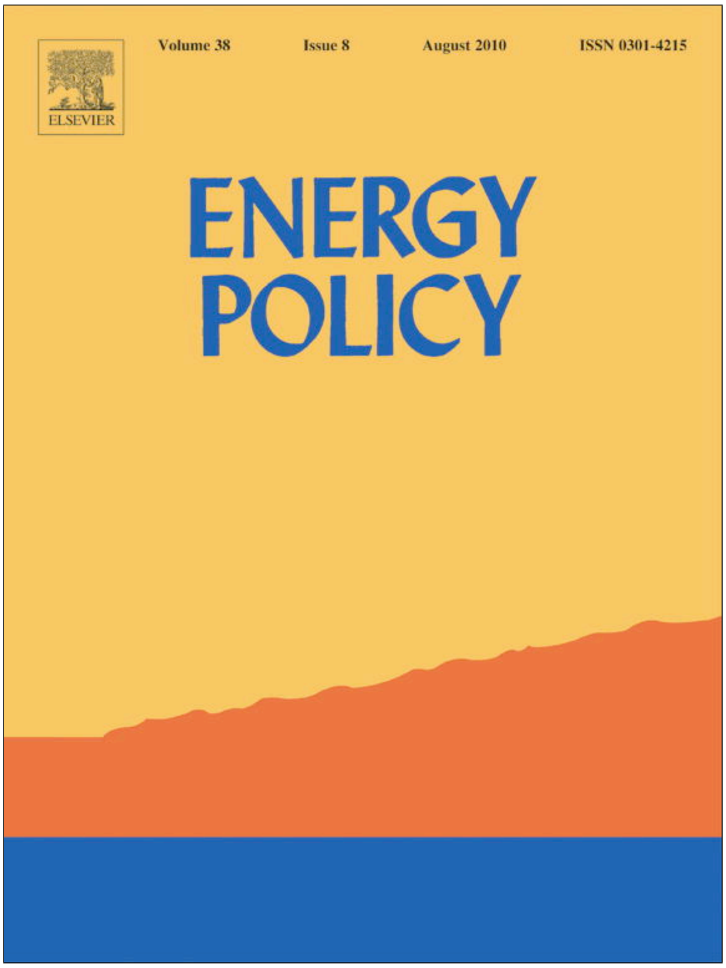
Volume 38
Issue 8
August 2010
ISSN 0301-4215
ELSEVIER
ENERGY POLICY

Energy Policy 38 (2010) 4107–4114

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Can renewables etc. solve the greenhouse problem? The negative case

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ARTICLE INFO

Article history:
Received 28 January 2010
Accepted 18 March 2010

Keywords:
Renewable energy
Greenhouse problem
Limits to growth

ABSTRACT

Virtually all current discussion of climate change and energy problems proceeds on the assumption that technical solutions are possible within basically affluent-consumer societies. There is however a substantial case that this assumption is mistaken. This case derives from a consideration of the scale of the tasks and of the limits of non-carbon energy sources, focusing especially on the need for redundant capacity in winter. The first line of argument is to do with the extremely high capital cost of the supply system that would be required, and the second is to do with the problems set by the intermittency of renewable sources. It is concluded that the general climate change and energy problem cannot be solved without large scale reductions in rates of economic production and consumption, and therefore without transition to fundamentally different social structures and systems.

1. Introduction

It is commonly assumed, although often implicitly, that the greenhouse problem can be solved by intensified conservation and efficiency effort, sequestration of CO_2, and by shifting from fossil fuels to renewable and nuclear sources. In addition Stern (2006) and others say the cost will be negligible. However little critical attention has been given to the potential and the limits of renewable energy. A review by Trainer (2007), and the updated summary in Trainer (2008a) offer support for the critical case.

The approach taken in this discussion is to explore how a probable 2050 energy supply target might be met by a combination of energy conservation, renewable energy, nuclear energy and geo-sequestration, within a safe greenhouse gas emission rate. After establishing working assumptions, two critical issues are discussed, firstly to do with whether the average quantities of alternative energy needed could be supplied in winter, in view of the capital cost of the redundant plant required. The second issue is to do with the gaps in supply left by the variability of renewable sources. On both counts there is a strong case that non-fossil fuels are not likely to be capable of sustaining an energy affluent society within safe greenhouse emission limits.

2. The quantity and investment issue

2.1. Assumptions

The following discussion of emission limits, alternative energy sources and their constraints is intended to establish the assumptions and values set out in Table 1.

2.1.1. The probable 2050 energy target

Various sources indicate that 2050 world energy demand is likely to be in the vicinity of 1000 EJ/yr (Moriarty and Honery, 2009, p. 31; European Commission, 2006; The IAEA, International Atomic Energy Authority, 2008, p. 53).

