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A Review of the Application of Lifecycle Analysis to Renewable Energy Systems

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The lifecycle concept is a "cradle to grave" approach to thinking about products, processes, and services, recognizing that all stages have environmental and economic impacts. Any rigorous and meaningful comparison of energy supply options must be done using a lifecycle analysis approach. It has been applied to an increasing number of conventional and renewable energy generation systems and in an increasing range of countries. There is now a good amount of research reporting the lifecycle environmental and economic aspects of power generation systems. This article reviews the existing lifecycle analyses of renewable energy systems to determine the current understanding of their full lifecycle impacts. These are then compared with each other and those of conventional power generation systems. The renewable energy systems reviewed include wind, solar photovoltaic, solar thermal (for electricity), hydroelectric, solid biomass, wave, geothermal, biogas, and tidal. The article also highlights the areas where more lifecycle analysis is needed.

Keywords: *lifecycle assessment; renewable energy; electricity generation*

The electricity industry contributes about 37% of the total world emissions of CO_2 (World Wildlife Fund [WWF], 2005a). Major options for reducing CO_2 emissions within the electricity industry are utilization of renewable energy sources, increased efficiency of generation and use, fuel switching to less carbon-intensive fuel cycles, and decarbonization of fossil fuel cycles (e.g., by capture and storage of CO_2). Each of these options presents the possibility of significant reductions in greenhouse gas (GHG) emissions.

The emissions associated with electricity systems using thermal methods are chiefly concentrated on the electricity generation stage of the system. Emissions associated with the extraction and production of the fuel are usually negligible over the lifetime of the thermal system when compared to the generation (Khan, Howboldt, & Iqbal, 2005). Renewable electricity generation systems do not emit significant GHG emissions; however, there may be considerable emissions associated with the material procurement, manufacture, and transportation.

The estimation of CO_2 emission from the electricity industry usually considers only a gate-to-grave approach. In recognition of the fact that upstream (i.e., cradle-to-gate) processes required for the operation of mining, transporting, and manufacturing also produce pollutants and consume energy and natural resources, lifecycle assessment (LCA) needs to be performed in a cradle-to-grave manner.

This article more specifically discusses the LCA of electricity generation from renewable energy technologies (RETs) in order to assess their environmental performance over the whole lifecycle. First, this article reviews the LCAs that have so far been carried out for RETs that generate electricity. Second, based on this literature research, the article identifies the areas where there is a need to carry out further LCA of RETs for enhancing the environmental performance of electricity generation in Australia and abroad. Third, this article compares the environmental performances of both RETs and non-RETs using LCA approach.

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LCA of Electricity Generation Technologies

An LCA study involves data collection and calculation to quantify relevant inputs and outputs or the environmental load of a product system (Greadel & Allenby, 2003a). It requires backtracking for a conventional process system. Lifecycle inventory (LCI) incorporates all foreground data, that is, all processes (e.g., mining, refining, transporting, plant construction, generating, distributing, decommissioning, etc.) involved in the production of a product, background data that support the foreground data, such as electricity, materials, transport processes, waste treatment, auxiliary materials, and meta data describing the foreground and background data. The functional unit in this case would be to assess the environmental impact (EI) of the production of 1 MWh of electricity.

Using a LCA methodology, environmental performance indicators, including energy intensity, energy payback time (EPBT), and EI, can be determined for energy technologies. The energy intensity is defined as the ratio of the requirement for construction, operation, and decommissioning and the electricity output of the plant over its lifetime (Lenzen & Munksgaard, 2002). This is mathematically expressed as

$$\eta = \frac{E}{E_1}, \quad (1)$$

where E = the energy requirement for construction, operation, and decommissioning, electricity output, $E_1 = P \times 8760hy^{-1} \times \lambda \times T$, P = power rating, λ = load factor, and T = lifetime.

