CAN RENEWABLE ENERGY SUSTAIN CONSUMER SOCIETIES? A NEGATIVE CASE

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1. Introduction

The current discussion of climate change and energy problems is generally based on the assumption that technical solutions are possible and that the task is essentially to determine the most effective ways. This view relies heavily on the expectation that renewable energy sources can be substituted for fossil fuels. This discussion improves on an earlier attempt to estimate the investment cost that would be involved in deriving total world energy supply from renewable sources. It is concluded that the investment cost would be unaffordable.

It is commonly assumed that greenhouse and energy problems can be solved by intensified conservation and efficiency effort along with a transition from fossil fuels to renewable energy sources. In addition Stern [1] and others assert that the cost will be easily afforded.

Little attention has been given to the critical assessment of the potential and the limits of renewable energy. Trainer, [2] attempted a critical overview, and an updated summary is given in Trainer [3]. The approach taken in this discussion is the same as that taken in Trainer [4] which explored a probable 2050 world energy supply target that might be met by a combination of energy conservation and renewable energy. After establishing working assumptions, two critical issues are discussed, firstly to do with whether the quantities of alternative energy capacity needed to meet average winter demand could be afforded, and secondly to do with the implications of solar and wind variability for plant quantities and total system capital costs.

This analysis improves considerably on that in Trainer [4]. Better information on some core issues has recently become available, especially through the modelling provided by NREL, [5], and the cost estimates reported by Hearps and McConnell, [6]. This information indicated that contrary to the assumption underlying Trainer [4] central receivers are likely to be preferable to big dishes, and it enables more confident conclusions regarding total system capital costs.

1.1. *Assumptions*

The main purpose of this analysis is to indicate the value of the approach taken to the derivation of an energy budget, so that future studies can refine this when better data becomes available. The assumptions and derivations are transparent enabling the exercise to be reworked using other assumptions.

2. The Probable 2050 Energy Target

The IPCC [7] anticipates a doubling of demand by 2050. Moriarty and Honnery [8] report several estimates indicating that world energy demand, presently in the vicinity

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of 500 EJ/y, is likely to approximately double by 2050. They also report that the ratio of final to primary energy is .69. The 2050 target will therefore be taken as delivering 700 EJ/y of final energy. It will be assumed that 2050 'business as usual' energy consumption in the electricity and transport sectors will be the same proportions of projected final energy as they are now, i.e., 21% (i.e. 147 EJ/y) and 33% (i.e. 233 EJ/y) respectively.

2.1. *Transmission losses*

Very large scale production of renewable energy, especially via solar thermal and PV farms located at the most favourable regions, will involve long distance transmission. European supply from solar thermal fields will probably have to come via several thousand kilometre long HVDC lines from North Africa and the Middle East. Losses in the vicinity of 15% are likely, along with another c. 7% for local distribution. (Mackay [9], Czisch, [10], Breyer and Knies, [11], NEEDS, [12], Ummel and Wheeler, [13], and Jacobson and Delucci, [14].) However, it will be assumed that losses from long distance plus local distribution will be 15%.

2.2. *Embodied energy costs*

From the gross output figures for a renewable energy device the amount of energy needed to produce the device must be deducted. Estimates need to take into account all "upstream" costs, e.g. the energy needed to produce the steel works that produced the steel used in plant construction. These factors can double cost conclusions for steel production. (Lenzen [15], Lenzen [16], Lenzen and Treloar [17], Lenzen and Munksgaard, [18].) Lenzen, [19] derives an all-inclusive embodied cost of 6.6% for wind, and 33% for PV. (See also Lenzen et al. [20]. Hall and Pietro [21], state an even higher figure for PV located in Spain. Crawford, Treloar and Fuller [22] and Crawford, [23] estimates that PV costs can range from 33% to 50% of lifetime output. He believes that he and Lenzen et al. provide the only estimates for PV attempting to take into account all upstream costs. Crawford, [24].) For wind a 5% cost will be assumed here, and for PV a 15% cost.

The situation regarding solar thermal plant is more uncertain as it does not seem that satisfactory studies have been carried out. The relatively few studies have indicated an up to 11% cost but assumptions have varied considerably. (Dey and Lenzen [25], Weinriebe, Bonhke and Trieb [26], Norton [27], and Vant-Hull [28], Kaneff [29], Herendeen [30], Lechon, de la Rua and Saezes, [31], Lenzen [32].) No study taking into account all upstream factors seems to have been carried out. (Lenzen, [33], Crawford [34].) The unsettled state of this field prohibits the confident assumption of a value for this discussion but a 10% embodied energy cost will be assumed.