Moriarty and Honery (2009) report that the ratio of final to primary energy is 0.69. The 2050 target will therefore be taken as delivering 690 EJ/yr of final energy. It will be assumed that 2050 energy consumption in the electricity and transport sectors will be the same proportions of projected final energy as they are now in Australia, i.e., 25% and 33% respectively.

2.1.2. Energy conservation effort

Significant reductions in energy supply are likely to be achieved by future improvements in energy use efficiency and conservation. Estimates vary considerably and an attempt to establish a confident figure for 2050 would be problematic and is beyond the scope of this discussion. Various sources loosely support the working assumption that a 33% improvement in energy use efficiency will be made (IPCC, 2007, Tables 1 and 2, p. 9; The Electric Power Research Institute, 2009; Jochem, 2007; Fig. 9.4 in Stern, 2006). This would mean that 462 EJ/yr would

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doi:10.1016/j.enpol.2010.03.037

Table 1
Assumed quantities.

Basic quantities:	
Gross energy target	1000 EJ/yr
Final energy target	690 EJ/yr
Final energy target after conservation effort	462 EJ/yr
Direct electricity demand	116 EJ/yr
Transport demand	154 EJ/yr
Including electricity	92 EJ/yr
Liquid fuel	62 EJ/yr
Electricity	
From geo-sequestration	51 EJ/yr
From hydroelectricity	19 EJ/yr
From nuclear energy	8 EJ/yr
Biomass	50 EJ/yr
Low temperature heat	
From solar sources	46 EJ/yr
Meeting electricity demand:	
Demand = 115 EJ/yr direct + 92 EJ/yr transport =	207 EJ/yr
Geo-sequestration + hydro + nuclear =	78 EJ/yr
Therefore to be generated	129 EJ/yr
Meeting demand for liquid fuel for transport:	
Demand =	62 EJ/yr
Available biomass	50 EJ/yr
Deficit	12 EJ/yr of liquid fuel

Situation:
Direct electricity + transport demand could be met using geo-sequestration, hydro and nuclear sources, and using 50 EJ/yr liquid fuel from biomass, if there is provision of 129 EJ/yr of electricity and 12 EJ/yr of liquid fuel from alternative energy sources.
Demand that would remain after meeting direct electricity plus transport energy plus low temperature contribution (i.e., 25% + 33% + 10% = 68% of 462 EJ/yr, = 146 EJ/yr, or 158 EJ/yr when the 12 EJ/yr transport liquid fuel deficit is included.

have to be supplied. Taking the present fractions, direct electricity supply would be 116 EJ/yr and transport 153 EJ/yr.

2.1.3. The probable "safe" CO_2 emission target

Around the mid-2000s a responsible greenhouse target was generally taken to be an atmospheric CO_2 concentration under 450 ppm. To achieve this the IPCC estimated that emissions would have to be cut by 50–80% by 2050 (i.e., possibly to around 5.7 GT/yr) and probably to below zero by 2100 (IPCC, 2007, SPM 5).

According to the IPCC (Metz et al., 2005, p. 107) geo-sequestration of CO_2 can capture only 80–90% of the CO_2 generated at power stations when coal is burned. Hazledine (2009) reports that when the whole cycle from mine to electricity use is considered, including for instance fugitive emissions from coal mining, the figure is 75%. Geo-sequestration can only be applied to stationary sources, such as power stations, so it cannot deal with emissions from c. 50% of carbon fuel use. It cannot for instance be applied to liquid fuel used in vehicles. If the 2050 release limit is taken to be 5.7 GT/yr CO_2, and a geo-sequestration rate of 80% is assumed, this corresponds to around 97 EJ/yr of electricity generated by coal. This figure does not deduct the energy cost of the geo-sequestration process, which has been estimated at 11–40% of the energy generated (Metz et al., 2005; Lenzen, 2009, p. 28).

However, since the 2007 release of the IPCC Fourth Assessment Report observations of global warming have tracked higher than the IPCC's maximum expectations. In the 1990s carbon release increased at around 1.9% p.a. but by 2008 the rate had risen to 3% p.a. (Pittock, 2009; Moriarty and Honnery, 2007). As a result some have begun to argue that targets need urgent revision. Hansen et al. (2008) for instance urge adoption of a 350 ppm target although emissions are already over 380 ppm. Others are arguing for complete elimination of emissions by around 2050 (Anderson and Bows, 2009; Climate Safety, 2009).

The Fourth Assessment Report was not able to take into account feedback mechanisms adequately, in view of uncertainties and difficulties in estimating them. These effects are likely to be substantial, including increased emissions of methane from drying tundra, reduced albedo due to diminishing snow and ice cover, warming and acidification changing the capacity of oceans to absorb carbon and the probable increase in forest fires. Forests and coral reefs are soon likely to change from being net absorbers of CO_2 to emitters. As improved models enable such effects to be taken into account it is likely that in the near future estimates of permissible emission rates will be significantly reduced.

