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Energy and the New Reality 2

Carbon-Free Energy Supply

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Chapter Highlights

Chapter 1 Introduction and key points from Volume 1

Significant and widespread negative impacts can be expected in association with continued emissions of greenhouse gases. Reducing these risks to a meaningful degree requires that human emissions be eliminated before the end of this century. Such a rapid reduction in CO_2 emissions will probably be sufficient to limit the atmospheric CO_2 concentration to no more than 450ppmv (parts per million by volume), compared to a pre-industrial concentration of 280ppmv and a concentration in 2010 of 390ppmv. Depending on how quickly we act, how large the climate sensitivity is and how sensitive the Greenland and West Antarctic ice sheets are to warming, it may or may not be possible to avoid triggering an eventual 10m or more sea level rise.

Assuming full implementation between now and 2050 of the energy savings potential identified in Volume 1, and taking into account structural shifts in national economies as wealth increases, the primary energy intensity of the global economy (primary energy use per unit of GDP) would decrease at an average annual compounded rate of 2.7 per cent/year between 2005 and 2050. Over the period 2005–2100, the primary energy intensity of the global economy could improve at an average compounded rate of 1.8 per cent/year. Depending on the growth in the human population and in average GDP per person, this implies that 1–5TW of additional C-free primary power will be needed by 2050 if the atmospheric CO_2 concentration is to peak at no more than 450ppmv. The total C-free primary power in 2050 would be 4–8TW. By comparison, the world primary power demand in 2005 was 15.3TW, of which 3.3TW were from C-free energy sources. To the extent that a 2.7 per cent/year average annual improvement in energy intensity is not achieved between now and 2050, more than 4–8TW of new C-free power will be needed by 2050.

Chapter 2 Solar energy

The amount of solar radiation intercepted by the earth is over 11,000 times present world primary energy demand. Solar energy can be used passively (to provide heat, ventilation and light) as well as actively (to produce electricity and hot water). Electricity can be generated from solar energy through large, centralized arrays of photovoltaic (PV) modules in sunny areas, using either flat collectors or concentrating collectors; through PV panels that are incorporated into the roofs and façades of buildings (a system called building-integrated PV or BiPV); and by concentrating solar energy with mirrors to make steam for use in a steam turbine (a system called concentrating solar thermal power or CSTP). PV electricity is currently expensive (25–30 cents/kWh in sunny locations), but costs can probably be reduced by a factor of two over the next decade or two. There are a number of different and promising PV technologies that could achieve these costs. Many PV technologies rely on rare elements, but by concentrating sunlight onto the PV modules by a factor of 100 or so, the required use of rare elements can be reduced by a similar factor, thereby allowing many different PV technologies to supply a significant fraction of future world electricity demand. BiPV is particularly attractive because it would generate electricity in the centre of the major demand centres at times of peak demand, thereby alleviating transmission bottlenecks. BiPV alone could provide 15–60 per cent of total present-day electricity demand in individual OECD (Organisation for Economic Co-operation and Development) countries.

CSTP is also attractive. A number of different CSTP technologies are under development, and it is reasonable to expect that electricity costs of 5–10 cents/kWh can be achieved in two decades. CSTP requires direct-beam solar radiation and so can be applied only in arid and semi-arid regions. However, by storing solar heat in hot molten salt or other media, electricity can be generated 24 hours per day and shorter-term intermittency in the supply of electricity from sunlight can be largely eliminated.

Solar energy can be used to produce hot water for household consumption, space heating and to drive various air conditioning and dehumidification systems. The first application is already economically attractive in many parts of the world, while solar air conditioning and dehumidification are still expensive. Solar heat can be provided at the range of temperatures needed for a wide range of industrial processes (including processing of metal ores and fixation of atmospheric nitrogen to produce nitrogen fertilizer), crop drying and cooking. The time required for the energy saved with various solar technologies to pay back the energy invested in building solar energy systems is two years or less in moderately sunny locations (southern Europe/northern US) and in the near future should drop to less than one year.

