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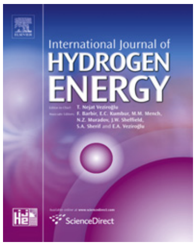

A hydrogen standard for future energy accounting?

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ABSTRACT

Present methods of energy accounting include both primary energy and final energy consumption. Both these methods have inconsistencies, although today their impact is minor. Some level of inconsistency and approximation in energy accounting is unavoidable when energy inputs come from such heterogeneous sources. We argue that in the decades to come, renewable energy will probably come to dominate the energy supply system, with most from intermittent energy sources, particularly wind and solar. In such an energy system, existing measures will become increasingly irrelevant for tracking energy use over time, for assessing a renewable energy source's technical potential, and in determining future energy infrastructure needs. Further, conversion of most primary electricity to a storable energy form will be needed, with some then perhaps converted back to electricity as needed. We propose that in this case energy production and demand, and technical potential for renewable energy sources, will be more accurately measured by use of a new energy accounting framework, based on the energy content of hydrogen.

1. Introduction

In both the world as a whole, and for individual countries, the composition of total energy used has changed drastically over time. As late as 1880, it is estimated that about half of all global energy used was still biomass, with the other half coal [1]. Since both fuels were combusted, adding the calorific content of each fuel was an obvious way of arriving at total fuel use. The addition of other combusted (but non-solid) fuels, oil and gas, beginning in the late 19th century, could also be readily accommodated. The next energy source was hydropower, which did not involve combustion at all. The units of energy used reflected the dominant fuel. Thus in a 1957 paper [2], energy was measured in tonnes (bituminous) coal equivalent, but today tonnes oil equivalent is often used [3], alongside measurement in joules.

Why does energy accounting matter? Given the importance of energy, with possible future restrictions on both production and/or use of various energy sources, we need answers to the following questions. Is our (national, global) energy use increasing or decreasing, and at what rate? How does our national per capita energy use compare with that for other countries? What is the annual technical potential for each of the various renewable energy (RE) sources? How can these potentials be summed to give a total RE technical potential? And most importantly, what type of infrastructure and how much of it will be required to meet our future energy needs? Only by using a consistent energy accounting method can we hope to answer these questions. Our present methods work fairly well; the question is whether they will continue to do so if the energy mix changes away from fossil fuels.

The rest of this paper first discusses (in Section 2) four very different possible futures for energy production that have been extensively discussed in the literature. The energy accounting method appropriate for the future will depend greatly on the future energy mix. One of these energy futures, one dominated by intermittent renewable energy (RE) electricity sources, particularly wind and solar, is regarded as most probable. Section 3 looks at present methods of energy

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accounting, particularly those of the International Energy Agency (IEA) and BP, discussing both their differences and limitations. In Section 4, the implications for energy accounting for each of the four energy futures is examined, and it is concluded that the most probable future needs a new energy accounting system based on hydrogen, because present methods would give ambiguous results. In the final main section (Section 5), the methanol alternative to hydrogen as an energy standard is considered and found wanting.

2. Possible futures for energy production

In 2007, the IEA estimated primary production of energy (see the following section for primary energy definition) as 504 EJ (EJ = exajoule = 10^{18} J). Fossil fuels accounted for 81.4% of this total [3]. What sources of energy will be used decades in the future are most uncertain, but from the point of view of future prospects for the hydrogen economy, four possibilities are relevant, and are discussed in turn in the following sub-sections:

1. 'Business-as-usual' with fossil fuels continuing to dominate primary energy supply
2. Non-intermittent electricity (from nuclear power plants, or renewable energy (RE) sources such as hydro or geothermal electricity) accounting for most input energy
3. Intermittent RE electricity sources (solar, both PV and solar thermal electricity conversion (STEC), wind and perhaps wave energy) dominating energy inputs
4. Direct production of hydrogen (from high-temperature nuclear reactors, from algae, or from photolysis) accounting for most energy inputs into the economy.

2.1. *Future energy: Business-as-usual*

Today, as we have seen, over 80% of primary energy is from fossil fuels, and official forecasts from organisations such as the IEA [3] and the US Energy Information Administration (EIA) [4], in their most recent forecasts, have seen this dominance as little reduced in the coming decades. The EIA, for example, forecast in their reference scenario that fossil fuels will still account for 79.0% in 2035, with similar or even higher values in other scenarios.

