Energy Policy 109 (2017) 539–544

Contents lists available at ScienceDirect

Energy Policy

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

'Can renewables meet total Australian energy demand: A "disaggregated" approach

Ted Trainer[1]

ARTICLE INFO

Keywords:
Renewable energy limits

ABSTRACT

Attempts to assess the possibility of deriving all energy from renewable sources typically deal only with the aggregate amount of energy required, and do not consider the implications and difficulties arising from the need for differing forms of energy. In a 100% renewable system some of these forms will have to be provided by conversion from others, mostly from electricity. Conversion involves inefficiencies, losses, and embedded energy costs of infrastructures, and thus energy and dollar costs. In this study an attempt has been made to determine the magnitude and effect of this general problem, by beginning with estimates of the quantities required by different sectors and of the different forms they use. How these needs might best be met in a renewable system is then considered. Although there is insufficient data to enable confident conclusions, this "disaggregated" approach indicates that a 100% renewable system to meet Australian energy demand would involve costs that would probably constitute an unacceptably large fraction of GDP.

1. Introduction

The recent simulations of a 100% renewable power supply system for Australia by Elliston et al. (2012, 2013) and by Lenzen et al. (2016) have significantly advanced understanding of the feasibility and cost of such a scenario. However at present electricity makes up less than 20% of total Australian energy demand in a rich country, and it is the form most easily provided by renewables. Biomass is the only renewable form that does not directly produce electricity. To provide all forms of energy needed (e.g., liquid fuel) from renewables would be a much more difficult task than simply scaling up the power supply system by a factor of five. This is mainly because most of the remaining 80% of energy needed sets problems to do with a) the nature and number of these other uses and forms, and b) costs and losses in switching uses to electricity c) the amount that cannot conveniently be switched, and d) the energy and dollar costs of converting electricity or biomass into these more difficult forms (e.g., hydrogen).

2. Method

To analyse the situation satisfactorily we would need to have confident answers to several unsettled questions, such as, what quantities of what kinds of energy are currently needed in the total energy budget, how much liquid fuel is needed for what purposes, and to what extent can electricity replace each of these. How might trucks, ships, aircraft, remote mines etc. be run? How much demand could be met by available biomass in an ecologically sustainable way? How much demand could not be shifted to electricity or available biomass and what transformations of electricity (e.g., to hydrogen) might be feasible, in what quantities and at what efficiencies and costs.

Unfortunately there is little information on several of these issues, especially the quantities of demand in the sectors other than power and transport. Therefore the following exploration is offered as uncertain and indicative only, but it does provide strong reasons for thinking that achieving a 100% renewable system will at best be very difficult and costly, and possibly unaffordable.

It is hoped that the approach being taken here will be followed by more thorough future studies. It might be regarded as a"disaggregated" approach as it does not work with a simple total energy figure but attempts to estimate what quantities of energy in what forms might be needed in Australia by 2050. A number of previous approaches to the issue of 100% renewable supply have given little or no attention to the significance of the differing forms needed. (For instance, Greenpeace, 2015, The Greens, 2016, Teske et al., 2016.) It will be seen below that significant difficulties and costs emerge when it is recognized that there is a need for much energy in forms that are not easily provided by renewable energy sources.

3. Data

Following is a summary of the data used and assumptions made regarding forms and quantities needed in the Australian economy by 2050, followed by derivations based on these. Almost all arithmetic is set out, possibly complicating the text but enabling all assumptions and

[1] No institution; retired lecturer at University of NSW.

http://dx.doi.org/10.1016/j.enpol.2017.07.040
Received 18 April 2017; Received in revised form 14 July 2017; Accepted 17 July 2017
0301-4215/

Table 1
Quantities assumed.

Final Australian energy consumption, 2015,	4130 PJ.
Electricity, 20% of final,	810 PJ
Transport, 39% of final,	1603 PJ
Population in 2050, c. 42 million, 1.82 times present. (ABS, 2012.)	

derivations to be transparent and capable of independent critical reassessment.

3.1. Estimating a 2050 Australian total energy budget

The 2050 "business as usual" (BAU) demand cannot be estimated with confidence. Australian power demanded from the grid declined in the 2010–2014 period, but this has been partly due to the lingering post GFC recession, the closure of some larger scale industrial power users, steeply rising electricity prices, and to the rapid uptake of rooftop PV. More recently demand has begun to increase again. The approach here is to consider what 2050 demand would be given continuation of the longer term BAU trend, then add the effect of various factors such as a shift to electric vehicles. It will be assumed that BAU demand will increase in proportional to population, and thus be 7520 PJ. There is reason to think this could be an underestimate because since 1974 energy consumption has shown a smooth increase that has been faster than population growth. Again this assumption is quite uncertain and the implications of taking a much lower 2050 BAU target will be discussed later (Table 1).

