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Article

A Comparative Analysis of Energy Costs of Photovoltaic, Solar Thermal, and Wind Electricity Generation Technologies

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Abstract: Global installed capacity of renewable energy technologies is growing rapidly. The ability of renewable technologies to enable a rapid transition to a low carbon energy system is highly dependent on the energy that must be "consumed" during their life-cycle. This paper presents the results of meta-analyses of life-cycle assessments (LCA) of energy costs of three renewable technologies: solar photovoltaic (PV), concentrating solar power (CSP), and wind. The paper presents these findings as energetic analogies with financial cost parameters for assessing energy technologies: *overnight capital cost*, *operating costs* and *levelized cost of electricity* (LCOE). The findings suggest that wind energy has the lowest energy costs, followed by CSP and then PV.

Keywords: renewable energy; solar photovoltaic; concentrating solar power; wind power; life-cycle assessment; LCA; meta-analysis; technology assessment; net energy analysis

1. Introduction

Technology assessment of energy production technologies is often computed as financial cost. The US Department of Energy (DOE) and the National Renewable Energy Laboratory have been aggregating data on cost estimates for electricity generation in an online application, the Transparent Cost Database [1]. In this database, four main metrics exist to assess the cost of, especially, electricity generating infrastructure investment:

- **overnight capital cost**—combines all the capital cost data without interest (as if built *overnight* [2], computed in \$/W;

- **fixed operating costs**—including such costs as salaries, general overheads, insurance, taxes [3], computed as $/W;
- **variable operating costs**—including such costs as purchase of consumables (particularly associated with the fuel cycle, e.g., natural gas) [3], computed as $/kWh and;
- **levelized cost of electricity** (LCOE)—total costs (including annualized capital and yearly operating) divided by total energy service production [1], computed as $/kWh.

Life-cycle "cost" metrics are developed in other fields for energy generation technologies. The metrics presented are often variable or incommensurate. In the field of net energy analysis, the *energy return on investment* (EROI) is often computed, which measures the ratio of the energy in a given amount of the extracted and delivered fuel to the total primary energy used in the supply chain (*i.e.*, the energy that is directly and indirectly required to extract, refine and deliver the fuel)" [4]. For photovoltaic (PV) technologies, the *energy payback time* (EPBT) is often reported instead, which measures the time necessary for an energy technology to generate the equivalent amount of *primary* energy used to produce it [5]. Within the field of life cycle assessment (LCA) a different set of metrics are reported, including the *cumulative energy demand* (CED), defined as the amount of *primary* energy consumed during the life-cycle of a product or a service [6], and the energy or greenhouse gas (GHG) intensity, defined as the ratio of the primary energy consumed, or CO2 emitted for the construction, operation, and decommissioning, per unit of output of electrical energy over the lifetime of the device [7].

The author believes that the multitude of different metrics and their incommensurability with financial metrics may be a barrier to more widespread use of physical information for electricity supply planning. This paper will advance the benefits of the computation of metrics for physical "costs" associated with electricity production by electricity generation technologies which are analogous to those published as financial cost described above.

A recent meta-analysis and harmonization project has been carried out by researchers at the National Renewable Energy Laboratory (NREL) and a number of other institutions to determine the distribution in greenhouse gases (GHG) emissions from a variety of electricity production technologies over their entire life-cycle. Methodological details are provided in Heath and Mann [8].

This paper presents the results of a meta-analysis of the energy requirements of electricity generation via PV, concentrated solar power (CSP) and wind. The process involved a number of stages, including: initial literature search, literature screening, data collection, and commensuration of system boundaries and units.

2. Life-Cycle Assessment

LCA is a methodology to evaluate the material flows and environmental impacts associated with the production of goods and provision of services over its full life-cycle from extraction and processing of raw materials through manufacture, operation and, finally, disposal [9,10]. The LCA is divided into four main phases:

- **goal and scope**—including the definition of the *functional unit*, which quantifies the service delivered by the product system, definition of system boundaries, clarification of assumptions and limitations, allocations methods, e.g., between co-products, and impact categories;

- **life-cycle inventory** (LCI)—tracking material and energy flows from and to the environment, often involving either the creation of a ”bottom-up” model of the production process, the use of input–output (I-O) tables to convert between financial and physical data, or some hybrid of the two;
- **life-cycle impact assessment** (LCIA)—evaluating the environmental impacts of flows associated with the LCI, including selecting appropriate impact categories, indicators and environmental impact models, classification and measurement of impacts using a common metric to place different categories on an equivalent basis and;
- **interpretation**—including identification of significant issues arising from the LCI and LCIA stages, evaluation of completeness, sensitivity and consistency, and conclusions, limitations, and recommendations.

For the purposes of the current analysis, data from the LCI stage has been used. The goal of the majority of the studies used is to determine the CED of the three renewable energy technologies under analysis. The functional unit is normally one kWh of electricity generation in order to generate an energy intensity metric [kWh_p/kWh_e]. Most of the studies within the meta-analysis are based on bottom-up models, though some of the data from [7] comes from hybrid models.