Nevertheless, we argue that this high share for fossil fuels is unlikely to continue for more than a few decades. Annual fossil fuel availability will probably peak and decrease for two reasons. First, geological reserves are being rapidly depleted, especially for conventional reserves of oil [5–7]. The Alternative World Energy Outlook [8] envisaged total fossil fuel use peaking in a few years. In their recent paper, Patzek and Croft [9] have argued that production of coal, the fossil fuel usually accorded the largest reserves to production ratio [10], will peak very soon. Others e.g. in Refs. [11,12] have also argued for an early peak for coal.

The view of most official international organisations, and even researchers, is of course, that coal reserves are so large that any peak in combined fossil fuels will be many decades away [6]. But geological resources are not the only factor. A second reason for reduction in availability is 'resource nationalism' [13], which could limit exports to importing countries as energy exporting nations either use their exports to gain political leverage (e.g. Russia), or become worried that their reserves are depleting too fast [1,6].

There are other reasons why fossil fuel use could decline to a minor role in a few decades. Concern over greenhouse gas (GHG) emissions from fossil fuel combustion, a concern which will become even more serious as non-conventional fossil fuel reserves are tapped, could greatly cut their future use. Much emitted carbon dioxide (CO_2) also finishes up in the oceans, where it causes acidification, potentially a problem as serious as climate change [1]. Further, fossil fuels are a vital feedstock for industry, a use which is growing with time [3]. It can be argued that remaining fossil fuels are too valuable to be combusted, and should be reserved for industrial feedstocks [14].

2.2. *Future energy: non-intermittent electricity*

In this possible energy future, energy is predominantly supplied in the form of continuously available electrical power (also called dispatchable power) that is not fossil fuel-based. Some researchers envision greatly increased outputs of nuclear power in the coming decades e.g. in Refs. [15,16]. It is unlikely however, that nuclear power will be more than a minor electricity source in the future. At present it provides about 5.5% of global primary energy, and 13.8% of net global electricity; both values have fallen in recent years. The 2010 International Energy Outlook produced by the US EIA envisaged nuclear power accounting for 6.4% of global energy in 2035 in the scenario most favourable for nuclear power [4]. Further, the International Atomic Energy Agency has projected only slow growth in nuclear power's share, even in the more optimistic case for nuclear, with a 3.6% growth in nuclear electricity out to 2030, compared with a 3.2% growth in electricity overall [17].

There are several reasons for these pessimistic official projections for nuclear power. First, as discussed by Schneider and colleagues [18], the world reactor fleet is ageing, so that an active reactor construction programme will be needed just to maintain present output. Second, costs for nuclear plant construction are now very high [19], and may exhibit 'negative learning by doing' [20], reducing its attractiveness as an energy source. Third, reserves of uranium, both proven and inferred, do not appear able to support nuclear energy based on thermal reactors as a long-term major energy source [1,21]. Breeder reactors could in principle greatly extend the life of nuclear power, but as recently argued by Cochran and colleagues [22] in their eponymous article, perhaps 'It's time to give up on breeder reactors'. The experience over the past half century has revealed them to be expensive and difficult to operate safely [23]. Fourth, greatly increasing nuclear power's share of world energy means that it will have to expand mainly in countries outside the OECD. This in turn could increase the risk of both nuclear plant accidents—or sabotage—and of diversion of weapons-grade nuclear material.

Other possible sources of continuously available electricity are geothermal power, hydroelectricity, and biomass. The technical potential for electricity from conventional hydrothermal systems is limited to a few EJ [16]. A 2006 US study [24] forecast a greatly increased role for enhanced geothermal systems (EGS) in energy production. While it is true that there is a vast amount of energy stored at depth in the Earth's crust, it is not at all clear that such EGS electricity can give a net return on energy invested [1,6]. Although a German study [8] gave a high technical potential (around 47 EJ) for hydro—and, incidentally, an even higher potential for geothermal electricity—most studies see the potential for hydro as much lower, at under 30 EJ. Even this value may prove to be far too high, as it ignores both any environmental constraints on further large dam construction, and any reduction in hydro output because of ongoing climate change [1,6]. Nevertheless, it is possible that in some small countries, most energy will come from these sources, as in Iceland today.