3. OUTPUT RATE ASSUMPTIONS

3.1. *PV Solar*

If 15% efficient PV panels in large power stations are assumed to be located in the world's best regions, such as Central Australia where total global solar radiation in winter is 7 kWh/m^2/day on average (ASRDHB, [35]), then the electricity produced would be 1.05 kWh/m^2/day, corresponding to a continual 24 hour flow of 44 W/m^2. After deducting a 15% transmission loss and the above 15% embodied energy cost a net 32 W/m^2 would be delivered at distance.

3.2. *Biomass*

Some studies conclude that the global biomass potential is very large, for instance 1,548 EJ/y according to Smeets and Faiij [36] (reported on p.16 of IPCC, [37], Chapter 2), but the IPCC report points out that these might best be regarded as defining theoretical maxima while achievable yields are another matter. It notes that the total net primary productivity of all vegetation on the planet is only about 1,550 EJ/y, so a realistic estimate of the amount that might be harvested for biomass energy is likely to be a small fraction of this. The difference between "technical" potential and a realistic figure which takes into account all the social, economic, political and ecological limiting factors is typically large. For instance Field, Campbell and Lobell [38] conclude that only 27 EJ/y can be obtained, under 2% of the Smeets and Faiij figure.

The IPCC Report estimates that the median estimate in its selected studies is 250 EJ/y. It says residues might make up 30% of the potential biomass resource, which means that the land area it assumes could be planted for harvest would be c. 700 million ha at its assumed c. 13 t/ha yield. Some analysts say this is possible, but the following reasons support the argument that this is a technically unlikely figure and is ecologically and socially/morally unacceptable.

- There is already great pressure on all the land on the planet, and it is commonly accepted that food production will have to double. Normal economic growth will deliver an economy in which there is three or four times as much producing and consuming going on in 2050 as there is now, with corresponding increases in resource demand. Rising energy costs will tend to move structural materials from steel, aluminium and cement to timber. Thus the demands on land for other than biomass energy will probably intensify greatly.

- The IPCC report notes that water is a problem for very large scale biomass production. It will be removed from ecosystems in the biomass.

- Large quantities of carbon would be removed from soils and ecosystems. Patzek [39] argues that over the long term carbon should not be removed and if it is soils inevitably deteriorate. (See also Pimentel and Pimentel [40].) In the coming era of probably severely limited availability of petroleum and fertilizers it is likely that agriculture will have to focus more intensively on the organic factors contributing to yields, as distinct from external and artificial inputs, meaning that maximum retention of soil carbon and therefore maximum recycling of crop "wastes" is likely to become crucial.

- The biodiversity effects are probably the most disturbing. The holocaust of species extinction humans are now causing is primarily due to the fact that we are taking so much natural habitat. Even decades ago humans were taking 40% of the land NPP. (Vitousek et al. [41].) We should be returning vast areas to natural habitat, not thinking about taking more.

- The IPCC [42] says that 80% of the present 50 EJ/y harvest of biomass energy is "traditional use" by tribal and peasant people. This is labelled "inefficient" use and the report anticipates shifting this land to the much more "productive" use characteristic of modern biomass energy systems. In view of the low yield/efficiency, that area is likely to correspond to 750 million ha. However this land provides crucial services sustaining the lives and livelihoods communities of the poorest billions of people on earth, the building materials, food, medicines, hunting, animal fodder, water and products to sell. The greatest onslaught of the global economy on the poorest billion is the taking of the land

> on which they depend. To move this land into modern "efficient" production would inevitably be to transfer the resource from the poor to the rich. The operation would be governed by "market forces", meaning that the rich would get the resource because they can pay more for it. This is already happening with respect to oil palm plantations. (The expropriation of native lands in colonial times was rationalised in terms of moving to more efficient use.)

For these reasons it is probable that only a relatively small amount of land should be put into global biomass energy production. It is therefore anything but clear how much biomass energy we should attempt to produce, but it would seem that the figure would be a small fraction of that yielding the 250 EJ/y the IPCC reports as the average of the estimates reviewed.

Biomass energy conclusions depend greatly on the assumed biomass growth yield. It would seem that the common biomass energy yield per ha assumption of c. 13 t/ha/y, also made by the IPCC, is unrealistic. It is easily achieved in good conditions, such as willows on cropland, or forests on good soils with adequate irrigation and fertilizer applications, but very large scale biomass energy will have to use large areas of marginal and/or damaged land. World average forest growth is only 2-3 t/ha/y. A more realistic biomass-energy yield figure might be 7 t/ha/y. Even if 13 t/ha/y is assumed, i.e., 234 GJ/ha/y, a 250 EJ/y harvest would require more than 1 billion ha, which is much more than is likely to be accessible.