Also highly uncertain is the likely effect of energy conservation effort. There is considerable scope for this and quite optimistic possible reductions are often claimed. However there seem to be few if any numerically based technical estimates of whole system savings (as distinct from discussions of specific areas in which spectacular achievements are likely to be made; Amory Lovins' works provide many of these, e.g. Lovins and Von Weisacher, 1997, Lovins, 2011.) The possible effect of this conservation factor will be considered later, and brief reference will be made to the many factors likely to increase energy demand and to overwhelm reduction achievements.

Thus 2050 final BAU energy demand will be taken as,

Electricity,	1472 PJ
Transport,	2917 PJ
Remainder	3131 PJ
Total	7520 PJ

3.1.1. Electricity provision

It will be assumed that 94% of electricity can be provided by wind, solar and hydro, plus 6% from biomass used for back up purposes. These figures are drawn from the simulations by Elliston et al. (2012, 2013) which assume up to 58% of electricity can come from wind. They are quite optimistic assumptions for wind and solar; others point to evidence of increasing difficulties and costs where wind contributes more than 30% of supply (Lenzen et al., 2016, refer to several studies making this point.) The biomass quantity is less challengeable, but is in the region of one-third of the amount found to be needed in the "real-world probable" scenario discussed by Lenzen et al. This means that the assumption made in this analysis leaves much more biomass available for use in meeting liquid fuel demand than might be realistic.

The Australian Energy Market Operator (Crawford et al., 2013) estimates that Australia could harvest c. 96 million tonnes p.a. for biomass energy, i.e., 1728 PJ/y, including municipal wastes. These figures are likely to be considerably too high as AEMO notes that they do not include energy costs for biomass production and transport, nor any embodied energy costs in plant, trucks etc. Farine et al. (2012) arrived at a figure around half as large. However Foran (2008) assumes much greater amounts could be provided (...considered again below.) It will be assumed here that a net amount of about 1600 PJ can be provided. Thus after backing up power (at c. 26% conversion efficiency; Crawford et al., 2013), about 1260 PJ of biomass would be left. (A larger assumption will be considered below.)

The amount of electricity to be generated from non-biomass sources is therefore 94% of 1472 PJ = 1384 PJ.

3.1.2. Transport energy provision

It will be assumed that a) all passenger vehicles can be electric, doubling energy efficiency (not trebling, in view of the high embodied energy cost of EVs (Sharma et al., 2013; Mateja, 2000), b) that electricity, ethanol and hydrogen can each power one third of light trucks, and c) half of heavy trucks run on ethanol and half on hydrogen. (Friedmann, 2016; and Bossel, 2004, below, explain the reasons for not assuming heavy truck transport based on electricity or hydrogen.) Transfer of much freight to rail is not accounted here; it would reduce heavy truck use but would greatly increase light truck use for distribution from rail heads. Air transport will be assumed to be fuelled by ethanol. No figures for shipping are included although the amount involved in the Australian economy would be significant. Almost all vessels carrying imports and exports to Australia are foreign owned so fuel quantities are not recorded in Australian accounts. In a 100% renewable world shipping fuel would have to be liquid or hydrogen etc., not electrical, so production from renewable sources would be problematic, given the scarcity of biomass.

From above the amount of transport energy required in 2050 would be 2917 PJ.

The breakdown of present amounts and proportions, (from Australian Bureau of Statistics, 2014), would be:

Road. 73% of transport energy, i.e.,				2129 PJ
Passenger,		58%	of transport energy	1235 PJ
Light trucks	17%		" " "	362 PJ
Heavy trucks	22%		" " "	468 PJ
Other	3%		" " "	64 PJ
Rail. 3% of transport energy, i.e.,				87 PJ
Air. 19+% of transport energy, i.e.,				**554** PJ
N.e.i. 4% of transport energy.				120 PJ

Amounts and forms of transport energy required in 2050:

