Distributed Generation Renewable Energy
Estimate of Costs

July 2012

Overview

Estimates of total installed costs and operation and maintenance costs are for grid-tied distributed generation (DG) scale systems appropriate for residential, commercial, industrial, and Federal facilities. Technologies considered are technically proven and commercially available. Electric generating technologies included are solar photovoltaic (PV) systems, wind energy, and biomass combined heat and power (CHP). Thermal technologies included are biomass heat, solar water heating (SWH), and solar ventilation preheat (SVP) using transpired solar collectors. Values provided are not to be interpreted as statistically significant. They are only meant to provide rule-of-thumb information, accurate enough for a first pass screen of economic viability.

Table 1 - Costs for Electric Generating Technologies

	Mean installed cost ($/kW)	Installed cost Std. Dev. (+/- $/kW)	Fixed O&M ($/kW-yr)	Fixed O&M Std. Dev. (+/- $/kW-yr)	Variable O&M ($/kWh)	Variable O&M Std. Dev. (+/- $/kWh)
Solar PV <10 kW	$4,779	$820	$29	$20	n/a	n/a
Solar PV 10 – 100 kW	$4,425	$537	$26	$19	n/a	n/a
Solar PV 100 – 1,000 kW	$3,671	$673	$24	$13	n/a	n/a
Solar PV 1 – 10 MW	$3,383	$614	$22	$10	n/a	n/a
Wind <10 kW	$8,286	$1,254	$38	$22	n/a	n/a
Wind 10 – 100 kW	$6,066	$887	$44	$11	$0.02	n/a
Wind 100- 1000 kW	$3,567	$887	$38	$6	n/a	n/a
Wind 1 – 10 MW	$2,242	$417	$46	$19	$0.01	$0.01
Biomass Combustion Combined Heat & Power*	$5,528	$459	$41	$27	$0.07	$0.02

*Unit cost is per kilowatt of the electrical generator, not the boiler heat capacity

Table 2 - Costs for Solar Thermal Technologies

	Mean installed cost ($/ft^2)	Installed cost Std. Dev. (+/- $/ft^2)	O&M
SWH, flat plate & evacuated tube	$137	$72	0.5 to 1.0 % initial installed cost
SWH, plastic collector	$55	$15	0.5 to 1.0 % initial installed cost
SVP	$27	$9	1 Watt/ft^2 fan power

Table 3 - Costs for Wood-Fired Heat System

	Mean installed cost ($/kW)*	Installed cost Std. Dev. (+/- $/kW)	Fixed O&M ($/kW)	Fixed O&M Std. Dev. (+/- $/kW)
Biomass wood heat	$1,000	$500	$43	$23

* Biomass wood heat converted from thermal energy capacity (Btu's/hr)

