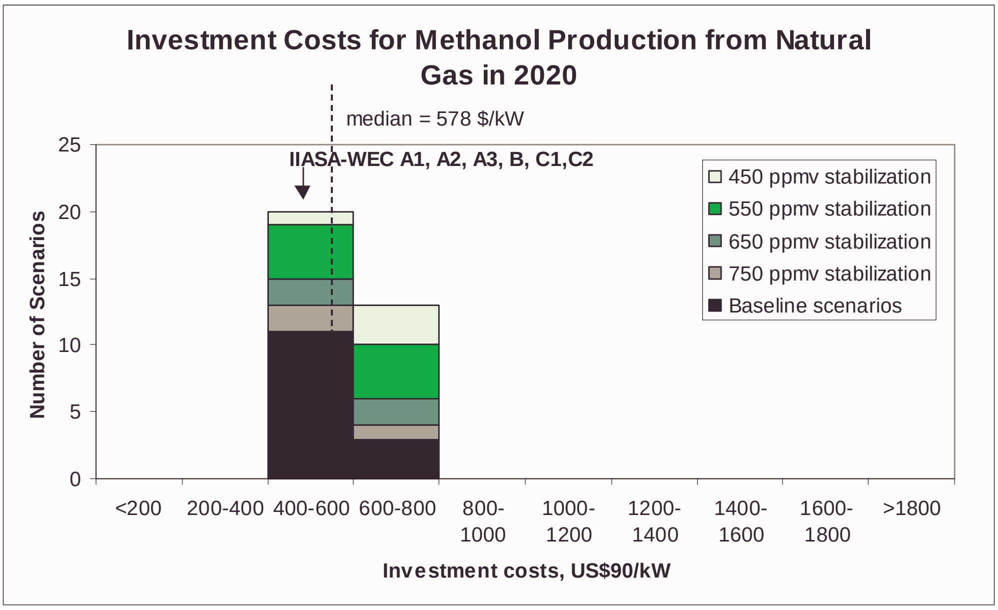

Figure A. Histogram of investment costs for methanol production from natural gas across scenarios in 2020.

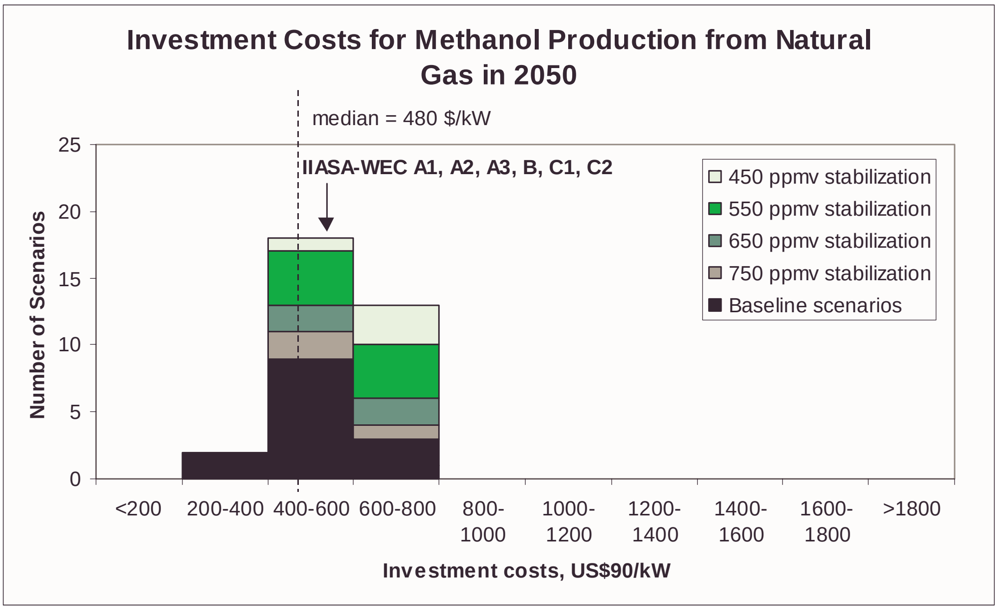

Figure B. Histogram of investment costs for methanol production from natural gas across scenarios in 2050.

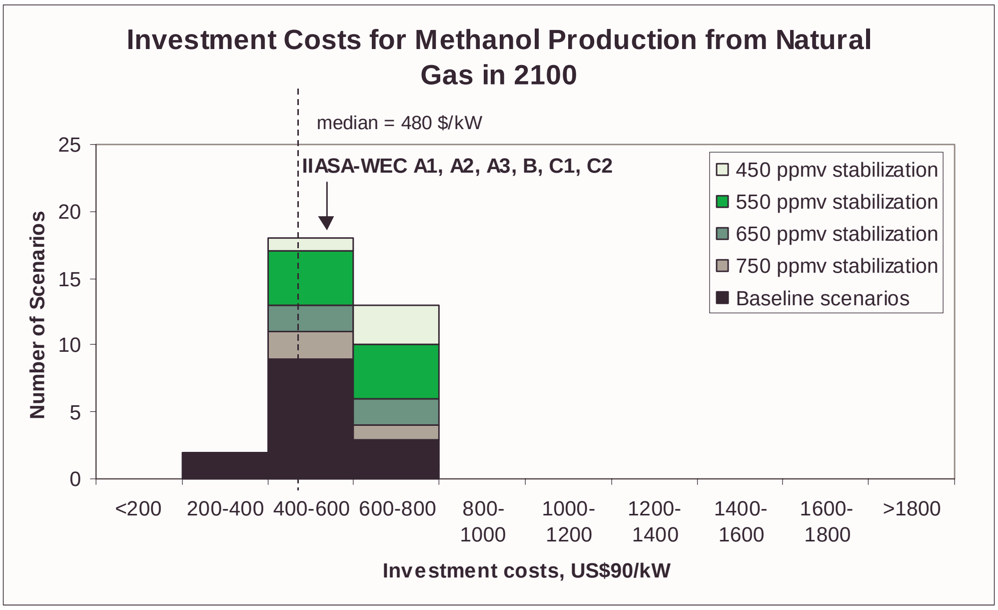

Figure C. Histogram of investment costs for methanol production from natural gas across scenarios in 2100.

Investment Costs for Syngas Production from Coal

Histograms of frequency distribution of the investment costs for syngas production from coal across scenarios number of scenarios (from a total of 34) and 1990 dollars per kW production capacity. Figure A shows the investment costs in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. Investment costs cluster during the whole time horizon. They are grouped within the interval of $600 and 1000 per kW production capacity in 2020 with a pronounced mode in the range of between $600 and 800 per kW. Later with the expansion in production capacities across all scenarios, in many of the scenarios from the first cost category ($600 to 800 per kW) costs decline down to $400 per kW leaving the upper end of the distribution essentially unchanged. The distribution of scenarios is initially skewed with a pronounced mode in the cost interval of $600 to 800 per kW. Later it becomes more symmetrical with the same mode which becomes much less pronounced. All IIASA-WEC scenarios cluster within the same interval where mode is situated except the A1 scenario that is situated in a lower cost category of $400 to 600 per kW. The median declines somewhat from $689 per kW in 2020 to $624 per kW by 2050 and beyond.

