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Intermittent renewable energy: The only future source of hydrogen?

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Abstract

In this paper we assess the feasibility of various future energy production pathways for hydrogen. We argue that neither nuclear energy, nor coal gasification with carbon collection and storage can provide sufficient climate-neutral energy to be probable routes to a hydrogen future. Their contributions are likely to be too little and too late to be of much help. Hydroelectricity, geothermal and biomass energy can all provide base-load power, but even combined have limited potential, and are not always climate-neutral in operation. On the other hand, the high-potential renewable energy (RE) sources, particularly wind and direct solar energy, are intermittent. Further, wind resources are poorly matched to the existing distribution of world population. Wind power's high potential compared with present electricity demand, high return on energy invested, intermittency, and mismatch with load centres all favour hydrogen conversion and transmission to load centres.
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1. Introduction

In 2005 world primary energy production, excluding non-commercial sources (mainly fuelwood) was 443 EJ, and rose 2.7% over 2004 [1]. In 2004, non-commercial energy was estimated by the International Energy Agency to provide around 10.6% of total energy [2]. Thus total primary energy use in 2005 was around 496 EJ. Given that the UN projects the world population to grow to 8.9 billion by 2050 [3] compared with 6.6 billion at mid-2006, and that average global per capita primary energy use today (even including non-commercial energy) is less than 25% of that of the US [4], by 2050 much higher levels of global energy use are possible [5,6].

Ewen and Allen [7] have recently reviewed a number of possible pathways for hydrogen production. Their indicative costs per tonne of hydrogen indicate much overlap of costs for hydrogen produced by various renewable energy (RE) sources, nuclear, and coal with carbon capture and storage (CCS) routes. Each of these pathways has its strong supporters [8–11].

At present the main source of hydrogen is from steam reforming of methane [7]. However, given that natural gas use for conventional purposes is expanding rapidly [1,2], and that its use is likely to peak by 2045 [12], or even as early as 2030 [13], natural gas steam reforming is unlikely to ever provide large amounts of hydrogen. Accordingly, this paper focuses on nuclear options, both conventional and novel, coal gasification with CCS, and RE sources as possible avenues to a hydrogen future. It does this by examining the feasibility of each route in providing a major share of future energy needs for the long-term, while minimising emissions of CO_2 and other trace gases. If an energy source cannot provide long-term more than a fraction of our present energy needs, it is unlikely to provide a route to a hydrogen future. The present study focuses on hydrogen production; it does not examine ways in which hydrogen might be consumed. Nevertheless, constraints on natural gas supply—which could occur in less than a decade, well before peak gas production [13]—could provide an important incentive for hydrogen production.

Our discussion on possible new energy-related technologies will be guided by the following principles:

- At the very minimum, a proposed energy source must give net energy, that is, the energy ratio (energy output divided by input energy) must exceed unity. Further, an energy source may presently give a high energy ratio, but

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as annual output (RE) or cumulative output (fossil fuels) is expanded, the energy ratio falls. Eventually the energy source can even become an energy sink, as lower-quality resources (lower yield uranium ores, lower average wind speeds) are tapped. Economic cost estimates are useful, but must be used with caution for energy decision-making. All energy sources—fossil carbon fuels, nuclear, and renewable—receive subsidies in one form or another. Also, all energy production produces externalities—costs and sometimes benefits—which are usually not included in cost calculations. Even if these corrections were made, monetary costs of energy still provide no signal that a given energy source has become an energy sink.
- Caution is needed in comparing technologies under development, or merely proposed, with existing, working technologies. Experience shows that the difficulties, costs, and side effects of new technologies are often badly under-estimated. For example, predictions for nuclear power made in the 1970s proved inaccurate because of unexpected technical difficulties and popular opposition [14].
- The introduction of a new technology to solve the problem of global climate change must not worsen other environmental problems, such as ocean acidification, groundwater quality deterioration and depletion, or species diversity loss. In other words, its sustainability must be assessed against all areas of environmental concern.
- All energy production plants, not only fossil fuels, have climate change impacts because of the energy inputs to construct, maintain and decommission them. Further, some RE sources as well as fossil fuels, emit greenhouse gases during operation. There is thus overlap on CO_2 equivalent emissions per unit of energy produced. Some proposed RE sources can even directly affect climate, in addition to greenhouse gas emissions. Therefore, all climate change effects of RE sources must be evaluated.
- The proposed energy sources must be politically feasible, as public support is needed for siting plants and often funding them. A related point is that it must be capable of being implemented in a time frame that is relevant to tackling effectively the issue of climate change—which may be only a few decades. New technologies that will only be significant later in this century do not satisfy this criterion.