The only other possible non-intermittent RE source is biomass, but the present authors [1,6,16] and others e.g. in Refs. [25,26] have argued that increasing competition for fertile, well-watered land for production of food, fibre and forage, as well as for forestry products, will greatly limit sustainable biomass production for energy at an acceptable energy return on energy invested. Also, rising human populations and adverse climate and other environmental changes will further act to limit future biomass energy production.

2.3. Future energy: intermittent RE electricity

All researchers acknowledge that the theoretical potential of solar energy dwarfs all other possible energy sources, whether renewable, nuclear or fossil. Although solar electricity output is growing strongly, its output is still tiny, as is the share of all intermittent electricity in total electricity output (Table 1). In Sections 2.1 and 2.2, we have argued that neither fossil fuels nor nuclear energy will play a large part in future energy supply. That leaves only RE sources, and we have also argued that the three non-intermittent sources—hydro, geothermal and biomass—will be of only minor importance globally, if energy use is similar to, let alone greater than, today's levels.

That leaves solar and wind energy as the dominant sources in the future, particularly if energy levels at or above the present are needed. Wind energy is at present much cheaper than solar electricity, and gives a better return on energy invested [1,27]. Even so, its technical potential is usually estimated at roughly 200 EJ or less when realistic environmental constraints on siting are added [1,8,27,28]. For high levels of energy demand, most will need to come from solar. As we discuss later, intermittent electricity production as the main energy source will require conversion into an energy form that can be stored.

Some researchers have proposed to convert intermittent electricity sources into continuously available electricity by using a worldwide grid or satellite-based solar PV systems [1]. Seboldt [29], for instance, envisaged a world wide grid connecting giant PV installations at different longitudes, and in both the northern and southern hemispheres, so as to overcome both the daily and seasonal variations in insolation. The costs, mainly for transmission, amounted to many trillions of dollars, and this ambitious scheme will most likely never be implemented. If it were to be, however, it would convert intermittent electricity into non-intermittent electricity, as in Section 2.2. Finally, even if extreme demand management could match electricity demand to instantaneous availability, conversion would still be needed for non-electric energy uses.

Table 1 – Gross global electric output, 1970–2008 (EJ) by input fuel [1,3,10].

Electricity source	1970	1980	1990	2000	2008
Total electricity	18.00	29.70	42.72	55.44	72.73
Fossil fuels	13.42	20.91	27.27	36.59	51.45
Nuclear	0.28	2.56	7.20	9.30	9.86
Total RE	4.30	6.23	8.25	10.46	13.75
Hydro	4.25	6.11	7.79	9.55	11.42
Wind	<0.01	<0.01	0.01	0.13	0.91
Biomass	0.04[a]	0.06	0.32	0.60	1.16
Geothermal	0.01[a]	0.05	0.13	0.18	0.20
Solar	<0.01	<0.01	<0.01	<0.01	0.06
Ocean	<0.01	<0.01	<0.01	<0.01	<0.01
RE share of total electricity (%)	23.89	20.98	19.31	18.89	18.90
Intermittent RE share of total electricity (%)	0.0	0.0	0.02	0.24	1.33

[a] Estimated.

2.4. Future energy: direct production of hydrogen

Hydrogen is presently made mainly from fossil fuels, and in future could be made from electrolysis of water using carbon-neutral electricity sources [14,30,31]. But it could also be made directly from either nuclear reactors or from renewable energy sources. Fossberg [15] has argued for the production of hydrogen from high-temperature nuclear reactors using a thermochemical cycle to dissociate water into hydrogen and oxygen. But as we have argued, it is doubtful that nuclear power use will ever rise much beyond its present low and declining share of global energy.