Passenger vehicles: 1235 PJ needed if BAU. It will be assumed all are electric vehicles, but at only double present energy efficiency, not treble (see above), therefore 617 PJ of electricity would be needed.
Light trucks: 362 PJ needed if BAU. Some trucks for light deliveries can be electric vehicles, but some for heavy distribution would have to be hydrogen or biomass-ethanol. It will be assumed one third each will be fuelled by electricity, hydrogen and biomass ethanol, therefore the need will be for 120 PJ of hydrogen and of biomass ethanol and 60 PJ electricity for EV light trucks. (This unrealistically assumes light trucks would use no more energy than passenger vehicles. It is assumed that short distances would enable frequent refueling by hydrogen, and thus avoidance of heavy tanks.)
Heavy trucks: Under the BAU assumption 468 PJ would be needed. Friedmann (2016) and Bossel (2004) detail the reasons why they are not likely to be ERVs or fuelled by hydrogen. Very large and heavy tanks would be necessary to store sufficient compressed hydrogen for long distance transport meaning that the net freight weight that could be moved long distances would be quite low. In addition the equipment needed to produce, compress, store and distribute hydrogen would significantly reduce net energy delivered. Finally the efficiency of the electricity-hydrogen-fuel cell path would be in the region of 30%. Therefore it will be assumed that the 468 PJ needed would have to be biomass ethanol.

Table 2
Total energy needed for transport.

Electricity for EVs	764 PJ
Biomass ethanol	1201 PJ
Hydrogen	179 PJ
Total.	2144 PJ

Rail. Assume all electrical. 87 PJ
Air. 554 PJ of liquid fuel (assume ethanol.)
Other transport. 117 PJ needed. Assume 59 PJ of ethanol and 59 PJ of hydrogen (Table 2).

Thus the total energy needed for transport would be, 764 PJ of electricity for EVs, 1201 PJ of biomass ethanol, and 179 PJ of Hydrogen, making a total of 2144 PJ.

Thus the total energy needed for transport would be, 764 PJ of electricity for EVs, 1201 PJ of biomass ethanol, and 179 PJ of Hydrogen, making a total of 2144 PJ.

3.1.3. Remaining energy provision

The amount of energy required in addition to power and transport energy is large, 3131 PJ and 43% of total demand. This sets the most difficult problems for 100% supply proposals, as much of the remainder presently takes a non-electrical form. Electricity is the easiest form for renewables to provide and converting it to many other forms involves significant inefficiencies and costs. Unfortunately there is little information on the present composition of energy forms and quantities in this category. A clearer understanding of this area will eventually enable estimates of how many functions could be converted to direct electricity use and how much provision would have to draw on fuels derived from electricity such as hydrogen. As has been noted the latter option can be highly energy inefficient and can require elaborate infrastructures and thus involve high embodied energy costs.

The issue is complicated by the fact that some of the electricity consumption accounted above would presently be going into low temperature heating. Let us attempt to take low temperature heat energy out of the estimation task by assuming (unrealistically) that it can all be provided without electricity, e.g. from simple solar thermal panels. There is considerable scope within Australian conditions for this to be done, but far less in Europe of North American winters.

The two most relevant figures available for estimating quantities here are, firstly residential heating plus cooling makes up about 5.6% of total Australian energy use, so the heating figure would be lower. Secondly industrial plus commercial energy uses add to about 32% of the total. If it is assumed that one quarter of this is low temperature heat that need not be provided via electricity, then residential + industrial + commercial low temperature heating might add to 12% of total energy. This would mean that 12% of the BAU target 7530 EJ, i.e., 904 PJ, could come from solar thermal panels. (The heat would be in the form of c. 3000 PJ of primary energy but getting it from solar thermal panels instead of electricity would reduce final electrical energy c. 904 PJ.)

However, firstly solar thermal panels might be highly effective in Australia but they would be of little value in European winters. Secondly in the real world much heating and cooling would be carried out by heat pumps, adding to the above electricity demand figure. Thus the above assumption that all low temperature heat is to be provided by solar thermal panels unrealistically reduces the total electricity demand to be met.

It should also be noted that if average solar radiation in winter was 6 kW h/m^2/d and could be collected at 100% efficiency, then to collect 904 PJ/y or 2.5 PJ/d would require a 107 million m^2 collection area, adding a significant embodied and dollar energy cost that will be ignored here. That area corresponds to almost 40 m^2 per Australian household.

Let us make the simplifying assumption that all of this reduced remaining category of 3331−904 = 2227 PJ can be provided by electricity. (Again this assumption is likely to be far from valid.)

4. Results

Before summarizing results it is necessary to discuss some complications involved in the foregoing analysis of data. As noted above, after providing biomass for backing up electricity provision 1260 PJ/y of biomass would be available for use. However from above 3344 PJ is needed. The shortfall of 1744 PJ would have produced 698 PJ of ethanol, if conversion efficiency is 40%. It will be assumed that this will now have to met by hydrogen, bringing that total to 179 + 698 = 877 PJ. (Whether or not this amount of hydrogen can be used will be ignored; for instance it is not likely to be used to run heavy trucks.)