The analysis by Meinshausen et al. (2009) would seem to be decisive. They conclude that to keep the probability of a 2° temperature rise by 2050 below 25% the cumulative total emission of CO_2 between the present and that date must not exceed 1000 Gt. This corresponds to a tapering from the present annual release to zero by 2050. (Yet they state that between 2000 and 2006 emissions increased 20%.) It is likely therefore that if 100% effective geo-sequestration of emissions from fossil fuel use is not achieved, this will mean use of all fossil fuels must cease by 2050.

Easily overlooked is the fact that there will continue to be a considerable carbon emission associated with the production of renewable energy technologies for many years, even if eventually the required energy can come entirely from renewable sources. Lenzen (2009) reports emissions ranging from c. 5 g/kWhe for wind to 100 g/kWhe for PV, with an average around 50 g/kWhe. Applying this figure to the quantity of renewable energy that would be required by 2050 indicates a considerable rate of carbon emission. If it is assumed that 58% of a 690 EJ final energy supply (see below) could be in electrical form, this 400 EJ/yr would correspond to the release of approximately 0.2 Gt/yr of CO_2e p.a. (This assumes use of fossil fuels to produce renewable plant in coming decades.) This factor will be ignored in the following discussion although taking it into account accurately would strengthen the negative case.

It will be assumed below that the permissible emission limit will be 3 GT/yr, corresponding to 51 GT/yr of coal generated electricity. (The effect of varying these assumptions will be considered below.)

2.1.4. Nuclear energy

Current estimates of accessible uranium resources (Zittel, 2006; Integrated Sustainability Analysis, 2006; Lenzen, 2009, p. 50) indicate a total of around 4–5+ million tonnes, sufficient to maintain the present approximately 8 EJ/yr output for 85 years. Current nuclear energy generation via present technologies is not therefore likely to make a major contribution to the 1000 EJ/yr goal. (On questions that would have to be resolved regarding the viability of the Fourth Generation or Integral Fast Breeder Reactor, see Trainer, 2008a.) For the purposes of the following discussion a nuclear contribution of 8 EJ/yr will be assumed. The CO_2 emissions associated with the nuclear industry will not be taken into account although they have been estimated at one-third those from gas-fired generation per kWh (Abbott et al., 2007).

2.1.5. PV

The budget represented in Table 1 assumes that PV systems function in 2.8 kWh/m^2 winter radiation, which is 4 times the level in much of Europe.

No account has been taken of the revised estimate of the energy cost of PV systems and thus the "pay-back" time reported by Lenzen et al. (2006). Lenzen and Treloar (2003) have pointed to the tendency for estimates of embodied energy costs to fail to take into account factors in the production chain that are some distance from fabrication, such as those involved in the construction of the factories producing the machinery that produces steel. A full accounting can double values otherwise arrived at. Lenzen et al. say that whereas it is commonly assumed that the energy return for PV is in the region of 8/1, when a full accounting is carried out it is 3.3/1. It is likely therefore that a full accounting would also lead to higher estimates than is commonly assumed for pay-back time for wind, nuclear and solar thermal technologies.

Except for solar thermal energy, embodied energy costs have not been added to the negative case in this discussion.

2.1.6. Biomass

It seems clear that ethanol produced from grain will not make a major contribution to global demand for liquid fuel, mainly due to the low energy return. The figure commonly reported is 1.3 (Shapouri et al., 2002) although some argue that when all inputs and costs are taken into account the figure is negative (Patzek, 2004).

Large scale supply of liquid fuel from biomass will therefore have to come mostly from cellulosic inputs produced by forest plantations. Probable crop and municipal waste inputs are only a small fraction of potential plantation quantities. Diesendorf (2007, p. 43) reports an estimate of potential Australian crop waste bio-energy inputs at 8% of total biomass energy potential, on the assumption that it is acceptable to leave 1 t/ha in the fields. Pimentel and Pimentel (1997, p. 241) argue that for long term sustainability of soil carbon levels no material should be removed.

Unfortunately estimates of land areas that could be devoted to biomass energy production vary greatly. Under some sets of assumptions Hoogwijk et al. (2005) anticipate over 1100 EJ/yr, whereas Field et al. (2007) derive an ecologically sustainable maximum of 27 EJ/yr. Hoogwijk et al.'s assumptions would seem to be implausible; e.g., that almost 4 billion ha of abandoned agricultural land and "rest" land will be available by 2100, when there are only c. 8 billion ha of productive land, and population will be much larger than at present. They state that biomass energy production could take 30–40% of all land.

A constant yield increase of c. 2% p.a. is assumed, indicating a factor 8 increase by 2100, when there would not seem to be good reason for confidence regarding such a prediction. Reference is made to the achievements of the Green Revolution but its gains have tapered after an approximate doubling of food yields, and as Field, Campbell and Lobell point those gains were in the proportion of plant mass in grain, not in total plant mass.