The inverse of energy intensity (i.e., $1/\eta$ or E_1/E) is known as the energy payback ratio (EPR). Because the EPR is less affected by upstream choices of energy supply, it should therefore be considered as one of the most reliable indicators of environmental performance (International Energy Agency [IEA], 2000). A high EPR indicates good environmental performance. If a system has an external energy ratio between 1 and 1.5, it consumes nearly as much energy as it generates, so it should never be developed.

EPBT is the time it takes for the energy technology to generate the primary energy requirement for construction, operation, and decommission of technologies (Schleisner, 2000). This is mathematically expressed as

$$EPBT = \frac{E * \varepsilon_{fossil}}{E_1} * T, \quad (2)$$

where ε_{fossil} is the conversion efficiency.

As the value of E in Equation 2 increases, EPBT and the environmental emission generated by a RET over its lifecycle increase. The concept of energy intensity and EPBT, based on the lifecycle paradigm, are operational and easy to interpret from the sustainability point of view. Both concepts focus on how much conventional energy we use today in order to obtain energy tomorrow. The value of E is affected by some factors such as lifetime, power ratings, load factor, type and maturity of technology, and country of manufacture, which influence the energy intensity of energy technologies.

An EI is divided into two phases: classification and characterization. Classification is the process of assigning and aggregating results from the inventory into impact categories (Greadel & Allenby, 2003b). This process involves identifying stressors and organizing them with respect to impact on the ecosystem. This includes the creation of an impact chain, as a single pollutant can have multiple impacts, and a primary impact can result in a secondary impact. The general categories are acid rain potential, photochemical oxidant impact, global warming potential (GWP), and so on. For example, CO_2, CH_4, and N_2O are gases having GWP, whereas CH_4 and N_2O have 21 and 310 times more EI than does CO_2, respectively (Biswas, Barton, & Carter, 2007). Characterization is the calculation of category indicator results. For example, a source emitting 3 units of CO_2 and 1 unit of CH_4 means that the GWP of the source is 24 units of CO_2 equivalent.

There are two major approaches to boundary settings in LCA: a process-based model developed most intensively by the Society of Environmental Toxicology and Chemistry (SETAC) and the U.S. Environmental Protection Agency (EPA) and an economic input-output analysis-based model referred to as EIO-LCA (Boyd & Dornfeld, 2005). The SETAC-EPA approach divides each product into individual process flows and identifies and quantifies EIs. This model captures all the various manufacturing, transportation, mining, and related requirements to produce a product or service. The EIO-LCA traces out the various economic transactions, resource requirements, and environmental emissions required for a particular product or service. However, this LCA approach has limitations. Even with 500 economic sectors, the amount of disaggregation may be insufficient for the desired level of analysis. EIO-LCA models include sectors of the economy rather than specific processes. Detailed analysis of the EIs of the activities of the individual members of the supply chain requires more traditional SETAC-LCA techniques. The use and disposal phases of certain products may be too difficult to analyze with EIO-LCA.

LCA Analysis of RETs

Review of the Literature

Biomass, photovoltaic (PV), and wind energy are the RETs for which most of the LCA work has been carried out in order to assess their environmental performance for electricity generation. People have conducted LCA analysis from different perspectives for electricity generation from RETs. These are discussed by category below.

LCA for determination of the environmental performance. A number of studies have been carried out to determine the lifecycle environmental performance of RETs. Schleisner (2000) assessed the energy consumption and emissions related to the production and manufacturing of materials for both offshore and onshore wind farms in Denmark using a LCA methodology. The lifecycle boundary includes the inputs and outputs of all stages of wind turbine production such as resource extraction and transportation, material processing, component manufacture and transportation, turbine construction, operation and decommissioning, and disposal. However, the LCA could not include materials such as glass and polyester in the LCI because of a relevant lack of data. EPBT (as shown in Equation 2) for onshore and offshore wind turbines is far less (0.26 to 0.39 year) than a year, and about 94% of the materials of the wind turbine can be recycled.