But to have 1 unit in the form of hydrogen about 1.7 units must be generated in the form of electricity (… even ignoring the large energy cost embodied in hydrogen production, storage, pumping equipment and losses. (Efficiency of conversion estimates vary; Honnery and Moriarty, 2009, state 55% which would mean the multiple is 1.82.) Thus generating the hydrogen would require 1490 PJ of electricity. The electricity total would then become= 5867 PJ.

For simplicity the present hydro contribution has not been taken into account but it is relatively small compared with this total, possibly around 1%.

Thus, to meet the final demand it would be necessary to produce 5867 PJ/y of electricity plus (a net) 1600 PJ/y of biomass (Table 3).

There are other factors that would tend to increase these numbers significantly. No provision has been made in this budget for any embodied energy costs or for the plant and special pipes involved in hydrogen production, storage, pumping and supply, and these would be substantial. No provision has been made for shipping energy. The dollar and energy costs of all the new transmission infrastructures needed to deliver from the many large scale wind and solar fields needed have not been included.

Two groups have recently carried out detailed simulations of a 100% renewable electricity supply system for Australia based on weather data. (Elliston et al., 2012, 2013; Lenzen et al., 2016). The reasons for basing the following case on the study by Lenzen et al. are given in Trainer (2017) Lenzen found that the production cost could be around 20c/kW h given the assumptions underlying the basic derivation, but might be a little above 30c/kW h for typical conditions. Trainer attempts to determine the implications of this production cost for the probable retail cost, taking into account factors not considered in the study (e.g., embodied energy costs were not included, and 2010

Table 3
Summary of totals (at this point).

	Energy forms to be generated		
	Electricity	Biomass	Hydrogen
To meet power demand.	1386 PJ	340 PJ as biomass	
To meet transport demand.	764 PJ > = 3004 PJ as biomass	1201 PJ as ethanol,	179 PJ
To meet remaining demand.	2227 PJ		
Totals.	4377 PJ	3344 PJ of biomass	179 PJ
…as final energy:	4377 PJ	88 PJ as electricity 1201 PJ as ethanol = 3004 PJ biomass	179 PJ
…that is, total final energy required:		5845 PJ.	

would not have been the worst year ever to occur), alternative assumptions (especially re the solar thermal component, see below), and several factors that determine the difference between wholesale and retail price. (For the present coal-fired supply the retail price of electricity is around 8 times the production cost determined by the four factors Lenzen et al. took into account, i.e., capital, O and M, transmission and "fuel" costs.) The limited evidence available on these factors enabled an estimation of cost increase implications for only four of the ten identified as increasing the Lenzen et al. production cost to a retail price. These were, the difference in the exchange rate between 2014 and the much more favourable value when the capital cost estimates for mostly imported plant used were made, a cost multiplier for remote area construction, inclusion of embodied energy costs, and an estimate based on Bureau of Meteorology data to take into account evidence on how much less favourable than 2010 weather patterns might at times be. The result was a retail price of at least 68c/kW h, (i.e., assuming a production cost of 20c/kW h) and reasons are given for anticipating 90c/kW h or even higher.

4.1. Estimating total energy supply costs

If the retail price is taken as 50c/kW h (rather than 68c/kW h), the cost of providing the amount derived above would be $814 billion p.a., or approximately 54% of GDP. For a retail price of 30c/kW h the cost would be over 18% of GDP. (See Note 1.)

To these sums various additional costs would need to be added, such as the cost of converting 1260 PJ of biomass to 504 PJ/y of ethanol (equivalent to 30% of current passenger car fuel use) and the cost of the renewables transmission infrastructure.

The present rich country total expenditure on energy is usually well under 10%. (After recent significant rises the Australian figure has been estimated at 8.2%. Pears, 2017.) But this includes sales taxes added on after all production and distribution costs. For example 40% of the retail price paid for petrol in Australia today is a tax added by government to the retail supply price. If taxes could be taken out of the calculation the retail price paid for energy in Australia today would probably be closer to 5% of GDP. Hall and Klitgaard (2014) are among others reporting that when energy expenditure remains above about 5.5% of US GDP for some time recession occurs.

4.2. More optimistic assumptions?

From here on BAU energy demand might not increase as fast as population. If the multiple is 1.4 rather than the 1.82 assumed above then the 2050 total energy cost would be c. 77% of the above figure, i.e., around 21% of 2050 GDP

The electricity generating task would be reduced if the biomass contribution could be greatly increased beyond the AEMO estimate (Crawford et al., 2013), which Foran (2008) believes is possible. However this would be unlikely to make a major difference. If 40 million ha could be planted at a yield of 10 t/ha/y, providing 7200 PJ/y (more than four times the Crawford et al. biomass energy conclusion) this would enable the above 3344 PJ/y of biomass required for electricity back up plus ethanol provision, with a surplus of 3856 EJ/y of biomass left over. If converted to electricity at the 0.26 efficiency AEMO assumes this would produce 1002 PJ/y. Thus after producing the 179 PJ/y of hydrogen needed the amount of biomass electricity that could be produced would be 698 PJ/y. (See note 2.) Therefore the amount of electricity to be generated from non-biomass sources would be reduced from 5867 by 12%.