Easily overlooked is the fact that the 250 EJ/y figure is for primary biomass energy and this would only yield about 80 – 100 EJ/y of final, useful energy in the form of ethanol, and an even lower quantity of electrical energy. (The IPCC Annex 111 gives four figures for the efficiency of biomass electricity efficiency, averaging around 28%. Harvey [43] gives a similar figure. El Bassam [44] reports the average efficiency of biomass electricity generators operating in the US at 18%.)

Fulton's review [45] concluded that the net yield of ethanol from cellulosic inputs is likely to be c. 7 GJ/t. Farine et al. [46] report 6.5 GJ/t. Foran [47] reports the belief among researchers that future yield could be in the region of 9 GJ/t. However the potential is debated. Patzek [48] says only two plants are in operation in the world, performance is not made public, and energy analysis indicates that the process will not be viable.

For the purposes of the following derivation it will be assumed that biomass ethanol is be produced at a net rate of 7.5 GJ/t, and therefore 48.75 GJ/ha, from c.700 million ha (which, again, is regarded as unrealistically high.) It will also be assumed that an additional about one-third of biomass energy inputs can come from wastes, bringing the total to the equivalent of a 1 billion ha harvested area. The biomass ethanol assumption will therefore be 50 EJ/y.

3.3 *Hydroelectricity*

It will be assumed that the proportion of world energy supply from hydro electric sources will remain about the same as it is now, and therefore that the 2050 supply will be c. 30 EJ. This is likely to be optimistic in view of the effects of the greenhouse problem. Because of the low embodied energy cost of hydro electricity and the usually closer proximity to demand no deduction will be made for these factors.

3.4. *Wind*

Lenzen's review [49] concludes that wind is not likely to be able to contribute much more than 20% of the electricity required within a system, because at higher penetrations integration problems rapidly increase. In unusual situations such as that of Denmark higher penetrations are achievable. In this discussion 25% will be assumed.

Not taken into account here will be the fact that globally a large scale use of wind energy would have to assume much off-shore capacity, which is around 2.5 times the cost of on-shore capacity (IPCC [50], Lenzen, [51].)

The world average wind capacity factor is in the region of .23. (Smil [52] estimates .2.) Mainly because in winter winds are stronger than average the figure assumed here for the discussion of the winter supply task will be .38, meaning that a 1.5 MW turbine would generate on average 570 kW. Applying the above 5% energy cost for wind makes this 542 kW. Wind farms are more easily located closer to demand than are large scale solar supply systems which would need to be in deserts to enable a reasonable winter contribution. The combined loss due to transmission and local distribution will be assumed at 10%. Therefore a delivery rate per turbine of 487 kW in a winter month will be assumed.

3.5 *Solar Thermal*

Because solar thermal systems can store energy as heat and thereby overcome to a considerable extent (but not entirely; see below) the intermittency and storage problems which most renewables involve, they will be major contributors. However the (limited) technical and climate data accessible indicates that even in the best locations such as the Sahara and Central Australia winter output will be problematic. Troughs are not likely to be viable given their typically low winter to summer ratio of output, in the region of ¼. (NREL, [53], Odeh, Behmia and Morrison [54], Trainer [55].) Contrary to the understanding informing Trainer [56] (i.e., that Big Dishes would be preferable), the estimates in the recent NREL [57] Solar Advisory Model seem to show clearly that the best option will be central receivers. This is confirmed by Wood et al. [58]. Unfortunately commercial operators of central receivers do not make performance data public.

Trainer [59] derives cost and output conclusions mainly from the NREL example theoretical modelling. This yields the fairly confident conclusion that the 24 hour flow rate of electricity delivered over long distance in winter from the best sites (e.g., Central Australia where winter DNI averages 5.7 $kWh/m^2/d$), net of a 10% embodied energy cost and a 15% transmission loss, but including interest charges and dry cooling dollar and energy costs, is likely to be in the close to 20 W/m^2 of collection area.

3.6. *Other Renewables*

It will be assumed that although other renewable energy sources might in future become significant contributors, at this stage that seems unlikely (Trainer [60], Trainer [61], IPCC [62], Greenpeace [63], Jacobson and Delucci [64], and Harvey, [65]).

3.7. Electric Transport

It will be assumed that around 60% of the 233 EJ/y business-as-usual 2050 transport energy demand assumed here 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 electricity. Rail can be electrified but it accounts for a small proportion of transport energy.