Similarly, Kannan, Leong, Osman, Ho, and Tso (2005) carried out a LCA of 2.7 kWp solar PV systems in three stages, namely construction, operation, and decommissioning. Energy consumption data for the production of materials that are required to manufacture a PV cell, inverter, and supporting structure were sourced from other countries' literature. Although a PV system consumes only 23% of the total primary energy consumed by oil-fired steam turbine plant, the EPBT of the former is only a couple of months higher than the later. This is because the oil-fired plant generates more electricity than does the PV system. Lifecycle GHG emissions for the conventional one (fossil fuel) are about 4 times those of the PV system.

In the case of LCA for biomass electricity, Matthews and Mortimer (2000) estimated complete energy and CO_2 budgets for electricity generation from wood fuel–fired power plants with ratings in the range 5 to 30 MW, based on the data available in Britain. They estimated energy and CO_2 budgets for representative examples of wood fuel production systems based on conventional forestry and short rotation coppice (SRC). The net energy requirement (or unit primary energy input) for generating an unit of electricity (kWh) from forest thinnings, branch wood, or SRC is in the region of 0.25 kWh to 0.27 kWh, whereas the CO_2 emission factor (unit CO_2 emission) is 65 g CO_2. Of the four stages for the electricity generation from the wood fuel, wood fuel supply contributes significant portion (53% to 56%) of the total emission, followed by the start-up fuel (33% to 34%), power station construction (6%), and power station maintenance (4%), respectively.

Following this work, Carpentieri, Corti, and Lombardi (2005) carried out a LCA of integrated coal gasification combined cycle (IGCC) and integrated biomass gasification combined cycle (IBGCC). Their analysis showed that IBGCC is superior to IGCC in terms of resource depletion and GHG emissions, whereas IGCC is superior to IBGCC in terms of acidification and eutrophication issues. The processes considered for IBGCC's LCI are biomass cultivation and transportation, plant construction and operation, energy conversion, and plant dismantling. The impact assessment of these processes showed a negligible contribution to the overall EI by plant construction and dismantling relative to biomass production and plant operation processes. However, the energy data obtained for this LCA research were based on literature values, and some important data for crop production were found to not be available. Like Carpentieri et al. (2005), Jungmeier, Resch, and Spitzer (1998) also found that the biomass fuel cycle accounts for the significant portion of the total environmental burden that is created by generation of electricity from a biomass-fired combined heat and power plant.

LCA for analyzing the factors of the environmental performance. The lifetime, power ratings, load factor, type and maturity of technology, and country of manufacture influence the energy intensity (as shown in Equation 1) of energy technologies. Lenzen and Munksgaard (2002), who had investigated the influence of these factors on the energy intensity of a wind turbine, found that the power rating varies with the specifications (i.e., height, mass, dimension) of components of the wind turbines (i.e., rotor blades, transmission components, controlling equipment, tower, and foundation) but that the energy intensity remains the same for a wider range of power ratings. Second, the capacity and the type of technology (i.e., horizontal axis or Darrius wind turbine) may be the same for the wind turbines, but their energy intensity will vary. The type of technology may not necessarily affect the energy intensity, but the type of material used in these technologies influences the energy intensity. For example, the value of E is 0.049 $kWh_{in}\ kWh_{el}^{-1}$ for a steel tower and 0.041 $kWh_{in}\ kWh_{el}^{-1}$ for a concrete wind turbine tower.

Third, the wind speed of the site where it operates and the energy mix of the country where it is manufactured influence the energy intensity of a wind turbine. The manufacture of a 500 kW German wind turbine in Brazil, for example, requires almost twice as much primary energy as one manufactured in Germany. Fourth, complete recycling, or a complete overhaul and reinstallation after the service life, is less energy intensive than the recycling of individual components of the wind turbine. Last, the use of different LCA methodologies will lead to different energy intensity results for the same wind turbine. For example, the energy intensity value of the same wind turbine that has been determined by using the input output analysis is more than that obtained using the process analysis. This is because the input-output analysis includes more detailed information on the inputs of all stages of wind turbine production than does the process analysis.