By 2050 there will probably be significant efficiency improvements other than those assumed here, which were 8+% for electric vehicles and 12% for low temperature heat supply. However these add to about two-thirds of the one-third reduction that conservation effort and efficiency gains are commonly assumed to be capable of making.

Some believe the conversion of biomass to methanol rather than ethanol is the preferred option, and efficiency might be raised to 50%. This would not make a major difference to the conclusions arrived at.

The biomass-gas-electricity path might be a more efficient path than the burning of biomass to generate electricity. The significant uncertainties regarding this path are discussed in (Trainer, 2015)

If the Elliston, Diesendorf and MacGill production cost finding is taken (10–15c/kW h), the above derivation would indicate a retail cost around 45–56.5c/kW h, which is lower than the price derived from the production cost Lenzen et al. arrive at, but it more or less corresponds to the 50c/kW h used above.

Several other optimistic assumptions could be explored, such as use of battery storage and storing hydrogen in metal hydrides. It is hoped that these will be included in future applications of this disaggregated approach.

4.3. More pessimistic assumptions?

Weighing against the optimistic possibilities there are several factors that are likely to greatly increase the magnitude of the future supply task. It is likely that in 2050 many functions will require greatly increased energy inputs, such as water desalination, mining poorer ores, processing poorer ores, and dealing with greater levels of mining waste material and environmental pollution. Denser settlements will involve much high rise construction and living, complex infrastructure upgrading, and high rates of movement of inputs and waste outputs. The present commuting rates to centralized cities are major sources of transport energy consumption, especially for infrastructures, and this pattern is likely to intensify. The quest to improve productivity will probably increase energy demand, as it has recently been realized that productivity growth is significantly due to adoption of more energy-intensive ways. Global freight and especially tourism and air traffic are expected to increase faster than population or GDP.

Another major category concerns the energy that will be needed to cope with accelerating ecological deterioration, especially climatic challenges to agriculture and food supply. Dealing with the many effects of climate change will add large energy costs that do not have to be met at present, including defensive works such as sea walls, settlement relocation, salt water incursions into agricultural land, remedying storm damage, dealing with environmental refugees, adapting to altered rainfall patterns (which for instance will make some dams redundant), dealing with pest surges and algal blooms, and developing new crops for altered conditions. Warming weather will significantly increase air conditioning use, adding greatly to the task of providing for peak supply. The need to deal with accelerating biodiversity loss will also add to demand on energy supply.

Probably the greatest problem will be set by the fact that the IPCC greenhouse targets assume taking very large amounts of carbon out of the atmosphere after 2050 and this would involve enormous energy costs. Anderson (2017) points to the general neglect of this issue, and the danger that it is being assumed to legitimize the avoidance of taking urgent measures in the near future. The magnitude of the task being left for future generations and technologies is easily overlooked. The required technologies are problematic and have not been demonstrated at scale, but Anderson points out that they will probably be called on to take 18 GT of CO2 out of the atmosphere each year, which is almost equivalent to half the amount currently being emitted.

In view of these considerations it is not obvious that conservation effort and technical advance will achieve reductions that outweigh these sources of increased energy demand. In addition it is necessary to give separate attention here to the reasons for believing that the CSP assumptions built into the Lenzen et al. derivation are unduely favourable.

4.4. The CSP issue

Given the complexity of the modeling and computing tasks involved in the Lenzen et al. analysis it made sense to proceed with commonly held assumptions regarding CSP, but following is a summary of the case that some of these assumptions are much too optimistic.

The foregoing derivation of costs is based on the Lenzen et al. findings, which depend significantly on the contribution of CSP in periods when renewable energy is least available. There are three important elements in the Lenzen et al. study which are questionable but could be refined when the approach is further elaborated.

Firstly Lenzen et al. assume the efficiency of generation to be 30%, based on a table given by Lovegrove et al. (2012, p. 49) However that text points out that this figure is an estimate of what technical advance might achieve. There is considerable evidence in reports on the CSP systems operating today that current efficiencies are around 14%. Some foresee possible improvements to the region of 19% (Lovegrove et al., 2007; Hinkley et al., 2012, Fig. 7; NREL Solar Advisory Model, undated; Kearney Consulting, 2010; Viebahn et al., 2004; Abengoa, 2016; Marin, 2015; De Castro, 2017; Solarstor, 2017).