Even if it is assumed that 4.5 billion ha can be used, a yield of 1115 EJ/yr corresponds to an average global biomass yield of 14 t/ha. For very large scale biomass fuel production which would have to use much land of relatively low quality yield is likely to be in the region of 7 t/ha (Foran, undated; Bartle, 2000).

Others have arrived at much lower estimates than Hoogwijk et al. A review by Berndes et al. (2003) concludes that 14–267 EJ/yr is achievable, and Hall et al. (1986) conclude that 0.4–1 billion ha might be used. As has been noted, Field, Campbell and Lobel derive a figure of 27 EJ/yr if environmental damage is to be avoided.

Foran notes the significant impact of large scale biomass production on the diversion of water from ecological flows into celulosic material that is removed from the region. Even more concerning would be the ecological and biodiversity impact of converting very large areas to monocultures that are cleared periodically.

For the purposes of the following analysis 1 billion ha and a yield of 7 t/ha will be assumed.

Fulton's review (2005) concluded that the net yield of ethanol from celulosic inputs would be c. 7 GJ/t (Foran, undated, anticipates a future yield that could be in the region of 9 GJ/t). Thus it will be assumed that very large scale biomass ethanol from cellulose might be produced at the rate of 50 GJ/ha. If 1 billion ha were continually harvested the ethanol yield would be 50 EJ/yr, under the above assumptions.

2.1.7. Hydroelectricity

It will be assumed that hydroelectricity rises from the present 10.7–19 EJ/yr (European Commission, 2006; Trainer, 2008a), although this will be uncertain in view of the probable effects of climate change. The hydroelectricity contribution to Australian electricity generation has fallen from around 10% to under 6% in recent years due to climatic effects.

2.1.8. Wind

Lenzen's review (2009, p. 86) reports that although the estimated global wind resource is large most of it is located in Siberia, Northern Canada and Patagonia, and only 5% is in regions where electricity demand is high.

Lenzen confirms that regardless of the resource size, wind is not likely to contribute more than 20% of electricity required, because integration problems rapidly increase at higher penetrations.

If one third of the 462 EJ/yr required was to come from wind then the wind sector would be 296 times as large as in the mid 2000s (Coppin, 2008, p. 379). It is not likely that more than a small fraction of this amount of capacity could be located within thousands of kilometres of demand. The limit set by site availability to Europe's total on and offshore wind potential has been estimated at 4 EJ (Trieb, undated, p. 48; Lenzen's figure is a little less, 2009, p. 86) Lenzen's figure is a little less, 2009, p. 86). Long distance transmission losses of 15% might be involved (Mackay, 2008), along with the embodied energy cost of the transmission lines and their maintenance, increasing required gross capacity accordingly.

2.1.9. Solar thermal

If renewable sources are to meet European demand then solar thermal sources located in Northern Africa and the Middle East would have to be the major contributors (Mackay, 2008). Mackay also concludes that the US could not function on renewable energy unless a very large contribution could come from solar thermal sources.

Because solar thermal systems can store energy as heat they will be valuable contributors with respect to the intermittency and storage problems most renewables involve. However the (limited) technical and climate data accessible indicates that even in the best locations such as Central Australia winter output will be problematic. Unfortunately in view of the lack of publicly accessible performance information it is necessary to make uncertain estimates of probable outputs and costs. Following is an indication of conclusions relevant to this analysis drawn from the more detailed attempt at derivations reported in Trainer (2008b).

The focal concern in the discussion of non-fossil fuel energy supply is how to meet demand in winter, when solar sources are at their weakest. In winter the daily output from solar thermal trough systems at the best US sites falls to the region of 20% of summer output (Odeh et al., 2003). It is important therefore to consider the potential of dishes, which are the most efficient of the three solar thermal systems (Lovegrove et al., 2006). However they are at present mainly used for immediate generation via Stirling engines, and if they are to contribute to solving the winter supply problem their potential for heat storage must be considered.

The most promising approach using dishes for heat storage seems to be to use ammonia dissociation (splitting into hydrogen and nitrogen) to store heat from dishes (Lovegrove et al., 2004). No commercial plant of this kind has been built but the potential energy efficiency of the chemical process has been predicted as 0.7, and half the energy entering the dish might be available for generating electricity after storage.

The probable energy efficiency of such a system in winter, net of all energy losses and costs, is problematic. For instance if the Mod dish–Stirling winter output figure of c. 18–25 W/m^2 (Davenport et al., undated) is reduced to 0.7 to take into account the above stated efficiency of the ammonia storage process, and reduced again to take into account the lower efficiency of steam generation (including possible losses in transmission of steam from fields of mirrors to power blocks) compared with Stirling engines, the winter output would probably be significantly lower than the 24 h average 18–25 W/m^2 flow reported for dish–Stirling systems.

Much the same conclusion can be derived taking the ANU Big Dish 400 square metre area, the future 0.19 solar to electricity conversion efficiency its designers expect to achieve, and a Central Australian winter direct normal irradiation (DNI) of 5.7 kWh/m^2/d.