Hydrogen can also be produced directly from solar or biomass energy. Direct photolysis involves splitting water with a suitable (and economic) catalyst [32]. It has been achieved in the laboratory, but it is uncertain whether it will ever be a viable source of hydrogen. Another approach is to use algae or other organic substrates to produce biological hydrogen [32,33], although actual results have been disappointing [34]. Larkum [35] in a review article on bioenergy production argued that 'the culturing of algae brings with it another set of problems such as stirring, nutrient supply, optimisation of the light field, optimisation of the growth conditions and protection from pathogens and nuisance 'weed' algae.' He concluded that algae and cyanobacteria are unlikely as a future source of bioenergy.

However, Larkum [35] thought that photobiohydrogen production and artificial photosynthesis could show more promise in the longer term. Others claim that combining the various biohydrogen approaches shows promise for increasing hydrogen production rates [33]. If any of these methods were to prove economically feasible in the longer term, it would give a boost to applications, such as fuel cells for transport vehicles or combined heat and power systems (CHP), that use hydrogen directly.

3. Present methods of energy accounting

The IEA defines total primary energy supply (TPES) as: 'production + imports − exports − international marine bunkers − international aviation bunkers ± stock changes. For the world total, international marine bunkers and international aviation bunkers are not subtracted from TPES' [3]. An estimate for non-commercial biomass fuels is included in the total. Hydro and other primary electricity (e.g. wind and solar PV) are converted on a 1:1 basis. Geothermal electricity is assessed in the same way as fossil and nuclear electricity by counting the heat input. If this input is not known, an average thermal efficiency of 10% is assumed. Thus one joule of electricity is counted as one joule of primary energy in the case of wind and hydro, around three joules for coal-fuelled electricity, and as much as ten joules for geothermal power. Although these inputs are resource specific, these differences have significant implications for resource management and infrastructure development for a particular level of future energy supply.

In contrast, BP excludes non-commercial fuels, and converts both nuclear and hydroelectricity to primary energy 'by calculating the equivalent amount of fossil fuel required to generate the same volume of electricity in a thermal power station assuming a conversion efficiency of 38% (the average for OECD thermal power generation)' [10]. (This percentage can be adjusted as fossil fuel power station conversion efficiency improves: for the 1930s, Hoffman [2] reported an efficiency of only 17.5%). BP estimates of global primary energy are thus lower than the IEA estimates, because as shown in Table 1, primary electricity is still very small, and its effect is swamped by the exclusion of non-commercial biomass energy. In 2007, global primary energy figures were given by the two approaches as 504 EJ (IEA) and 466 EJ (BP).

The BP approach makes some sense for hydro compared with nuclear given that at present, both only produce electricity (and in similar amounts), yet nuclear's share of global primary energy is evaluated by the IEA method as several times higher, which gives a very misleading picture. On the other hand, the IEA evaluates one kWh of geothermal electricity as worth several times more in primary energy terms than one kWh of fossil fuel or nuclear electricity, because of its very low conversion efficiency. Given the very low output of geothermal electricity (Table 1), this bias does not matter much. Yet another problem is that pointed out by supporters of exergy analysis who claim that these existing accounting systems lack inclusion of the limits imposed by the second law of thermodynamics; in other words, we must account for the role of the environment in modelling our energy flows. While we acknowledge these limits, the present energy accounting methods work reasonably well in our fossil fuel economies. In summary, the anomalies do not matter much today (see Table 1), but will become important as RE increases its share of global primary energy. (Note that 'primary energy' when used in this paper will refer to the IEA definition of the term.)

One possible way around this problem is to use secondary energy (or total final consumption (TFC) as the IEA terms it) for energy accounting, since all kWh of electricity are here counted equally, regardless of source. The IEA defines TFC as: 'the sum of consumption by the different end-use sectors. Backflows from the petrochemical industry are not included in final consumption' [3]. Thus petroleum fuels such as petrol and diesel, and delivered natural gas and electricity are all included in TFC, as is traditional fuel wood. It is only TFC that can provide the energy services that are needed by households and businesses. In line with TPES, TFC is growing: in 2007 the IEA estimated TFC to be 346 EJ [3], up from 196 in 1973. But TFC can also be misleading for interpreting time series if the share of electricity in the TFC mix is changing, since conversion energy losses for generating electricity from oil for example, are far higher than those for converting oil to transport fuels. In 1973, the 'other' category of TFC, nearly all electricity, was only 11.0%, but by 2007 this category had almost doubled to 20.5%. The lower conversion efficiency of electricity and its increasing dominance is further reflected in the TFC/TPES ratio which has fallen from 0.765 in 1973 to 0.689 in 2007 [3]. This trend will continue if, as expected, electricity continues to increase its share of TFC in the coming decades [4].