The remainder of the paper has four main sections. The first two look in turn at hydrogen production from nuclear energy (both fission and fusion) and from coal gasification with CCS as a means of averting serious climate change, and show that both have uncertain environmental effects, costs, timetables for implementation, and technical potential. The third examines the three RE technologies capable of providing base-load electricity or heat—hydro, geothermal and bioenergy—and shows that they are not only of limited potential but also emit significant greenhouse gases, compared with the fossil fuel systems they would replace. The fourth main section looks at intermittent sources of energy, and shows that potentially wind could provide primary electricity far in excess of present global electrical use. Solar electricity potential is much larger, but energy and money payback times are presently high. We conclude that wind energy will be the most probable pathway for large-scale introduction of hydrogen energy.

2. Nuclear energy

2.1. Fission reactors

Nuclear power could produce hydrogen by either electrolysis of water, or by direct thermal decomposition of water using heat from high temperature reactors [7]. Nuclear power in 2005 produced 10.0 EJ of electricity, around 15.4% of the world total, from about 440 operating reactors, nearly all of the light water type [1,15]. Nuclear energy has proved unpopular in many western countries, and hence the share of electricity generated by nuclear power is falling in Western Europe and the US, and even in the world overall in the last decade [1]. Evidently, a vast expansion of nuclear energy could be limited by popular opposition or a lack of official support, but it could also be limited by uranium (U) supplies. A recent nuclear industry estimate for proven reserves is 2.85 million tonnes (MT), and for ultimately recoverable conventional resources, 17.1 MT [16]. If, as in a recent review article [15], nuclear plants were to provide 10 TW (terrawatt $= 10^{12}$ W) thermal power output by the year 2050, available U in present reactor types would only last for 30 years for ultimately recoverable conventional resources, and a fraction of this if only proved reserves are considered. On the other hand, at present rates of nuclear electricity production, 17.1 MT would last for nearly 300 years [16].

The foregoing analysis assumes that uranium concentrations lower than roughly 500 ppm by weight would be uneconomic. U ores presently mined are typically around 2000 ppm [15,17]. With very low concentrations, not only the cost, but also the energetics of extraction become important, in addition to the environmental problems of mining, milling and disposing of such huge volumes of soil or rock. The present energy ratio for nuclear electricity is satisfactory. An early but very thorough analysis by Chapman [18] for a number of UK reactor types gave a range of energy ratios from 10.2 to 16.5 for electrical energy output compared with thermal energy inputs. A recent analysis for Japan [19] found that energy for enrichment dominates the inputs to nuclear power, accounting for 62% of the 24.2 g-CO_2/kW h life cycle emissions. Emissions from mining and milling, in contrast, were under 5%. But the energy ratio for nuclear power, and thus its CO_2 emissions compared with fossil fuel electricity, is very sensitive to U ore grade [17,18,20]. The mining and milling energy requirements for U rise exponentially as ore grades decrease [18]. For concentrations below 100–200 ppm they are so high that CO_2 emissions from nuclear power plants exceed those from an equivalent natural gas power station [17].

The resource constraint can in principle be surmounted in two ways: use the vast amounts of uranium in seawater, and to a lesser extent, phosphate rocks, or use breeder reactors. From the discussion above, it seems doubtful that mining of low U-concentration phosphate rocks would give net energy in present reactors [17]. The world’s oceans contain an estimated

4–5 billion tonnes of U, at 3 μg/l [15–17]. For 10 TW thermal power from nuclear energy, about 200,000 km^3 of seawater would therefore need to be processed each year, even assuming a 100% extraction rate [15]. The energy and the environmental costs of doing so would both rule out extraction of U from sea water as a solution [17].