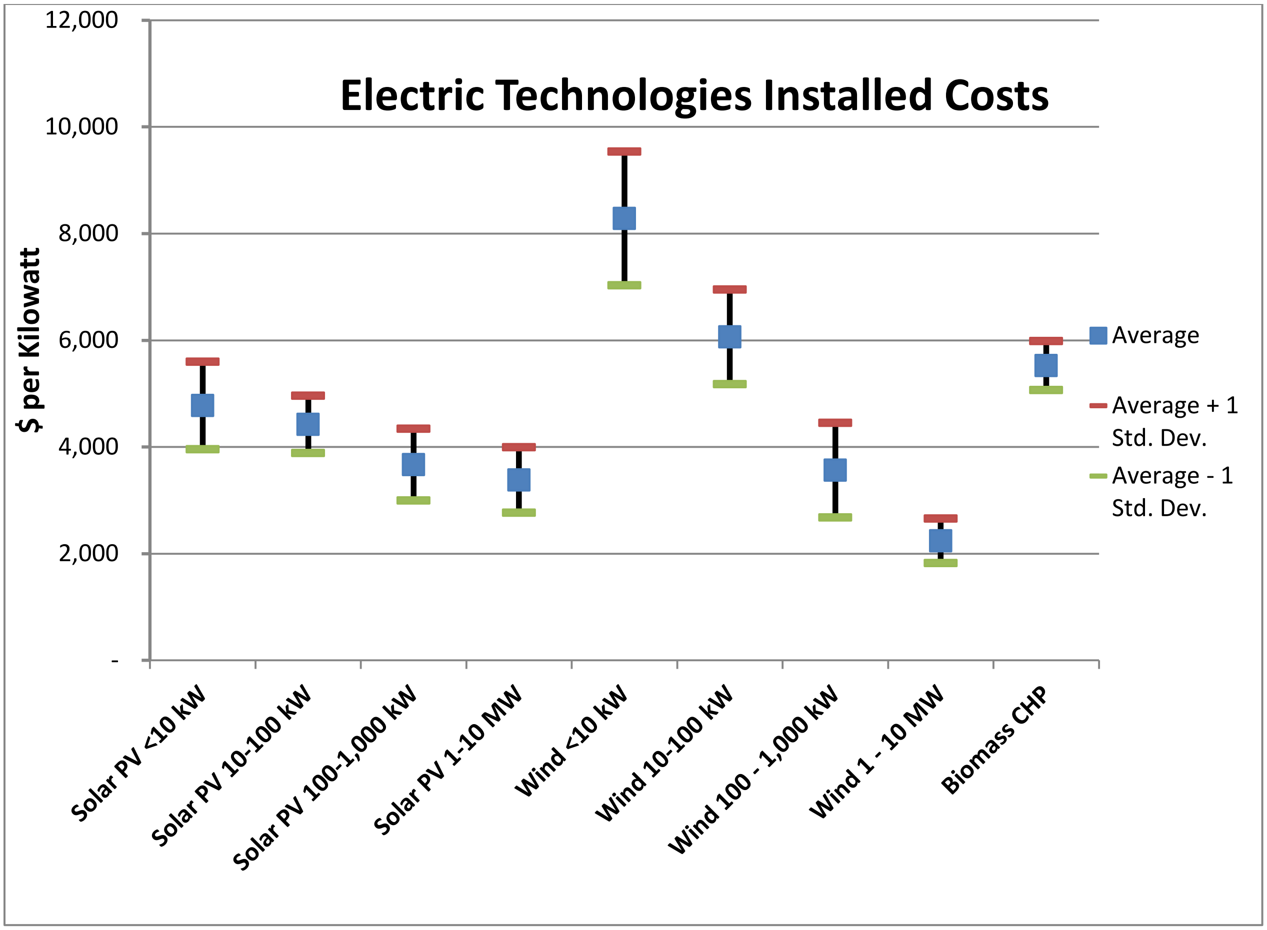

Figure 1- Installed Costs for Electric Generating Technologies

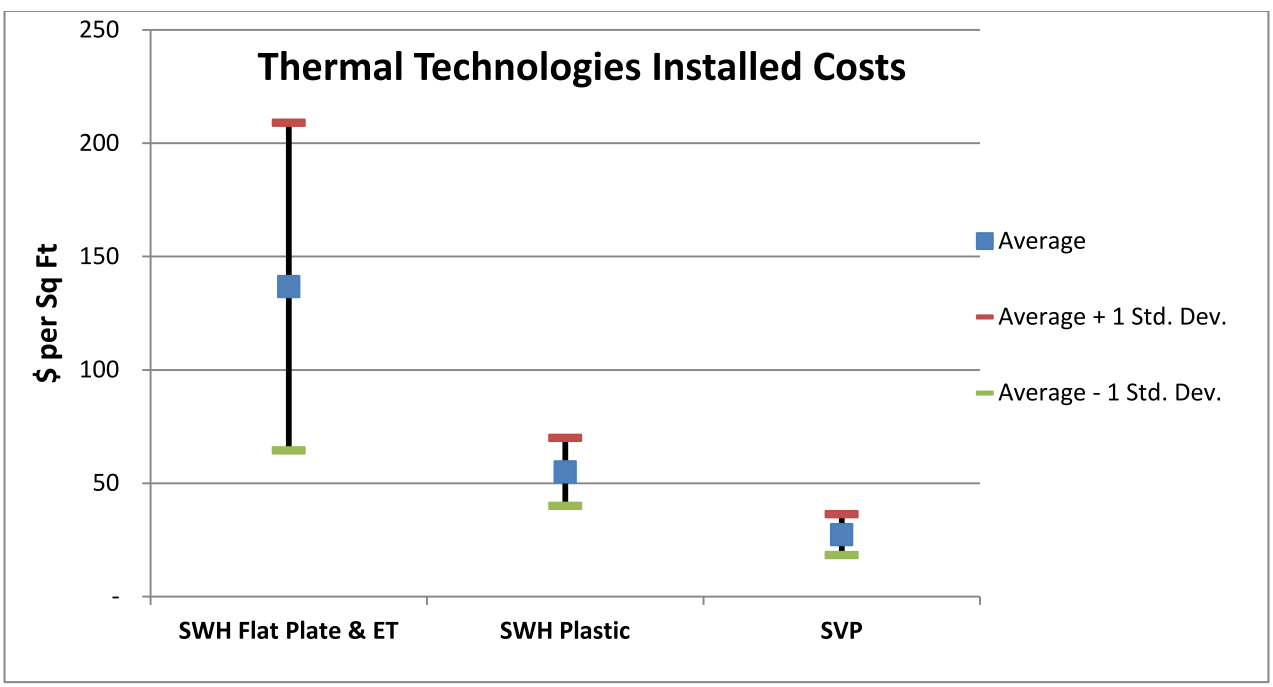

Figure 2- Installed Costs for Solar Thermal Technologies

General Discussion

Many often-cited cost studies and reports for renewable energy focus on systems deployed at utility scale. Both initial capital costs and operations and maintenance (O&M) costs can vary significantly with project size and geographic location. In states and regions with strong financial incentives (e.g., PV in Colorado, New Jersey, and California) or particularly suited for a given technology (e.g., SWH in Florida), there are cost differences that result from local market maturity and competition. This study reports cost information at a national level; most regional differences are captured in the standard deviations, especially as system sizes increase.

DG electrical generation was set at 0 to 10 MW, a fairly large upper limit that may be appropriate for large, multi-building sites such as a military base or Federal laboratory.

In general O&M costs are not as available as total installed costs. The O&M cost information is mostly from interviews with industry experts and contractors.

Cost and useful life information was gathered from the following reference types:

1. Published document
2. Actual project information – publically available in on-line case studies, public presentations, database, or articles
3. Actual project information – internal, not publically available
4. Discussion with or quote from vendors
5. Informed opinion or experience of NREL experts, or screening or assessment report by NREL experts that relies on some or all of the above reference types

Methodology

All capital cost data used in the calculations are from the 2012 updated sources (see Table 4). The data behind the DG cost estimates were given as an average or as a typical high/low range. When cost information was given as a high/low range, it was entered as a high value and a low value for that particular category. The mean installed cost presented in the Installed Costs charts was calculated from the average and the high/low data, as was the +/- 1 standard deviation.

Data for O&M were similarly given as an average or as a typical high/low range. These data were combined with the O&M data from the 2011 update (Table 5) because of the lower number of sources for O&M data, as well as the general assumption that O&M for most renewable energy technologies has not significantly changed over the last few years. The +/- 1 standard deviation is also given.

