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Hydrogen's role in an uncertain energy future

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ABSTRACT

This study explores global energy demand, and hydrogen's role, over the 21st century. It considers four illustrative cases: a high (1000 EJ) and a low (300 EJ) energy future, and for each of these conditions, a high (80%) and low (20%) fossil fuel energy share. We argue that neither high energy future is probable, because of resource limitations, and rising energy, environmental and money costs per unit of delivered energy as annual energy demand rises far beyond present levels. The low energy/low fossil case is most likely, followed by the low energy/high fossil case, although both require large cuts in energy use, and most probably, lifestyle changes in high energy use countries. Hydrogen production would be best favoured in the low fossil fuel options, with production both greater, and implemented earlier, in the higher energy case. It is thus least likely in the low energy/high fossil fuel case.

1. Introduction

Two questions are of crucial importance in discussing the future of energy in the 21st century: how much energy will we consume annually, and what sources of energy will we use? The answers to these questions are by no means certain. In 2006, total global primary energy consumption was about 493 EJ [1,2]. (EJ = exajoule = 10^{18} J.) Following the International Energy Agency (IEA) convention, energy generated from hydroelectricity and other renewable primary electricity sources is converted to primary energy on a one-to-one basis [2]. Again following IEA practice, primary energy in this paper includes non-commercial fuel wood. Table 1 shows total global primary energy from 1970 to 2006, illustrating both the steady growth in energy use over this period, and the recent rising share of fossil fuels. For electricity production, their share has been rising for several decades [1,3].

How much energy will we need in the future? A more equitable future world would require reductions in the present large differences in per capita primary energy consumption. Among the high-income countries, in 2004 Italy had the lowest per capita energy use at 132.7 GJ [2]. (GJ = gigajoule = 10^9 J.) The UN median estimate for 2050 global population is 9191 million [4]; if all used energy at this rate, global primary energy use would be 1220 EJ. This value is similar to the maximum value of 1173 EJ in 2050 in the various scenarios in Riahi et al. [5]. Various other researchers present futures with roughly 1000 EJ or more primary energy for 2050 [6–11], with some envisaging even higher values later in the century. While these researchers do not necessarily view their

Abbreviations: ASPO, Association for the Study of Peak Oil; CCS, carbon capture and storage; CO_2, carbon dioxide; EIA, Energy Information Administration (US); EJ, exajoule (10^{18} J); EWG, Energy Watch Group; FC, fuel cell; GJ, gigajoule (10^9 J); Gt, gigatonne (10^9 tonne); H_2, hydrogen; H_e, high energy (1000 EJ); H_f, high fossil fuel (80%); IEA, International Energy Agency; IPCC, Intergovernmental Panel on Climate Change; L_e, low energy (300 EJ); L_f, low fossil fuel (20%); Mt, megatonne (10^6 tonne); RE, renewable energy; WETO, World Energy Technology Outlook.

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Table 1 – Global primary energy use, EJ, 1970–2006.

Energy source	1970	1980	1990	2000	2006
Coal	64.2	75.7	93.7	98.2	129.4
Oil	94.4	124.6	136.2	148.9	162.9
Natural gas	38.1	54.9	75.0	91.8	107.8
Fossil fuels	196.7	255.1	305.0	339.0	400.1
Nuclear	0.7	6.7	19.0	24.5	26.6
Renewable[a]	29.4	37.6	48.5	55.6	66.2
All energy	216.8	299.5	372.4	419.0	492.9
Fossil %	90.7	85.2	81.9	80.9	81.2

Sources: Refs. [1,3].
a Values are only approximate: fuel wood data not accurately known.

figures as projections, they clearly regard 1000 EJ by 2050 as at least possible.

Because of the various serious constraints facing high energy use, low energy futures must also be considered. The energy conservation needed for these can occur in two ways; from increasing technical energy efficiency of power generation and energy-using equipment, or from less use of energy-consuming equipment. One recent study [12] estimated that for their '2 °C' scenario, global primary energy consumption in 2050 could be held to 422 EJ, lower than today's value. Amory Lovins is a strong advocate of the potential for technical energy efficiency, arguing that energy efficiency in a variety of applications can be increased by a factor of 10–100, and that an overall four-fold reduction in energy use is possible [13]. An annual primary energy use of 300 EJ could thus be considered as illustrative of a low energy future.