Breeder (fast) reactors could potentially extend the uranium reserves by a factor of perhaps 30. They would also allow use of fertile thorium resources—presently estimated at 4.5 MT—to produce fissile material for use in reactors [16]. Recently, countries which account for most of the world's nuclear power have joined together to form the Global Nuclear Energy Partnership (GNEP). The aim of the consortium is to select and design research prototypes of new high-temperature reactors. The five reactor types on the short list include three breeder reactor designs. But as the head of France's Atomic Energy Commission commented: 'This is long-term research; if we have a working demo by 2030 we will be doing well' [21]. An American nuclear expert from MIT is even blunter about US prospects from this program: 'Even if the government can find the funds, GNEP is unlikely to succeed in meeting its goals' [22].

The conclusion reached here, that for fission reactors to be a major producer of climate-neutral energy, a shift to breeder reactors is necessary, has been argued for at least the past 25 years [5,15,23]. The only commercial breeder reactor built, France's Superphenix, was shut down in 1998 after experiencing numerous problems. Decommissioning the reactor will take a century, and will cost an estimated $2.75 billion (in 1999 $US) [24]. Fast reactors are not only presently much more expensive than thermal reactors, but because of the reactivity of the liquid sodium coolant, high power density, and high operating temperatures, are also inherently more difficult to operate safely. The need for multiple cycles of reprocessing to extract plutonium and other fissile material, would increase the risk of plutonium diversion.

2.2. *Fusion reactors*

In 2005 an international consortium finally decided to locate the International Thermonuclear Experimental Reactor in southern France. But even proponents of fusion energy do not expect the first commercial fusion energy plant to be operational before 2050 [25]. Critics of the project claim that the extremely high operating temperatures, stresses from thermal recycling, radiation-induced degradation of the structural materials, and the thick shield of expensive materials needed to protect against the neutron flux cast doubt on the viability of the design. Even if successful, capital costs could be very high—one estimate is \$15,000/kW h$_e$ [26,27]. In summary, fusion power could only make a significant contribution to world energy needs toward the end of this century, and quite possibly never, because its costs appear to be far higher than most alternatives.

2.3. *Discussion*

Overall, the present low-temperature light water reactors in use around the world cannot directly produce hydrogen. The very high temperature helium cooled reactor, which is to be investigated under the GNEP, could do so, but is not a breeder reactor [21]. Abundant nuclear hydrogen requires breeder reactors, very high temperature operation, and multiple fuel reprocessing and fissile material recycling. Further, reprocessing rates have to be matched to reactor fuel needs. These multiple conditions are unlikely to be met any time soon. All fission reactors also have energy costs for decommissioning and waste storage, which must eventually be paid.

Nuclear power will also inevitably spread to countries with weak or even non-existent effective central governments. This spread will evidently heighten the risks of reactor safety, waste disposal, fuel reprocessing, and terrorist activity, presently experienced by all countries with nuclear programs [28]. Even the US, with its long experience in nuclear matters, has had great difficulty in simply storing its enriched uranium safely [29]. It therefore seems unlikely that fission reactors will form the basis for the world's future carbon-neutral energy needs. Fusion reactors would share many of these problems, particularly if fission–fusion hybrids were used [23]. Large amounts of energy from high-temperature breeders, and especially fusion plants, could only be available in the second half of this century, but some climatologists argue that we may have only a decade or two to take effective action to avoid irreversible and serious climate change [28]. Most probably, nuclear energy will simply supply a declining share of base-load electricity, as forecast by the International Energy Agency [13].

3. Coal with carbon sequestration

The advantage of coal gasification with CCS is that it would enable continuation of the present fossil fuel economy, and the use of coal, the most abundant fossil fuel. The carbon dioxide content of the atmosphere can be lowered by general sequestration in plants and soils. Alternatively, CO_2 can be captured at point emitters such as coal-fired power stations. It should be possible to gasify coal in an oxygen-blown gasifier, then after cleaning, separate out both the hydrogen and the CO_2. After capture, the CO_2 can be stored in the deep ocean, or in geological reservoirs such as disused oil and gas fields, salt mines or saline aquifers [15].

Carbon sequestration in plants and soils would merely help reverse the loss from these carbon reservoirs over the past two centuries [30]. However, the storage may only be temporary, as any rise in temperatures could increase respiration in both plants and soil heterotrophs [15,31]. Deep ocean disposal would attempt to solve one problem by worsening another—ocean acidification. Apart from other stresses on ocean life, acidification could eventually lead to plankton with calcium carbonate skeletons being unable to form their calcareous shells [32]. Deep ocean disposal is probably also far more expensive than geological disposal, and in any case would not be permanent [33].