The second issue concerns efficiency and net output in poor conditions, especially winter. The Lenzen et al. findings depend considerably on the contribution that CSP can make in periods when the renewable resource is at its lowest. Their Fig. 6 representing five difficult days shows that due to the lack of wind and PV input CSP is called on to provide a lot of electricity, almost always over 15 GW and at times apparently up to 19.4 GW, which is 84% of average demand.

In this initial investigation it was in order to minimize the already complex computational task by assuming that CSP generation efficiency would be the same at all seasons and levels of DNI and times of the year. However this is not the case; the actual efficiency of a plant in winter is in general significantly lower than in summer and varies according to the priorities underlying its design (Jones et al., 2001; Wood et al., 2012, 4–14; Siangsukone and Lovegrove, 2003; Odeh et al., 2003; Kaneff, 1991).

That the effect is not trivial is evident in data from the Torresol generating company which operates Gemasolar in Spain (Marin, 2015), and from Solarstor, .) (2017) The Solarstor device has an average"Field efficiency" in summer that is twice its winter value i.e., the ratio of heat collected to solar radiation intersected by heliostats. This falls sharply as DNI falls, that is, faster than the fall in DNI. For instance at 400 W/m^2 "field efficiency" is 61% below its level when DNI is 1000 W/m^2, and heat is being collected at only 15% of the 1000 W/m^2 rate.

The data on Gemasolar confirms the indication from Solarstor that the effect is marked. When DNI is 463 W/m^2 the efficiency of heat delivery is only c. 20%. If a turbine efficiency of 33% is added the efficiency of solar to electricity generation would appear to be under 7% (…and this does not take into account loss of parasitic energy.) If this reasoning is more or less valid the CSP contribution represented in Fig. 6 in Lenzen et al. would have required more than four times the 61 GW capacity found to be needed (or would have required resort to be made to some other storage strategy.) Note that average Australian demand is 23 GW.

Finally the capital cost assumption (taken from AETA 2012 and 'Scenario 1 2030′ in AEMO 2013) represents a large (56%) fall from the present cost given by AEMO, which is almost double that assumed for the other renewable technologies. The 20 MW Gemasolar Plant in Spain was the first to be equipped with15 hour storage, assumed by Lenzen et al., and its capital cost has been reported as $(US)419 million, or a remarkable $21,000/kW (Wilson, 2011) and three to four times the Lenzen et al. cost assumption.

Thus if future applications of the Lenzen et al. approach can incorporate more complex CSP assumptions they are likely to arrive at a significantly higher production cost estimate than that informing the above derivation.

5. Conclusion and policy implications

This analysis does not arrive at confident conclusions as much depends on uncertain assumptions regarding the situation in 2050. However it does indicate grounds for suspecting that the total cost of 100% renewable energy supply will be very high, probably seriously economically disruptive, and possibly unaffordable. Note that these estimates apply to Australia, which has possibly the most favourable renewable energy conditions in the inhabited world, including approximately five times the world per capita biomass potential**.** (IPCC, 2011; European Biomass Industry Association, undated). Some estimates of future European biomass potential put it at sufficient to meet at most a mere 3% of transport fuel demand, and possibly only a quarter as much (European Commission, 2013; Wetterlund et al., 2012; Bentsen and Felby, 2012).

Without their considerable access to this renewable energy source for the purposes of getting through difficult periods the scenarios from Elliston, Diesendorf and MacGill, and from Lenzen et al. would have yielded much higher production costs for electricity.

The probably surprising magnitude of these cost findings is due primarily to the previously largely neglected consideration of the differing forms of energy required, and the difficulties and costs in meeting some of these requirements via energy and dollar costly conversions from electricity. It is important that future attempts to simulate 100% total energy supply systems should take an approach of this kind, that is, one which "disaggregates" and deals with the differing forms of energy required and conversion costs.

The belief that 100% renewable energy supply is possible and affordable is probably the main element in the "tech-fix" faith which seems to be held by most governments and people, including those who are technically sophisticated and participants in green and left energy camps. The dominant assumption is that there is no need to shift from something like the present energy and resource intensive lifestyles and systems, or from an economy driven by market forces, the profit motive and growth. The immensity of the policy implications of the above findings requires little elaboration. If the position arrived at in this reassessment is sound then it would seem that if a solution is to be sought on the supply side it will have to be in the form of breeder reactors. This commitment would have to be very large, given the above finding that to run everything on electricity would require a great deal of generating capacity to enable conversion to non-electrical energy forms.