We focus here on primary energy because our chief concern is with climate change impacts and fossil fuel depletion. But what relation does primary energy have to the energy available for consumption? In 1973, the ratio of global primary energy to total final consumption (secondary energy) was 1.34, but had risen to 1.47 by 2004 [2]; primary energy rose faster than final energy use. If all energy was derived from coal fired power stations this ratio would approach 3.0; but if derived solely from hydroelecticity, the ratio falls to 1.0. Greater use of renewable energy does not necessarily guarantee a better secondary energy return, as it is likely that increased renewable energy would see greater need for energy storage and conversion. Each additional process will act to reduce the energy available for consumption. Increased fossil fuel use would ultimately need greater use of coal and non-conventional oil sources, again raising the primary/secondary ratio.

Within the range of possible energy futures, what role will hydrogen play? In this paper we limit primary energy consumption in 2050 to two cases: a high energy energy future ($H_e = 1000$ EJ) and a low energy future ($L_e = 300$ EJ). Other values for future energy are of course possible, but they will probably fall within these limits. We then explore hydrogen's role by considering the energy supply mix for each energy future. To do this we define two energy supply mixes, namely a high (H_f) and a low (L_f) fossil fuel share, where 'high' means 80% fossil fuels (roughly their present share in global energy supply—Table 1) and 'low', 20% fossil fuels. We impose one final limit on future energy; for simplicity we assume the primary/secondary energy ratio remains constant, while acknowledging that it may alter with primary energy level and mix.

We argue that neither high energy case is probable, because of resource limitations, and rising energy, environmental and money costs per unit of delivered energy as annual energy demand rises far beyond present levels. The low energy/low fossil case is most likely, followed by the low energy/high fossil case, although both require large cuts in energy use, and most probably, lifestyle changes in high energy use countries. Hydrogen production would be best favoured in the low fossil fuel options, with production both greater, and implemented earlier, in the high energy case. It is thus least likely in the low energy/high fossil fuel case.

2. Challenges to future sustainable energy provision

As shown in Table 1, the present global energy system is dominated by fossil fuels, and the official forecasts discussed above see little change in this pattern before 2030. An important question is for how long these business-as-usual projections can continue without running into constraints in the form of limited reserves of fossil fuels, or severe environmental problems from their combustion, including not only global climate change from CO_2 and methane emissions, but also air pollution problems. In this section we examine the implications for 21st century fossil fuel use of resource depletion and greenhouse gas emissions.

The Association for the Study of Peak Oil (ASPO) [14] project that combined global annual production of oil and natural gas (even including that from unconventional sources, such as oil sands) will peak around 2010 at about 290 EJ (47.5 billion barrels of oil equivalent), before falling to around 245 EJ in 2030 and 140 EJ in 2050. Their combined production was 271 EJ in 2006 [1]. Oil production has not risen over the past three years. Simmons [15] stresses that much of the world's present oil and gas supplies 'come from large fields now too old, and new fields that are too small.'

For coal, the Energy Watch Group (EWG) from Germany forecast that if present trends continue, global production will peak around 2025, at about 152 EJ, compared with the 2006 level of 129 EJ [1,16]. By 2050, production will not be much lower than 2025, but by 2100 the EWG study projects it to have fallen to about half its 2006 value. For fossil fuels overall, production in 2006 was 400 EJ [1]. Combining the ASPO and EWG projections, peak production could occur as early as 2020 at about 423 EJ, and by 2050 could have fallen to 286 EJ. The EWG authors stress that peak coal production in China, the largest producer, will determine the timing of global peak production. Their conclusions thus receive some support from recent Chinese research which forecasts peak coal production in China occurring between 2025 and 2032 [17]. Also, Rutledge [18] has applied 'Hubbert linearisation' to coal production forecasting, and has come up with similar results to EWG [19]. Both ASPO and EWG stress that accurate data on reserves for all fossil fuels are lacking for many countries [14,16].

Of course, many estimates forecast much higher possible fossil fuel use until well into the future (e.g. [6,20,21]). These in turn are based on assessments of recoverable reserves (and future additions to reserves) far more optimistic that those discussed above [1,6,21,22]. (However, even the annual BP reports caution the reader about the unaudited nature of the reported reserves.) They are also far more optimistic about the rate of technical progress and annual production from unconventional resources, such as oil from tar sands and natural gas from coal seams. Two energy authorities, the IEA [2] and the US Energy Information Administration (EIA) [3], have recently projected both total primary energy use and its composition out to 2030. For 2050, projections are available from the European Commission in their 2006 World Energy Technology Outlook—2050 (WETO) [20], and a 2007 IEA study [11]. The EIA report projects fossil fuel use at 638 EJ and the IEA 563 EJ, both for their 2030 base case [2,3], similar to the WETO study reference case values of 564 EJ for 2030, rising to 660 EJ in 2050 [20].