3. Methodology: Meta-Analysis

The three areas of interest for this analysis were energy requirements for the production of capital infrastructure, energy requirements for operation of the system, and total life-cycle energy requirements for the system. The aim is to produce metrics of energy “costs” analogous to the financial metrics used to characterize energy production technologies. The capital energy cost [kWh_e/W_p] serves as the analogy for the overnight capital cost [$\$/W_p$]. The operating energy cost [kWh_e/kWh_e] serves as the analogy to the financial operating cost [$\$/kWh_e$]. The LCEC [$kWh_e/kWh_e$] serves as the analogy to the LCOE [$\$/kWh_e$].

3.1. Literature Search and Screening

Searches were made for a number of publication types including peer-reviewed journals, industry reports, reports by national agencies, such as the US Department of Energy (DOE), and unpublished work, including conference papers and doctoral theses. The search terms included the energy technology, e.g. “PV”, with the following phrases: “embodied energy”, “cumulative energy demand”, “life cycle inventory”, “life cycle assessment”, “energy payback time”, “net energy ratio” (NER), “energy yield ratio” (EYR), “energy return on investment” and “EROI”.

A number of criteria were used to screen the initial results: the study should be in English, the study should be original research or should reference data used, the study should give numeric data on net energy metrics, e.g., cumulative energy demand (CED), or net energy ratio (NER). Cross-referenced estimates were also eliminated.

The studies remaining after screening are presented in Table 1.

Table 1. Studies found from search and screening process.

Reference	Year	Technology	Location	Analysis type
[11]	1995	PV	India	Process
[12]	1997	PV	Japan	Process
[13]	1997	PV	US	Process
[14]	2000	PV	Unspecified	Process
[15]	2001	PV	Europe	Process
[16]	2001	PV	US	Process
[17]	2002	PV	India	Process
[18]	2002	PV	Europe	Process
[19]	2004	PV	Europe	Process
[20]	2004	PV	India	Process
[21]	2004	PV	Europe	Process
[22]	2005	PV	Europe	Process
[23]	2006	PV	US	Process
[24]	2006	PV	Europe	Process
[25]	2006	PV	US	Process
[26]	2006	PV	Singapore	Process
[27]	2007	PV	Europe	Process
[28]	2007	PV	US	Process
[29]	2007	PV	Europe	Process
[30]	2008	PV	China	Process
[31]	2008	PV	Many	Process
[32]	2009	PV	Europe	Process
[33]	2009	PV	US	Process
[34]	2009	PV	Europe	Process
[6]	2010	PV	US/Canada	Process
[35]	2010	PV	US	Hybrid
[36]	2010	PV	China/Japan	Process
[37]	2011	PV	Europe	Process
[38]	2011	PV	Europe	Process
[39]	1990	CSP	US	I-O
[40]	1999	CSP	Australia	Hybrid
[41]	2002	CSP	Australia	Hybrid
[42]	2008	CSP	Europe	Process
[43]	2011	CSP	US	Hybrid
[44]	2011	CSP	Europe	Process
[45]	2011	CSP	Chile	Process
[46]	2011	CSP	China	Process

Table 1. *Cont.*

Reference	Year	Technology	Location	Analysis type
[7]	2002	Wind	Many	Meta-analysis
[47]	2004	Wind	Europe	Process
[48]	2005	Wind	Canada	Process
[49]	2006	Wind	Europe	Process
[50]	2006	Wind	Europe	Process
[51]	2008	Wind	Taiwan	Process
[52]	2008	Wind	Europe	Process
[53]	2009	Wind	Europe	Process
[54]	2009	Wind	Europe	Process
[55]	2009	Wind	Europe	Process
[56]	2009	Wind	Australia	Hybrid
[57]	2010	Wind	Many	Meta-analysis
[58]	2011	Wind	Europe	Process
[59]	2011	Wind	Europe	Process
[60]	2011	Wind	Europe	Process
[61]	2011	Wind	Europe	Process
[62]	2011	Wind	China	Process
[63]	2011	Wind	China	Process
[64]	2011	Wind	Europe	Process
[65]	2012	Wind	Europe	Process
[66]	2012	Wind	Canada	Process

3.2. Commensuration of Study Boundaries and Data

A number of methods were used to allow comparison of results. Data was aggregated by converting to electrical energy equivalents. Data given in terms of primary energy was changed to electricity equivalents using conversion factors given in the study. If no conversion factor was given, a standard conversion factor of 30% was used. For reference, the conversion factor for Europe's grid is 31% and for the US is 29% [67]. Where data was given in terms of energy inputs per unit of PV system area, e.g., MJ/m^2, this was converted to per unit capacity inputs by using rated PV system efficiency and standard test conditions (STC) irradiance of 1000 W/m^2. If no efficiency was given, the study was not used. If data was given in terms of an energy intensity, *i.e.*, energy inputs per unit of electricity produced, e.g., [MJ/kWh$_e$], this was converted to per unit capacity inputs by one of the following methods: using the capacity factor, *i.e.*, the ratio of the average power output to nameplate capacity of the system; using the total lifetime electricity production of the system; or, using the annual electricity production of the system and the lifetime of the system, and, if no lifetime was given, the system was assumed to have a nominal lifetime of 25 years.