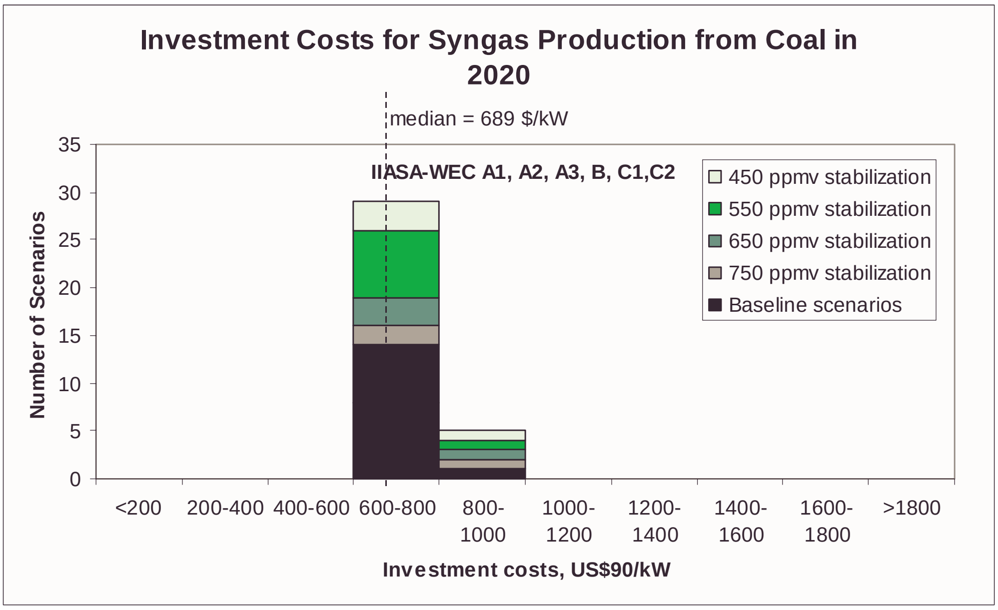

Figure A. Histogram of investment costs for syngas production from coal across scenarios in 2020.

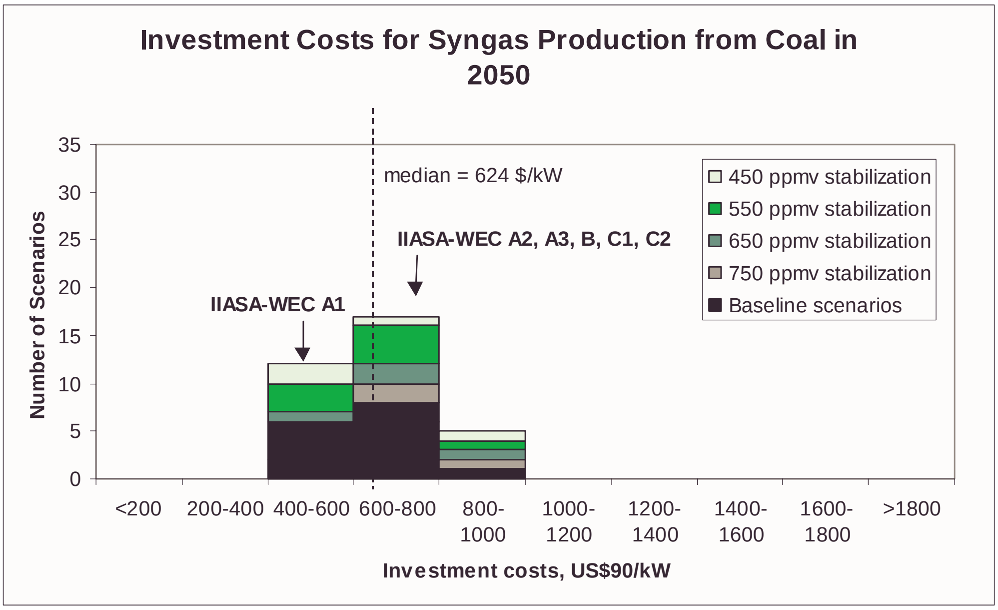

Figure B. Histogram of investment costs for syngas production from coal across scenarios in 2050.

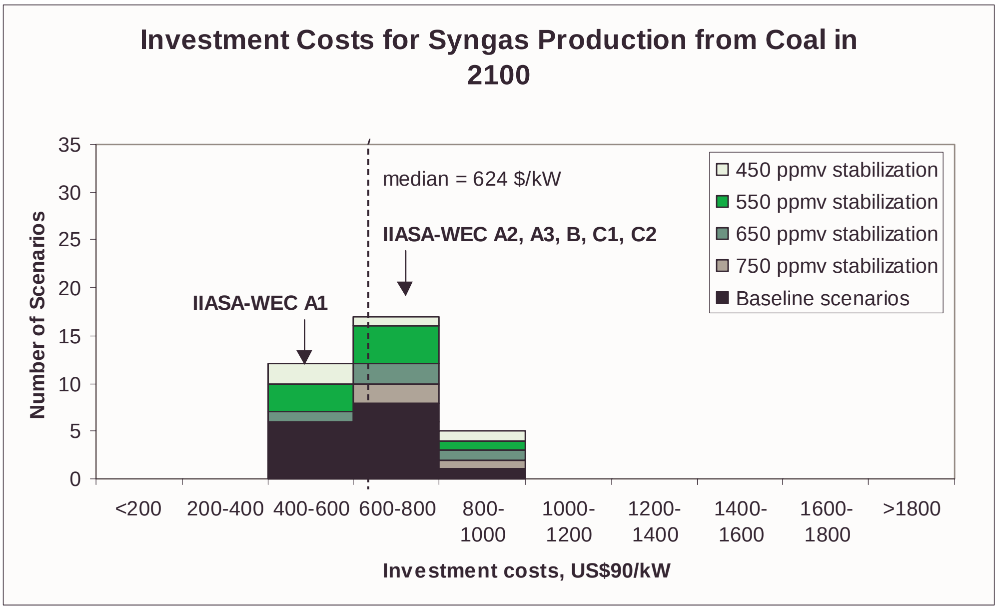

Figure C. Histogram of investment costs for syngas production from coal across scenarios in 2100.

Investment Costs for Syngas Production from Biomass

Histograms of frequency distribution of the investment costs for syngas production from biomass across scenarios number of scenarios (from a total of 34) and 1990 dollars per kW production capacity. Figure A shows the investment costs in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. Investment costs cluster during the whole time horizon. Initially, they are grouped relatively evenly within the interval of $400 and 800 per kW production capacity in 2020. Later with the expansion in production capacities in some mitigation scenarios, the clustering becomes even more focused within the lower cost category of $400 to 600 per kW. It is notable that there is this relatively narrow distribution of investment costs by 2050 and beyond. This explains to an extent why the larger utilization of syngas from biomass is limited to mitigation cases where decarbonization is another technology selection factor in addition to the costs. The median declines somewhat from $548 per kW in 2020 to $446 per kW by 2050 and beyond.