So far, it has been implicitly assumed that if needed, reserves will be produced at the maximum rate, limited only by geological constraints, economics and good field development practices. But fuel-exporting countries could well decide to limit their annual production to levels far less than the maximum, even if reserves are much greater than the pessimistic estimates of ASPO/EGS. Limiting output would help both maximise their total revenue and reserve some fossil fuels for future generations. Output reduction could also occur by damage to infrastructure, whether natural- or human-caused. For example, Hurricane Katrina in 2005 did extensive damage to oil rigs in the Gulf of Mexico.

Increasingly, future petroleum will need to come from unconventional sources, such as oil sands, deep water and polar oil. The Canadian oil sands are a vast deposit covering 141,000 km^2 with an estimated 1.7 trillion barrels (10,400 EJ) of bitumen in place, of which about 10% is recoverable with current technology. However, the rate of development of new annual capacity is limited by several factors including labour shortages and environmental constraints [22,23]. Even optimistic projections only see 8.9 EJ (four million barrels/day) of oil from Canadian oil sands by 2020, compared to the 1.6 EJ produced in 2006 [22]. Any further weakening of oil prices will adversely affect their economic viability.

A growing proportion of natural gas will either need to be shipped to market in the form of liquids such as liquefied natural gas or methanol, because of remoteness from markets, or come from unconventional sources such as 'tight' gas, coal bed methane, or even methane hydrates. Liquefaction uses up 7–13% of the energy in the input natural gas, with further energy expended in carrying the liquid to markets [22]. For coal, official estimates of ultimately recoverable reserves are vast, at around 100,000 EJ or more [6,16,22]. Only a small share of reserves can be recovered by open-cut mining; the rest requires underground mining, which has higher extraction costs and lower labour productivity. Bockris [24] also stresses that only a small proportion of the coal in place can be economically extracted, particularly if seams are thin. Fuels extracted will have increasingly higher sulphur content (oil and coal), or for natural gas, carbon dioxide content. The monetary, environmental and energy costs (and risks) of delivering a unit of secondary energy to users will all rise as premium reserves are depleted.

Fossil fuels also produce a number of environmental problems associated with their exploration, extraction, transport and combustion. The 2007 Intergovernmental Panel on Climate Change (IPCC) reports argue that avoiding a rise of more than 2 °C above pre-industrial values could require cuts in global greenhouse gas emissions by the year 2050 to as low as 15% of the year 2000 emissions [25]. The European Union has proposed such a cap of 2 °C as necessary to avoid dangerous anthropogenic change [26]. Reductions of this magnitude would require emissions peaking in a few years [25] with substantial cuts in place by 2030. Hansen and colleagues [27] go further, arguing that atmospheric CO_2 concentrations must be *reduced* from the 385 ppm present level to 350 ppm. In brief, there are time limits for emission reductions; major cuts are needed in two decades or less, not by the end of the 21st century [26].

3. High fossil fuel supply mix

The reports discussed above all assume high energy consumption in the future, with 80% or more coming from fossil fuels in their reference scenarios in 2030, and for the WETO report, still over 70% in 2050 [2,3,20]. Since fossil fuel use in recent years has grown strongly, forming a rising share of primary energy, a high energy future based largely on fossil fuels (H_e–H_f case) deserves serious consideration. This option also benefits from the massive past investment in the energy supply system. But given the possible constraints discussed both in the preceding section and by several other researchers [24,28], we need to ask how likely such an energy future is, and if implemented, for how long could it be maintained?

Clearly, if drastic greenhouse gas reductions are needed, high fossil fuel use requires some form of carbon sequestration, as there is no other way of reducing the resulting emissions to the atmosphere. Carbon can be sequestered in soils and forests, but in a warming world there are doubts about the permanence of these sinks; a number of coupled carbon cycle-climate models show annual terrestrial carbon uptake declining before 2050, and sinks becoming carbon sources later in this century. The authors reviewing these models conclude: 'Overall, it is likely that, at least on a global scale, terrestrial ecosystems will provide a positive, amplifying feedback in a warming world, albeit of uncertain magnitude' [29]. It thus seems unwise to rely on soil or biomass carbon sinks to offset energy/industry emission reductions.

We are left with carbon capture and storage (CCS), either by capture of CO_2 from large power stations and industrial plants, or directly from the air. The three methods for CO_2 capture from large plants include: using absorbants such as amides to extract CO_2 from the exhaust gas stream (the most developed method and the only one that can be retrofitted); combusting the fuel in pure oxygen; and gasifying the coal fuel into H_2 and CO_2, followed by separation of the CO_2 [30,31]. It is even possible that coal gasification could proceed in the absence of CCS [30], given the energy efficiency advantages of combined-cycle gas turbines.