Two components of geological sequestration, storage and transport of CO_2, have been, respectively, demonstrated in Norway's Sleipner West gas field in the North Sea, and in enhanced oil recovery schemes in North America. But CO_2 capture from power stations has not been commercially attempted. Costs (both in monetary and energy terms) and technology for this part of CCS are therefore speculative. The Intergovernmental Panel on Climate Change estimate that by 2050, 'around 20–40% of global fossil fuel emissions could be technically suitable for capture' [33]. Not only emissions from power plants, but also those from large industrial plants, were included as suitable.

However, the technical potential for geological sequestration is highly uncertain. Both to assess capacity and to ensure that the injected CO_2 will not soon leak to the surface, each underground storage site will need to be very thoroughly surveyed, as it is very difficult to generalise from one site to another. Estimates for the technical potential of geological sequestration range from a low of 320 to a high of 10,000 billion tonnes (GT) of CO_2 [34]. These values need to be compared with the 2004 annual emissions of CO_2 into the atmosphere of 26.6 GT from fossil fuel combustion alone [2]. It is clear that CCS can only play a very minor role in averting climate change if the lower estimates for storage capacity turn out to be more realistic.

In fact, geological sequestration of CO_2 faces a number of obstacles that both limit its scope and delay the likely timeframe for implementation [28,33–35]:

- Injected CO_2 must not be able to enter shallow potable aquifers, since CO_2 can change their geochemistry.
- Many of the most promising sites will need to be excluded, since they will be needed for storage of natural gas (or hydrogen), helium, or for chemical or nuclear wastes.
- The rate at which CO_2 can be introduced into underground storage may also limit the rate of storage increase, since local overpressure could fracture the caprock which ensures storage integrity.
- Adsorption of CO_2 on to coal in presently non-economic coal measures will foreclose the option of later use of this coal for gasification.
- Areas at risk from seismic activity will need to be excluded.
- Given the low-probability but high human impact of sudden CO_2 releases, location of storage near populated areas is likely to be politically difficult to implement.

Overall, then, CCS faces several severe difficulties, including great uncertainty in both its realisable storage potential and the permanence of CO_2 storage. Retro-fitting of coal power plants is expensive [33], yet the many coal-fired plants presently under construction world-wide are not designed for carbon capture. Even for specifically designed plants, there is a large drop in efficiency—and increased CO_2 emissions. Like nuclear energy, there is a non-negligible risk of a catastrophic accident, which ensures that there will be local political opposition to construction. Without CCS, hydrogen from coal cannot offer a low-CO_2 emission path to the future.

4. Non-intermittent RE

Three forms of RE, biomass, hydro, and geothermal are capable of providing electricity on a continuous basis. Biomass is unique among RE sources in that it can be used directly as a solid fuel, or converted into liquid or gaseous fuels. The following sub-sections examine the global technical potential for each of these well-established energy sources.

4.1. Biomass energy

Biomass is the largest RE source, providing in 2004 around 10.6% of global primary energy [36]. What is its global technical potential? Photosynthesis produces a total global net primary production (NPP) of roughly 3000 EJ annually. (NPP measures the net conversion of atmospheric CO_2 by photosynthesis into plant biomass over a given time period.) Total NPP on land is presently estimated to be about 120 billion tonnes dry matter annually, corresponding to about 1900 EJ [37,38].

The terrestrial NPP of mainly *natural* vegetation can be used as a proxy for biomass theoretical potential, since it appears that intensive agriculture cannot produce higher annual biomass yields/hectare than natural systems. A satellite-based NPP study of all the earth's vegetated surface at 1.0 km resolution showed that the average biomass yield for cropland is similar to that for 'needleleaf forest', but far below those for savanna or 'evergreen broadleaf forest' [38]. Natural systems do not need the network of roads, small dams, or farm buildings necessary for agricultural production; all reduce output on a km^2 basis. Natural ecosystems also mostly recycle their nutrients and carbon, whereas the whole point of agriculture and forestry is to remove crops and timber, and unavoidably, the plant nutrients and carbon they contain. Consistent with this argument, Haberl [37] reports NPP before agriculture as higher than today.