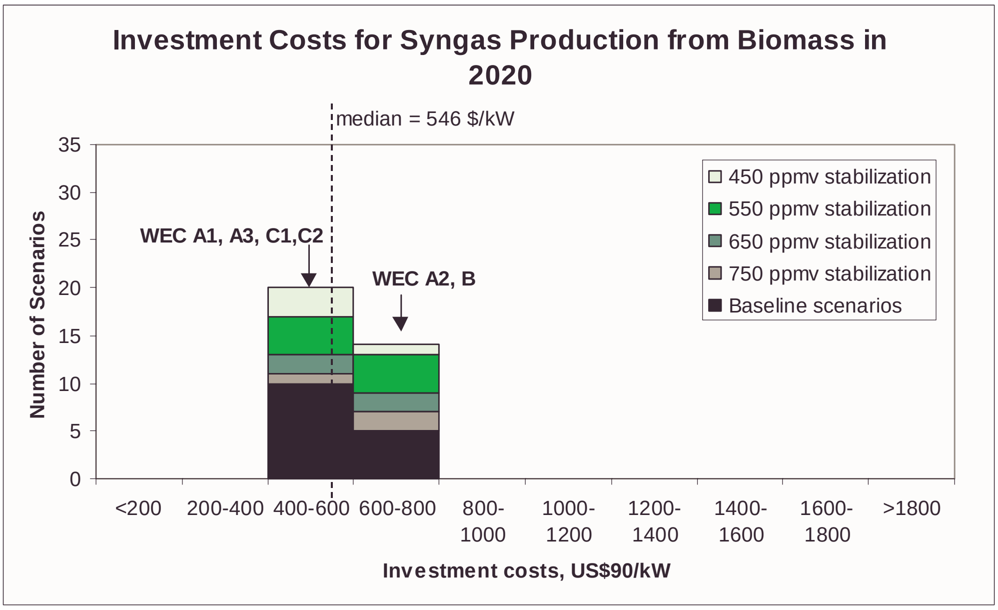

Figure A. Histogram of investment costs for syngas production from biomass across scenarios in 2020.

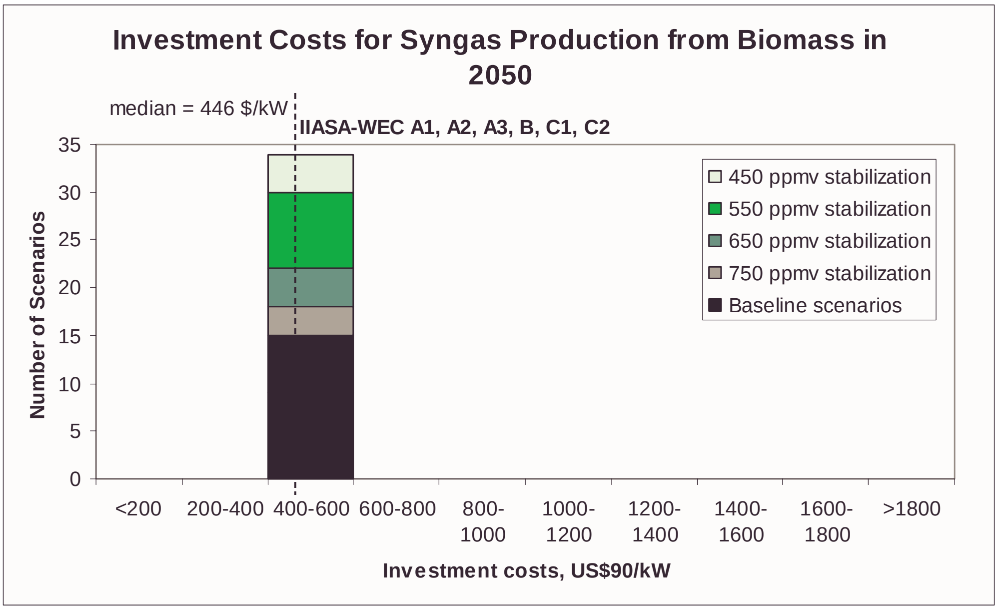

Figure B. Histogram of investment costs for syngas production from biomass across scenarios in 2050.

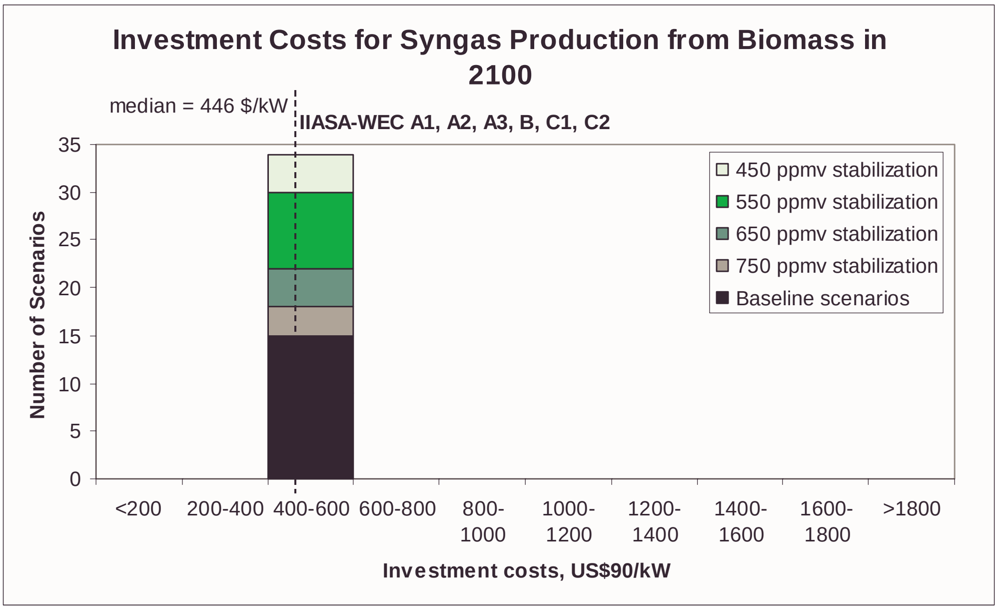

Figure C. Histogram of investment costs for syngas production from biomass across scenarios in 2100.

Investment Costs for Hydrogen Production from Natural Gas

Histograms of frequency distribution of the investment costs for hydrogen production from steam reforming of natural gas across scenarios number of scenarios (from a total of 34) and 1990 dollars per kW production capacity. Figure A shows the investment costs in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. Investment costs cluster during the whole time horizon. They are grouped within the interval of $200 and 600 per kW production capacity in 2020 and 2050. Later with the significant expansion in production capacities across many scenarios, costs decline down to less than $200 per kW leaving the upper end of the distribution unchanged. The distribution of scenarios is initially skewed with a pronounced mode in the cost interval of $200 to 400 per kW, but is fairly even across the cost categories (initially two and later three) with IIASA-WEC scenarios clustering in the cost interval of $200 to 600 per kW. The median declines from $578 per kW in 2020 to $480 per kW by 2050 and beyond.