Photovoltaics (PV)

PV cost data is more numerous because it is a widely deployed technology. The data, however, are often out of date as a result of significant decreases in the price of modules and moderate decreases in the price of inverters and balance of system components over the last few years. Installation costs have also decreased due to scale, learning curves, and increased competition. The 2012 report shows that the average cost of solar PV has dropped by a third compared to 2011. The most recent publication documenting current U.S. market prices is Green Tech Media's quarterly Market Insight report. Other references include the Intergovernmental Panel on Climate Change's Annex III report, and numerous interviews with NREL experts and solar project developers/installers. For this 2012 update, PV has been broken down into four size categories to reflect the effect of project scale on price.

Wind

There is a steep declining unit cost curve ($/kW) as the size of a wind turbine and wind project increases. References reported a wide range of O&M costs for wind systems, and O&M costs do not necessarily decrease with increased installed project size at the DG scale. Older installations tend to have higher yearly O&M costs. Newer wind turbines are better designed and have lower installed and lifetime O&M costs than machines deployed in the last decade. This is likely the reason that the cost of fixed O&M for wind has declined by 40% compared to 2011. Total installed costs for utility scale wind projects are readily available but more challenging to find for smaller systems. References include the American Wind Energy Association report as well as interviews with NREL experts and wind project developers/installers.

Biomass

The most technically mature and widely deployed biomass systems are direct combustion units that use woody biomass as their fuel. A wood-fired boiler can generate hot water or steam. Water and steam can be used in heat only applications or steam can be used to turn a turbine generator for production of electrical power. When considering biomass renewable energy, it is also important to identify a reliable fuel source / feedstock and look at their costs over the expected lifetime as part of the economic viability assessment.

Other feedstock and plant technologies exist; however, they are not yet commercial, widely deployed, and/or economically viable at DG scale. Anaerobic digestion is a commercial technology used to create methane from wet feedstock, including solids from wastewater treatment plants; however, wastewater loads need to be on the order of 5 million gallons per day (or approximately the wastewater load of 50,000 people) to consider developing an economically viable digester and power plant (Ref: *Opportunities for and Benefits of Combined Heat and Power at Wastewater Treatment Facilities*; Eastern Research Group and Energy and Environmental Analysis, U.S. Environmental Protection Agency: Washington, DC, USA, 2007; pp. ii–10).

There are some commercially operating gasification and pyrolysis systems in Europe, but there is no significant capacity installed in the US to gather good rules-of-thumb on costs. A few domestic vendors are currently developing kilowatt-sized gasification systems to generate a renewable fuel (liquid or gas) from waste, wood, or other feedstock. The resultant fuel could then be used in conventional engines, gas turbines, or fuel cells. Although these DG-sized systems show promise, they are still in the research and development phase with a few units deployed as test beds. No standardized costs are available.

Biomass Combined Heat and Power (CHP)

A review of the literature reveals that the most common biomass generators at the DG scale make use of the power plant's waste heat to provide needed thermal energy, which allows projects to be economically viable. CHP is described in some of the references as a technically sound and economically competitive technology that has not yet experienced wide-scale deployment. In the US, most CHP systems are installed in large industrial facilities with both significant electrical and thermal loads. CHP is also often installed at facilities that have a significant waste stream (such as a lumber or paper mill) that serves as a free fuel that would otherwise incur a disposal cost. Cost information for renewable wood-fired steam systems is reported here for system sizes between 100 kW and 10 MW.

Biomass Heat

Wood fired heat systems are technically mature and their costs have not changed significantly over the last few years.

Solar Water Heat (SWH)

Installed cost data on SWH systems were found from installers and NREL engineers who have access to a significant number of system costs. However, O&M costs are difficult to find. Two references (Bircher, Perlman) provided O&M estimates for residential sized systems only in cost per system. O&M as a percent of initial cost was estimated from these reports (1% and 0.9%, respectively). For commercial systems, economy of scale is assumed to achieve a minimum O&M of 0.5% of capital cost. O&M for systems with plastic collectors is assumed to be the same.