Chapter 3 Wind energy

Wind energy is a rapidly growing C-free energy source for the generation of electricity, the installed capacity having grown at an average compounded rate of 25 per cent/year from 1994 to the end of 2008. This rapid growth has been due to its relatively low cost among renewable-energy options, with electricity costs reaching a highly competitive 5–8 cents/kWh in many jurisdictions. The potential wind resource at a cost of up to 7 cents/kWh (taking into account expected future cost reductions) is probably greater than present world electricity demand, and larger still with higher cost ceilings. The difficulties with regard to wind relate to its intermittency and to the fact the some of the best wind regions are 1000–3000km from major electricity demand centres.

There are a number of strategies available for dealing with wind variability. Fluctuations at a timescale of seconds can be reduced by aggregating the output of several wind turbines in a wind farm, or by using short-term storage such as flywheels, supercapacitors and superconducting magnetic storage. Fluctuations at longer timescales will be reduced when geographically dispersed wind farms are linked together. Underground compressed air energy storage (CAES) is a proven technology that could be used for storing excess wind energy on a large scale and generating electricity when needed. Current CAES systems require supplemental fuel (natural gas now, biogas in the future), but advanced adiabatic CAES systems under development would store the heat that is generated when air is compressed and use this, along with the compressed air, to generated electricity later without the use of supplemental fuel. Flexible loads, including heat pumps with thermal energy storage, can also be employed to match fluctuations in wind energy. Parked plug-in hybrid vehicles could provide important regulation (voltage and frequency control) and storage functions.

The average output of a wind turbine is typically only 20–40 per cent that of the peak output, so it is possible to oversize a wind farm compared to the transmission capacity with little wasted electricity-generation potential. Although wasting some potential generation due to transmission limitations would increase the generation component of the electricity cost, it would reduce the transmission component of the cost because more energy would be transmitted through the given transmission link. By locating oversized wind farms in the regions with the best winds and transmitting electricity with high-voltage DC power lines, average power output as a fraction of peak power in the order of 70 per cent can be achieved at a cost in the order of 8 cents/kWh, which is comparable to that expected from wind farms located next to major demand centres but with much less favourable winds.

Chapter 4 Biomass energy

Biomass energy is perhaps the most complicated of the (net) C-free energy options. Complications arise from the many different possible kinds of biomass that can be used, the different forms in which biomass can be used (as solid, liquid or gaseous fuels), the variety of energy conversion processes available, the many potential end-use applications, the potential adverse and beneficial environmental impacts, social considerations through competition with land for food and impacts on the price of food crops, and uncertainties related to long-term sustainability and the impacts of climatic change during the coming century and beyond.

One of the most difficult issues with regard to biomass energy is the determination of the net energy gain using biomass. In spite of the resulting uncertainties, there are clear differences in the relative benefits of using biomass in different applications. Use of biomass as a solid fuel is superior to its conversion to liquid fuels. However, liquid fuels from biomass represent one of the few options for displacing petroleum-based fuels in the transportation sector.

The use of corn (maize) to produce ethanol is the least effective of the possible uses of biomass, and is also the least effective of the possible ways of reducing transportation energy use. Ethanol from sugarcane is substantially more attractive, as would be ethanol from lignocellulosic materials (grasses such as switchgrass or *Miscanthus*, corn stover and wood) if this technology (which is still under development) performs as projected. Direct use of woody biomass as a fuel for heating, or for subsequent gasification and use in the generation of electricity or for cogeneration, provides the greatest net energy benefit. If biomass used for electricity generation displaces coal, this would provide the largest CO_2 emission reduction per unit of biomass grown.

The use of plantation-scale biomass energy is fraught with numerous potential environmental and social problems. Its development should therefore proceed in a gradual, well-planned manner and with minimal government subsidies so as to avoid distortions that create unexpected and undesirable side-effects. Enforceable restrictions in the development of bioenergy resources will be needed so as to prevent destruction of forests or other natural areas that are better left intact.