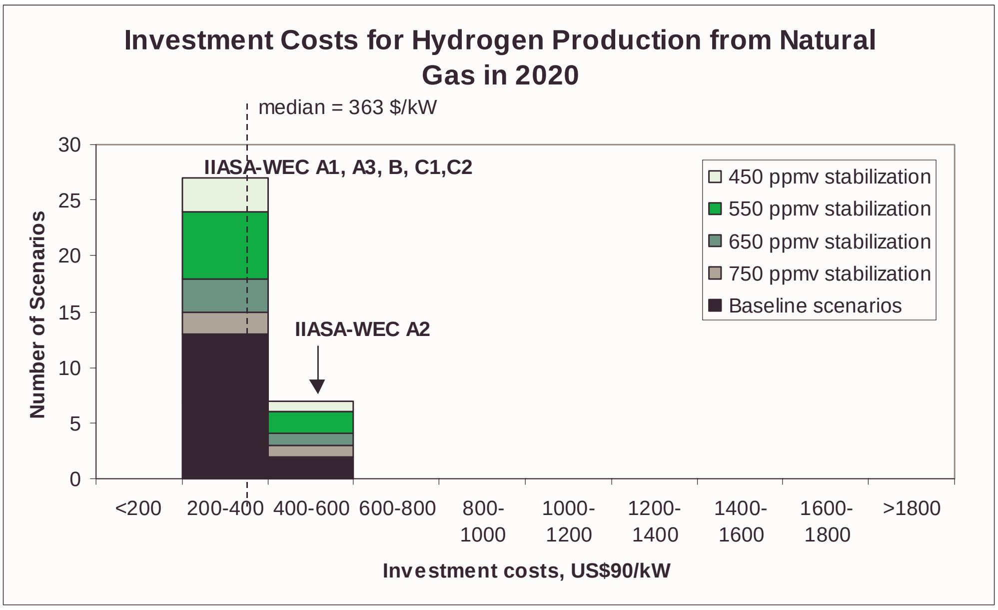

Figure A. Histogram of investment costs for hydrogen production from natural gas across scenarios in 2020.

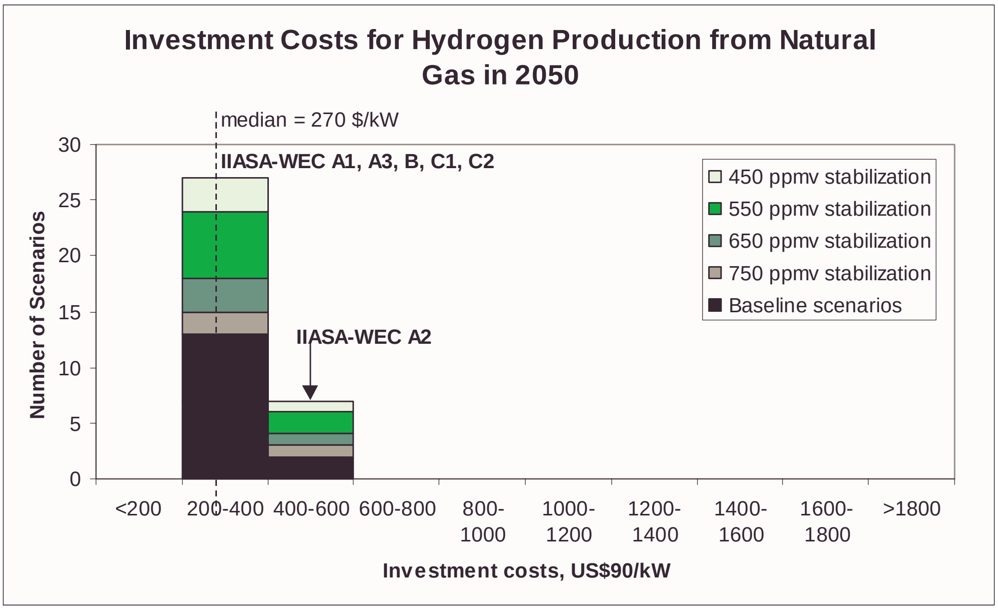

Figure B. Histogram of investment costs for hydrogen production from natural gas across scenarios in 2050.

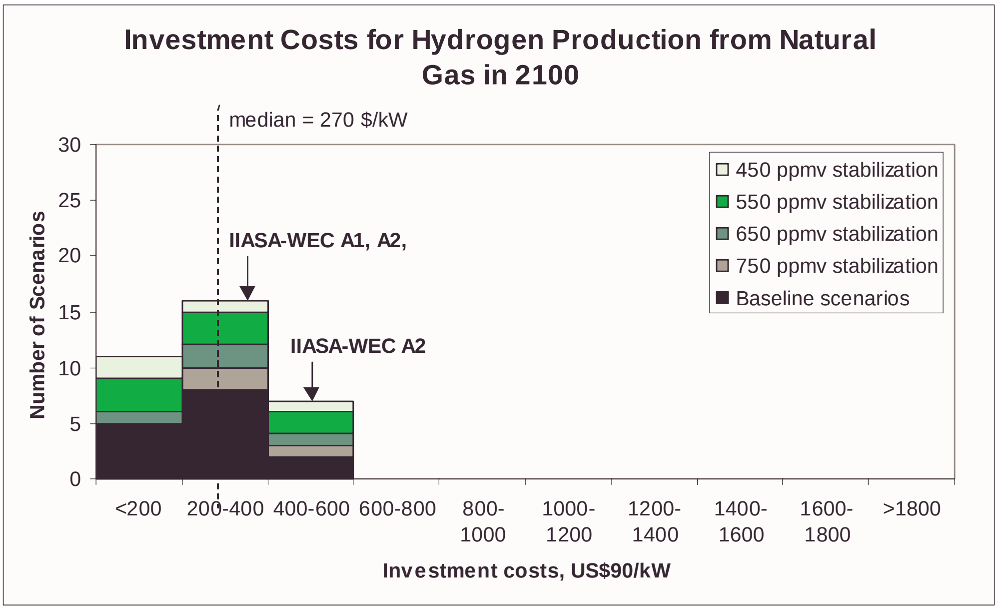

Figure C. Histogram of investment costs for hydrogen production from natural gas across scenarios in 2100.

Investment Costs for Hydrogen Production from Biomass

Histograms of frequency distribution of the investment costs for hydrogen production from biomass across scenarios number of scenarios (from a total of 34) and 1990 dollars per kW production capacity. Figure A shows the investment costs in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. Investment costs cluster during the whole time horizon. They are grouped within the interval of $600 and 1000 per kW production capacity in 2020. Later with the expansion in production capacities across some scenarios, costs decline down to less than $400 per kW leaving the upper end of the distribution unchanged. The distribution of scenarios is skewed with a pronounced mode in the cost interval of $400 to 600 per kW in 2020. The mode shifts to the lower category of between $400 to 600 per kW by 2050 and beyond. The distribution of scenarios is fairly even across the cost categories (initially two and later three) with IIASA-WEC scenarios also extending over all three cost categories.. The distribution of the scenarios remains unchanged between 2050 and 2100. The median declines from $752 per kW in 2020 to $565 per kW by 2050 and beyond.