Information on solar radiation in winter in the regions that would have to provide large scale solar thermal energy are somewhat unsatisfactory in view of differences between data sources. For the best US region winter DNI is between 5 and 6 kWh/m^2/d (ASRDHB, undated). The Australian Radiation Data Handbook (ASRDHB, 2006) states 5.5 kWh/m^2/d for Central Australia. Mamoudou (undated) indicates that for the best North African region the rate is under 6 kWh/m^2/d. Data from Meteonorm (2008) indicates 5.5 kWh/m^2/d in the best Sahara regions, close to the Egyptian border.

From the gross average flow several loss factors must be deducted to arrive at an estimate for net power delivered at a distance in winter. Evidence on the embodied energy cost of building the plant and associated systems is scarce, varied and uncertain. Foran (2009) reports 3.2% for troughs and Lenzen and Dey (1999) report c. 4%. Lenzen (2009) reports10.7% for a central receiver field (i.e., not including tower, generator, heat storage, etc.), and derives 6% for a dish proposal (for the collection field only).

Also to be deducted are the embodied energy costs of the long distance transmission lines, e.g., from central Australia to Eastern coasts, and the energy losses in transmission. For North West European supply from the best North African sites, in the Eastern Sahara, involving a Mediterranean crossing, the latter could be 15% of energy generated (Mackay, 2008). Transmission systems could add one-third to solar thermal plant dollar costs (Trieb, undated). If embodied energy cost is more or less proportional to dollar costs as Lenzen and Dey indicate this could subtract another 2–3+% of gross plant lifetime output for transmission lines.

A major concern regarding embodied energy analyses is to do with the thoroughness in accounting "upstream" factors, such as the energy required to product plant required to produce the item in question. Lenzen and Treloar (2003) argue that for steel such an analysis can double the figure arrived at by taking inputs at the steel plant. Lenzen et al. (2006) say that a full accounting for PV raises the embodied energy cost estimate from the commonly assumed c. 13–33%. Such analyses have not been reported for solar thermal systems. It would seem that a thorough accounting of a solar thermal system including ammonia storage and long distance transmission lines might cast doubt on their viability.

Other losses include the energy costs of constructing the power generating plant, the piping to it, and the energy costs for the construction and operation of the ammonia heat storage system, heat losses from large scale storage, the transmission lines and the piping of heat to the power block and to and from the ammonia plant. Down time for repairs been not been taken into account for any energy source mentioned in this discussion, although for coal-fired power this can subtract 20% of capacity. It would seem that taking these factors into account could more or less halve the above probable flow of electricity delivered at distance in winter, to a net received/delivered flow in the region of 10 W/m^2.

However for the purposes of the following derivation a 20 W/m^2 flow will be assumed for energy delivered at distance in winter net of all energy costs and losses, i.e., 8 kW per dish, or 21 GJ/month. A plant large enough to deliver 1000 MW to a distant region in winter would therefore need a 50 million square metre collection area and would include125,000 Big Dishes.

Luzzi (2000, p. 83) states the cost of a proposed commercial dish-steam plant at $1100 per metre of collection area, indicating a present cost of $55 billion for the equivalent of a system capable of delivering1000 MW at distance in winter. He indicates that future costs might fall to one-third this amount, which aligns with the estimate Lenzen's review presents (2009, p. 119). Taking this cost estimate means that the future cost of the collection field, structure and generator for a 1000 MW Big Dish plant solar power plant would be $18 billion. This does not include the cost of the ammonia storage facility assumed in the system under discussion, nor the several cost factors noted which could not be estimated.

2.1.10. *Electric transport*

Around 60% of transport energy could be shifted from fossil fuels to electricity by use of battery powered cars (if long distance car travel can be included). Sea transport, heavy road vehicles and aircraft are not likely to be powered by batteries. It will be assumed that cars will be powered electrically requiring 97 EJ/yr and that the 50 EJ/yr biomass contribution will meet the remaining transport demand with a deficit of 15 EJ/yr of liquid fuel. (To simplify, the difference in efficiency for the electricity-battery-wheels path and the petrol-engine-wheels path has not been taken into account.)

2.1.11. *Low temperature heat*

A proportion of low temperature space and water heat could be derived directly from solar sources. In the high latitude countries where most rich country populations are located it is not likely that a large proportion of winter heating energy could be derived from this source (Mackay, 2008 shows that heat pumps would could not solve the probem). Available energy statistics do not indicate confident figures but it will be assumed that 10% of final energy demand can be provided to meet low temperature heat demand from direct solar passive panels plus insulated storage tanks.

2.1.12. *The conversion and dumping problems*

Discussions of the potential of renewable energy sources usually do not take into account the need to convert energy from forms that are available to forms that are needed. Conversion is typically quite energy-inefficient, meaning that much more primary energy needs to be generated than might appear to be the case. For instance according to Bossel (2004) fuelling transport by hydrogen produced from electricity would require generation of about 4 times the amount of energy that is to power wheels.