An advantage of air capture is its unrestricted location, allowing it to be done near sequestration sites [32], thereby largely eliminating transport costs. Annual CO_2 sequestration is restricted neither by annual emissions from large CO_2-emitting plants, as is conventional CCS, nor even by total global emissions. It is thus in principle possible for one country, or one group of countries, to actively reduce global CO_2 atmospheric concentrations, rather than merely slowing their build-up. But while CO_2 burial would be identical to conventional CCS, air capture would likely be much more energy-intensive. Italian researchers [33] have analysed the energy costs of two possible designs for air capture, and found that the process energy required per tonne of CO_2 was larger in both cases than that obtained by combusting the coal. Its high energy and monetary costs can be illustrated by the need to process almost 12,000 Gt of air per year to remove the CO_2 emitted from current annual global transport alone. It will therefore only play a supporting role to centralised emission capture.

CCS introduces what has been termed 'moral hazard' into the energy question [34]. Already in the UK, some environmentalists see CCS as a convenient excuse for building new coal-burning power stations, even though CCS on the huge scale required—billions of tonnes sequestered annually—still faces a variety of serious technological, legal and public acceptance challenges [35]. Air capture would compound the problem, by providing a plausible reason for even further delay in tackling today's emissions from fossil fuel combustion. The slow progress on nuclear waste disposal also suggests that these fears are well-founded.

A related point is the technological optimism shown in many discussions on energy futures. The costs and time frames required for implementing radically new technologies like CCS, or orders of magnitude scale-ups of existing ones, such as those that have been proposed for RE, are systematically under-estimated [36]. Also under-estimated is the political opposition likely to siting CO_2 storages, liquefied natural gas terminals, or new nuclear power or reprocessing plants. And although the difficulties facing technologies which allow continuation of large-scale energy systems are usually understated, the difficulties facing social change solutions to energy problems (e.g. energy conservation, discussed below) are often overstated [37].

The quantities of CO_2 involved are enormous. In 2004 the fossil fuel mix averaged 71.5 Mt CO_2/EJ [2]. Assuming a similar fossil fuel mix in 2050, 800 EJ of fossil fuels would emit 57.2 Gt CO_2 annually. If emissions of CO_2 from fossil fuels had to be cut to 15% of their year 2000 value (in line with similar cuts in CO_2-equivalent emissions from all sources), the world could only release 3.6 Gt [1], thus needing sequestration of 53.6 Gt annually.

Clearly, the low energy future (300 EJ of global primary energy in 2050), whether fossil- or non-fossil based, would require massive energy reduction efforts, given present and projected energy trends. The favoured approach is to improve the technical efficiency of all energy-using equipment, including power plants [22]. However, while the overall energy efficiency of the world economy has risen greatly in recent decades, as measured by Gross World Income/EJ, so has total energy use and emissions [2]. A second approach is to drastically curtail use of energy-using equipment, which would inevitably require significant lifestyle changes in OECD countries. We have presented some ideas on how this could be achieved, particularly for transport, in recent papers [26,37]. Both technical efficiency and reductions in use of energy-using equipment need to proceed in step.

In the low energy (L_e–H_f) future, only 240 EJ fossil fuel energy is required, but even this level could not be maintained for long if production was limited by ASPO/EWG assumptions. CCS would still be needed, at an annual rate of 13.5 Gt, given the assumptions of the previous paragraph. Since the rate of construction of new fossil fuel power stations would be small, CCS would mainly have to come from add-on technology to existing power plants, or from air capture, both energy-intensive.

Fig. 1 shows historical global consumption of fossil fuels, together with likely limits to annual production in the decades up to 2100, following the assumptions of ASPO/EWG. Also shown are limits to fossil fuel combustion for energy-related CO_2 emissions if (i) $\leq$15% or (ii) $\leq$50% of their year 2000 value by 2050 or thereafter, assuming 71.5 Mt CO_2/EJ. These correspond to the 85% (upper) and 50% (lower) of year 2000 CO_2 emissions cuts given by the IPCC for 2 °C maximum rise [25]. The down-sloping curve after 2025 gives the maximum possible annual fossil fuel (EJ) use. Maximum use would require most CO_2 emissions to be sequestered, the amount diminishing with time. If emissions are not sequestered, annual fossil fuel (EJ) use must be limited to 51 EJ (170 EJ) for 15% (50%) of year 2000 CO_2 emissions.