The alternative policy option is to seek a solution on the demand side, that is to opt for a "De-growth" transition to some form of "Simpler Way". From this perspective energy is only one of the major global problems currently threatening and these cannot be solved unless there is dramatic reduction in rich world per capita levels of consumption, the present economy is largely abandoned, there is a shift to mostly self-governing localized communities, and there is immense cultural change away from individualistic, competitive acquisitiveness to frugal, cooperative and non-material values. Such an option is far from the centre of policy debate at present but this might change if the global situation deteriorates as some anticipate (see especially Ahmed, 2017.) The case that an alternative of this kind would be workable and attractive is detailed at thesimplerway.info/. In particular the item "Remaking Settlements" (Trainer, 2016) derives the tentative conclusion that the suburbs of cities might be restructured in ways that cut per capita energy, resource and dollar costs to the region of one-tenth their present typical values.

Notes.

1. To provide 5867 PJ/y of electricity, i.e., 1629 billion kW h/y, at 50c/kW h would cost $814 billion p.a., which is around 54% of 2015 GDP, or 27% of 2050 GDP assuming 2% economic growth. (An approximate crosscheck; this amount of electricity is about 8.5 times the 2015 c. 200 TWh electricity production which retails at c. 25c/kW h indicating a cost of $50 billion/y. If the 2050 retail price was 50c kW h, i.e., twice as high, total annual energy supply would cost 8.5 x $50b × 2= c. $850 billion.) If a retail price of 30c/kW h had

been assumed, total energy provision would have cost over 18% of GDP.

2. From the 1002 PJ/y derived via the AEMO 0.26 assumption 179 PJ/y × 1.7 = 304 PJ/y of biomass energy would be needed, i.e.698 PJ/y.)

References

Abengoa, 2016. PS 10 Solar Power Plant, Wikipedia. ⟨https://en.wikipedia.org/wiki/PS10_solar_power_plant⟩.

Ahmed, N.M., 2017. Failing States, Collapsing Systems. Springer, Dordrecht.

Anderson, K., 2017. Paris, Climate and Surrealism; How numbers reveal another reality, Resilience, 21 March.

Australian Bureau of Statistics, 2014. Australian Energy Statistics. ⟨https://industry.gov.au/Office-of-the-Chief-Economist/Publications/Pages/Australian-energy-statistics.aspx⟩.

Bentsen, N., Felby, C., 2012. Biomass for energy in the European Union –A review of bioenergy resources. Biotechnol. Biofuels 5, 25, (doi:2,10.1186/1754-6834-5-25).

Bossel, U., 2004. The hydrogen illusion; why electrons are a better energy carrier, Cogeneration and On-Site Power Production, March – April, pp. 55 – 59.

Crawford, D., Janovic, T., OConnor, M., Herr, A., Raison, J., Baynes, T., 2013. Potential for electricity generation in Australia from Biomass in 2010, 2030, and 2050, AEMO 100% Renewable Energy Study, 4 Sept. CSIRO Report EP – 126969.

De Castro, C., 2017. Personal communications.

Elliston, B., Diesendorf, M., MacGill, I., 2012. Simulations of scenarios with 100% renewable electricity in the Australian National Electricity Market. Energy Policy 45, 606–613.

Elliston, B., MacGill, I., Diesendorf, M., 2013. Least cost 100% renewable electricity scenarios in the Australian National Electricity Market. Energy Policy 59, 270.

European Commission, 2013. Agricultural and Rural Development; Biomass potential. ⟨http://ec.europa.eu/agriculture/bioenergy/potential/index_en.htm⟩.

Farine, D., et al., 2012. An assessment of biomass for bioelectricty and biofuel and for greenhouse gas emission reduction in Australia. Bioenergy 4, 148–175. http://dx.doi.org/10.111/j.1757-1707.2011.o1115/x.

Foran, B., 2008. Australian Forestry for a Better Future Challenges, Opportunities and Strategies. Institute for Land Water and Society, Charles Sturt Univ, Albury.

Friedmann, A., 2016. Diesel is finite. Trucks are the bedrock of civilization. So where are the battery electric trucks? energyskeptic, July 1.

Hall, C.A.S., Klitgaard, K.A., 2014. Energy and the Wealth of Nations. Springer, Dordrecht.

Hinkley, J., et al., 2012. Concentrating Solar Power Drivers and Opportunities For Cost Competitive Electricity. CSIRO, Canberra.

Honnery, D., Moriarty, P., 2009. Estimating global hydrogen production from wind. Int. J. Hydrog. Energy 34, 727–736.

Kaneff, S., 1991. Solar thermal process heat and electricity generation performance and costs for the ANU big dish technology. A comparison with Luz System costs. Report EP-RR-57, Energy Research Centre, Research School of Physical Sciences ad energy, Institute of Advanced Studies, ANU, Canberra.

