Renewable and Sustainable Energy Reviews 13 (2009) 1082–1088

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Assessment of sustainability indicators for renewable energy technologies

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ARTICLE INFO

Article history:
Received 11 March 2008
Accepted 25 March 2008

Keywords:
Renewable energy
Sustainability
Emissions
Price
Social impacts

ABSTRACT

The non-combustion based renewable electricity generation technologies were assessed against a range of sustainability indicators and using data obtained from the literature. The indicators used to assess each technology were price of generated electricity, greenhouse gas emissions during full life cycle of the technology, availability of renewable sources, efficiency of energy conversion, land requirements, water consumption and social impacts. The cost of electricity, greenhouse gas emissions and the efficiency of electricity generation were found to have a very wide range for each technology, mainly due to variations in technological options as well as geographical dependence of each renewable energy source. The social impacts were assessed qualitatively based on the major individual impacts discussed in literature. Renewable energy technologies were then ranked against each indicator assuming that indicators have equal importance for sustainable development. It was found that wind power is the most sustainable, followed by hydropower, photovoltaic and then geothermal. Wind power was identified with the lowest relative greenhouse gas emissions, the least water consumption demands and with the most favourable social impacts comparing to other technologies, but requires larger land and has high relative capital costs.

Contents

1. Introduction

In 2005 the worldwide electricity generation was 17 450 T W h out of which 40% originated from coal, 20% from gas, 16% from nuclear, 16% hydro, 7% from oil and only 2% from renewable sources such as geothermal, solar, wind, combustible renewables and waste [1]. The current fuel mix has fossil and nuclear fuels contributing to nearly 70% of total generation. Coal is known to have the highest carbon dioxide emissions per kW h, as well as emitting other pollutants at high levels. Still, it continues to dominate the market due to its low cost and high availability, while at the same time challenging the principles of sustainability. If significant efforts are not made to reduce the amount of emissions produced, the number of coal fired power stations will continue to

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doi:10.1016/j.rser.2008.03.008

rise and in developing countries alone will produce more CO_2 than the entire OECD power sector for the year 2030 [2].

In order to direct future investment, it is necessary to understand the environmental footprint of projected energy growth scenarios, focusing on sustainable energy generation practices. The full environmental footprint accounts for the entire energy chain lifecycle, from mining and processing to direct and indirect emissions, waste disposal and/or recycling. In the assessment of each stage of the chain, key indicators must be identified to allow quantification of impact. The indicators will be based upon environmental and societal impacts, greenhouse gas emissions, resource depletion, availability of renewable energy sources and the value that they add to the economy.

Significant research has already been given to understand the impacts of electricity generation to the environment and economy. Most work seeks to quantify parameters such as emissions [3,4], energy payback periods [5] and costs [6]. Several authors have completed full life cycle analysis (LCA) of individual energy generation technologies [7,8]. Life cycle analysis (LCA) is an internationally accepted tool for evaluation of the impact for a product or service. LCA of energy generation technologies allows direct comparison of a range of impacts by breaking them down into relative consequences, i.e. effect of wind power generation on migratory birds [9,10], potential incidence of leukaemia clusters surrounding nuclear power plants [11,12], etc. There are other methods of assessing sustainability, such as input–output analysis, mass and energy balances, emergy (embodied energy) accounting [13], however LCA is a combination of these tools, providing the most comprehensive method currently available.

Life cycle analysis as a tool to assess sustainability is not without its limitations, as identified by Bergerson and Lave [14]. It is the responsibility of the analyst to ensure all necessary inputs and outputs are considered and weighted. Gagnon et al. [15] highlighted the fact that LCAs are unable to account for the dual function of hydroelectric dams or the reliability of electricity supply. As with all analysis methods, there is also difficulty attributing full value to more flexible generation options [16].

The most comprehensive examples of previous LCA studies on electricity generation have been produced by Bilek et al. [3], Hondo [4], Gagnon et al. [15], Denholm and Kulcinski [17], Uchiyama [18] and Weisser [19]. These studies used one or more indicators to provide assessment, typically greenhouse gas emissions and possibly energy accounting. Gagnon et al. [15] consider the widest range of indictors of sustainability in their assessment, but avoid consideration of social impacts. The previous studies discuss only small number of indicators and limited variation of energy generation technologies to gain a full understanding of the sustainability of all modern electricity generation technologies.