The energy efficiency of electric cars is commonly claimed to be in the region of 4 to 5 times as great as for petrol driven cars. However such figures typically apply to "battery to wheels" and do not include losses due to distribution, transforming from 240 volt to 12 volt, battery charging and discharging, discharge from idle batteries, the embodied energy costs of batteries and cars (claimed by Matej [66] to be high), battery lifetime and replacement multiple per car life, and global supply of the relatively scarce element Lithium. If vehicle batteries are intended to store energy for later supply to the grid, equipment for reconversion from 12 volt to mains voltage would impose additional costs and losses. Especially problematic are the dollar and energy costs of Lithium-ion batteries, estimated by Smil [67] to cost $35,000 and to last around three years. (Jacobson and Delucci [68] believe future battery cost will be half this sum, and that batteries will last the life of a car.) In view of these uncertainties it will be assumed that the present energy efficiency of cars can be trebled. (For a supporting analysis see Trainer, [69].) Bossell [70] argues that it can only be doubled.)

Consequently it will be assumed that the 60% of the "business as usual" 233 EJ/y transport energy budget, i.e., 140 EJ/y, will require 46 EJ/y. Another 40%, i.e., 93 EJ/y, will be required for transport in non-electrical form.

3.8 *Low temperature heat*

In the absence of clear data it will be assumed that 10% of final energy demand, i.e., 70 EJ/y, will be in the form of low temperature heat supplied by passive solar etc. means, and therefore will not add to the need for electricity generation.

3.9 *Energy conversion.*

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, or that can be stored. This would not be so relevant if large scale direct storage of electricity was available. 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 [71] fuelling transport by hydrogen produced from electricity would require generation of about 4 times the amount of energy that is delivered to wheels. (This aligns with the figures in Harvey [72].)

It will be assumed that in those scenarios where conversion is necessary it will take place via the generation of hydrogen with an overall energy efficiency of .5, taking into account losses in electrolysis, compression, pumping and distribution. (Harvey also states this figure [73].) Where hydrogen is used as an energy store for later regeneration of electricity via fuel cells, a further .4 - .5 efficiency reduction factor would apply. Where liquid hydrogen is required, for instance for aircraft fuel, the overall efficiency for wind turbines-to-engines would be in the region of .2. If the embodied energy cost of all equipment on this path was deducted it is possible that there would be no net energy return, given the low energy density of hydrogen gas and therefore the need for large pressurised tanks, and for cooling of liquid hydrogen containers.

3.10 *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 arrive at a confident figure for 2050 is beyond the scope of this discussion. However the evidence discussed in Trainer 2011a indicates that for present purposes a working assumption of a 33% improvement in energy use efficiency would be reasonable, for all but the 60% of transport energy assumed here to be converted to electricity for which a 67% reduction will be assumed.

4. Summarising the Demand Situation

The foregoing assumptions and conclusions are summarised in Table 1. This enables others to assess the derivation of conclusions, and to consider the effects of differing assumptions.

Table 1. **Annual Supply and Demand Assumptions**

Demand

Primary energy demand, 2050	1000 EJ/y
Final energy demand, 2050, assuming a .7 ratio	700 EJ/y
Demand for low heat, temperature (e.g., space and water)	70 EJ/y

The provision of this energy will be ignored in the following estimating, on the (questionable) assumption that it can all come from solar passive designs and renewable sources at relatively low cost.

Demand for transport, 33% of total	233 EJ/y
Demand for electricity	
Direct (21% of final)	147 EJ/y
Transport (assuming 60% of the 233 EJ/y transport energy)	140 EJ/y
Remaining demand for energy, i.e., other than the above direct electricity, transport electricity and low temperature heat; 700 – (147 + 140 + 70) =	343 EJ/y

Demand after applying conservation assumptions:

Direct electricity, 147 EJ/y reduced by one-third to	99 EJ/y
Transport;	
Electricity, i.e., 140 EJ/y, 60% of transport, reduced by two-thirds to	46 EJ/y
Remaining demand, i.e., 343 EJ/y, reduced by one third to	229 EJ/y

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Therefore totals needed:

Electricity, 99 EJ/y direct + 46 EJ/y transport	145 EJ/y

Remaining, non-electrical energy	229 EJ/y
Totals needed after allocating hydroelectricity, and biomass (50 EJ/y),	(30 EJ/y)
Electricity, 145 EJ/y - 30 EJ/y	115 EJ/y
Non-electrical energy, 229 EJ/y – 50 EJ/y	179 EJ/y

5. Capital Cost Assumptions

Evidence and claims regarding the present and likely long term future construction costs of PV, wind and solar thermal technologies vary considerably and estimates cannot be taken with confidence. Use will be made of studies reported by the IPCC [74] and Hearps and McConnell, [75]. On average these loosely anticipate a 50% fall in capital costs for PV and solar thermal, and a 20% fall for wind.