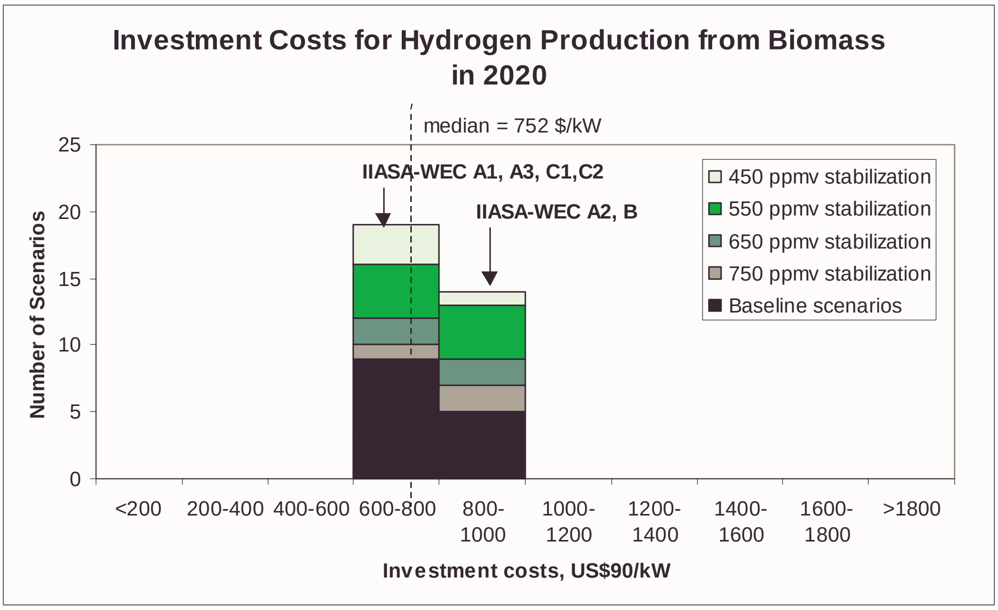

Figure A. Histogram of investment costs for hydrogen production from biomass across scenarios in 2020.

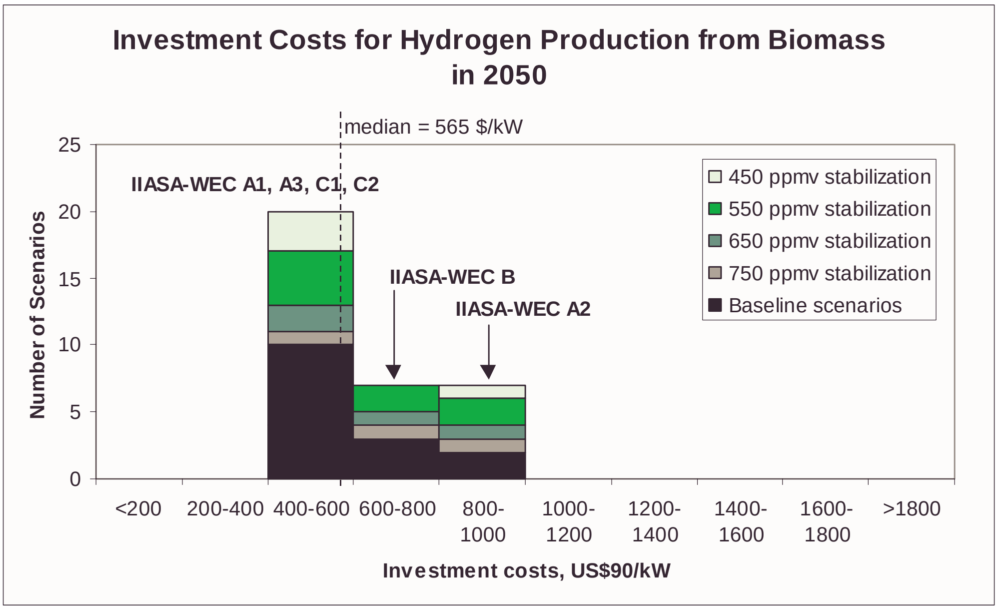

Figure B. Histogram of investment costs for hydrogen production from biomass across scenarios in 2050.

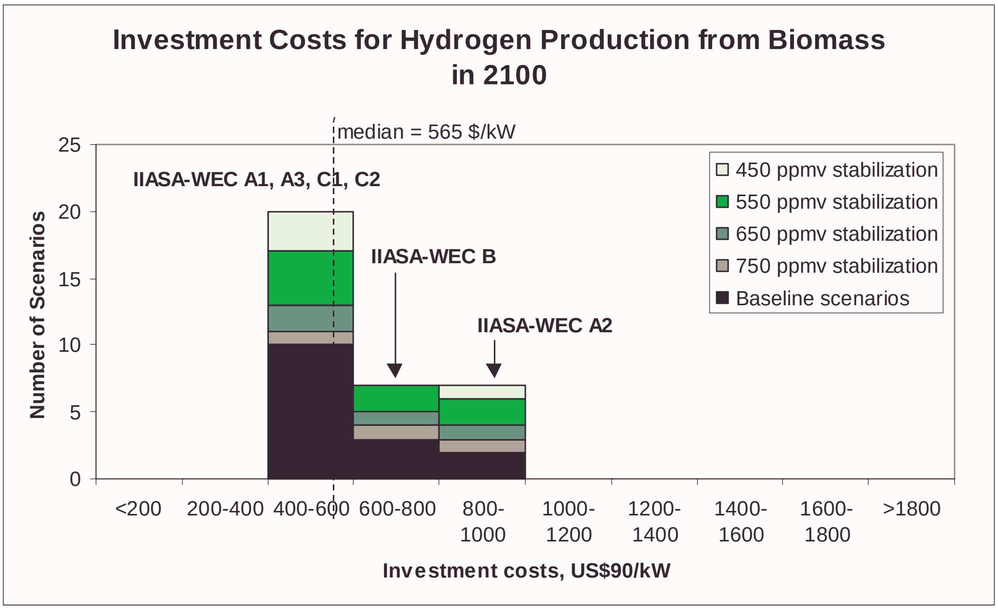

Figure C. Histogram of investment costs for hydrogen production from biomass across scenarios in 2100.

Investment Costs for Hydrogen Production from Electricity

Histograms of frequency distribution of the investment costs for hydrogen production by electrolysis across scenarios number of scenarios (from a total of 34) and 1990 dollars per kW production capacity. Figure A shows the investment costs in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. Investment costs cluster during the whole time horizon. They are grouped within the interval of $200 and 600 per kW production capacity in 2020 and 2050. The scenario distributions are marked with pronounced modes both in 2020 and 2050, but with complete asymmetry reversal. The mode is in the interval of $400 to 600 per kW in 2020 and in the interval $200 to 400 per kW in 2050. This reversal of the asymmetric distributions reduces the median value from $428 in 2020 to $380 per kW in 2050. The expansion of electrolysis is negligible also in the following periods through 2100. Nevertheless, investment costs decline in some of the scenarios making the distribution almost completely symmetrical by 2100. The distribution of scenarios is fairly even across the cost categories (initially two and later three) with IIASA-WEC scenarios also extending over all higher two cost categories.