(That this is a plausible figure can be seen by assuming an efficiency of 0.7 for the production of hydrogen from electricity, 0.8 for compression, distribution and storage of hydrogen and 0.4 for fuel cell operation, yielding an overall efficiency of 0.22.)

It will be assumed that the conversion problem will be solved by using renewable electricity to generate hydrogen with an overall energy efficiency of 0.5. This would seem to be an implausibly favourable assumption, possibly double the actual figure. Note that this figure does not take into account the embodied energy cost of the elaborate plant that would be required for hydrogen production, compression, pumping, distribution, pipes, storage and reconversion, or the energy costs associated with embrittlement, leaks and seals, and especially fuel cell production which is at present quite expensive.

2.1.13. Summary of assumptions

The foregoing discussion of demands, sources and constraints has established the elements in the energy budget set out in the first parts of Table 1.

None of this remaining 158 EJ/yr would be needed in electrical form, yet most renewables produce only electricity. This sets the problem of conversion, and the associated inefficiencies and losses. At the above assumed 0.5 efficiency of energy conversion, to provide the 158 EJ/yr in non-electrical form would require generation of 316 EJ/yr of electricity.

Thus the total electrical generation task would be 129 EJ/yr+316 EJ/yr=445 EJ/yr.

2.2. The winter supply task

The focal question in the discussion of a 2050 budget is what alternative generating capacity would be required to meet the 445 EJ/yr total demand in the period of the year when total renewable supply is most constrained, i.e., 37 EJ/month in winter.

Let us assume a system in which wind and PV sources each contributes 25%, i.e., 9.25 EJ/month, and solar thermal contributes 50%, i.e., 18.5 EJ/month. (Different assumptions will be explored below.)

Wind: Although the present world average wind capacity factor is 0.23 (IPCC, 2007, Section 4.3.3.2), in winter in several European countries it rises to around 0.38 (Wind Stats, 2008). At this rate a 1.5 MW turbine would generate 1.5 TJ/month (less when down time for repairs is taken into account). Therefore to generate the required 9.25 EJ per winter month 6.17 million turbines would be needed, and the total cost might be in the region of $13.8 trillion.

PV: Even in the most favourable US regions in winter solar radiation on a square metre tilted at latitude is only around 2.8 kWh/m^2/day. However in mid European countries it is around 0.7 kWh/m^2/d (Morrison and Litwak, 1988). The higher figure will be used here although this invalidates the application of the conclusions arrived at to the European situation.

Assuming a solar to electricity efficiency of 13% and radiation of 2.8 kWh/m^2/d, PV systems would generate 41 MJ/m^2/month. To provide 9.5 EJ/month 232 billion square metres of PV panels would be needed. At an all-inclusive cost of c. $1000/m^2 (approximately the same as Lenzen's stated $7/W, 2009, p. 111), the cost would be $232 trillion.

Solar thermal: If beam radiation in winter of 5.5 kWh/m^2/d is assumed, then given the assumptions made above (i.e., including only the losses quantifiable here), indicating a 21 GJ/month winter output per dish, 896 million dishes comparable to the ANU Big Dish would be required to contribute 18.5 EJ/month. At the estimated present commercial cost of $440,000 per dish (Luzzi, 2000) the total cost would be $394 trillion. On the assumption that future costs will be one-third present costs the sum would be in the region of $131 trillion.

The total would be $377 trillion. When averaged over an assumed 25 year plant lifetime this would be 33 times the present amount of world annual energy investment, $450 billion (Birol, 2003). Some analysts asssume 20 year lifetimes for wind and solar thermal systems (Lenzen, 2009).

There are several major components of the total energy supply system assumed here whose costs have not been taken into account, in addition to the omitted costs for solar thermal systems mentioned above. These include the embodied energy and dollar costs of the systems for biomass energy production, geosequestration, nuclear power (equivalent to present capacity), hydroelectricity, long distance transmission lines, low temperature heat collection panels and tanks and the components of the hydrogen processing equipment, such as electrolysers, compressors and pumps, storage facilities, nation-wide pipeline systems and equipment for converting stored hydrogen back into useful energy, such a fuel cells. Losses in transmission from distant wind farms or PV power stations have not been taken into account. Nor have operations and management energy costs for the lifetimes of any plant or components within the total energy system been accounted, except for solar thermal. Down time for repairs has not been taken into account for any component. Finally the cost of the coal-fired power stations plus coal capable of providing 51 EJ/yr which is 82% of present world electricity generation have not been included.