There is a range of other significantly important indicators that must be considered when evaluating sustainability of energy generation technologies. It is not only the traditional form of the environment that is impacted by electricity generation, the human social and economic environment are also significantly impacted by the choice of production method. The work presented here seeks to assess and rank the relative sustainability of non-combustion renewable energy technologies, photovoltaic, wind, hydro and geothermal, using data collected from the literature. The key indicators of sustainability used in this assessment with the main justification for their selection are:

- Price of electricity generation unit must be considered since unfavourable economics are not sustainable.
- Greenhouse gas emissions are increasingly becoming one of the key parameters that define sustainability of energy generation.
- Availability and limitations of each technology must be considered since some technologies or fuels may be heavily resource constrained.
- Efficiency of energy transformation must be known for meaningful comparison. Efficient processes will typically have lower process requirements, capital and operating costs. Less efficient processes may have more significant room for technological advancement and innovation.
- Land use requirements are important as renewable energy technologies are often claimed to compete with agriculturally arable land or to change biodiversity.
- Water consumption is particularly important in arid climates such as Australia. It is not sustainable to have high water consumption and evaporation rates to support the energy generation process when already water shortages are problematic. Previous LCAs often ignore the high water requirements of thermal technologies such as coal when it must be considered.
- Social impacts are important to correctly identify and quantify the human risks and consequences will allow better acceptance and understanding of some technologies that are often subject to public objection.

After assessment of selected indicators, the renewable energy technologies were ranked against each other, with each indicator given equal importance.

Table 1
Mean price of electricity and average greenhouse gas emissions expressed as CO_2 equivalent for individual energy generation technologies

	USD/kW h	g CO_{2-e}/kW h
Photovoltaic	$0.24	90
Wind	$0.07	25
Hydro	$0.05	41
Geothermal	$0.07	170
Coal	$0.042	1004
Gas	$0.048	543

2. Sustainability indicators of renewable energy technologies

2.1. Price of electricity generation

Average prices for electricity generation for each energy generation technology are shown in Table 1. Each technology offers production of electricity at a very wide range of costs. The range of costs, shown in Fig. 1, were collected from an extensive number of literature sources [2,3,20–63] comprising of a range and an averaged cost of production of electricity over the full life cycle of each energy generation technology accounting for construction, installation/commissioning, operation, maintenance, decommissioning, recycling and/or disposal. The price for electricity generation from coal and gas in Fig. 1 are shown for comparative

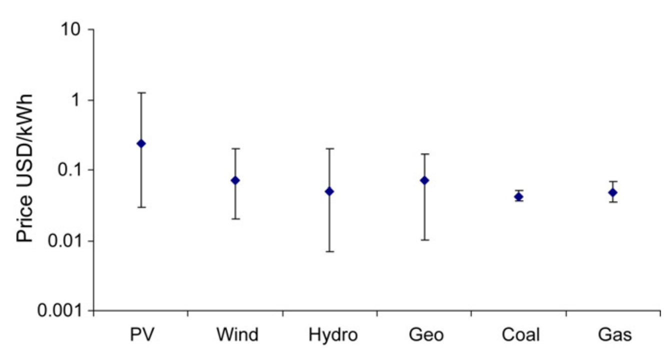

Fig. 1. Cost of electricity generation per kW h.

purpose only. Most figures found in the literature also include interest calculations on capital, but none of them accounts for the cost of transmission, which can add up to 1.5 c/kW h [2] when long transmission lines are necessary. Long distances for transmission are more common with renewables than non-renewables, particularly off-shore wind farms [2]. Intermittent renewables such a photovoltaics and wind may require backup, these have not been included in cost calculations. The upper limit for photovoltaics was cropped for convenience, the highest value found was $1.25/kW h [59], with no explanation as to why the value is so high. The next greatest value found was from Kannan et al. [44] at $0.57/kW h, however this was given with an explanation of calculations and assumptions. Photovoltaics have the widest range in prices for electricity generation due to the large range of types of solar cells available, and location specific variations such as the cost of electricity to manufacture the cells and sunlight intensity during operation.

Price profiles for each non-combustion renewable energy technology show high capital intensity and low running costs, due to zero fuel requirements. For photovoltaics, the most significant cost is silicon purification, using 60% of the production energy of a frameless multi-crystalline module [64]. Overall capital costs account for over 95% of the life cycle costs for photovoltaics, meaning that interest rate variations have a large impact on life cycle prices [44]. This would be expected with all other capital-intensive technologies. Wind costs can be minimised by careful selection of suitably sized generators, according to the quality of the site-specific wind resource. Hydro dam construction accounts for nearly all hydro costs, with the low operation, maintenance and refurbishment costs and long plant lifetimes [65]. Geothermal prices are heavily increased by the long project development times, high costs and risk of exploratory drilling [66]. Drilling can account for up to 50% of the total project cost [67].