A significant concern for those assuming cost reductions is set by recent trends for wind turbines as these run contrary to the conventional wisdom. In the early 2000s the commonly stated cost was c. $1,500 per kW of capacity. Wind might be regarded as a "mature" technology now enjoying the "learning curve" benefits of a rapidly increasing production scale. However in recent years turbine costs have risen not fallen, and ABARE [76] reports the average cost or units built in Australia at a remarkable $2,900/kW, including a 30% increase in one year. The cost has actually been as high as $3,500/kW (Wood, et al. [77]), possibly due to temporary scarcity in supply. It is often assumed that technical advance and scaling up to mass production will have a marked reducing effect on unit price, but the NEEDS report [78] does not anticipate a marked effect for solar thermal systems. Wood et al. [79] show that solar thermal costs fell spectacularly some years ago but have plateaued since, invalidating the projections made by Sargent and Lundy [80].

Easily overlooked is the fact that all these cost figures refer to present materials, construction and energy costs, and in future materials and energy inputs are likely to be considerably more expensive than they are now. Given that all inputs into production involve energy it would be difficult to estimate the total multiplier effect on renewable plant cost that might be brought about by significant increase in energy costs.

The following cost working assumptions focus on the quantity of plant needed to provide a unit of energy in winter conditions, net of transmission and embodied energy (but not dollar) costs. It has been assumed that these costs include the cost of raising capital although this is usually not made clear in the estimates consulted.

5.1 *Wind*

Because wind power technology might be regarded as relatively "mature", estimates of future cost tend not to be markedly lower than present cost per kWe of capacity. The estimates of present and 2030 capital cost per kW(p) given by the IPCC [81], and Hearps and McConnell [82] for future onshore wind are fairly close to $1,500/kW(peak). No account will be taken of the need to use a lot of offshore capacity, which at present costs about twice as much as onshore capacity.

Given the above assumptions of a winter capacity of .38, and energy costs of 7% for distribution and 5% for embodied energy, a 1.5 MW(p) turbine would deliver 487 kW in winter and would cost $2.25 million, meaning that the net cost for electricity delivered at distance would be $4.62/W.

5.2. *PV*

Unfortunately the five accessible estimates for present and for future PV capital cost, those reported by Hearps and McConnell, the IPCC, and Harvey vary greatly. For present installed utility scale cost the high and low figures are $8,000/kW(p) and $3,200/kW(p). For future cost the range is from $1,060/kW(p) to $5,500/kW(p). The Wyld Group, [83] estimate future cost at $2,700/kW. The assumption for future cost used here will be $2,700/kW(p), which is less than the average of the above values.

This means that panels costing $2,700 will produce 1kW in 1 kW/m² global radiation. But the average 24 hr global radiation in Central Australia in winter is 7kWh/24h = 291.7 W, so the area of panels needed to produce a constant/average 1 kW of continuous output would have to be 3.43 times the area that can be purchased by $2,700; i.e., it would cost $9,256.

Taking into account a 15% transmission loss and a 15% embodied energy cost that area would deliver at distance a net .72 of 1 kW, meaning that the cost of the collection area to deliver a 24 hour average net 1 kW supply at distance would be $12.81/W.

(The common claim that rapid reductions in PV costs are likely refers to module production costs and not to balance of system costs, which make up about half the installed cost at present. This largely explains Smil's [84] point that in general the total system cost for installed PV has not fallen in a decade.

5.3. *Solar Thermal.*

Again cost estimates vary considerably. NREL [85] and AEMO [86] state $6,800/kW(p) and $6,410/kW(p) respectively for present cost, but the IEA states $3,085/kW. If $5,500 is assumed, along with the estimated 50% average decline for future cost reported by Hearps and McConell, then $2,750/kW(p) is arrived at.

This means that in peak solar radiation the investment of $2,750 in a central receiver will produce an average 1 kW. However over a 24 hour period in winter at the best sites DNI will average (5.7kWh/m²)/24h = 238 W/m². Therefore the area of collector for plant capable of delivering a constant flow of 1 kW over 24 hours would have to be 4.2 times as big, and thus would cost $11,550. Taking into account the above transmission loss and embodied energy costs yields $15,986/W, i.e., $16/W, delivered in winter net of embodied energy costs and transmission losses but not including transmission dollar costs.

It should be noted that this derivation assumes that solar-electricity generating efficiency in winter DNI is the same as for peak DNI. However the output data given by NREL shows that it is significantly lower.

6. QUANTITIES AND COSTS FOR WINTER SUPPLY

From Table 1 above the supply task is 115 EJ/y of electrical energy and 186 EJ/y of non-electrical energy. Three possible renewable supply strategies will be explored.

6.1 *The Hydrogen Strategy*

From the above discussion of conversion efficiency, to produce the required quantity of non-electrical energy in the form of hydrogen, (186 EJ/y x 2) = 372 EJ/y of electricity would need to be generated. The total amount needed would therefore be 116 EJ/y + 372 EJ/y = 488 EJ/y, corresponding to 15,500 million kW. If divided equally between wind, PV and solar thermal, each would have to provide approximately 5,200 million kW in winter.