2.2.1. Using more favourable assumptions

Following is a brief summary of conclusions deriving from more optimistic assumptions, arrived at in a more detailed version of this discussion (Trainer, 2010). The assumptions made were, installed PV cost reduced from $6.5/W to $5/W, solar to electricity efficiency increased from 0.13 to 0.2, PV contribution reduced to 10%, wind contribution increased to 40%, ethanol yield increased from 50 to 90 GJ/ha, efficiency of converting electricity to needed energy forms increased from 0.5 to 0.6, average amount of energy needed to perform functions reduced by 50% rather than 33%, long distance transmission loss reduced from 15% to 12%, solar thermal cost reduced to 10% of present cost and plant lifetime increased from 25 to 30 years.

The resulting capital costs would be 4 times present world annual energy investment.

Trainer (2010) also explores the effect of having wind, PV and solar thermal meet different proportions of total energy demand. An option relying on wind for 60% and solar thermal for 40% of supply would require 13 times present world investment, but would set significant problems of oversupply in winter, and of storage. A 100% wind system with hydrogen storage would result in an investment multiple of 8, although this omits several cost factors including those to do with the hydrogen components, and makes the implausible 0.5 conversion efficiency assumption. A 100% solar thermal system would overcome storage problem s but would create a large oversupply situation in summer. It is associated with an investment multiple of 24.

2.3. General conclusion re-investment cost

Although these have been crude estimates based on uncertain assumptions and omitting several major components, they illustrate the magnitude of the overall task. It is not likely that energy-intensive economies could sustain the required multiples of present investment indicated. In future more confident data and estimates will enable clarification of the issue, so if the present exercise turns out to have arrived at significantly invalid conclusions its immediate value is in indicating the kind of approach that is required.

2.4. The implications of 9 billion on rich world "living standards"?

The target taken in the foregoing exercise, 1000 EJ/yr, would be well below the quantity of energy needed to provide energy equity and affluence to the whole world. If the expected 2050 world population of 9 billion were to consume energy at the per capita rate Australians are likely to rise to by 2050 under a business as usual projection, world energy supply would have to be in the region of 4000 EJ/yr.

The effect on the global energy investment budget would be disproportional to this four-fold multiple for the quantity of energy required. The above assumed nuclear, hydro, biomass and geo-sequestration contributions would still account for only 129 EJ/yr, 3% of the required amount, and allowing for conversion the amount of electricity to be generated would be 2163 EJ/yr, five times the amount derived in the first budget above and some 35 times the present world total.

2.5. The implications for redundant generating capacity

A major implication of the foregoing analysis is that the amount of alternative generating plant that must be built to cope with the intermittency of sources and with winter is likely to be much greater than might be imagined from an initial understanding of the required supply quantity. For instance in the above budget 445 EJ/yr needs to be provided after taking into account nuclear, biomass, hydroelectricity and electricity via geo-sequestration. If this was to be provided by coal-fired or nuclear power stations the peak generating capacity required to be built would be 17.5 billion KW, assuming 20% down time.

However the average rate of generation for coal or nuclear plant can be above 0.8 but for wind, PV and solar thermal the average values range between 0.13 and 0.23 (IPCC estimate for average global wind capacity, 2007, Section 4.3.3.2). A net winter delivered flow of 20 W/m^2 from a solar thermal plant is c. 7% of the peak rating that is sometimes given for such plant (i.e., c. 24% solar to electricity efficiency in 1 kW/m^2 radiation).

In addition as we have seen there are times, especially in winter, when wind for example will be contributing little or nothing, meaning that a sufficient amount of solar plant to meet demand at such times would need to have been constructed. Indeed given the very low capacity credit for wind (Lenzen, 2009, p. 92) there will be times when alternative generating plant almost equivalent in magnitude to the wind system would need to be available, and its construction would add greatly to the capacity and investment costs of a wholly or largely renewable system. In other words the intermittency of the renewable sources creates a very significant need for redundant plant.

The combined effect in the above budget is that much more *peak* generating capacity must be built than the 17.5 billion KW of coal or nuclear capacity that would suffice. In fact the amounts of peak capacity in the above budget are, wind 9 billion kW, PV 26 billion kW and solar thermal 64 billion kW, making a total of 101 billion kW, some 7.3 times as much as would have been needed in the form of coal or nuclear plant.

In addition this creates a problem of energy dumping. At times of good wind and solar radiation when all renewable components of the system under examination are functioning at peak output, supply would be 6 times demand.

The crucial point here is that the task is not to *average* a flow of kW, it is to *maintain it at all times*.

2.6. The implications for levelised cost estimates

Similarly it can be quite misleading to think in terms of the levelised cost of electricity from specified renewable sources when estimating total system costs. Advocates of renewables typically do this, for instance claiming that the levelised cost of wind power is comparable to that of coal fired power. This might be so if lifetime outputs at *average* capacity are compared, but that overlooks the point stressed above that the crucial task is to maintain the required level of output. Because there will be times when wind cannot contribute much and resort must be made to redundant plant, the cost of providing that plant needs to be somehow included in the cost of the wind sector. It is an essential part of the wind sector if that sector is to be able to make its contribution continually, just as an emergency generator must be understood as part of the total energy supply cost of a hospital (Lenzen, 2009 recognises this in passing).