High fossil fuel energy futures seem unlikely, given both the possible resource constraints and the massive CCS effort required for 800 EJ fossil fuel use. Further, the energy costs of energy will continue to rise with cumulative fossil fuels extracted, since such large annual outputs require tapping progressively more unconventional (and more difficult-to-extract) sources. A litre of petrol from oil sands requires 3–4 times more energy inputs than does a litre from conventional oil. For shale oil, energy costs would be even higher [22]. Per unit of primary energy, less secondary energy will be delivered than is the case today, and the economic and environmental

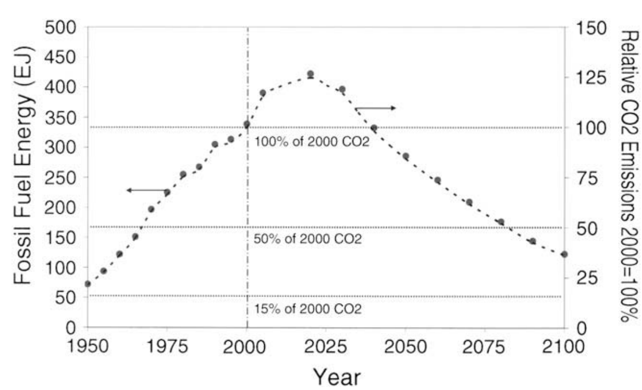

Fig. 1 – Fossil fuel use 1950–2006 and projected ASPO/EWG [14,16] limits, 2020–2100. Also shown are the CO_2 emissions relative to the year 2000 emissions. The 15% and 50% limits correspond to the IPCC [25] limits for a 2 °C maximum temperature rise.

costs of final energy will accordingly rise. Much of this hard-won delivered energy will then be needed for CCS. On the other hand, resource limitations and CCS difficulties in the low energy future, although present, are far smaller, but would involve major societal change if technical efficiency cannot deliver enough reductions in the very short time frame available [26].

4. Low fossil fuel energy supply mix

The H_e–L_f future could be based on renewable energy (RE) sources and/or nuclear energy. Several researchers think that RE sources could readily supply the 800 EJ required [38,39]. Fossil fuels would supply 200 EJ, only half today's use, but still unsustainable under ASPO/EWG assumptions (Fig. 1). If CO_2 emissions were held to 15% of year 2000 values, 10.7 Gt of CO_2 would need to be captured and sequestered.

We doubt that non-carbon sources could supply 800 EJ by 2050, or even later. RE sources can be conveniently divided into two groups: intermittent and non-intermittent [35]. An important problem facing the non-intermittent RE sources hydro and biomass is the effect of ongoing climate change on their potential in 2050 and beyond. Since it is unlikely that we will be able to prevent a rise of 2 °C or more above pre-industrial [5], significant climate changes will occur despite even our best efforts.

Hydropower production depends not only on average annual precipitation, but on its inter- and intra-annual variability, and on the frequency of extreme precipitation events. In general, while all general circulation models show increased overall precipitation in a warmer world, many areas will have reduced rainfall. Decreased precipitation translates into decreased hydro potential, as has been shown for both southern Europe and tropical Africa [40,41].

Climate change can influence hydro production in several other ways. Intense rainfall events are expected to increase in relative frequency, and such occurrences cause disproportionate soil erosion [42,43]. It follows that reservoir siltation in future will be even more of a problem than today, where 0.5–1.0% of reservoir capacity is lost annually [43]. Increasing siltation rates will both lower the output from existing hydro schemes, and affect the economic viability of proposed new schemes.

Global warming will both lower the share of precipitation that falls as snow on mountain ranges such as the Rockies and the Himalayas, and bring forward the discharge due to annual snowmelt, resulting in more temporally skewed streamflows [44]. Unlike regional precipitation, increased regional temperatures are predicted with high confidence [45] and higher temperatures will increase reservoir evaporation. The effect of all these changes will be reduced hydro potential, not only because of projected reduced flows, but also because the uncertainty of flows and their variation under changing climate increase the economic risk of hydro projects. In some river basins, it may even be difficult to maintain existing hydro output, although for Arctic-draining rivers, flows and hydro potential are anticipated to rise [44].

With 40–80 million people displaced to make way for large hydro schemes over the past half century and their often high environmental costs [38], major hydro electric expansion will continue to face serious public acceptance issues. Recently, the serious environmental problems of the Three Gorges Dam in China have received attention, and more relocation is likely because of slope instability as the watertable rises [46]. The WETO report [20], even in the most favourable case, projects only 19 EJ hydro globally for 2050, compared with 10.7 EJ today. Given that the economic potential is only 25–30 EJ [38], and is nearing its limits in the OECD, this projection seems reasonable.