Similarly, Krauter and Ruther (2004) showed how the environmental performance of PV technology produced in different countries would differ from each other. For operation in Germany, the low irradiance value reduces the EPR; on the other hand, the substitution of a relatively dirty grid allows a reduction up to 10.1 tons of CO_2 per kWp of PV installed. For operation in Brazil, the effect can be poor in the case of PV grid injection (especially when the equipment used was manufactured in a country where energy consumption is from sources with high carbon dioxide emissions) or considerable in the case where a fossil fuel–driven power plant is substituted by PV power (up to 27 tons/kWp).

Scenario analysis through LCA. There are some LCA studies that not only assesses the environmental performance of RETs but also include alternative energy efficiency scenarios into the lifecycle boundary in order to reduce the lifecycle environmental burden. According to Kannan et al. (2006), for PVs, the CO_2 emission per kWh of electricity production can be reduced from 217 in the base case to 68 using three improvement scenarios:

1. technological improvement (i.e., 50% reduction in energy consumption for manufacturing PV modules)
2. changing the supporting structure (i.e., aluminium use reduced to 10%)
3. efficiency improvement (i.e., if the solar cell efficiency is increased to 10.6%)

Matsuhashi, Hikita, and Ishitani (1996) showed that the energy balance could be increased from 2.4 (i.e., 2.4 times more than the fossil energy required to manufacture PV) to 6.7 using a solar breeding system. A solar breeding system is a system in which PV technologies supply electricity in order to produce PV technology.

In the case of bio-energy, Mann and Spath (2001) conducted a LCA of a fuel mix scenario, which shows how the emission levels of a coal-fired power plant can be reduced by cofiring the coal with biomass. At rates of 5% and 15% by heat input, cofiring reduces GHG emissions on a CO_2 equivalent basis by 5.4% and 18.2%, respectively. In addition, total system energy consumption is lowered by 3.5% and 12.4% for the 5% and 15% cofiring cases, respectively. Following this work, Heller and Keoleian (2003) conducted the LCA of willow biomass crop production systems in New York for inorganic and organic fertilizer scenarios. The LCI includes the field preparation, plantation, weed control, coppicing, fertilization, and harvesting stages of willow production and electricity generation from willow. Inorganic nitrogen fertilizer inputs have a strong influence on overall system performance, accounting for 37% of the nonrenewable fossil energy input into the system. This study shows that the substitution of inorganic N fertilizer with sewage sludge bio-solids could increase the net energy ratio of the willow biomass crop production system by more than 40%.

LCA for comparative analysis. LCAs of different types of RETs have been carried out in order to compare their environmental performances. Sorensen (2005) used a state-of-the art LCI methodology to assess the lifecycle environmental performance of multicrystalline and amorphous silicon solar cells. The LCI included direct and indirect impacts from mining to recycling of decommissioned cells, for current technologies and for projected future ones (characterized by smaller material inputs and larger-scale production). These LCA results show that the amorphous silicon solar cells have less EI (e.g., 44 g of CO_2/kWh of electricity generation) than do the multicrystalline ones (e.g., 75 g of CO_2/kWh of electricity generation). Sorensen has also found that the manufacturing process of the PV technology dominates more than the manufacturing process for the wind turbines. Similarly, Boyd and Dornfeld (2005) found that the installation of 2.5 kW of ground-based PV yields about 141 kg of CO_2 equivalent per kWh of electricity output, which is an order of magnitude higher than hydro and wind power but an order of magnitude lower than coal.