4. A proposed hydrogen standard for energy accounting

If the future energy production mix is similar to today's, with most energy derived from fossil fuels, there will be little reason to change existing energy accounting methods, which were derived for fossil fuels being the main energy source. (The only difficulty would arise if *in situ* combustion was widely practiced, as has been suggested for Canadian tar sands and other heavy oils [36]. In this case the primary input fossil energy combusted would often be unknown, as the process is difficult to control [37], so that only a system based on final energy could be used.) It is the remaining three possible energy futures given in Section 2 that will test existing methods of energy accounting.

Even in our present fossil fuel economy, electricity is increasing its share of final energy consumption, though at present it only accounts for about a fifth of TFC. Electricity can be used for most final energy consumption: it can be used (and is sometimes being used) for space heating and cooling, water heating and for transport vehicle propulsion. As documented by many papers in this journal, hydrogen is also a convenient energy carrier, along with electricity, and the two are readily interconvertible see, for example, [30,38,39]. Winter [38], in his paper *Electricity, hydrogen energy—competitors, partners?* distinguished 'three realms where hydrogen and electricity:

a) have their respective domains,
b) are partners,
c) compete with each other.'

What is noteworthy is that the domain he described for electricity is far larger than that for hydrogen. The two energy carriers he saw as partners in fuel cells, but competitors in the transport field. According to Winter, an important exception in transport is air travel, where electricity is not an option [38]. Thus, if nearly all energy is initially supplied as electricity, and is continuously available, as in the future described in Section 2.2, an electricity standard of energy accounting would make sense, just as the present one, based on fossil fuels, suits a fossil fuel-based energy supply system. Since there are energy losses in the conversion of electricity to hydrogen, such conversion would likely only occur if a given energy need could not be met with electricity. Total electricity produced would correspond to TPES, and the same value, less losses, would correspond to TFC in the IEA scheme. This implies that one joule of electricity is considered equivalent to one joule of hydrogen, a point we will take up in Section 5.

Now consider the third energy future (Section 2.3), in which electricity from intermittent sources, especially wind and solar, dominates energy production. Some of this electricity can be fed directly into the electricity grid, with the amount varying seasonally in the case of STEC, where heat storage could enable round-the-clock electricity production in summer, even at middle latitudes. In addition, any electricity from hydro, geothermal, biomass and nuclear would also be continuously available. Smart grids can be used to manage and distribute these inputs to supply base-load and peak load requirements [40]. If available, distributed power storage systems based on, for example, electric vehicle battery systems can be used to maximise the instantaneous input of the intermittent sources [41]. Nevertheless, a large share of the wind/solar electricity (the exact value depending mainly on their share in total electricity production) would need to be converted to another energy form—here assumed to be hydrogen—and stored. If the continuously available electricity is not sufficient to meet the economy's total demand for electricity, some will need to be converted back from hydrogen to electricity. The remaining hydrogen would be used to meet the non-electrical energy needs currently met by natural gas, and possibly coal and oil.

The key difficulty is that any primary electricity that must be converted to another energy form cannot be treated the same as electricity that is continuously available, such as hydro, geothermal or nuclear. This difficulty could, in principle, be overcome by again using an electricity standard, and assigning each TWh of converted electricity a fraction of a continuously available TWh, with the value of the fraction perhaps based on the reduction factor in the intermittent electricity→ hydrogen→ non-intermittent electricity conversion chain. An important problem with this approach is the confusion in having two types of electricity. Given this difficulty, we propose a new energy accounting system: a *hydrogen standard*, using hydrogen joules (EJ_h). The basic idea, to repeat, is that if intermittent electricity dominates the energy system, as in the future described in Section 2.3, most primary electricity will need to be converted to another energy form such as hydrogen that can be readily stored, and if needed, a fraction converted back to electricity.