Kearney Consulting, 2010. Solar Thermal Electricity 2025, ⟨http://www.estelasolar.eu/fileadmin/ESTELAdocs/documents/Cost_Roadmap/2010-06%20-%20Solar%20Thermal%20Electricity%202025%20-%20ENG.pdf⟩.

Lenzen, M., McBain, B., Trainer, T., Jutte, S., Rey-Lescure, O., Huang, J., 2016. Simulating low-carbon electricity supply for Australia. Appl. Energy 179, 553–564.

Lovegrove, K., Zawadsky, A., Coventy, J., 2007. Parabolic dish solar concentrators for multi-megawatt power generation, Solar World Congress, Beijing, Sept .18- 223.

Lovegrove, K., Watt, M., Passy, R., Pollock, G., Wyder, J., Dowse, J., 2012. Realising the Potential of Solar Power in Australia. IT Power, for the Australian Solar Institute.

Jones, S.A., Blair, N.J., Pitz-Paal, R., Schewarzboezl, P., Cable, R., 2001. TRNSYS modeling of the SEGS VI parabolic trough solar electric generating system, Proceedings of Solar Forum 2001, Solar Energy: The Power to Choose, April 21-25, Washington DC.

Lovins, A., Weisacher, E. Von, 1997. Factor Four: Doubling Wealth - Halving Resource Use: A New Report to the Club of Rome. Allen and Unwin, St Leondards.

Lovins, A., 2011. Reinventing Fire; Bold business solutions for the new energy era, Rocky Mountains Institute, Chelsea Green.

Marin, O.C., 2015. (Personal Communication), Corporate Communication, Calle Servoi, Ochoa 4, FORAN, ⟨www.sener.es⟩.

Mateja, D., 2000. Hybrids aren't so green after all, ⟨www.usnews.com/usnews/biztech/articles/060331/31hybrids.htm⟩.

NREL, undated. System Advisor Model (SAM),Case Study: Gemasolar Fuentes De Andalucía. ⟨https://sam.nrel.gov/sites/sam.nrel.gov/files/content/case_studies/sam_case_csp_salt_tower_gemasolar_2013-1-15.pdf⟩.

Odeh, S.D., Behnia, M., Morrison, G.L., 2003. Performance evaluation of solar thermal electric generation systems. Energy Convers. Manag. V44, 2425–2443.

Pears, A., 2017. 2017 will be a big year for Australia's energy system: here's what to look out for, The Conversation, January 25.

Sharma, R., Manzie, C., Bessede, M., Crawford, R.H., Brear, M.J., 2013. Conventional, hybrid and electric vehicles for Australian driving conditionsPart 2: Life cycle CO_2-e emissions. Transp. Res. Part C: Emerg. Technol. 28, 63–73.

Siangsukone, P., Lovegrove, K., 2003. Modelling of a 400m^2 steam based paraboloidal dish concentrator for soar thermal power production, Centre for Sustainable Energy Systems, Australian National University. ANZES Destination Renewables Conference, 26-29 Nov.

Solarstor, 2017. Personal communications.

Trainer, T., 2015. Comments on the proposal for 100% renewable energy electricity supply for Australia, by Elliston, Diesendorf and MacGill. thesimplerway.info/EDMcrit.htm.

Trainer, T., 2016. Remaking Settlements: The Potential Cost Reductions Enabled by The Simpler Way. thesimplerway.info/Remaking.htm.

Trainer, T., 2017. Estimating the retail price for 100% Australian renewable electricity. ⟨http://thesimplerway.info/REretailprice.htm⟩.

Teske, S., Dominish, E., Ison, N., Marish, K., 2016. 100% Renewable Energy for Australia: Decarbonising Australia's Energy Sector Within One Generation, Prepared for: Getup! and Solar Citizens, Sydney. University of Technology, Sydney.

Viebahn, P., Kronshage, S., Trieb, F., Lechon, Y., 2004. Final report on technical data, costs, and life cycle inventories of solar thermal power plants, New Energy Externalities Developments for Sustainability, Sixth Framework Programme, Project no: 502687. ⟨http://www.needsproject.org/RS1a/RS1a%20D12.2%20Final%20report%20concentrating%20solar%20thermal%20power%20plants.pdf⟩.

Wetterlund, E., Leduc, S., Dotzauer, E., Kindermann, G., 2012. Optimal localisation of biofuel production on a European scale. Energy 41, 462–472.

Wood, T., Mullerworth, D., Morrow, H., 2012. No Easy Choices: Which Way to Australia's Energy Future? Technology Analysis. The Grattan Institute.