Biomass energy could supply a significant fraction of future energy needs and at attractive costs in the long run (generally $3–6/GJ for solid fuels, less than $15/GJ for liquid fuels and about 5 cents/kWh for electricity). Most of this biomass will have to come from bioenergy plantations, but if existing forests are to be protected, the plantations will have to be limited to surplus agricultural and grazing lands. Whether or not there are surplus lands in the future will depend on (1) the future human population, (2) future diet (in particular, the proportion of food energy provided by meat and the kinds of meat consumed), (3) future agricultural productivity, and (4) the future efficiency in converting animal feed into animal food products. Diet emerges as a significant factor in determining both the future potential of biomass energy and the environmental impacts associated with the food system.

Chapter 5 Geothermal energy

Geothermal energy occurs in several different forms: hydrothermal, geopressurized, hot dry rock and magma. Geothermal heat can be used directly to provide domestic hot water and space heating, or can be used indirectly to produce electricity by first generating steam that is used in a steam turbine. Hot dry rock systems (also known as enhanced geothermal systems (EGSs) involve (1) drilling an injection borehole, down which water will be injected; (2) fracturing the rock in the region at the bottom of the injection borehole, so that water can flow through the rock and become hot in the process; and (3) drilling an extraction borehole in the vicinity of the injection borehole, from which the heated water will be drawn. The key for geothermal energy to make a significant contribution to world energy needs is the development of hot dry rock technology. If this technology can be developed according to industry projections, geothermal energy could provide one to several 100EJ/yr for many centuries. Electricity costs of 8–10 cents/kWh might be feasible. In heating applications, the geothermal resource could be significantly extended through the use of heat pumps to extract additional heat from the already-used water that is returned to the ground.

Chapter 6 Hydroelectric power

Existing hydroelectric powerplants already constitute a large renewable source of electricity – about 16 per cent of current global electricity demand. Projects under construction or planned will increase electricity production by about 50 per cent, while the economic potential is more than three times current global hydroelectric electricity supply under current conditions. However, not all of the economic potential can be developed, because of adverse environmental or social impacts. Further hydro development should be critically scrutinized to make sure that there is a large benefit to cost ratio, including minimal greenhouse gas emissions from decomposition of organic matter in flooded terrain. Hydropower projects should only go forward based on negotiated and legally binding agreements with the affected people based on their free and informed consent. Displaced peoples should be fully and fairly compensated, and the cost of such compensation should be included in the projected cost of hydroelectric energy and taken into account, along with the cost of other renewable or C-free supply alternatives and energy efficiency measures, when deciding whether or not to proceed. Hydroelectric developments are particularly advantageous when they serve to compensate for variable wind or solar electricity production, as they then serve to leverage greater renewable energy contributions without requiring greater fossil fuel spinning reserve.

Chapter 7 Ocean energy

Ocean energy in the form of waves, tides, tidal currents and energy from vertical thermal and salinity gradients can be converted to electricity. All of these forms of energy are at a very early stage of development, and intensive research would be needed to bring them to commercial viability. The greatest challenge is to build systems that work reliably for 10–20 years in a continuously harsh environment. The smallest technical glitch can undermine otherwise promising designs. The various forms of renewable energy from the oceans are not likely to form a large fraction of the renewable energy mix, except locally where there are particularly good and economical energy resources. The technical potential is largest (up to several times current global electricity demand) for wave energy, but the realizable potential is likely to be a very small fraction of the technical potential. Ocean thermal energy conversion (OTEC) could be broadly applicable in low-latitude regions and could make an important contribution but requires significant further research, development and testing before a clearer picture of its potential emerges.