In future, water availability will increasingly constrain bioenergy production, whether it is produced from foodstuffs or purpose-grown cellulosic energy plantations. Around 40% of food production today is provided by irrigation, which already requires massive overdrafts of fossil groundwater—around 200 km^3 globally. In both India and China, boreholes are being sunk as far as 1 km, chasing falling watertables [47]. In a recent paper [48], we showed that for borehole depths of greater than about 167 m, pumping energy alone would require all the biomass energy that could be grown from the extracted water. For greater depths, the energy return is negative. In the US, much controversy exists as to whether corn ethanol even gives a net energy benefit. But even the optimists agree that the net energy return is small—and this for corn grown on prime rain-fed farmland.

The conflict between food and bioenergy is already apparent. Corn prices have risen, as grain is increasingly diverted to ethanol production [49]. This conflict can only intensify in the future, if an expanding global population tries to increase agricultural and forestry production as well as bioenergy fuels in the face of the adverse hydrological changes discussed above. Temperature increases during the growing season can also adversely affect grain yields because of reductions in photosynthetic activity at high temperatures [47]. In view of all these factors, Field and colleagues [50] recently estimated that only about 27 EJ of biomass could be harvested annually without threatening food supplies or worsening climate change—less than today's use, which is often produced unsustainably [21]. In an earlier paper [48] we have presented a fuller case for our argument that global bioenergy potential (including waste and residues) will be of minor importance in an increasingly environmentally constrained world.

The only other source of non-intermittent RE is geothermal energy. Conventional geothermal energy can only supply minor amounts of electricity [35], but considerably more direct heat. However, a recent MIT study [51] saw enormous potential for Enhanced Geothermal Systems. The total estimated resource base for the US alone is in the millions of EJ, far above estimated global reserves for fossil fuels, or even the total fossil fuel resource base [51]. Two parameters are crucially important for assessing the cost (in both money and energy terms) for developing these resources: the depth of the heat source, and its temperature. Electricity production needs temperatures of at least 150–200 °C. The report shows that there is no resource at or above 200 °C at depths ≤4 km in the US, and only small amounts at 4–5 km depth. It also shows that the cost of wells rises roughly exponentially with depth, so the energy costs of produced electricity will probably also show disproportionate increases with depth. Disappointingly, there was no discussion of energy costs in this report of over 300 pages. The IEA [11] give the global potential of geothermal electricity production as only 85 GW (about 2.4 EJ/year) over the next 30 years.

Another possible source of constant output energy is nuclear power, which in 2006 provided about 5.4% of global primary energy [1]. van der Zaan [10] looked at a 10-fold linear expansion of nuclear power between 2000 and 2075. Even this optimistic assumption only gave nuclear energy providing 15% of total (commercial) primary energy by 2030, and 20% by 2075. But Fieveson [52] points out that nuclear plants often take decades to plan and build, and despite much talk, 'there is little evidence of a vast surge in construction before 2030, the farthest point in time where the projections at least roughly can be based on actual plans'. Hence nuclear energy is very unlikely to provide anywhere near 15% of primary energy by 2030. The IPCC [25] also see negligible change in nuclear energy's share by 2030. Finally, greatly expanding nuclear power worldwide inevitably means that some plants will have low security and safety standards. As Socolow and Pacala [53] put it, 'the world's least well run plant can imperil the future of all the others'. The high energy costs of nuclear plant construction also place limits on the rate of nuclear power introduction [21].

For nuclear energy, proven recoverable reserves of uranium are only 2210 EJ. Adding undiscovered conventional resources would still only give 7830 EJ [54], or roughly 3000 EJ of electricity [21]. Orders of magnitude higher values are theoretically possible if unconventional resources in phosphate rock and seawater are included, but such resources would probably not deliver net energy in conventional reactors. Breeder technology could also extend uranium reserves, but these reactors are unlikely to make a significant contribution before the middle of the century, since working prototypes are not expected before 2035, and probably never, given their many problems [8,9,35].

It seems likely that intermittent sources of RE, chiefly wind and direct solar, will have to supply most non-fossil energy in 2050 and beyond. The technical potential for these sources is undoubtedly very large [39], but would increasingly require conversion (probably to hydrogen) and storage as they assumed steadily larger shares of total primary energy [35]. This would both raise costs and decrease net energy delivered. A number of other problems, which may or may not prove serious threats, include: public opposition to siting; the possible need to import energy from solar farms thousands of kilometres away; availability of fresh water for solar cell/ mirror cleaning and hydrogen production in desert areas; dust/grit damage to solar cells and mirrors in desert areas; deterioration of PV cell output with very high temperatures [55,56]. Trainer [56] has stressed the very high costs of solar energy, even in a favourable location such as northern Australia. Wind and solar electricity in 2006 together amounted to less than 0.8 EJ globally, or 1/1000 of the 800 EJ needed in the H_e–L_f future. We simply do not know what difficulties will face such a huge scale-up.