Solar Ventilation Preheat (SVP)

SVP, also known as transpired solar collectors, is the least deployed, and has the fewest publications, of those technologies included in this study. Cost information is difficult to acquire. The values were reported from actual installed projects and the typical high/low ranges are supported by discussions with a major vendor. In general, systems installed in new construction would be lower than the average installed cost, while retrofit systems that may have significant integration costs (e.g. additional ductwork and fans) would price above the average installed cost. It is assumed there is no maintenance cost for the transpired collectors; however, there is an operating cost for the fan power required to draw intake air through the collector. This is estimated to be 1 Watt per square foot of collector when the system is operational (collector is operated only when useful energy is available; collector is bypassed at all other times).

Table 4 - Bibliography of publically accessible references for System and O&M Costs – 2012 update

	Bibliography of publically available cost references	**Technologies***
1.	Agrawal M., C. Bolman. (2012) Photon Consulting. *Solar Annual 2012 The Next Wave*	PV
2.	American Wind Energy Association. (2010). *US Small Wind Turbine Market Report*	wind
3.	American Wind Energy Association. (2012) *AWEA U.S. Wind Industry Annual Market Report Year ending 2011*.	wind
4.	Bruckner, T., H. Chum, A., et al. (2012) Intergovernmental Panel on Climate Change Special Report on Renewable Energy Sources and Climate Change Mitigation *Annex III Recent Renewable Energy Cost and Performance Parameters.* Cambridge University Press	PV, wind, bCHP

5.	Daniel Steinberg and Gian Porro. (2012). *Preliminary Analysis of the Jobs and Economic Impacts of Renewable Energy Projects Supported by the §1603 Treasury Grant Program, National Renewable Energy Laboratory (NREL)*	PV, wind
6.	Energy Information Administration (EIA) (2010) *Updated Capital Cost Estimates for Electricity Generation Plants*	PV, bCHP
7.	Lantz, E., R. Wiser. (2012). *IEA Wind Task 26 Work Package 2* NREL, Lawrence Berkeley National Laboratory (LBNL)	wind
8.	Photon Consulting. (2011). *True Cost of Solar Power: The Pressure's On*	PV
9.	RETScreen Intl Case. (2010). http://www.retscreen.net/ang/case_studies_capital_cost_incentive_policy_usa.php	SWH
10.	S. Tegen, M. Hand, et al. (2012) *NREL 2010 Cost of Wind Energy Review*	wind
11.	Solar Energy Iindustries Association /Green Tech Media Research(2012) *U.S. Solar Market Insight Q1 2012*	PV
12.	SolarBuzz (2012) *Solar Electricity Prices* http://www.solarbuzz.com/facts-and-figures/retail-price-environment/solar-electricity-prices March 2012	PV
13.	U.S. Department of Energy *(2012) SunShot Vision Study* http://www1.eere.energy.gov/solar/pdfs/47927_chapter5.pdf	PV

Table 5 - Bibliography of publically accessible references for O&M Costs – 2011 update

	Bibliography of publically available cost references	**Technologies***
1.	Bolinger, M., R. Wiser, et al. (2010). *Preliminary Evaluation of the Impact of the Section 1603 Treasury Grant Program on Renewable Energy Deployment in 2009*, LBNL.	wind, PV
2.	California Solar Initiative (CSI) (2011). CSI Solar Thermal Projects Data Review.	SWH
3.	EIA (2010). *Assumptions to the Annual Energy Outlook 2010*.	PV
4.	EIA (2010). *Updated Capital Cost Estimates for Electricity Generation Plants*.	PV
5.	EPA (2007). *Biomass Combined Heat and Power Catalog of Technologies*.	bCHP
6.	International Energy Agency (2008). *Deploying Renewables: Principles for Effective Policies*.	wind, PV
7.	International Energy Agency (2008). *Energy Technology Perspectives 2008: Scenarios and Strategies to 2050*.	bCHP
8.	Intron Inc. (2009). *CCSE Solar Water Heating Pilot Program: Interim Evaluation Report*, California Center for Sustainable Energy.	SWH
9.	Kozubal, E., M. Deru, et al. (2008). *Evaluating the Performance and Economics of Transpired Solar Collectors for Commercial Applications*. Preprint. Golden, National Renewable Energy Laboratory (NREL).	SVP