Wide-ranging values for the price per kW h are seen for all technologies, however the greatest range is for photovoltaics. For each technology, the average value was much closer to the lowest than highest price. Hydro had the lowest average cost, geothermal and wind the same average cost with geothermal exhibiting lower range in price variations. Photovoltaics are by far the most expensive technology.

2.2. Greenhouse gas emissions

Greenhouse gas emissions, shown as grams of CO_2 equivalent (CO_{2-e}) in Fig. 2 were generally estimated according to the full operational life cycle of each renewable energy technology including CO_{2-e} emissions from manufacturing of the plant to full operation of the technology [3–5,8,9,15,18,19,30,33,37,41,42,44,53,59,62,67–97]. The emissions are found to vary widely within each technology. The mean values of CO_{2-e} emissions for each technology are summarised in Table 1. Overall, wind has the lowest CO_{2-e} emissions, with only around 25 g/kW h CO_{2-e}. Hydro and photovoltaics also have low emissions, with average reported values at less than 100 g/kW h CO_{2-e}. The average emissions from geothermal are fair at 170 g/kW h, however the range includes all possible values for gas emissions and may even be as high as a low-emitting coal fired power station. For all technologies except hydro, CO_{2-e} emissions account for all significant carbon emissions.

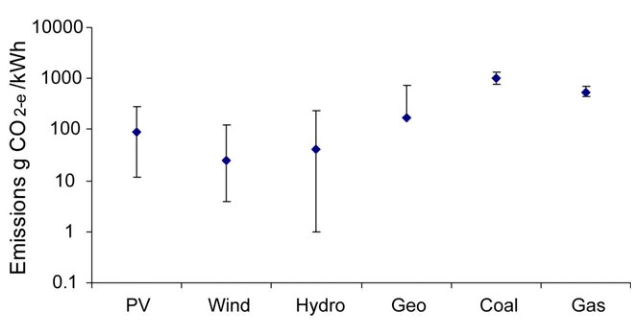

Fig. 2. Carbon dioxide equivalent emissions during electricity generation.

For photovoltaics and wind power most of the emissions are the result of electricity use during manufacturing. In these cases, an average grid mix for the region of manufacture is typically used to calculate emissions. Grid mixes vary widely with location, for example the typical grid mix in Australia in 2005 was 76% coal, 15% natural gas, 2% oil, 6% hydro and 1% non-hydro renewables [98].

In the case of hydroelectricity, cooler climates, lower biomass intensities and dams with higher power densities (a ratio of the capacity of the dam to the area flooded) have lower emissions per kW h [99]. The type of terrain flooded in dam construction significantly impacts CO_{2-e} emissions, the more biomass present during dam inundation and the higher draw down zones, the higher emissions. Tropical and Amazonian reservoirs typically have the highest emissions [100]. Most greenhouse gas emissions from dams are methane from the anaerobic decomposition of biomass at depth and generally decrease with the age of the dam, as initial biomass stocks are decayed [100]. According to the IPCC [101], methane has a global warming potential 25 times higher than CO_2, over 100 years. Therefore, small changes in methane emissions will result in large changes to CO_2 equivalent emissions.

Geothermal emissions are most significantly impacted by technology choices. Waste gases are over 90% CO_2 by weight [37], so if directly released, emissions will be high. Most modern plants, however, either capture the CO_2 and produce dry ice, or reinject it back into the well [102].

2.3. Availability and technological limitations

Availability of renewable energy technologies and their limitations to produce base power are another limiting factor that needs assessing. It is known that Earth intercepts over 170 000 T W h/year from the sun [46], with irradiation varying greatly according to location and season. However, photovoltaics are currently limited by storage complications during nights and cloudy days when the sun cannot power the cells.

Wind also suffers from intermittency problems, however Edmonds et al. [31] suggest distributed capacity over a wide geographical area to alleviate fluctuations. Turbines must not operate when wind speeds are too high (>25 m/s) as turbine damage may result and will not turn when wind speeds are too low (<3 m/s) [62]. The IEA [103] estimate a global wind potential of 40 000 T W h/year.