LCA for hybrid systems. Because both wind and solar provide intermittent services, the current trend in electricity generation is toward an integrated energy system. A backup or an alternative power generation unit needs to be coupled with them in order to provide an uninterrupted electricity supply. Khan et al. (2005) assessed the lifecycle EIs of a wind–fuel cell integrated system for power generation. The LCI included extraction, production, transformation of materials for manufacturing the wind turbine, electrolyser, accessories, and fuel cells, and utilization and disposal of the wind–fuel cell hybrid generators. The production of the electrolyser, which is used to produce hydrogen for the fuel cell, consumes a significant amount of energy (95%) compared to the energy required by the wind turbine and fuel cell. Therefore, a hybrid system may provide uninterrupted power supply, but the EBPT increases because of the energy requirement for the accessories.

LCA for design for the environment. Boyd and Dornfeld (2005) found that the GWP of PV solar cells can be reduced to 30% by energy efficiency in the supply chain. The LCA analysis found that the semiconductor sector itself (the recipient of the majority of the direct economic input) is admirably environmentally friendly, whereas the economic sector that it purchases its materials from is not. According to their study, about 85% of the toxic releases to the environment come from other sectors of the economy. If the suppliers of these key commodities were selected based on their environmental performance, the environmental burden of the PV system would be easily reduced by 50%, without any change to the semiconductor sector itself.

LCA for other emission assessment purposes. Other than the emission of GHGs, there are other pollutants that may affect the environment. Fthenakis (2004) specifically studied the flow of cadmium during the extraction, refining, and purifying of raw materials through the production, use, and disposal or recycling of cadmium telluride (CdTe) PV modules. This study found that the environmental risks from CdTe PV are minimal (i.e., 0.02 g of Cd per GWh produced). Disposal of CdTe PV module does not even have any environmental effect because cadmium and telluride are encapsulated between two glass sheets and are unlikely to leach to the environment under normal conditions. Large-scale use of CdTe PV modules does not present any risks to health and the environment, and recycling the modules at the end of their useful life completely resolves any environmental concerns.

Methodologies used for LCA analysis. The SETAC LCA method is usually used to assess the environmental performance of a product when the input-output data for all stages of product production are available. Boyd and Dornfeld (2005) assessed the lifecycle EI of PV production using a hybrid LCA methodology that consisted of a combination of the SETAC method and the EIO method. Where aggregation problems were identified in the cell manufacturing stage, the EIO-LCA method was supplemented by process-based data. The main lifecycle impact was determined using a SETAC method. Another objective of EIO-LCA in this research is to quantify direct and indirect contributions of all economic sectors in the supply chain of a product in order to improve the environmental performance.

Using this hybrid LCA approach, Lankey and McMichael (2000) also assessed the environmental performance of primary and rechargeable batteries. The model uses an EIO-LCA in order to quantify direct and indirect relationships among industry sectors, whereas the EI method assesses the associated environmental burdens through the materials extraction and manufacturing phases. This study found that the resource use and environmental emissions are substantially lower if a rechargeable battery can be substituted for a primary battery. Consumer use patterns will affect the environmental performance of rechargeable batteries. The effect of consumer behavior also determines where uncertainties may lie in the analysis because behavior is difficult to predict.

Lessons Learned and Future Research Opportunities

The available literature on RETs reviewed above shows that there is a need to carry out LCA for geothermal and marine energy technologies, including run-of-river hydro, tidal energy, and wave energy resources. Countries such as Australia, Indonesia, New Zealand, the United Kingdom, and the Pacific island nations that are surrounded by the ocean have a huge potential to harness marine energy sources. This can be done provided the resources are developed in a sustainable matter, have minimal adverse impact on marine wildlife, and do not affect the integrity of internationally and nationally important marine and coastal sites. LCA of these promising marine technologies needs to be carried out to determine the GWP. The WWF believes that all marine energy projects can and should be sited sensitively and sensibly in areas where they capture a lot of energy and minimize the potential impacts to the marine environment, with full EI assessment and strategic environmental assessments completed (WWF, 2005b). Therefore, an appropriate LCA methodology, which will include wildlife impact, loss of biodiversity, water quality, and so on, needs to be developed in order to locate them in a sensible area.