PV = photovoltaics, SWH = solar water heat, bCHP = biomass combined heat and power, bHeat = biomass heat, SVP = solar vent preheat

Useful life

Useful life of the technology was estimated by interviewing NREL experts who have been working with the technologies and also by performing a literature search. Limited information on actual lifetime studies was found. The bulk of the literature referenced included an assumed useful life for a given technology. These numbers are useful since they provide conventional thinking of experts in each field; it is important to understand that they do not include lifetime statistical data of actual projects. The bibliography table shows the reports and papers that were reviewed to establish the conventionally accepted lifetimes.

Table 6 - Useful Life

System Useful Life	Years
PV	25 to 40
Wind	20
Biomass combustion Combined Heat and Power	20 to 30
Biomass heat	20 to 30
SWH	10 to 25
SVP	30 to 40

Table 7 - Bibliography of publically accessible references for Useful Life

	Bibliography of publically available Useful Life references
1.	Agarwal, P. and L. Manuel, *Empirical wind turbine load distributions using field data.* Journal of Offshore Mechanics and Arctic Engineering, 2008. **130**(1).
2.	Agarwal, P. and L. Manuel, *The influence of the joint wind-wave environment on offshore wind turbine support structure loads.* Journal of Solar Energy Engineering, Transactions of the American Society of Mechanical Engineers, 2008. **130**(3): p. 0310101-03101011.
3.	Allen, S.R., et al., *Integrated appraisal of a Solar Hot Water system.* Energy, 2010. **35**(3): p. 1351-1362.
4.	Allen, S.R., et al., *Integrated appraisal of a Solar Hot Water system.* Energy, 2010. **35**(3): p. 1351-1362.
5.	Ancona, D. and J. McVeigh, *Wind turbine—materials and manufacturing fact sheet*. 2001, Princeton Energy Resources International for the Office of Industrial Technologies. US Department of Energy.
6.	Asif, M., J. Currie, and T. Muneer, *Comparison of aluminium and stainless steel built-in-storage solar water heater.* Building Services Engineering Research and Technology, 2007. **28**(4): p. 337-346.
7.	Azzopardi, B. and J. Mutale, *Life cycle analysis for future photovoltaic systems using hybrid solar cells.* Renewable and Sustainable Energy Reviews, 2010. **14**: p. 1130-1134.
8.	Clyne, R., *Transpired Solar Collectors: Office of Power Technologies (OPT) Success Stories Series Fact Sheet.* 2000, National Renewable Energy Laboratory (NREL): Golden.
9.	Crawford, R.H., *Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield.* Renewable and Sustainable Energy Reviews, 2009. **13**(9): p. 2653-2660.
10.	Crawford, R.H. and G.J. Treloar, *Net energy analysis of solar and conventional domestic hot water systems in Melbourne, Australia.* Solar Energy, 2004. **76**(1-3): p. 159-163.
11.	Czanderna, A.W., *Reliability and lifetime issues for new photovoltaic technologies*, in *Future Generation Photovoltaic Technologies: Proceedings of the First NREL Conference, 24-26 March 1997*. 1997. p. 55-69.
12.	Czanderna, A.W. and F.J. Pern, *Estimating service lifetimes of a polymer encapsulant for photovoltaic*