Dutch researchers [39] examined a number of studies giving the technical potential for biomass in 2050. They found a range from 33 to 1135 EJ annually, with varying land availability and yield levels explaining the spread. The lower value is even less than current total biomass use—but even present biomass may be being produced unsustainably.

'Modern' biomass energy can be derived from either wastes/residues (municipal, farm, or forest), or from dedicated energy plantations of short-rotation trees or grasses. Unlike biomass plantations, agricultural/forestry residues and municipal wastes often have a low opportunity cost, and in some cases may be free. Municipal wastes are likely to be only a minor energy source, given the growing interest in recycling [30]. Agricultural wastes are very large, but often have existing uses. In any case, a large fraction of crop, animal, and even forestry wastes may need to be left in place for soil fertility maintenance and erosion control. Soil carbon loss can be prevented only if crop residues are recycled rather than removed and burnt as a fuel. Hence, not only does removing residues require energy intensive fertilisers to restore fertility, but combusting residues for fuel is usually not carbon neutral [30].

Competition from greatly expanded agricultural and silvicultural systems to meet future world demand for food, fibre, and forestry products will greatly affect biomass availability from energy plantations. Agricultural output growth has been largely achieved by intensification: increasing output per hectare by increasing inputs of energy-intensive fertiliser, pesticides, irrigation water, and machinery. But the energy ratio is lower for intensive agriculture—or energy plantation—systems, even if output/hectare is higher [40].

Because future production of food, fibre and forestry products will increasingly compete with energy plantations for inputs, the two should be analysed together when considering greenhouse gas emissions. Consider the case of a food-exporting country which decides to use some prime farmland for energy crops (e.g. ethanol from corn) rather than for food crops for export. A food-importing country, however, may now have to grow additional food on unsuitable land with high-energy inputs, particularly for water. The result may be that the total global greenhouse gas emissions from the energy and food sectors combined are even greater than if no energy plantations had replaced fossil fuel use [6]. A key energy input into present agriculture is irrigation water—some 40% of global food is grown using irrigation. Energy plantations grown on marginal land will increasingly require irrigation, which can have very high energy inputs [30]. And forest energy plantations in high latitudes will have a lower albedo than the snow-covered ground they replace. Thus boreal-zone planting could enhance global warming, negating the CO_2 absorbtion of the biomass [31].

In summary, while there is scope for more use of wastes such as bagasse, land fill and sewage methane, and municipal organic wastes, the total additional energy will be small—all are already used to some extent. Large biomass energy production needs energy plantations, but even the present agriculture/forestry system is causing severe environmental damage. Further, humans already appropriate as much as 26% of the entire global NPP [41]. There seems little scope to sustainably expand both agriculture/forestry to meet the needs of a growing population and develop vast energy plantations. Time also works against biomass energy plantations—in the several decades it would take to establish these as major sources of energy, the competing demands of food and fibre will rule them out as an energy source.

4.2. Hydroelectricity

Hydroelectricity in 2005 provided 10.7 EJ of primary electricity, or 16.5% of global electricity production [1], but its share has steadily fallen over the past century. Hydropower is unusual among RE sources, not only because it is a mature and major electricity source, but also because estimates for technical potential vary little from study to study. For large hydro schemes, it is estimated at some 50 EJ/year, about one third of the resource base of 130–150 EJ/year. Much of the total gravitational energy can not be tapped because of frictional losses from downstream water flow, because a minimum flow rate is needed if rivers are to perform their various ecological functions (and allow shipping), and because much of the flow is too diffuse to be collected in very small tributaries. The realisable potential is much smaller, with estimates ranging from 25 to 31 EJ electric [6].

Hydro schemes themselves are not always climate-neutral. Most remaining hydro potential is in the industrialising countries, mainly in tropical or sub-tropical regions [6,42]. At many potential sites, tropical forests would be inundated. As trees die, they release their carbon to the atmosphere. If decay is aerobic, CO_2 will be released, but if anaerobic, CH_4, a much more potent, if shorter-lived, greenhouse gas. Emissions of both gases from tree decay will fall over time. But additional CH_4 will be released each year as vegetation grows on land uncovered, then covered again by varying water levels [43]. For some hydro plants in South America, total greenhouse gas emissions can rival those from a gas-fired power plant of equal electric output [44].