Some LCA studies were found to use secondary data sources for energy and materials. Secondary data sources do not always represent the true situation, as their values may vary with the energy mix, transportation system, and production processes. Although it is never possible to obtain an absolute result for LCA because of the truncation error, the use of primary or measured data on energy and materials for important processes yields reliable results. In some cases, EIO-LCA has been carried out to develop a database where aggregation problems were identified in the production processes. The EIO-LCA models include sector-specific data of the economy rather than data for specific processes, whereas the detailed analysis of the EIs of the activities of the individual members of the supply chain requires more traditional SETAC-LCA techniques.

Different energy-efficient scenarios have been developed for biomass and PV electricity generation technologies in order to improve the environmental performance. The same analysis can be carried out for electricity generation from the hybrid systems and wind turbines. Like the case for a wind turbine, it is also important to investigate how influencing factors, including lifetime, power ratings, load factor, type and maturity of technology, and country of manufacture, could affect the environmental performance of biomass and PV technologies. The health impact from PVs has been done using a LCA methodology; however, the investigation should be undertaken for other RETs.

Because the electricity generated by RETs is intermittent and less energy intensive, electricity generation by these technologies may not be the same over the lifecycle as a conventional system of the same capacity. Therefore, EPBT may not always represent a true environmental performance indicator. Even if the EPBT is high, the pollutant emission may be found to be less, or vice versa. Hybrid renewable energy systems can overcome this situation, as they offer uninterrupted electricity supply, but lifecycle EIs of some hybrid systems are many times more than the single renewable energy system. In the case of a wind–fuel cell hybrid system, the production of the electrolyser, which is used to produce hydrogen for fuel cell, consumes a significant amount of energy (95%) compared to the energy required by the wind turbine and fuel cell. In all bio-energy LCAs, it appears that the biomass production stage accounts for a significant portion of the total atmospheric emissions.

Almost all of the LCA work that has been reviewed included a complete cycle assessment of RETs instead of streamlined LCA (which includes only the essential processes). Different RETs have significant effects in different stages or processes of the supply chain. Electricity generation from biomass has a significant impact during the crop cultivation stage, PV technologies during the semiconductor manufacturing stage, and wind during the tower manufacturing stage.

LCA of Clean Conventional Power Plants

A great deal of attention has recently been paid to the LCA of clean conventional power plants as a solution for GHG emissions and global warming. LCAs of clean conventional power plants that incorporate environmental technologies have also been reviewed in order to compare their environmental performance to that of the RETs.

Natural gas–fired combined cycle (NGCC). Spath and Mann (2000) examined the full chain of operations that must occur for a NGCC power plant to produce electricity. These operations include the extraction, refining, and distribution of natural gas, construction of the pipeline and power plant, ammonia production and distribution, and upstream grid energy production. Of the total CO_2 emissions (which are 499 CO_2 equivalent) emitted from all stages, the operational stage accounts for 74.6% of total emissions, 24.9% for natural gas production and the rest (0.5%) for construction and decommissioning of the plant. The EPR of NGCC is only 2.2, which indicates that upstream processes are large consumers of electricity. On the other hand, the EPR of direct-fired biomass residue is 27 because the energy used to provide a usable residue biomass to the plant is fairly low.

Clean coal technologies. Spath and Margaret (1999) carried out a LCA of a coal power plant in order to examine the GWP and energy consumption of a complete power generation system that incorporates CO_2 capture and sequestration in conjunction with a coal-fired power plant while maintaining constant power generating capacity. This analysis shows that capturing CO_2 from power plant flue gases and sequestering it in underground storage such as a gas field, oil field, or aquifer can reduce the GWP of electricity production, but the penalty is an increase in fossil energy consumption. In order to produce 600MW of electricity, GWP for a coal-fired plant could decrease from 4.44 million tons to 1.8 million tons by introducing geo-sequestration, but the net energy consumption will increase from 2,090 MW to 2,607 MW. This is because capturing and compressing flue gas CO_2 results in a large decrease in the power plant efficiency. Second, maintaining a designated plant capacity means that additional electricity production must come from another source, most likely fossil fuels.