We can illustrate the differences between existing methods and our proposal by looking at a hypothetical case in which the global energy system is derived from the various sources shown in Table 2. For simplicity, it is assumed that fossil fuels supply no energy in this mainly solar/wind energy future. Also omitted are any non-electric contributions from solar, biomass and geothermal. Further discussion on the various conversion factors used in Table 2 is needed. For the IEA method, nuclear primary energy is assessed as 'the primary heat equivalent of the electricity produced by a nuclear power plant with an average thermal efficiency of 33%' [3], thus TFC is 33% of TPES. Hydroelectricity is converted on a 1:1 basis to primary energy, and for biomass/geothermal electricity, a combined average conversion efficiency half that of nuclear (16.6%) of heat to electricity is arbitrarily assumed. As observed above, some of the wind/solar sources could be used directly but the amount will ultimately depend on grid acceptability, which based on existing grids in Europe is limited typically to around 20%. Improvements to the grid to increase this proportion will need to be balanced by the cost of energy storage, but on a global scale it is likely to be always far smaller than the total amount of intermittent energy produced. In the example below we assume direct use to be 9% of the total wind/solar supply giving rise to 10,000 TWh of direct electricity, equivalent to roughly half the total electricity currently used. The balance of this energy is intermittent, and despite the differences, the IEA would convert both these on a 1:1 basis, as for hydroelectricity.

For the proposed hydrogen standard calculation, the first four row entries are converted to hydrogen equivalents on the basis that hydrogen and electricity are equivalent. Each EJ of continuously available electricity, including that from 'wind/solar-direct' is thus equivalent to one EJ_h. The first four row entries are thus identical to the first four row entries in the final demand (TFC) IEA method. For the fifth row entry, in which it is assumed that there is no other option but to convert the intermittent electricity to hydrogen and store it for later use, a 60% overall efficiency for conversion to hydrogen and storage is assumed. Although all methods use EJ as the energy unit, the final value for calculated world energy is very different. Of course, the exact value for the proposed hydrogen standard depends on the assumed fraction of electrical energy lost in converting to hydrogen and storing it; this fraction can be expected to change over time.

The current IEA energy accounting system separates out primary (TPES) and secondary (TFC) energy, but the distinction is not really clear-cut. Reticulated electricity is regarded as final demand, but much electricity is in fact then converted to mechanical energy (in the electric motors used in households, factories, and electric public transport), or simply into heat.

Table 2 – Comparison of IEA TPES and TFC calculations and a proposed hydrogen standard for a future world energy system based mainly on intermittent electricity. Units: EJ.

Energy source for electricity	Elec energy output (TWh)	IEA method (EJ TPES)	IEA method (EJ TFC)	H_2 standard (EJ_h)
Nuclear	10.8 (3000)	32.4	10.8	10.8
Hydro	18.0 (5000)	18.0	18.0	18.0
Biomass/geothermal	7.2 (2000)	43.2	7.2	7.2
Wind/solar-direct	36.0 (10,000)	36.0	36.0	36.0
Wind/solar-converted	360 (100,000)	360.0	360.0	216.0
Total world energy	432 (120,000)	489.6	432.0	288.0

Analogously, in a hydrogen economy, much reticulated hydrogen could be converted to electricity (in stationary or vehicular fuel cells) in homes or factories, much of which would in turn be transformed into mechanical energy. (If, however, hydrogen was converted to electricity in centralised gas turbines or large fuel cell power stations, and then reticulated as electricity, it would make more sense to think of the final demand as being electricity.) Where exactly is the point of final energy demand?

Finally, what about the fourth energy future, discussed in Section 2.4, in which the main input fuel is primary hydrogen? Just as direct production of electricity favours its use in as many applications as possible (for example, for transport and space and water heating), so direct production of hydrogen will favour its use for these same purposes. Only for applications where electricity is essential, such as powering electronic equipment, will hydrogen be converted to electricity. But because, again, some electricity must be converted to hydrogen, a hydrogen energy accounting standard will be more convenient. Clearly, the availability of a direct hydrogen supply would act synergistically with the development of technologies/applications that could use such hydrogen directly.