Equally important are the impacts of future climate change *on* hydro potential. Past annual river flow rates, and especially seasonal flow rates, can no longer be assumed to be stable over the long planned life of hydro schemes. There is evidence [42] that annual river flow rates in some regions are already changing, with increases for rivers flowing into the Arctic Sea. On the other hand, for the European Union, recent research suggests that hydro production is likely to fall if climate change continues [45]. Harrison and Whittington [46] stress that 'most hydropower schemes are designed for a particular river flow distribution', and conclude that because of hydropower's reliance on climatic conditions, any changes can adversely affect hydro project financial viability, and hence the likelihood of their construction.

Also, any further global temperature rise means an increasing share of total precipitation falling as rain rather than snow, as well as earlier snow-melting, leading to river flows much more temporally skewed than formerly. Potential evaporation from catchment areas and reservoirs will also increase [42]. All these changes—as well as land-use changes unrelated to climate change—can have significant implications for hydro power output. In summary, at most hydro can provide about 30 EJ of primary electricity, but any climate change could reduce this potential. Further, hydro schemes themselveses can have significant greenhouse gas emissions.

4.3. Geothermal energy

Geothermal energy flows in small amounts from the Earth's interior as a result of heat generated during the Earth's formation, and from heat released by decaying radioactive isotopes in the upper crust. In 2004, geothermal electricity production was about 0.2 EJ, with a somewhat larger production of thermal energy used directly as heat [36,47]. Like bioenergy, geothermal energy can provide both electrical power and direct heat on a continuous basis over the life of the installation.

Although estimates for global electricity technical potential vary greatly, the most detailed estimate calculated an annual total of only 3.9 EJ for conventional geothermal power [6]. This low technical potential estimate is supported by the recent data from the four OECD countries with decades of experience in geothermal power: Italy, Japan, NZ, and the US. Installed capacity in these countries rose from 3.7 to 4.6 GW between 1990 and 2000 [48]. Yet electrical output rose more slowly, implying a declining capacity factor. Indeed by 2005, effective installed capacity itself was probably less than in 2000 [47]. The reason is that although geothermal energy will be renewable for millions of years, for economic reasons power plants usually extract heat faster than it is locally replenished. World potential for direct heat is higher, but low-temperature heat cannot be transmitted far, because of heat losses. This drastically limits its useful potential [49].

Geothermal energy potential is not affected by climate change. However, like hydro power, geothermal energy can release CO_2 during its operation, compared with emissions before construction of the plant. The emissions vary greatly from plant to plant, and the reported range is from 0–400 g CO_{2eq}/kW h, compared with about 450–1250 g CO_{2eq}/kW h for a typical natural gas plant [50].

Hot dry rock technology is sometimes seen as a way of providing abundant base-load electric power. But no such systems are in commercial use anywhere, and estimated costs of electricity produced are several times higher than for conventional geothermal systems. The net energy from such systems is problematic, particularly for greater depths and lower sink temperatures [49]. In summary, geothermal electricity will always only be able to meet a very small part of global and even regional electricity demand.

5. Intermittent RE

Growth in installment of photovoltaic (PV) cells has been rapid (30% over the past decade), but the baseline is small. At mid-2006, total installed capacity was about 5 GW [51]. Total electrical output from all forms of solar electricity in 2004 was negligible at 0.01 EJ electricity [52] which is equivalent to a capacity factor of around 10%. Nevertheless, the technical potential for solar electricity, whether from PV cells or solar thermal, is enormous relative to total world energy use. The problem is that solar electricity is still far more expensive than other RE, and further, its present energy payback times are much longer than, for example, wind [6]. One recent study [53] found payback times for building-integrated PV cells of from 4.5 to 16 years. However, recent research holds promise of breakthroughs in reducing both the energy and money cost of PV electricity [51,54]. A variety of approaches are being adopted, but all aim to reduce the energy costs of silicon wafers per unit of electric output while maintaining or enhancing conversion efficiency. Higher efficiency is necessary for lowering the balance-of-system costs [51]. PV cells have found ready markets in off-grid electricity generation [51], and could be an important part of local, distributed generation [28]. However, in line with our principles for new energy sources outlined above, we cannot say that PV cells presently provide a probable route for hydrogen, but may do so in the future.