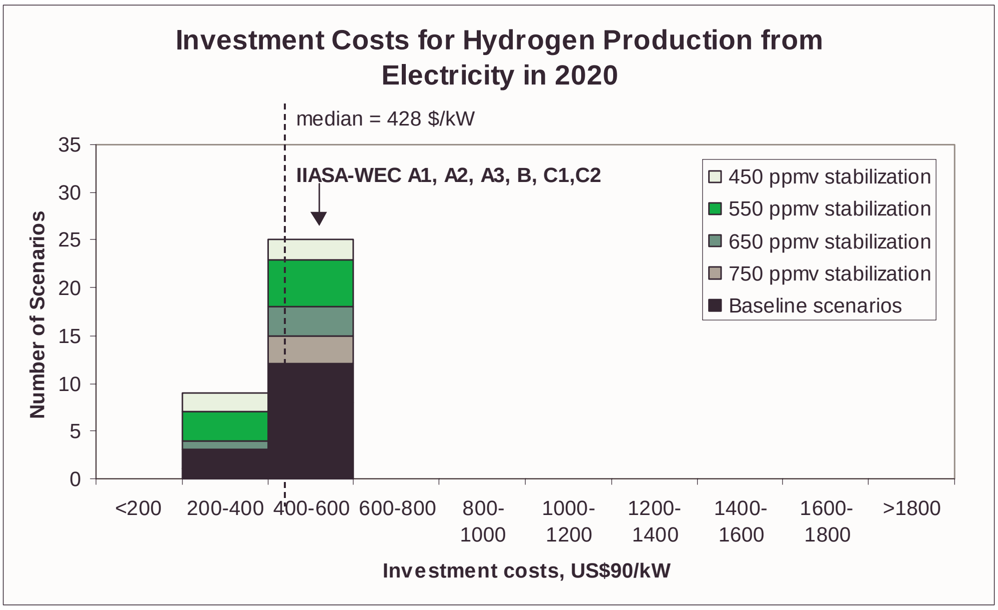

Figure A. Histogram of investment costs for hydrogen production by electrolysis across scenarios in 2020.

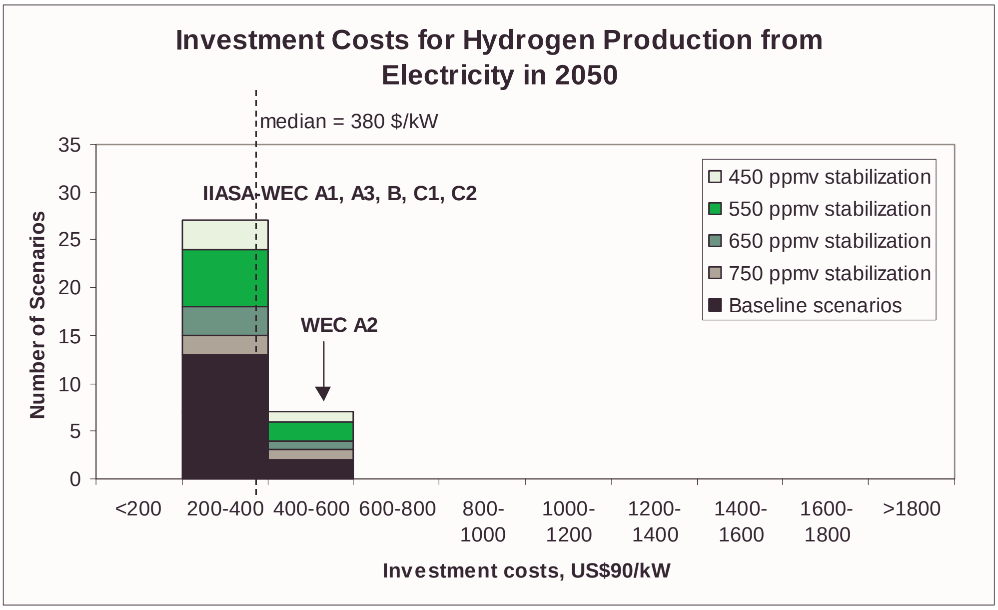

Figure B. Histogram of investment costs for hydrogen production by electrolysis across scenarios in 2050.

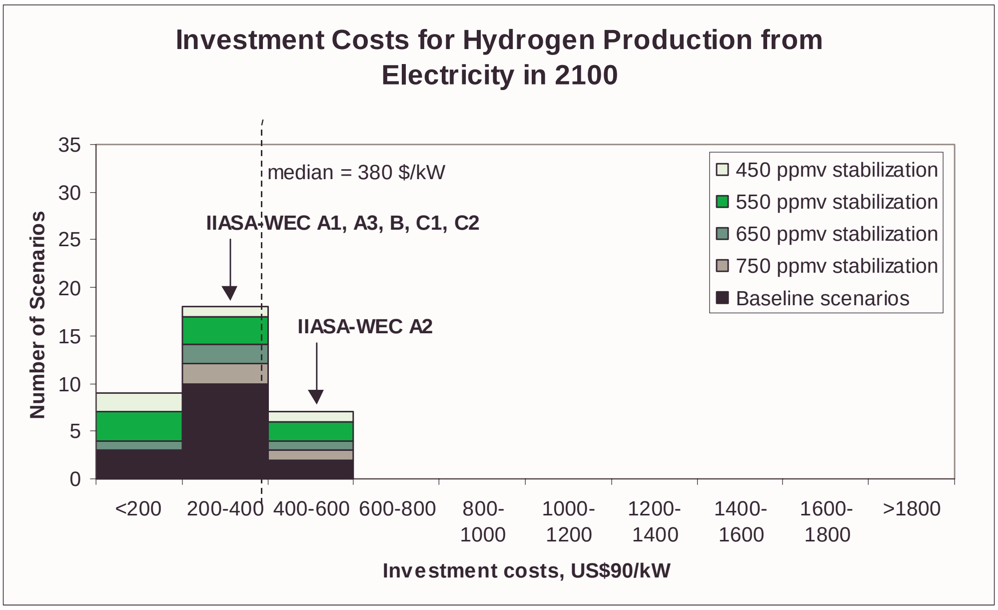

Figure C. Histogram of investment costs for hydrogen production by electrolysis across scenarios in 2100.

Investment Costs for Hydrogen Production from Nuclear Energy

Histograms of frequency distribution of the investment costs of hydrogen production from high-temperature reactors across scenarios, number of scenarios (from a total of 34) and 1990 dollars per kW production capacity. Figure A shows the investment costs in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. Only four IIASA-WEC scenarios assume that hydrogen production form high-temperature reactors will be available at the market before 2020. Their investment costs cluster within a narrow interval between $1000 and $1200 per kW production capacity. The costs are higher for other scenarios with the most expensive facilities extending to more than $1800 per kW production capacity in 2050 (see Figure B). The distribution is almost bi-modal. Most of the scenarios occupy the highest (more than $1800 per kW) and the lowest category ($1000 to 1200 per kW) with only two scenarios situated half way in-between, the adjacent categories remaining unoccupied. The distribution of scenarios is asymmetric even across the cost categories (initially one and three in 2050 and 2100) with IIASA-WEC scenarios also being situated in the lowest category over the whole period. Most of the mitigation scenarios are in the highest cost category.