As RE sources that deliver primary electricity, such as wind, hydro and photovoltaic, increase their share of primary energy, comparisons with a fossil fuel-based system become increasingly problematic. As the share of renewable primary electricity rises, the ratio of primary to secondary energy will fall, so that the 300 EJ of primary energy in the L_e–L_f case will deliver more secondary energy than will the L_e–H_f case. As has been noted, partly offsetting this will be the eventual need for energy conversion and storage.

Even in the L_e–L_f case, 0.7 Gt CO_2 CCS would still be theoretically needed. In fact, on the assumptions used here, CCS could only be avoided if fossil fuels provided $\leq$50.9 EJ or less of primary energy. Such a level of fossil fuels would also be sustainable for several centuries (Fig. 1), making it an attractive option.

5. Implications for the future of hydrogen

Given the various possibilities for future energy, what do the official reports mentioned in Section 1 have to say about hydrogen production? Only the WETO study provides detailed projections. For their hydrogen (H_2) case—the most optimistic for H_2—the report projects that production globally will rise from about 4.6 EJ in 2030 to 43.8 EJ in 2050, compared with total primary energy production in 2050 of 850 EJ [20]. The reference case has H_2 production in 2030/2050 of only 1.3/14.7 EJ. The hydrogen case assumes optimistic technology advances, particularly in H_2-based transport, where nearly all the H_2 would be used. Even so, production would still only be 5.1% of primary energy demand in 2050. The EIA study does not give total H_2 production, but projects negligible use in 2030 in transport, even in the high oil price scenario [3]. The 2007 IPCC mitigation report contains little discussion on H_2, but notes that it 'will only begin to make an impact around 2050' [22].

Researchers on H_2 energy have far been more optimistic. Momirlan and Veziroglu [8], in a paper discussing the transition from the present fossil fuel era to extensive H_2 utilisation, present an indicative graph showing 200 EJ H_2 production in 2030 (about 23% of total primary energy), and 750 EJ in 2050 (75% of total energy). Interestingly, they forecast a decline in primary energy production after 2050 if no H_2 is produced. Their scenario for 2050 is similar to our H_e–L_f future, having 1000 EJ primary energy, with 250 EJ coming from fossil fuels and the rest from RE converted to H_2.

Possible routes to large-scale introduction of H_2 can be conveniently reduced to three. First, H_2 could be introduced because of various technical breakthroughs, either leading to strong direct *demand* for H_2, or to direct *production* of H_2. Many H_2 researchers consider that because of oil depletion discussed above, transport represents the earliest opportunity for large-scale introduction through the use of H_2 fuel cells (FCs) (e.g. [9,20,28,57]). But H_2 faces a number of competitors for supplying future transport energy, including non-conventional oils such as oil sands and liquid fuels from biomass. Both are already in production, and are more readily fitted into the existing transport system. Recently, interest has shifted to plug-in hybrid vehicles, largely powered by mains electricity [58]. H_2 even has a strong competitor for fuelling FC vehicles in methanol.

Of course, these competitors also face serious obstacles to large-scale introduction, as already discussed for oil sands and biomass fuels. Plug-in hybrids are still not available, and the favoured lithium ion batteries have relatively short lives

[58]. Methanol is a liquid and so avoids the on-board storage problems of H_2—but methanol FCs are a long way from commercial deployment. Several major technical breakthroughs are needed for H_2-FC vehicles, and could occur, but such breakthroughs are just as likely in competitor vehicle fuels. Nevertheless, hydrogen could well be an important fuel for truck, bus, rail or ship propulsion, where on-board hydrogen storage volumes are less constrained [20]. Similarly, hydrogen could also be important for stationary FC power generation, but cost reductions are needed. An additional benefit here would be the potential for combined heat and power, giving very high overall efficiencies [9].

If technology breakthroughs make direct photolysis (water-splitting with a photocatalyst) [21], or biological H_2 from algae or other organic substrates [59,60] economically feasible, H_2 would be produced directly, and so could become a preferred energy carrier. Combining the various approaches shows promise for increasing H_2 production rates [61]. CCS has also been seen as 'the essential bridge to the hydrogen economy' [62]. It is at least possible that any direct supply could act synergistically with direct demand for H_2 for stationary or vehicular FCs and thus create a major opportunity for H_2 even before 2050. Lewis [63], for example, envisages H_2 from nuclear reactors powering FC vehicles.

Second, increasing the share of intermittent RE in electricity grids would eventually require either dumping of electricity if excess to requirements, or else conversion to some other energy form and storage—with H_2, a strong contender. Depending on the particular grid, this conversion might need to occur at quite low levels of intermittent RE in the energy mix, thereby hastening its introduction.