<u>Table 2</u>

<u>Meeting Strategy 1 Demand</u>

<u>Wind:</u>	
Required:	5,200 GW
Cost assumption for delivery per Watt in a winter month,	$4.62/W
Therefore cost	$24.9 trillion.
<u>PV:</u>	
Required:	5,200 GW.
Cost assumption for delivery per Watt in a winter month,	$12.81/W.
Therefore cost	$66.6 trillion.
<u>Solar thermal</u>:	
Required in winter	5,200 GW
Cost assumption for delivery per Watt in a winter month,	$16/W
Therefore cost	$83.2 trillion
<u>Total cost</u>	$174 trillion
Average cost p.a. assuming 25 year plant lifetime	**$7 trillion**
Percentage of 2011 world GDP, approximately:	11%

The 2011 annual investment sum is 16 times the early 2000s ratio of rich country energy investment to GDP (i.e., for building and maintaining plant, not for purchase of energy). (Pfuger, [87], Birol, [88].)

There are several major cost factors which have not been included in this exercise and if they could be quantified confidently these would probably multiply the above cost conclusion a number of times. These include:

- The above exercise assumes average winter demand but extra capacity would be needed to meet peak demand, and this factor can multiply the total system capacity required by 1.3-1.5. (The Australian ratio is 1.8/1. ABARE, [89].)

- The exercise has been based on long term average radiation levels but in some winter months solar radiation is 40% below the long term average for that month. (NASA [90], ARDHB [91].)

- The cost of the many long distance transmission lines from deserts where solar plant would have to be located to enable winter supply. Czisch [92] estimates that this could add 33% to solar thermal generating plant cost, for relatively short distances such as Egypt to Turkey or Morocco to Spain. Harvey [93] and Jacobson and Delucci [94] estimate a global average of c. $.5 per kW-km. However Wood et al. [95] estimate Australian costs at up to 5.5 times as high. If the $.5 figure is taken then two-thirds of the above 15,500 GW capacity located 2000 km from users would add an approximate $14 trillion for transmission to the above system capital cost sum.

- The capital cost of the biomass production system, and the generators to produce electricity from biomass, have not been included. These would have to be large enough to deliver in the form of ethanol energy almost equivalent to current world electricity consumption.

- The cost of the plant needed to provide low temperature heat equivalent to 1.6 times current world electricity supply has not been included.

- The cost of twice the present global hydroelectric capacity is not included.

- The capital cost of the hydrogen production, distribution and storage system, has not been included. This would have to be large enough to deal with almost the equivalent of the present world energy supply. No account has been taken of the increase in these numbers that would be due to the probable need for liquid hydrogen for some forms of transport, notably aircraft.

- The cost of the plant needed to convert stored hydrogen into electricity when sun and wind inputs are too low to meet electricity demand has not been taken into account.

- Much wind capacity would probably have to be located offshore but the much cheaper onshore wind cost has been used.

- There would be a need for much redundant plant to deal with intermittency (discussed below.)

- The derivation assumes long term average winter DNI, but sufficient plant would have to be built to cope not just with winter months that are below average, but with periods within the worst of these months when DNI is below that month's average. That is, plant sufficient to cope with long term minimal DNI conditions would need to be built.

- The solar – electricity efficiency of generation for solar thermal plant assumed in the derivation is that reported for peak DNI, but NREL example data [96] shows that in winter DNI it is significantly lower.

- Although not an up-front capital cost, the lifetime operations and management costs would add to energy price. These are estimated by the IPCC [97] at 25-33% solar thermal construction cost.

If these factors could be quantified reliably the total capital investment cost would be several times the figure derived above.

Since the wind component is much cheaper than the solar thermal or PV components, it might be thought that the whole task should be given to wind. However the average summer wind capacity factor is well below the global annual average, which is in the vicinity of .23 or less. If the exercise is reworked assuming wind provides all the electricity required, corresponding to 15,500 GW, and that the summer wind capacity is 15%, then in summer the capital cost would be $181 trillion, corresponding to $7.3 trillion p.a. In other words the wind strategy would not seem to make a significant difference to the situation, mainly because its lower peak capital cost is slightly outweighed by its lower summer capacity.

Thus the hydrogen path would clearly seem not to be viable.

6.2. *Electrify as much of the economy as possible*

It is likely that in future the proportion of electricity in the total energy supply will be increased significantly. Let us again assume that conservation effort reduces the 700 EJ/y final demand by one-third by to 466 EJ/y, that biomass provides 50 EJ/y of final energy, hydroelectricity 30 EJ/y, and 70 EJ/y of low temperature heat can all come from solar panels. The remaining energy supply task would be 316 EJ/y, corresponding to a flow of 10,000 GW. If we assume that all of this demand can be met by electricity (which is not plausible), then electricity would constitute 68% of total final energy supply.