Chapter 8 Nuclear energy

Nuclear energy is beset with a number of adverse environmental impacts and risks, concerns over nuclear weapons proliferation and terrorism and the continuing inability to find an acceptable long-term method for the isolation of high-level nuclear waste. The probability of a serious accident during the operation of nuclear powerplants is thought to be extremely low as long as proper procedures are followed and there is a culture of safety. However, these conditions may break down somewhere at some point in time.

It will be difficult for nuclear energy to play a significant role in reducing greenhouse gas emissions at a global scale. Indeed, the industry will be hard pressed to maintain the current electricity production over the coming two decades. Currently, nuclear energy provides 16 per cent of world electricity demand. However, the current fleet is old (average age is 25 years), and a new reactor would have to be built once every five weeks over the next ten years and once every 22 days over the following decade just to maintain the current capacity.

If, in spite of the above, the nuclear power capacity were to increase to 1500GW (almost four times the current capacity of 370GW) by 2050, known and speculative uranium supplies available at a cost of $130/kg or less would last about 40 years with once-through use of uranium fuel. The supply could be expanded by up to a factor of 75 with reprocessing of spent fuel to separate and use plutonium in fast breeder reactors, but this would create enormous risks of nuclear materials sufficient to build a crude bomb getting into the hands of terrorists. Alternative reprocessing schemes that would provide some resistance to proliferation of nuclear weapons and that would stretch the existing uranium supply (to perhaps the end of this century for a nuclear capacity of 1500GW) have been proposed. However, these would require significant technological development.

The savings in primary energy when nuclear-generated electricity displaces fossil fuel-generated electricity at 40 per cent efficiency, divided by the primary energy inputs throughout the nuclear lifecycle from mining to decommissioning and isolation of wastes, averages about 15 at present. This ratio, referred to as the energy return over energy invested (EROEI), is quite uncertain. However, the EROEI decreases as the grade of ore used decreases because the mass of ore that must by mined and processed, and the mass of tailing that must be treated for land reclamation, increases faster than the inverse of the ore grade. By the time uranium prices have reached $130/kg, the grade of much of the remaining ore will probably have dropped to about 0.02 per cent and the EROEI will have dropped to about three to five (except for uranium that is co-mined with other minerals). Further decreases in ore grade would see an accelerating drop in the EROEI.

The cost of new nuclear powerplants is uncertain. Recent assessments indicate a cost of about $4000/kW to over $10,000/kW. Decommissioning costs are also uncertain but are likely to be at least as expensive as the lower estimates of the cost of constructing a nuclear powerplant.

Development of a new generation of nuclear reactors will require another 15–20 years or more to reach the pilot demonstration stage, and then perhaps ten years of operation before such reactors could begin to be produced on a large scale. Another 20 years or more would be required before the new generation could provide a significant fraction of the total nuclear fleet. Thus, a major change in the technology of the operating fleet cannot be expected before 2050 at the earliest.

Chapter 9 Carbon capture and storage

Capture of carbon dioxide from new fossil fuel powerplants using existing technologies would increase fuel requirements by 11–40 per cent according to various estimates, while retrofitting existing coal-fired plants is estimated to increase fuel requirements by 43–77 per cent. With future technologies the energy penalty in new plants might be reduced to 2–12 per cent. Additional energy would be required to compress or liquefy and transport the captured CO_2 to its disposal sites. Costs are highly uncertain but are likely to be large, increasing the cost of new coal or natural gas powerplants by 50–100 per cent.

Potential sites for storage of CO_2 include depleted oil and gas fields, deep saline aquifers, coal beds, sediments in the seabed and deep ocean water itself. The amount of CO_2 that can be securely stored in terrestrial sediments or coal beds is highly uncertain. Among the environmental issues associated with sequestration on land are potential leakage through the thousands of drill wells that are found in most populated regions, potential displacement of saline groundwater into freshwater groundwater supplies and mobilization of toxic elements in saline aquifers due to the increase in groundwater pH associated with CO_2 injection. Other issues are the preclusion of the future use of saline groundwater through desalination, preclusion of future mining of saline groundwater for trace elements and interference with compressed air energy storage or geothermal energy. Disposal of CO_2 in the oceans as anything more than a supplement to a major shift from fossil fuels to renewable energy sources is not acceptable. However, burial in sub-seabed aquifers would probably pose negligible environmental risks and risks of leakage, but is also likely to be the most expensive storage option.