Spath, Mann, and Kerr (1999) also performed a LCA of the production of electricity from coal in order to assess the environmental aspects of current and future pulverized coal boiler systems. They examined three systems:

1. an average system
2. a new source performance standards (NSPS) system
3. a low emission boiler system (LEBS)

They estimated that the generation of CO_2 is 1,022 g/kWh for a plant that represents the average emissions and efficiency of currently operating coal-fired plants in the United States, 941 g/kWh for a new coal-fired plant with NSPS, and 741 g/kWh for a highly advanced coal-fired power plant utilizing LEBS. Even though the clean coal technologies are evolved, their lifecycle CO_2 emission is far more than that generated by the RETs.

Hydro power. IEA (2000) did a comparative study of the lifecycle impact of different power generating plants, including hydropower (with reservoir and run-off river) power plants, bituminous coal power plants, nuclear power plants, NGCC plants, wind power, and PV plants. Reservoir-based hydropower clearly has the highest performance, where its EPR varies between 48 and 260, whereas those of systems based on fossil fuels are in a range of 7 to 21. Increasing the lifetime of a hydro power plant increases its environmental performance. The emission factors for hydropower, with reservoir or run of river, would be much lower if a life span of 100 years were used (many studies use 50 years).

Therefore, it can be concluded that the energy and GHG performance of renewable power generation is better than that of clean conventional fossil fuel power plants. The following section gives a comparison between RETs and clean conventional technologies using EPR and GWP indicators.

Comparison Between RETs and Nonrenewable Technologies for Power Generation

EPR and GWP have been used to compare the environmental performance of RETs and non-RETs, where EPR is more related to natural resources scarcity and allocation.

EPR. Table 1 shows the comparison of EPRs of RETs and non-RETs for electricity generation. As can be seen in Table 1, EPRs of RETs are higher, in general, than the EPRs of non-RETs. This is because no fuel is fed to the former during the operational phase. Both hydropower with reservoir and run-of-river hydropower have the highest EPRs of both RETs and non-RETs. This is essentially because hydropower plants are bigger in capacity and have a longer lifetime, so their EPRs are higher than those of other RETs. Waste biomass and wind turbines with 35% capacity utilization factor have the second highest range of EPRs (18 to 34), although the maximum value of EPR for plantation biomass is only 5. This is because a significant amount of energy is required to grow the biomass as a dedicated crop.

EPRs of renewable and clean non-RETs, such as solar PV, NGCC turbine (55% of efficiency), coal-fired conventional boiler with sequestration (35% efficiency), and coal gasification combined cycle (43% efficiency), vary from 1.6 to 9.0. With a thermal efficiency higher than the conventional coal-fired plant, NGCC has the same EPR as the conventional plant. This may be because the material required to build two power generation units in the combined cycle plant is higher than the material required to build a single unit in a conventional plant. If both these plants were manufactured in the same region or country with the same energy mix, there would be no advantage, from the lifecycle environmental point of view, to be gained in replacing the conventional one by the combined cycle plant. Oil-fired plants are usually small capacity plants used as peak power plants; therefore, their EPRs are very small, with ranges between 0.7 to 2.9.

GWP. Because the main objective of the use of RET is to combat climate change, the lifecycle GWPs of these technologies have been compared to those of conventional technologies. Table 1 also shows the existing scenario of lifecycle emissions from 1 MWh of electricity generation from both renewable energy– and

Table 1. Energy Payback Ratios and Global Warming Potential of Renewable and Nonrenewable Energy Power Plants