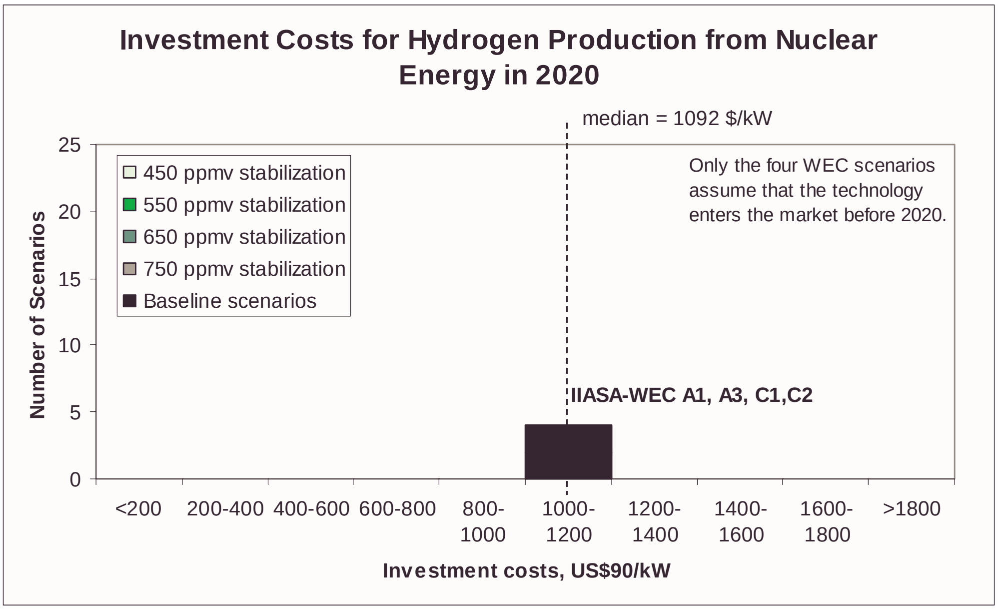

Figure A. Histogram of investment costs for hydrogen production by nuclear energy across scenarios in 2020.

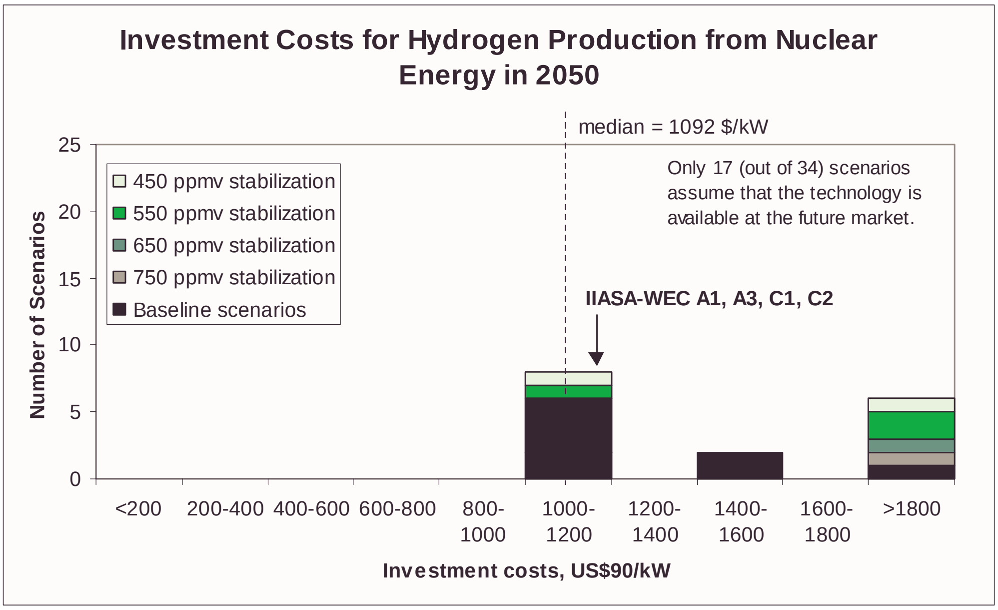

Figure B. Histogram of investment costs for hydrogen production by nuclear energy across scenarios in 2050.

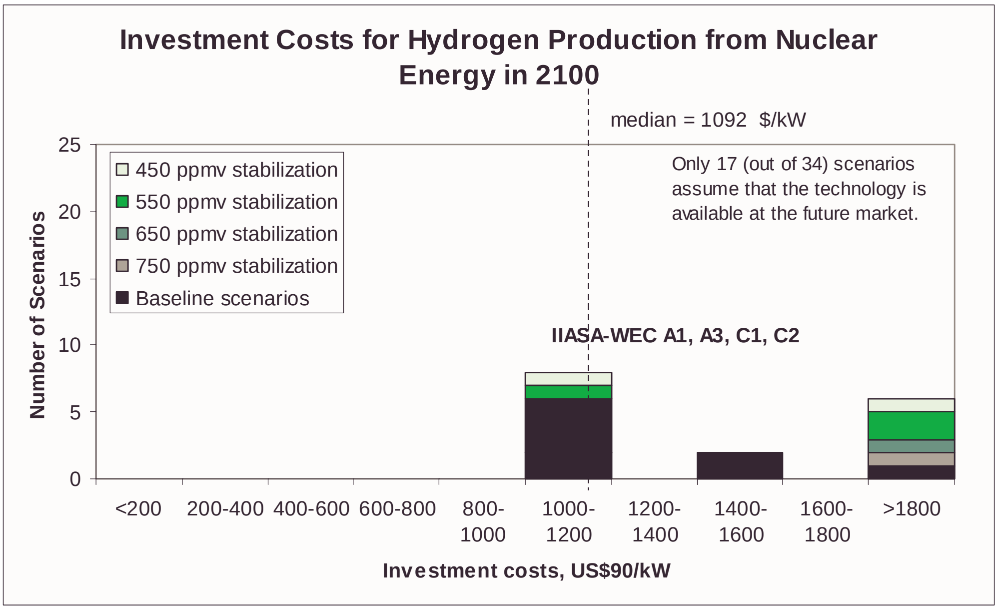

Figure C. Histogram of investment costs for hydrogen production by nuclear energy across scenarios in 2100.