5. Methanol as a possible alternative to hydrogen

Apart from electricity, there are other alternatives to hydrogen, and several of these are discussed in Veziroglu and Sahin [30]. Olah [42] proposed a 'methanol economy', the methanol derived either from conversion of fossil fuels, or from the 'reductive conversion of atmospheric carbon dioxide with hydrogen'. The CO_2 would be carbon-neutral, and could come from either the CO_2-rich exhaust emissions of fossil fuel power stations, or from air capture. Bockris [43] has recently argued for methanol derived from hydrogen, calling it a 'liquid form' of hydrogen. Like hydrogen, methanol has a precise chemical formula and physical properties, unlike oil, coal or biomass. It is also a liquid, making it much easier to transport and store. In fact all liquid hydrocarbons are an efficient method of storing hydrogen at high volumetric density. Further, methanol can be directly used in the Direct Methanol Fuel Cell, without the need for reforming to hydrogen [44]. One often-noted drawback is the toxicity of methanol.

Methanol from fossil fuels is not a sustainable long-term option, for both resource depletion and climate change reasons, as we briefly discussed in Section 2.1. The remaining options are either to produce it from biomass, or to convert hydrogen to methanol using CO_2. At present, up to 40% of CO_2 released from fossil fuel combustion is available for carbon capture and storage, or about 11.6 Gt of CO_2 in 2007 [3]. Clearly, availability of concentrated CO_2 will not be a problem any time soon, but it does have to be collected. Capturing this CO_2 from large fossil fuel power stations would require from 25%–40% of the power output of the plant, with the higher value for plants not optimised for CO_2 capture [1].

In the longer term, however, production of hydrogen, and CO_2 emissions from power plants will move in opposite directions, since hydrogen will increasingly come from RE sources, either directly as discussed in Section 2.4, or from electrolysis, and fossil fuels will be phased out. The CO_2 needed will have to come from air capture, where its concentration is orders of magnitude lower than that from power station flue gas. This low concentration greatly raises the energy needed for capture, such that a coal-fired power plant without carbon capture would require roughly its power output to capture its CO_2 emissions directly from the air [45]. Given the additional energy losses in conversion of hydrogen to methanol, it seems probable that methanol will deliver less energy to the economy than hydrogen, even allowing for its lower storage and transport costs.

6. Conclusions

All energy accounting methods will inevitably have some inconsistencies and anomalies, as these cannot be avoided when energy inputs come from such heterogeneous sources. The present approaches will, however, become increasingly unreliable for charting regional, national or global energy production and consumption over time, or for comparing the energy use of different countries or regions. Some decades in the future, fossil fuel use could well be a minor share of total energy, both because of depletion of high-quality reserves, and because of their major contribution to anthropogenic climate change. The IEA method, we have suggested, overestimates the primary energy contribution of fuels with low conversion efficiency to electricity like geothermal heat, and underestimates that for hydroelectricity. Nevertheless, these two effects today partly cancel out. The real challenge to existing methods will occur when intermittent sources of RE become the main energy supply, as we argued was likely in Section 2.3.

During the transition from fossil to RE, energy accounting could prove difficult, because neither the existing system, nor any proposed modification to it, will work well. We argue that for a future in which most energy input takes the form of intermittent primary electricity, an energy accounting system based on hydrogen would be superior to alternatives. The key reason for change is that at present one unit of intermittent electricity is counted as equivalent to one unit of electricity available on a continuous basis. So, hydro and wind electricity, both primary electricity sources, have their outputs treated identically, as shown in Table 2. Our proposed hydrogen standard avoids this problem. It does, however, treat one unit of continuously available (dispatchable) electricity as equivalent to one unit of hydrogen energy—the two are regarded as interchangeable.

The justification for this approach is that, at certain times, or in certain regions, conversion of hydrogen to electricity will be occurring, while for different times, or for different regions, conversion of electricity to hydrogen will be occurring. Further, conversion of hydrogen to electricity can occur with high overall efficiency if CHP schemes are used. As in clear from Table 2, any intermittent electricity joule that must be converted to hydrogen is not equivalent to one joule of hydrogen, because of high conversion losses. While not the same, our proposed standard is closer to a secondary energy accounting framework, in that some (primary) intermittent electricity is converted into another energy carrier. Nevertheless we stress that as long as most energy is fossil fuel-based, we have little choice but to continue using the IEA (or similar) energy accounting framework.

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