Energy technologies	Energy Payback Ratio	Global Warming Potential (Tons of CO_2/GWh)	Source of Data
Renewable energy technologies			
Hydro power			
With reservoir	48-260	4-18	International Energy Agency (IEA, 2000)
Run of river	30-267	9-18	
Photovoltaic	6-9	44-217	IEA (2000), Kannan, Leong, Osman, Ho, and Tso (2005), Krauter and Ruther (2004), Meier (2000), and Sorensen (2005)
Wind power			
Onshore	34	9.7	ExternE (1997), Schleisner (2000), and White and Kulcinski (1999)
Offshore	18	16.5	
Biomass			
Direct wood fired	27	400	Mann and Spath (2000), Matthews and Mortimer (2000)
Integrated biomass gasification combined cycle	15	50	
Nonrenewable energy technology (conventional)			
Oil-fired plants	0.7-2.9	937	Kannan et al. (2005)
Coal-fired plants	2.5-5.1	1,001-1,154	Spath, Mann, and Kerr (1999), Lee, Lee, and Hur (2004)
Clean nonrenewable technologies			
Coal gasification combined cycle	3.5-7.0	—	Spath et al. (1999)
Conventional boiler with carbon capture and geo-sequestration	1.6-3.3	340[a]	IEA (2003), Spath et al. (1999)
Natural gas–fired combined cycle	2.5	440	Spath and Mann (2000)

a. A 600 MW coal-fired plant with geo-sequestration emits 1.8 million tons a year (Spath et al., 2001). Assuming 8,760 operating hours per year, the emission factors for a conventional boiler with carbon capture and geo-sequestration has been calculated.

conventional energy–driven plants. Conventional coal power plants have the highest emission factor, followed by diesel, natural gas, biomass, hybrid, hydro, and wind. As can be seen in Table 1, hydropower and wind have the same level of GWP, which indicates that the same level of emissions, because of construction and installation of these plants, is emitted in order to generate 1 GWh of electricity. Interestingly, the GWP of biomass is negative, which indicates that the absorption of CO_2 by the standing biomass is more than the CO_2 emission because of the combustion of biomass.

Several lifecycle studies of renewable energy systems versus nuclear power and conventional fossil fuel plants have been published for Europe and America. Some of these have been compiled from other published data (Fthenakis, 2006; World Energy Council, 2004), and others have been directly calculated (Dones, Heck, & Hirschberg, 2003). These results are shown in Table 2.

Conclusions

LCA of electricity generation from RETs has been mainly conducted for biomass, PV, and wind technologies. These studies have identified the processes and technologies that need to be improved in order to reduce the lifecycle emission of GHGs. RETs are, in general, 1 to 2 orders of magnitude less polluting than are conventional fossil fuel plants. Even with clean development mechanisms, non-RETs would pollute more than RETs. Lifecycle analysis for the electricity generation from marine resources needs to be conducted to investigate whether it is environmentally superior to the existing RET power plants. As it is sensitive to the local conditions, LCA research needs to be undertaken for a range of RETs in a range of countries. There is therefore significant scope, and need, for more LCA studies of renewable and conventional energy electricity generation systems.

Table 2. Lifecycle CO_2-e Emissions of Renewable, Fossil Fuel, and Nuclear Energy Power Plants

	Tons of CO_2/GWh		
Energy Technology	**World Energy Council (2004)**	**Fthenakis, Alsema, and De Wilde Scholten (2005)**	**Dones, Heck, and Hirschberg (2003)**
Renewable energy technologies			
Hydro power			3-27
With reservoir	3.5-19.0		
Run of river	3.3-5.1		
Photovoltaic			79
Thin film	12.5-44.0	25	
Single or multicrystalline	43-55	32	
Wind power		11	14-21
Onshore	6.9-22.0		
Offshore	9.1		
Biomass			92-156[a]
Direct wood fired		45	
Integrated biomass gasification combined cycle	15.1-49		
Nonrenewable energy technology (conventional)			
Oil-fired plants	777-866		519-1190
Coal-fired plants			
Lignite	1,062-1,372		1,060-1,690
Hard coal	757-1085		949-1,280
Natural gas–fired combined cycle	398-499	400	485-991
Nuclear			
Nuclear	3-40	6-25	8-11

a. Wood cogeneration.

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