	modules from accelerated testing, in *Conference Record of the Twenty Fifth Institute of Electrical and Electronics Engineers Photovoltaic Specialists Conference, 13-17 May 1996*. 1996. p. 1219-1222.
13.	Demtsu, S., S. Bansal, and D. Albin, *Intrinsic stability of thin-film CdS/CdTe modules*, in *35th IEEE Photovoltaic Specialists Conference, PVSC 2010, June 20, 2010 - June 25, 2010*. 2010: Honolulu, HI, United states. p. 1161-1165.
14.	Dunlop, E.D., *Lifetime performance of crystalline silicon PV modules*, in *Proceedings of 3rd World Conference on Photovoltaic Energy Conversion, 12-16 May 2003*. 2003: Osaka, Japan. p. 2927-30 Vol.3.
15.	Dunlop, E.D. and D. Halton, *The performance of crystalline silicon photovoltaic solar modules after 22 years of continuous outdoor exposure.* Progress in Photovoltaics: Research and Applications, 2006. **14**(1): p. 53-64.
16.	Enzenroth, R.A., et al., *Performance of in-line manufactured CdTe thin film photovoltaic devices.* Journal of Solar Energy Engineering, Transactions of the ASME, 2007. **129**(3): p. 327-330.
17.	Florides, G.A., et al., *Modelling, simulation and warming impact assessment of a domestic-size absorption solar cooling system.* Applied Thermal Engineering, 2002. **22**(12): p. 1313-1325.
18.	Gill, G.S. and A.S. Fung, *30-Year Life Cycle Cost of Solar Based Domestic Hot Water Systems for Ontario.* ASME Conference Proceedings, 2008. **2008**(43192): p. 183-189.
19.	Guinivan, D., *Life expectancy.* Engineering, 2008. **249**(10): p. 32-34.
20.	Hammond, G.P., et al., *Integrated appraisal of a building integrated photovoltaic (BIPV) system*, in *1st International Conference on Sustainable Power Generation and Supply, SUPERGEN '09, April 6, 2009 - April 7, 2009*. 2009: Nanjing, China.
21.	Kablan, M.M., *Techno-economic analysis of the Jordanian solar water heating system.* Energy, 2004. **29**(7): p. 1069-1079.
22.	Kaldellis, J.K., K.A. Kavadias, and G. Spyropoulos, *Investigating the real situation of Greek solar water heating market.* Renewable and Sustainable Energy Reviews, 2005. **9**(5): p. 499-520.
23.	Kalogirou, S., *Thermal performance, economic and environmental life cycle analysis of thermosiphon solar water heaters.* Solar Energy, 2009. **83**(1): p. 39-48.
24.	Kaul, A., S.A. Pethe, and N.G. Dhere, *Outdoor monitoring of a-Si:H thin film photovoltaic modules in hot and humid climate of Florida*, in *Reliability of Photovoltaic Cells, Modules, Components, and Systems, August 11, 2008 - August 13, 2008*. 2008, The International Society for Optical Engineering (SPIE): San Diego, CA, United States.
25.	Koehl, M., et al. *Indoor and outdoor weathering of PV-modules*, in *Reliability of Photovoltaic Cells, Modules, Components, and Systems, August 11, 2008 - August 13, 2008*. 2008. San Diego, CA, United States: SPIE.
26.	Köhl, M., et al., *Advanced procedure for the assessment of the lifetime of solar absorber coatings.* Solar Energy Materials and Solar Cells, 2004. **84**(1-4): p. 275-289.
27.	Kong, C., J. Bang, and Y. Sugiyama, *Structural investigation of composite wind turbine blade considering various load cases and fatigue life.* Energy and Buildings, 2005. **30**(1): p. 2101-2114.
28.	Kong, C., et al., *Investigation of fatigue life for a medium scale composite wind turbine blade.* International Journal of Fatigue, 2006. **28**(10 SPEC ISS): p. 1382-1388.
29.	Kong, C., Y. Sugiyama, and C. Soutis, *Structural design and experimental investigation of a medium scale composite wind turbine blade considering fatigue life.* Science and Engineering of Composite Materials, 2002. **10**(1): p. 1-9.
30.	Kozubal, E., et al., *Evaluating the Performance and Economics of Transpired Solar Collectors for Commercial Applications. Preprint*. 2008, National Renewable Energy Laboratory (NREL): Golden.
31.	Mayer, P. *Durability - Solar hot water systems*. 2010; Available from: http://www.greenspec.co.uk/solar-hot-water-systems.php.
32.	Mayer, P., *CHP (combined heat and power systems)*. 2010, GreenSpec.
33.	Michaud, M., G.J. Sroka, and R.E. Benson, *A novel approach to the refurbishment of wind turbine gears*, in *American Gear Manufacturers Association Fall Technical Meeting 2010, October 17, 2010 - October 19, 2010*. 2010: Milwaukee, WI. p. 28-37.
34.	Miller, D.C., et al. *Durability of poly(methyl methacrylate) lenses used in concentrating photovoltaic*