Again Lenzen's review [98] concludes that because of the difficulties integrating the highly variable wind resource into supply systems wind is not likely to be able to provide more than 25% of demand, possibly only 20% Lenzen indicates that the PV limit might be somewhat higher. If the 10,000 GW task is allocated 25%, 30% and 45% to wind, PV and solar thermal sectors the supply from each would have to be 2,500 GW, 3,000 GW, and 4,500 GW respectively. Applying the reasoning in Table 2 to the winter monthly supply task results in a total annual investment cost of $4.7 trillion, which is 64% of the cost of the hydrogen path. Again this does not include the many omitted items noted above except for those to do with hydrogen generation and handling.

At first sight this is counter-intuitive as the task of generating twice as much electricity as is needed in the form of hydrogen has been avoided. However, firstly this only reduces the amount of electricity that needs to be generated by 35%. Secondly strategy 1 assumed wind, the cheapest of the three renewable, contributing 33% of demand (after biomass, hydro and low temperature heat), whereas in strategy 2 it only contributes 25%.

However, strategy 2 would not seem to be viable due to problems of intermittency and storage set by the occurrence of long gaps in solar and wind energy availability. There can be periods of several consecutive days when there is negligible wind or solar energy anywhere within continental sized regions. Lenzen's review refers to a number of studies documenting this phenomenon. For instance Oswald, Raine and Ashraf-Ball, [99] shows that for the first 6 days of February 2006 there was almost no wind energy generated from Ireland to Germany, and one of these days was the coldest of the year in the UK. Although not reported, it would probably also have been a period of negligible solar energy. Similar documentation is given by Soder et al., [100] for West Denmark, Sharman [101] and Mackay [102], for the UK, E On Netz [103] for Germany, and for Australia Davey and Coppin, [104] and Lawson [105].

This gap phenomenon invalidates analyses commonly based on annual average quantities of energy required from PV, wind and solar thermal sectors. These studies proceed as if there will be no interruptions to their contributions and thus no need for back up plant.

An economy heavily dependent on electricity could function through such weather events only if extremely large quantities of electricity could be stored. At present this is not possible and it is not foreseen. For instance, the magnitude of the task greatly surpasses the potential of pumped storage (shown by Mackay for the UK, [106].) The difficulties in storage via hydrogen have been dealt with above.

Even if it is assumed that the gaps could be plugged by biomass generation then a significant problem of redundancy remains. During periods when the sun and wind failed to provide energy sufficient biomass-burning generating plant would be needed to meet total demand, only to remain idle most of the time. However the global biomass contribution assumed above is too low to be capable of filling this role to any significant extent, constituting only 50 EJ/y in a 466 EJ/y budget. In addition the lower efficiency of biomass generation of electricity (above) would further limit potential.

6.3 *Electrify and rely on solar thermal generation and storage*

A third conceivable strategy would be to use as much electricity as possible and to solve the intermittency, storage and redundancy problems by relying on the capacity of solar thermal power stations to store heat.

Despite its storage capacity solar thermal generation also suffers an intermittency problem. The discussion of solar thermal potential is typically carried out in terms of annual and at times monthly average levels of solar radiation whereas what matters most are minima and their frequency of occurrence.

The ASRDHB [107] provides tables on the probability of sequences of cloudy days at Australian sites. At Alice Springs the probability of a 5, 7 or 9 day run in which average daily global radiation in winter is under 4.86 kWh/m^2/d is 100% in all cases. (DNI data is not given but other tables show that DNI is around 15% lower than global.) There is a 90% chance of a 4 day run averaging under 3.75 kWh/m^2 (i.e., under c 3.2 kWh/m^2/day of DNI), and in each of the 4 winter months there is a 25% chance of a 4 day run with global radiation averaging under 3.75 kWh/m^2/d. Even on a 4.86 kWh/m^2 (global) day DNI would rarely reach 700 W/m^2, a level at which dish-Stirling output falls to 50% of peak. At 3.2 kWh/m^2/d DNI virtually no output would be produced by solar thermal systems. (Odeh, Behmia and Morrison [108] show that under 600 W/m^2 trough output plunges.) There is a 100% chance that in June there will be a sequence of 14 days in which global radiation is under 5.5 kWh/m^2 day. This means DNI would be under 4.8 kWh/m^2/d, i.e., under 85% of the 5.7 kWh/m^2/d winter average for central Australia.