Wave energy potential may also be large compared with present world primary energy demand, but with no installed commercial plants, energy and money payback times are speculative. Shore-based small ocean thermal energy conversion units could provide continuous energy, but large scale implementation would require plants on ships that continuously moved around the tropical seas. Conversion of electricity to some other energy form would be needed. Energy and money costs are even more speculative than for wave energy, and large deployment could have serious environmental consequences [23,55]. Tidal energy is intermittent but occurs at known times. Its technical potential is very small relative to world energy demand, and will be of only local importance [6].

Wind power is the most successful of the new forms of RE, with recent annual growth rates averaging around 30%, rising to 40.5% in 2005. Installed global capacity has risen from 1.9 GWe in 1990 to nearly 60 GWe at the end of 2005. Wind generators produced some 0.45 EJ of primary electricity in 2005, almost 0.7% of global electrical output [13]. Even large wind energy outputs would only have a minor effect on global climate. The modelled globally-averaged temperature change from even two TW of installed wind turbine capacity is negligible, although small local temperature changes could occur. Even these could be beneficial 'because they can act to reduce, rather than increase, aggregate climate impacts' [56]. Similarly, further climate change will have a negligible effect on wind potential.

Recent estimates of the global technical potential for onshore wind depend heavily on assumptions about the extent of land with suitable winds that must be excluded. The 2001 Intergovernmental Panel on Climate Change study [42] estimated the global theoretical terrestrial potential as 480,000 TW h, from land with mean annual wind speeds $\geqslant 5.1$ m/s at 10 m above the ground. Based on the experience of the Netherlands and the USA, it was then assumed that only around 4% of this potential could be developed, or 20,000 TW h (72 EJ of primary electricity). In contrast, a recent Dutch study estimate is 346 EJ primary electricity [57]. Not only was the cut-off mean annual wind speed at 10 m height lower (4 m/s), but land use constraints were far more relaxed.

Given the evidently arbitrary basis for the exclusions, it is more useful to estimate maximum global wind potential initially ignoring any land use constraints. Such an approach is then consistent with that used for estimating hydro power potential. The recent data of Archer and Jacobson [58] allow such an estimate. At 80 m above ground level, class 3 winds and higher ($\geqslant 6.9$ m/s average wind speed) occur on 12.2 million km^2 of the inhabited continents. Assuming a turbine spacing of one 2.0-MW turbine per km^2 and an average capacity factor (actual annual electricity output as a % of rated full-power output) of 30% [59] for class 3 winds and higher, global potential wind energy can be calculated as 230 EJ primary electricity. Energy analyses of wind turbines [59–61] based on detailed life-cycle analysis (ISO14040–14043) give for a 2.0 MW turbine an electrical energy output to primary energy input energy ratio of around 30. This value is derived via consideration of all material and energy inputs over a 20 year turbine life time for a typical on-shore installation in Denmark. Turbine installation requirements are strongly linked to energy inputs and turbine electrical power output varies relative to the cube of wind speed. Energy ratios will therefore vary considerably with location, and could fall below 20 for a class 3 wind, where the turbine capacity factor is expected to be around 20%. Further, larger-capacity turbines, already in use, give even higher energy ratios

[60,61]. For higher turbine energy densities (e.g. 4 MW/km^2 used in Hoogwijk et al. [57]), far higher outputs are possible, but at some reduction in energy ratios.

Making wind a major global energy source will not be easy. To reach (say) 90 EJ annually, output would have to rise 200 times above the 2005 level of 0.45 EJ. Even if the recent 30% annual growth rate in wind energy output were to be sustained, it would take over 20 years to reach this annual level. Already in the European Union, US, and Australia, there are protests against wind farm siting—although farmers usually welcome the extra income from turbines on their land. The protests arise from concerns about effects on wildlife, particularly bird kills, visual intrusion, and turbine noise. Deaths resulting from birds (and bats) colliding with turbines need to be put in perspective. Assume one death per turbine each year, and uniform use of 2.0 MW turbines. About 6 million turbines would be required for 90 EJ, resulting in 6 million bird deaths annually. Yet annual deaths of wild birds resulting from impact with road vehicles and buildings, and from hunting by humans and domestic cats, run into *billions* per year [62].