At least 20 years of demonstration projects involving carbon capture from powerplants using a variety of different types of coal, and carbon storage in a variety of different geological settings, would be required before large-scale deployment of carbon capture and storage (CCS) could begin. Another 20 years would be required before a significant fraction of the world's powerplants would (through normal retirement and replacement) be equipped with CCS. Thus, even if it proves to be viable, CCS could not make a significant difference before mid-century. Carbon sequestration could nevertheless be used as an emergency measure to accelerate the later stages in the phase-out of fossil fuel CO_2 emissions. In conjunction with the capture of CO_2 released from the use of biomass, it could create negative CO_2 for many decades, if this is needed in order to reduce atmospheric CO_2 concentration.

Chapter 10 The hydrogen economy

Hydrogen has the potential to serve as an energy currency, replacing fossil fuels in all the ways in which they are used for energy today and, in combination with biomass, replacing them as a chemical feedstock. Hydrogen could be produced by electrolysis of water when solar- and wind-generated electricity are in excess, stored and later used in a fuel cell to produce electricity when there is a shortage of wind or solar power. It could also be transported from distant sunny or windy regions to demand centres. In this way, it could serve to close the spatial and temporal mismatch between intermittent renewable sources of electricity and the demand for electricity. However, much of this gap could also be closed through alternative strategies, such as long-distance high-voltage DC power transmission to link regions of good wind and solar energy with dispatchable hydroelectric facilities and electricity demand centres, and by using CAES.

The use of hydrogen in automobiles presents major challenges, particularly concerning the current high cost of fuel cells and onboard storage, as well as the difficulties of creating a whole new infrastructure to supply hydrogen fuel. Nevertheless, there are indications that the total cost of driving using hydrogen in fuel cell vehicles could become competitive with gasoline or diesel alternatives. Advanced hydrogen fuel cell vehicles are projected to be almost four times as efficient (in terms of km driven per unit of energy in the fuel tank) as current vehicles and about 1.75 times as efficient as advanced gasoline vehicles, which reduces the problem of the much greater bulk of hydrogen storage systems compared to gasoline. However, the overall effectiveness in using renewably based electricity to make hydrogen (produced by electrolysis) for subsequent use in automobiles would be only about half that of the direct use of renewably based electricity to charge batteries. Thus, the optimal solution will probably be a plug-in hybrid vehicle using onboard hydrogen in a fuel cell only to give extended driving range. Hydrogen as a transportation fuel is more promising in various niche applications, such as in railway locomotives and to power auxiliary power units in trucks. There are also important industrial niche applications for hydrogen in a fossil fuel-free world, such as its use as a reducing agent in the manufacture of iron (in place of coke), in the manufacture of nitrogen fertilizer (in place of natural gas or coal) and in the manufacture of a variety of biomass-based chemicals (in place of petroleum).

Chapter 11 Community-integrated energy systems with renewable energy

Community-integrated energy systems involve centralized production of heat and possibly chilled water that are distributed to individual buildings through district heating and cooling networks. District heat networks can be coupled with large-scale underground storage of heat that is collected from solar thermal collectors during the summer and used for space heating and hot water requirements during the winter. Heat can also be supplied with biomass (as part of a biomass cogeneration system) or from geothermal heat sources. If both heat and coldness are stored, then heat pumps can be used to recharge the thermal storage reservoirs (or to directly supply heat or coldness to the district heating and cooling networks) during times of excess wind energy. This in turn permits sizing of the wind system to meet a larger fraction of total electricity demand without having to discard as much (or any) electricity generation potential during times of high wind and/or low demand. In the long run, district heating systems with cogeneration will make it easier to make the transition to a hydrogen economy, as a new infrastructure to supply hydrogen to individual buildings would not be needed.