Investment Costs for Hydrogen Production from Solar Thermal

Histograms of frequency distribution of the investment costs of hydrogen production form solar thermal plants across scenarios, number of scenarios (from a total of 34) and 1990 dollars per kW production capacity. Figure A shows the investment costs in 2020, Figure B in 2050 and Figure C in 2100. The relative positions of IIASA-WEC scenarios are indicated in the histograms. Only four IIASA-WEC scenarios assume that hydrogen production from solar thermal will be available at the market before 2020. Their investment costs cluster within a very high interval extending above $1800 per kW production capacity. Thereafter, the costs decrease in the majority of scenarios. In fact, the distribution becomes tri-modal and almost completely symmetric and invariant between 2050 and 2100. The lowest mode falls in the interval between $600 and 800 per kW. The majority of the scenarios are mitigation cases. The middle mode is between $1200 and 1400 per kW. It includes only baseline scenarios including all IIASA-WEC scenarios. The highest modes continues to extend over the region beyond $1800 per kW production capacity. Here again the majority of scenarios are mitigation cases. The spaces between the three modes are unoccupied. Consequently, the median falls from $1960 per kW in 2020 to $1200 per kW production capacity.

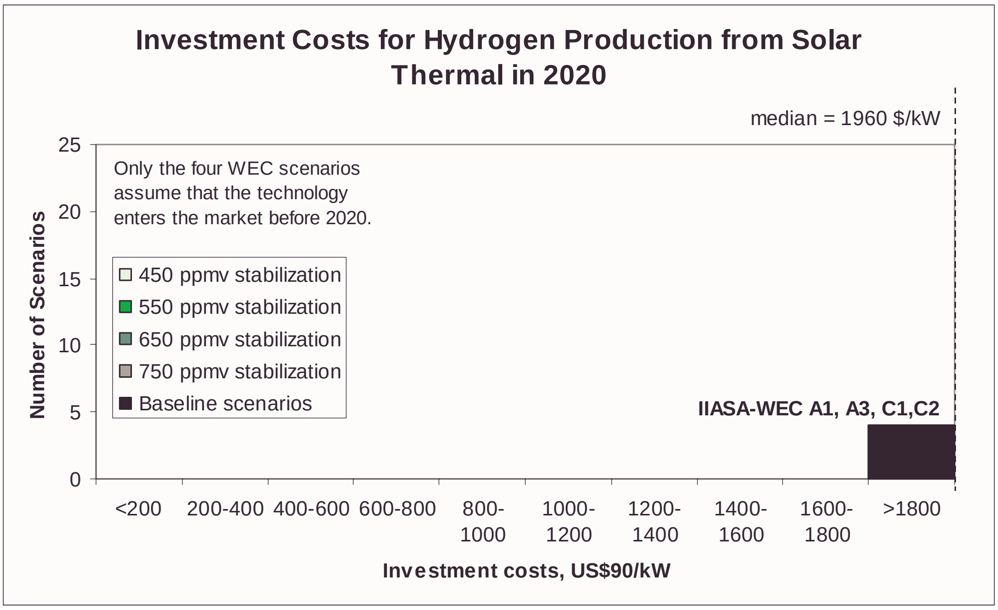

Figure A. Histogram of investment costs for hydrogen production by solar thermal across scenarios in 2020.

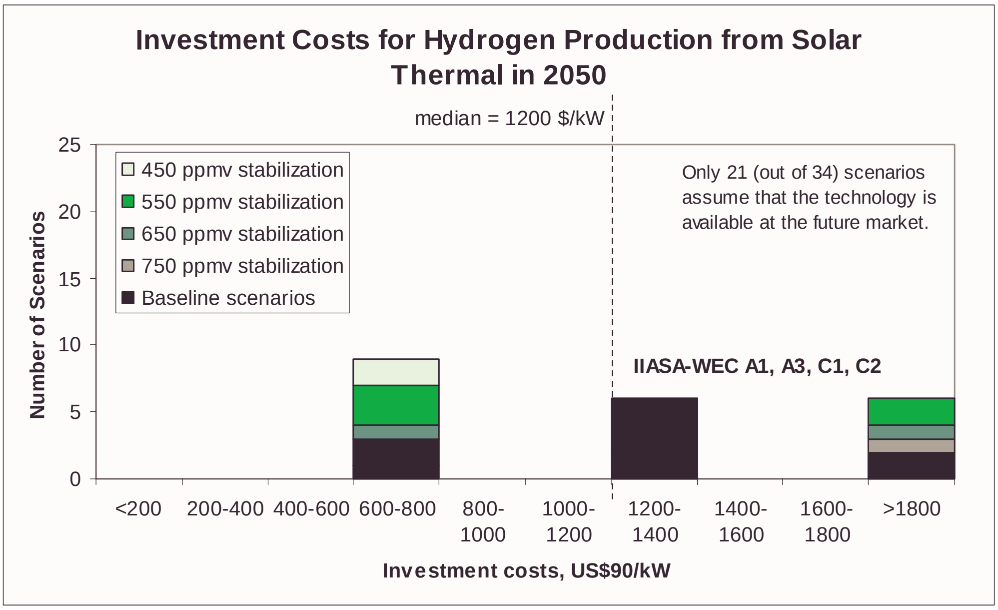

Figure B. Histogram of investment costs for hydrogen production by solar thermal across scenarios in 2050.

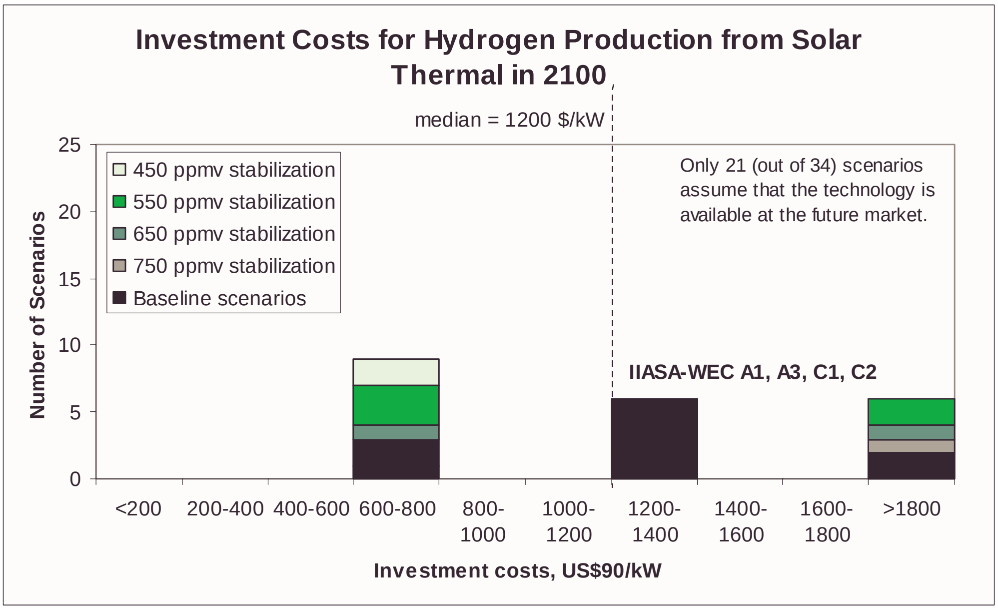

Figure C. Histogram of investment costs for hydrogen production by solar thermal across scenarios in 2100.

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