People can also change their minds over wind turbines. It is generally agreed that the early Californian turbines were often poorly sited and constructed with minimal regard for the environment. The case of Palm Springs in California is instructive. There was initially much opposition to the siting of turbines in the San Gorgonio Pass, but over time, opposition lessened and the wind farms are now both a tourist attraction and a source of revenue for the city [63]. Nevertheless, a global expansion by a factor of 200 would require major changes in attitudes. On the other hand, opposition to wind power is less deeply based than is the case for nuclear power, or perhaps even carbon sequestration. In both these cases—in contrast to wind turbines—there is a finite chance of catastrophic accident from each installation, as well as some hazard from their normal operation.

Opposition to wind farms is not the only obstacle to be overcome. Much wind potential is in remote, high-latitude locations [58]. Remote location, intermittent supply, and large technical energy potential compared with electricity demand eventually necessitate conversion and storage of wind energy, and transmission to load centres, thus providing an opportunity for hydrogen. Electrolysizer units today operate at 65–80% efficiency, with greater efficiencies promised [7,64]. If, on average, we assume that only half the wind-generated primary electricity finishes up as hydrogen after electrolysis and transmission to load centres, energy ratios will be halved. Additional reductions in energy ratio will occur should the hydrogen be converted either thermally or chemically to electricity for end-use. Both this halving of delivered energy, the substantial money investments needed for electrolizer units, compressors, and transmission pipes, and for some hydrogen storage at both points of production and end-use, will lead to further cost increases for hydrogen. Underground storage of hydrogen would use much the same locations as natural gas or CO_2 storage [64], and would encounter similar problems. Unlike CO_2, however, hydrogen would require much less storage capacity than CO_2 since storage needs only to match rate of use rather than cumulative use.

A comparison with petroleum is instructive. If the energy content of petroleum crude is ignored, the average energy ratio of US oil has fallen from 100 or more in 1930 to only 20 in 2000. For gasoline, it falls further to 6–10 [65]. Presumably, these present energy ratios are still regarded as satisfactory. As we have shown, wind turbines could deliver over 200 EJ of intermittent electricity at a minimum energy ratio of at least 20, and thus hydrogen to load centres at energy ratios of ten and above. The average energy ratio for wind will, of course, be higher than these minimum values. The ratios compare well with US gasoline—and far better than corn ethanol [65]. Hydrogen energy from wind will not be cheap, but except for minor amounts from some base-load RE sources, neither will any other climate-neutral energy source.

6. Conclusions

Given that about 80% of global primary energy is provided by fossil fuels, replacement by one or more alternatives will entail massive changes and many problems. The challenges become particularly acute if, as some scientists believe, the conversion to a new energy system must be made in a few decades to avert serious climatic change. Given the time-frame, much of the reduction in fossil fuel use will have to come from energy conservation.

Uranium resources are not sufficient for conventional light water reactors to generate for the long-term more than a fraction of existing electricity requirements. Both breeder and fusion reactors could potentially provide large quantities of high temperature heat for climate neutral hydrogen production, but both look doubtful as viable energy sources—at least in the time-frame of interest. Another possible route, coal gasification with CCS, entails a large energy penalty (and hence CO_2 and cost penalty) associated with proven methods of CO_2 separation. Many of the most desirable storage sites are needed for other purposes—including hydrogen storage. The lower limit for the amount of CO_2 that can be safely and permanently stored may be only an order of magnitude larger than current annual CO_2 emissions. Finally, even supporters only see 20–40% of CO_2 emissions sequestered by 2050. CCS is thus likely to be both too little and too late for avoiding global climate change.

The three RE sources which can provide base-load electricity—hydro, biomass and geothermal—will together be unable to satisfy even existing electricity demands, and in any case are not climate-neutral when operating. The only remaining route is thus from intermittent RE sources. Solar energy is abundant, but is presently costly, with a low energy ratio compared with wind, although promised improvements in energy ratio could change this. Even the minimum technical potential for wind turbines is several times present annual electricity consumption. It is not only intermittent but also unevenly distributed compared with population settlement patterns. Fortunately, its high energy ratio allows conversion of wind electricity into hydrogen by electrolysis, while still providing an acceptable energy ratio. Although many challenges remain, the lack of realistic alternatives means that wind turbines are the most probable route to a hydrogen future.

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