Chapter 12 Integrated scenarios for the future

Based on the observation that almost no region in the world is more than 3000km from regions of either good winds or semi-arid or arid regions where CSTP is applicable (and most regions are no more than 2000km from such sites), supply scenarios consisting of the following elements are constructed (with the amounts depending on the demand scenario):

- 6000–12,000GW of wind energy capacity;
- 6000–12,000GW of CSTP capacity;

- 3000–4000GW of BiPV or PV capacity;
- minor amounts of geothermal, biomass and additional hydroelectric generation;
- interconnection of the major renewable energy source regions and the major demand with a high-voltage DC power grid;
- retirement of all existing nuclear reactors at the end of an assumed 40-year lifespan.

Two scenarios for the supply of fuels for transportation, heating and industry are considered: a hydrogen-intensive scenario and a biomass-intensive scenario, with hydrogen produced through some combination of low-temperature electrolysis largely from wind-generated electricity and high-temperature electrolysis using CSTP-generated electricity. Rates of increase in the supply of C-free energy and in C-free fuels are prescribed so as to completely eliminate fossil fuel emissions by around either 2080 or 2120, with emissions in 2050 ranging from a 15 per cent increase to an 85 per cent decrease compared to emissions in 2005 (depending on the demand scenario).

Annual material flows required to build up the renewable energy system in these scenarios are not excessive compared to current material flows, and all supply components of the system quickly become a significant net source of energy. However, water could be a significant limiting factor for the biomass-intensive scenarios. The amount of biomass required in the biomass-intensive supply scenario and the higher demand scenarios considered here is unlikely to be available unless there is a worldwide shift to diets with low meat consumption.

The CO_2 emissions produced from these scenarios are used as input to a simple coupled climate–carbon cycle model in order to calculate changes in atmospheric CO_2 concentration, global mean temperature and acidification of the oceans. The CO_2 concentration peaks at values of about 430–530ppmv and, for the lowest emission scenario considered here (peaking at 8.4GtC/yr in 2015), global mean warming peaks at a value of 1.2–3.7°C before slowly declining and ocean surface water pH declines by 0.13 relative to the pre-industrial value. For the highest emission scenario considered here (peaking at 11.5GtC/yr near 2030), global mean warming peaks at a value of 1.6–4.9°C before slowly declining and ocean surface water pH declines by 0.26 relative to the pre-industrial value. If CO_2 can be removed from the atmosphere at a rate of 1GtC/yr by 2050 through geological or biological sequestration, and the sequestration sustained at this rate, then, for the lowest emission scenario, the atmospheric CO_2 concentration, global mean warming and ocean surface water pH would return to close to present conditions by the year 2500 if there are no major releases of methane or other positive climate–carbon cycle feedbacks between now and then. Otherwise, yet larger rates of CO_2 sequestration would be required, but there is a risk that methane emission rates could be such that countermeasures would be ineffective, causing global warming to slip beyond human control, with globally catastrophic impacts.

Chapter 13 Policy sketch and concluding thoughts

Although great strides have been made in the development of C-free technologies for electricity generation, research and development is needed in many areas in order to improve performance and bring down costs. The development of 'clean' coal technologies and carbon capture and storage for coal, in contrast, is not recommended. Instead, the overarching policy goal should be to phase out the use of coal altogether as rapidly as possible. Similarly, research and development related to nuclear energy should be terminated, with the possible exception of research related to the use of nuclear powerplants to consume discarded plutonium and highly enriched uranium from nuclear weapons.

We need three large transformations: a transformation to vastly greater levels of energy efficiency than at present in all end-use sectors, a rapid deployment of C-free energy sources (primarily wind and solar energy), and a whole new way of thinking that places stabilization of greenhouse gas concentrations at levels below the equivalent of a CO_2 doubling ahead of promotion of economic growth.