	modules. in *Reliability of Photovoltaic Cells, Modules, Components, and Systems III, August 3, 2010 - August 5, 2010*. 2010. San Diego, CA, United States: SPIE.
35.	Naveed, A.T., E.C. Kang, and E.J. Lee, *Effect of unglazed transpired collector on the performance of a polycrystalline silicon photovoltaic module.* Journal of Solar Energy Engineering, Transactions of the ASME, 2006. **128**(3): p. 349-353.
36.	Nawaz, I. and G.N. Tiwari, *Embodied energy analysis of photovoltaic (PV) system based on macro- and micro-level.* Energy Policy, 2006. **34**: p. 3144-3152.
37.	Otanicar, T.P. and J.S. Golden, *Comparative Environmental and Economic Analysis of Conventional and Nanofluid Solar Hot Water Technologies.* Environmental Science & Technology, 2009. **43**(15): p. 6082-6087.
38.	Oyague, F., D. Gorman, and S. Sheng, *NREL Gearbox Reliability Collaborative Experimental Data Overview and Analysis*, in *To be presented at Windpower 2010 Conference and Exhibition, Dallas, Texas, May 23-26, 2010*. 2010. National Renewable Energy Laboratory (NREL): Golden.
39.	Peacock, A.D., et al., *Micro wind turbines in the UK domestic sector.* Energy and Buildings, 2008. **40**(7): p. 1324-1333.
40.	Petrone, G., et al., *Reliability Issues in Photovoltaic Power Processing Systems.* IEEE Transactions on Industrial Electronics, 2008. **55**(7): p. 2569-2580.
41.	Ramirez-Vargas, R., et al., *Durability and reliability of solar domestic hot water heaters: Survey results. Final report, Part 1*. 1998.
42.	Rydh, C.J. and B.A. Sanden, *Energy analysis of batteries in photovoltaic systems. Part II: Energy return factors and overall battery efficiencies.* Energy Conversion and Management, 2005. **46**(11-12): p. 1980-2000.
43.	Saranyasoontorn, K. and L. Manuel, *Design loads for wind turbines using the environmental contour method.* Journal of Solar Energy Engineering, Transactions of the ASME, 2006. **128**(4): p. 554-561.
44.	Schleisner, L., *Life cycle assessment of a wind farm and related externalities.* Renewable Energy, 2000. **20**(3): p. 279-288.
45.	Vazquez, M., et al., *III-V concentrator solar cell reliability prediction based on quantitative LED reliability data.* Progress in Photovoltaics: Research and Applications, 2007. **15**: p. 477-491.
46.	Wiles, J.C. *Designing and installing safe, durable, and cost-effective photovoltaic power systems*. in *2006 IEEE 4th World Conference on Photovoltaic Energy Conversion, WCPEC-4, May 7, 2006 - May 12, 2006*. 2007. Waikoloa, HI, United States: Inst. of Elec. and Elec. Eng. Computer Society.