This evidence indicates that even in the best sites, in winter solar thermal systems would experience lengthy periods of low or negligible output. Even if these were infrequent they would seem to set insurmountable challenges for storage capacity. At present 7 hour storage is being built into new solar thermal plants, so to get through a four day gap 14 times as much capacity would need to be provided, and this might treble plant cost. (Derived from the figures given by Foran [109] and NREL [110].)

A 4 day task would involve a significant heat loss from storage. At present heat loss is a negligible 1%, but this is for c. 7 hour storage, indicating that for the much greater volume needed for 96 hour storage it could be c. 14%.

Even if these storage issues are ignored the capital costs for strategy 3 would be unacceptable, mainly because the capital cost of delivered electricity appears to be some four times that of wind. To provide 15,500 GW at $16/W would cost $248 trillion, or $9.9 trillion p.a., which is a higher proportion of GDP than for the hydrogen option.

7. THE PEAK VS DELIVERED COST ISSUE

These capital cost conclusions might appear to be irreconcilable with the frequently stated claim that some predicted capital costs for renewable plant, such as wind, are comparable with those of coal-fired plant. Easily overlooked is the fact that those are typically statements about cost per *peak* watt, not per *delivered* watt. The output from a coal-fired plant in winter can be 100% of its peak capacity whereas for a solar thermal plant it will be around 20%. Thus the capital cost of sufficient solar thermal plant to deliver a kW in winter is much higher than that which the "nominal" or peak value would indicate. Thus the coal fired plant required to produce 1 kWh in winter would cost c. $2000x (1/.8) = $2,500, but the NREL example solar thermal plant required to do this would cost c. $6,580x(1/.2) = $32,900.

Similarly the 'levelised cost' of renewable energy is a misleading indicator of total system capital cost as it does not indicate the cost of the required redundant back-up plant when wind or solar resources are making negligible contributions. As Lenzen [111] indicates, the cost of a component such as wind should include the cost of the back up systems it requires to make its allocated contribution.

These considerations show that analyses which simply divide the supply task into fractions to be provided by wind, PV, solar thermal etc. will grossly under-estimate the amount of plant required. They make the implicit assumption that each component can make its contribution at any time that wind or solar radiation is available. This is an invalid assumption. For instance, even on a sunny day there are about 16 hours when PV can make no contribution, and if in this period there is also no wind then enough solar thermal and/or biomass plant must have been built to meet total demand. This would probably double the amount of plant that needed to be built, and most of it would sit idle most of the time.

8. DIFFERENT ASSUMPTIONS?

The most uncertain assumptions in the above derivation are listed below, along with much more optimistic assumptions.

- The 2050 supply target; assume this is reduced by 25%.
- PV efficiency; assume 20% rather than 15%.
- Future solar thermal cost; assume 50% lower than above, i.e., a fall to 25$ of present cost.

Combining these assumptions would reduce the capital cost conclusion for Strategy 1 by 43%, again not including the many additional cost factors listed above, and not taking into account the problem of dealing with intermittency.

9. CONCLUSIONS

The total investment sum arrived at above is considerably less than that derived in Trainer [112], but the derivation is much more soundly based mainly due to recent access to more confident estimates of output and future capital costs. The general conclusion supported by this discussion is that the capital costs for a totally renewable global energy supply would be far beyond affordable. This means that greenhouse and energy problems cannot be solved by action on the supply side, i.e., by technical developments which promise to provide quantities taken for granted in energy-intensive societies. This general "limits to growth" perspective is that these and the other major global problems can only be solved by action on the demand side, i.e., by moving to ways, values, institutions and systems which greatly reduce the need for materials, energy and ecological resources.

It should be stressed that the 700 EJ/y supply target would give the world's expected 10 billion people by 2050 a per capita energy consumption of 70 GJ/y, which is around only one-third of the present Australian level. Thus if renewable sources were to provide all the world's people in 2050 with the present Australian per capita energy consumption, the supply target would have to be three times that taken in this exercise.

This analysis is not an argument against transition to full reliance on renewable energy sources. It is only an argument against the possibility of sustaining high energy societies on them. Trainer [113] and [114] detail the case that the limits to growth predicament cannot be solved by technical reforms to or within consumer-capitalist society and that there must be radical social transition to some kind of 'Simpler Way.' This vision includes developing mostly small and highly self-sufficient local economies, abandoning the growth economy, severely controlling market forces, shifting from representative to participatory democracy, and accepting frugal and cooperative lifestyles. Chapter 4 of Trainer [115] presents numerical support for the claim that footprint and energy costs in the realm of 10% of those in present rich countries could be achieved, based on renewable energy sources. Although at this point in time the prospects for making such a transition would seem to be highly unlikely, the need to consider it will probably become more evident as greenhouse and energy problems intensify. It is not likely to be considered if the present dominant assumption that high energy societies can run on renewable energy remains relatively unchallenged.

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