The dumping issue similarly indirectly increases total system capital cost because it means that some of the generating capacity built supplies energy that is wasted, or stored inefficiently, meaning again that plant constructed has to be greater than the amount that would meet demand if all its output could be used.

These problems could be reduced to the extent that some processes such as steel, cement and fertilizer production and freezer boosting could be carried out only when surpluses are available. There is some scope for this but the implications for intermittent operation of furnaces etc. are problematic.

3. The intermittency issue

It must be stressed that the foregoing discussion has been to do with the cost of an energy supply system capable of providing the *average* quantity of energy needed in one winter month. There is in addition the problem of ensuring that the energy is *continually supplied* at the required rate. This is the problem of being able to deal with those periods when the input from highly intermittent wind and solar sources falls to zero, or close to it.

The limits set by intermittency with respect to wind have been documented by Sharman (2005), E.On Netz (2004, 2005), Lenzen (2009), Oswald Consulting (2006), Oswald et al. (2008), Mackay (2008, pp. 186–187), Davy and Coppin (2003), Coelingh (1999) and Hayden (2004, p. 150). Lenzen's review concludes that these problems of intermittency and therefore of integrating wind into supply systems will generally limit the contribution of wind to providing around 20%+ of electricity demand.

The output from photovoltaic systems varies between 0% and 100% of capacity on a sunny day. When combined with wind variability this would set formidable integration and storage problems if the two components were contributing significant fractions of demand.

Although solar thermal systems have the important merit of being able to store heat, they are challenged by the occurrence of sequences of cloudy days, especially in winter. At present storage capacity is around 7.5 h at a number of sites but up to 12 h is being built into some new systems. The climate data discussed in Trainer, 2008b indicates that in central Australia in each winter month there are likely to be two sequences of 4 continuous days with little sunlight. Heat storage capacity capable enabling continued average power supply through such periods would have to be 8 times as substantial as the c. 12 h storage planned for near-future systems. Foran (2009) reports solar thermal storage costs at one-seventh generation cost, which suggests that the embodied energy cost of a four day storage capacity could be more than twice the present cost of the field plus turbine.

Heat losses from storage would also be significant. They are only c. 1% for the c. 6 h storage presently used, according to Sargent and Lundy Consulting Group (2003), but this suggests that for 4 day storage losses might be in the region of 16%.

If it is assumed that solar thermal systems are going to solve the intermittency problem set by all the other renewables sources in a total supply system a far greater storage problem is set. If it is assumed that solar thermal provides on average one-third of electricity demand then to enable total electricity demand to be met from solar thermal storage over a four day period there is little sun or wind, storage capacity would have to be about 24 times as great as would be necessary to enable the solar thermal component to operate continuously for 24 h, or almost 50 times as big as the 6 h storage built into solar thermal plants operating today.

It is therefore not likely that solar thermal systems will be able to plug gaps left by the other renewable sources and thereby to guarantee electricity supply in winter from a wholly renewable system, even in highly favourable solar regions.

The contributions from nuclear, hydro and coal via geo-sequestration sources assumed above could be reserved for bridging gaps caused by calm and cloudy periods but their combined contribution of 71 EJ/yr (or 21 EJ/yr if geo-sequestration is not acceptable) to the 445 EJ/yr budget would represent only 16% of the electricity required. In other words they could not meet demand in periods of little or no sun or wind. There would also be considerable redundancy with further implications for total investment cost, as these three sources would remain idle in reserve until contributions from wind and sun became insufficient to meet demand.

4. Conclusions

It is concluded that although the foregoing figures are not precise or confident, their magnitudes indicate that it will not be possible to meet a1000 EJ/yr energy target for 2050 from alternative energy sources, within safe greenhouse gas emission levels.

Energy is only one factor within the general "limits to growth" analysis of the global situation. This attends to a range of major problems in addition to the energy and greenhouse issues, including depletion of many resource items, especially the likelihood of "peak oil", the prospects for Third World "development" in a resource-constrained world, ecological deterioration and its unsustainable "footprint" implications, global conflict over resources and markets, and a deteriorating quality of life.

Belief in the capacity of renewable energy sources to meet future energy demand has been a major pillar supporting the "tech-fix" faith that solutions can be found "on the supply side" and that there will be no need to question the affluent lifestyles and systems generating the demands on resources and energy. The general "limits to growth" case is that the problems cannot be solved without dramatic reduction in demands on the planet's resources and environmental services, and therefore in the rich world's per capita resource consumption. Such a goal could not be achieved without radical change in social, economic, political and cultural systems. The argument that viable and satisfying alternatives exist and could be implemented relatively easily if there was the will to do so, is elaborated in The Simpler Way website (2006) (see also chapter 13 in Trainer, 2007).

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