Hydropower has the highest availability, reliability and flexibility of any technology [104]. Hydro plants can be started, stopped, or output rates changed within minutes. For this reason, where water resources are plentiful enough, hydropower can provide both base and peak load power. For the year 2005, hydropower provided 20% of the world's electricity demand with 2600 T W h and has a global economically feasible potential of over 8100 T W h/year [105].

Geothermal power is geographically limited to appropriate sites where the resource is present, however there are many such sites worldwide, spread over 24 countries with an operating potential of 57 T W h/year [106]. Geothermal is attractive for its ability to provide base load power 24 h a day. Extraction rates for power production will always be higher than refresh rates, reinjection helps restore the balance and significantly prolongs

Table 2
Efficiency of electricity generation

Photovoltaic	4–22%
Wind	24–54%
Hydro	>90%
Geothermal	10–20%
Coal	32–45%
Gas	45–53%

Table 3
Water consumption in kg per kW h of electricity generation

Photovoltaic	10
Wind	1
Hydro	36
Geothermal	12–300
Coal	78
Gas	78

the lifetime of geothermal sites. The site of reinjection must be carefully selected to ensure short-circuiting does not occur. Reinjection also increases the frequency, but not severity of seismic activity [107].

2.4. Efficiency of energy generation

The range of efficiencies of energy generation technologies are summarised in Table 2 [24,30,42,50,57,67,74,77,78,81,85,88,92,108–128]. Hydropower has the highest efficiency of all electricity generating technologies currently available. Wind has the second highest efficiency, which is generally comparable to coal or gas. Photovoltaics and geothermal power have the lowest efficiencies, far less than other technologies.

Photovoltaic efficiency is highly variable due to the large range of cell types available, with an ideal cell efficiency of 30% [59]. Crystalline silicon cells (including multi- and poly-crystalline) have the highest efficiencies and amorphous silicon the lowest. Wind efficiency is also wide ranging due to the wide variation in quality of wind resources at different locations. A good wind resource, with location carefully selected will give greater than 40% efficiency. Geothermal values are low due to the low temperatures of the steam [67].

2.5. Land use

Photovoltaics and wind power have similar land use characteristics, with impacts from materials for unit manufacture and disposal/recycling. Neither requires any further mining footprint. Both are also characterised by the opportunity for dual use sites. Solar can be roof-mounted, providing a negligible footprint during use and wind can be incorporated into agricultural lands, reducing its share of the footprint. Gagnon et al. [15] give a total footprint of 72 km^2/T W h for wind power, without allocating any share of this to agriculture. Similarly, Lackner and Sachs [46] find a photovoltaic land occupation of 28–64 km^2/T W h with no dual purpose allocation.

Hydro footprints vary significantly, depending on local topography. A generic land requirement is given as 750 km^2/T W h per year by Evrendilek and Ertekin [34], however Gagnon and van de Vate [80] give land requirements as low as 73 km^2/T W h.

Geothermal power plants have relatively small surface footprints, with major elements located underground [106]. Due to the risk of land subsidence above the field, the whole geothermal field is used in the footprint calculation. A typical geothermal footprint is in the range 18–74 km^2/T W h [106].

2.6. Water consumption

Accurate data quantifying water consumption during electricity generation is difficult to obtain, particularly for renewable energy technologies. As discussed by Inhaber [129], it is difficult to distinguish between water withdrawal (water that is taken, then returned to circulation) and water consumption (water removed from circulation outside the plant/unit). Water consumption seems to be a more accurate indicator of sustainability, since it is water 'lost' from circulation that will have an impact. A summary of water consumption values, as given by Inhaber [129] is shown in Table 3.

The storage dam is essential to large hydroelectricity plants. These dams withhold enormous volumes of water from surrounding areas. They also cause large water losses due to surface evaporation, the magnitude of which varies greatly according to dam size, volume per square meter and ambient temperatures [129]. However, this water may have naturally evaporated from rivers and lakes.

Geothermal power consumes large amounts of water required for cooling [130]. Water consumption can be controlled by the total reinjection of polluted and foul smelling wastewater, non-evaporative cooling, general pressure management and closed-loop recirculating cycles [50]. Both Inhaber [129] and Axtmann [131] concluded that geothermal plants produce more wastewater than thermal power plants, at up to 300 kg/kW h.

Water is also consumed in the production of photovoltaic modules and wind turbines, however little is used during operation and maintenance, giving very low life cycle water consumptions. Wind power has the lowest water consumption of the technologies considered, followed closely by photovoltaics.