Third, in what we have argued is the unlikely event [35] that non-intermittent RE sources such as hydro, biomass or geothermal, together with nuclear power, account for most energy production, conversion of electricity to H_2 would seem unlikely any time soon. H_2, and new energy sources generally, are late-comers and so face 'entrenchment' from established energy sources and energy carriers, namely fossil fuels and electricity. Only after electricity needs were fully met by CO_2 emission-free sources would hydrogen production from any excess electricity generation be considered, since otherwise, available energy (and CO_2 reductions) would always be maximised by using carbon-free electricity directly [64]. Such might be the case for Iceland, which already has 100% electricity from hydro and geothermal, and no scope for directly exporting electricity. However, export of energy-intensive aluminium is an alternative to H_2 production.

We can now discuss the implications for H_2 of the four case studies:

1. The H_e–H_f future is unlikely to lead to major H_2 production, not only because of possible supply and environmental constraints. Large CO_2 emitters such as coal power plants could only capture about one third of global emissions [30], so large-scale air capture, an untried and energy-intensive technology, would be necessary. However, it is possible that coal gasification (and thus H_2 production) could be adopted for power plants, even without CCS, because of higher plant efficiencies.
2. For the L_e–H_f future, supply constraints, although far less likely than in case (1), might still be a problem (Fig. 1). If emissions are kept to 15% of year 2000 levels, 13.5 Gt CO_2 of CCS is still needed. As in the H_e–H_f future, coal gasification might still be adopted for the small number of new plants required, but the quantities of H_2 produced would be much smaller.
3. The H_e–L_f future would be most advantageous for hydrogen, but like the H_e–H_f future, we argue is unlikely to occur. If implemented, H_2 production would mainly come from either the need for conversion and storage of large amounts of intermittent RE, or possibly from high-temperature reactors. Fossil fuel use would be similar to (but smaller than) the L_e–H_f case, with similar H_2 production possibilities.
4. The L_e–L_f future is in our view the most likely, and would require little or no CCS. The 240 EJ from non-fossil sources would probably need large quantities of H_2 production, from conversion/storage of intermittent RE.

In summary, we need to consider not only which energy pathways favour H_2 production, but, just as importantly, how likely they are to occur. In general, the maximum future production of hydrogen depends on total primary energy use, since as a derived fuel, production must be less than this. We have argued that high levels of energy, from whatever source, are unlikely by 2050, or even later, and that the L_e–L_f case is the most probable future for energy in 2050 and later. H_2 prospects also depend to an important extent on the shares of the various energy sources, with large amounts of intermittent RE most favourable. Nevertheless, breakthroughs in direct supply of H_2, or H_2-FCs, could allow much earlier introduction.

6. Conclusions

Energy use in this century and beyond faces deep uncertainties. There are widely conflicting opinions on the size of ultimately recoverable fossil fuel reserves, and the extent to which unconventional resources can be tapped. If, as expected in most forecasts, fossil fuel use continues to grow, the sequestration of vast amounts of CO_2 would be needed if we are to limit global warming. Large emitters such as power plants could probably only capture around a third of the amount needed, requiring the deployment of air capture, an untried and energy-intensive technology.

Non-carbon sources face their own uncertainties. The future of nuclear energy depends heavily on the successful and timely development of either breeder reactors or fusion energy. Yet after nearly half a century of effort, neither are near commercialisation, and fission technologies face deep public opposition. Ongoing climate change will adversely affect hydro and biomass energy expansion. Geothermal energy could only be significant if EGS, another untried technology, is deployed on a large scale. The potential for intermittent RE sources, wind and solar, is far greater, but is unevenly distributed spatially, and both face orders of magnitude scale-up to be major energy suppliers. They will eventually also need conversion and storage, which will greatly raise the costs of delivered energy. For all these reasons, we have argued that a low energy future is more likely.

This study considered four illustrative cases: a high (1000 EJ) and a low (300 EJ) energy future, and for each of these conditions, a high (80%) and low (20%) fossil fuel energy share. We argue that high energy futures are very unlikely, because of resource limitations, and rising money and energy costs per unit of delivered energy as annual energy demand rises. The low energy cases are technically more achievable, although both require large cuts in energy use, and most probably, lifestyle changes in high energy use countries. H_2 production would be best favoured in the low fossil fuel options, with production both greater, and implemented earlier, in the high energy use case. But in contrast to the L_e–L_f case, which we see as the most probable future underpinning a hydrogen economy, H_2 production is least likely in the L_e–H_f case.

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