2.7. Social impacts

There is a wide range of social impacts, both positive and negative, from the production of electricity. In some places, renewables offer the opportunity for electricity supply that otherwise may not exist. Many countries are less fortunate than Australia in their reserves of thermal fuels. Renewable technologies offer independence from fossil–fuel imports and price fluctuations. Impacts and their relative magnitudes for the technologies under consideration are summarised in Table 4.

Solar cells offer an attractive source of power without fuel dependence, the need for conventional power plants and reduced mining. The manufacture of solar cells involves several toxic, flammable and explosive chemicals. With constantly reducing mass requirements during cell manufacture due to thinner cells,

Table 4
Qualitative social impact assessment

Technology	Impact	Magnitude
Photovoltaic	Toxins	Minor–major
	Visual	Minor
Wind	Bird strike	Minor
	Noise	Minor
	Visual	Minor
Hydro	Displacement	Minor–major
	Agricultural	Minor–major
	River Damage	Minor–major
Geothermal	Seismic activity	Minor
	Odour	Minor
	Pollution	Minor–major
	Noise	Minor

Table 5
Sustainability rankings

	Photovoltaics	Wind	Hydro	Geothermal
Price	4	3	1	2
CO_{2-e} Emissions	3	1	2	4
Availability and limitations	4	2	1	3
Efficiency	4	2	1	3
Land use	1	3	4	2
Water consumption	2	1	3	4
Social impacts	2	1	4	3
Total	20	13	16	21

masses involved and hence risks are reduced however, all chemicals must be carefully handled to ensure minimal human and environmental contact. Solar farm locations must be carefully selected to reduce competition with agriculture, soil erosion and compaction.

Wind suffers from public outrage due to aesthetic degradation, noise and potential bird strike. Krohn and Damborg [132] found that public acceptance increased following local wind farm installation. Bird strike risk can be heavily mitigated by thorough research of the proposed site prior to installation. Noise is typically heavily masked by the noise of the wind itself.

The installation of hydropower is controversial. Rates of development of large hydro have slowed significantly following lack of public acceptance. Dam inundation usually results in the displacement of people and animals from the homes/habitats, the numbers affected can be very large. Agricultural pastures can also be affected either by direct inundation or loss of river and fertilising silt flow down river. However, hydro dams may also benefit communities due to improved flood control, access to irrigation water year round and recreational water sports.

Geothermal adversely affects communities where wastes are not properly managed as geothermal process waters are offensive smelling from hydrogen sulfide and contaminated with ammonia, mercury, radon, arsenic and boron. Geothermal fluids can be processed in a completely closed-loop system and then reinjected, mitigating these problems.

2.8. Ranking

Accounting for the selected sustainability indicators, each technology was ranked from 1 to 4 according to the corresponding indicator as shown in Table 5, with 1 being the best technology for that indicator. Where values were quantifiable, the average and range were considered together, as there was often significant overlap between values. Impact categories that are unable to be quantified, that is, availability and limitations as well as social impacts, were assessed qualitatively. In case of limitations, hydro was chosen as the least limited, due to its ability to provide base load power, flexibility of operation and number of suitable sites worldwide. Wind was considered the second best for similar reasons. Geothermal is slightly more limited worldwide, with less suitable locations. Solar is considered the most limited, since excess power during daylight hours is not yet able to be stored enough to provide adequate power during nights and on cloudy days. When social impacts were considered, wind was allocated the least negative social impacts, due to its benign nature. Solar was second, as careful management during manufacture and proper site selection mitigate its potential negative impacts. Geothermal placed third due to increased seismic activity and pollution potential. Hydro had the largest impact, primarily due to the large number of people and animals displaced during dam inundation.

The ranking in Table 5 suggests electricity production from wind is the most sustainable followed by hydropower. Geothermal was found to rank the lowest from the four non-combustion renewable energy technologies. It should be highlighted here that the ranking was provided for the global international conditions, while each technology can be significantly geographically affected. For a certain geographical location, some of the listed sustainability indicators may become more important than others.

3. Conclusions

The renewable energy technologies were assessed based on several critical sustainability indicators. The selected indicators were price of generated electricity, greenhouse gas emissions during the full life cycle of the technology, availability of renewable sources, efficiency of energy conversion, land requirements, water consumption and social impacts. Each indicator was assumed to have equal importance to sustainable development and used to rank the renewable energy technologies against their impacts. The ranking revealed that wind power is the most sustainable, followed by hydropower, photovoltaics and then geothermal. The relative ranking was provided using data collected from extensive range of literature and considers the global international conditions only.

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