4. Results and Discussion

Data found by the meta-analysis is presented in the supporting information. Studies on PV were disaggregated by technology: single-crystal silicon (sc-Si), multi-crystalline silicon (mc-Si), amorphous silicon (a-Si), ribbon silicon, cadmium telluride (CdTe) and copper indium gallium (di)selenide (CIGS). Studies on CSP were disaggregated by technology: parabolic trough, tower, dish and fresnel. No data was found for either dish or fresnel CSP technologies. Studies on wind were disaggregated based on wind farm location: onshore or offshore. The data from the studies was categorized according to appropriate stage in the technology production process: capital energy cost, operating energy cost and LCEC.

4.1. Capital Energy Costs

Capital costs include the energy requirements to extract and process all raw materials, manufacture and install the capital equipment including any site preparation and grid interconnection. Energetic inputs associated with operating and maintenance (O&M) and disposal are not included. Units of measurement for capital costs are kWh_e per unit of nameplate capacity, W_p. Data taken from [6,7,11–66].

Figure 1. Capital cost [kWh_e/W_p] of various wind, PV and CSP technologies.

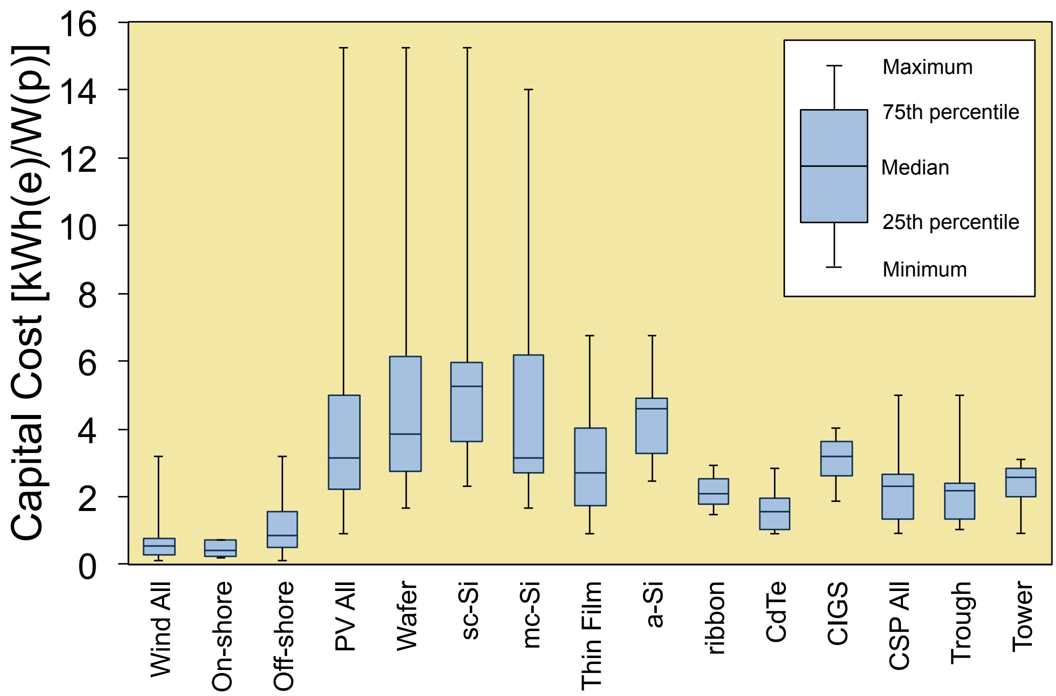


Figure 1 shows the distribution in estimates of capital cost for the various renewable technologies. In general, wind has the lowest capital costs, followed by CSP and then PV. Looking at each of the specific technology categories, we see that onshore wind has lower capital costs than offshore. Thin film PV has lower capital costs than wafer-based PV, with CdTe having the lowest cost. Trough CSP has a lower median value than tower systems, but a larger range in estimates. The crystalline silicon PV technologies have the greatest range in values. The most likely reason for this is due to their having estimates from a wide range of years. The spread in values fails to capture the evolution of decreasing CED through time. For more details on this issue, see [68]. Ranking the technologies by median value we find:

1. onshore wind
2. offshore wind
3. CdTe PV
4. ribbon silicon PV
5. trough CSP
6. tower CSP
7. mc-Si PV
8. CIGS PV
9. a-Si PV
10. sc-Si PV

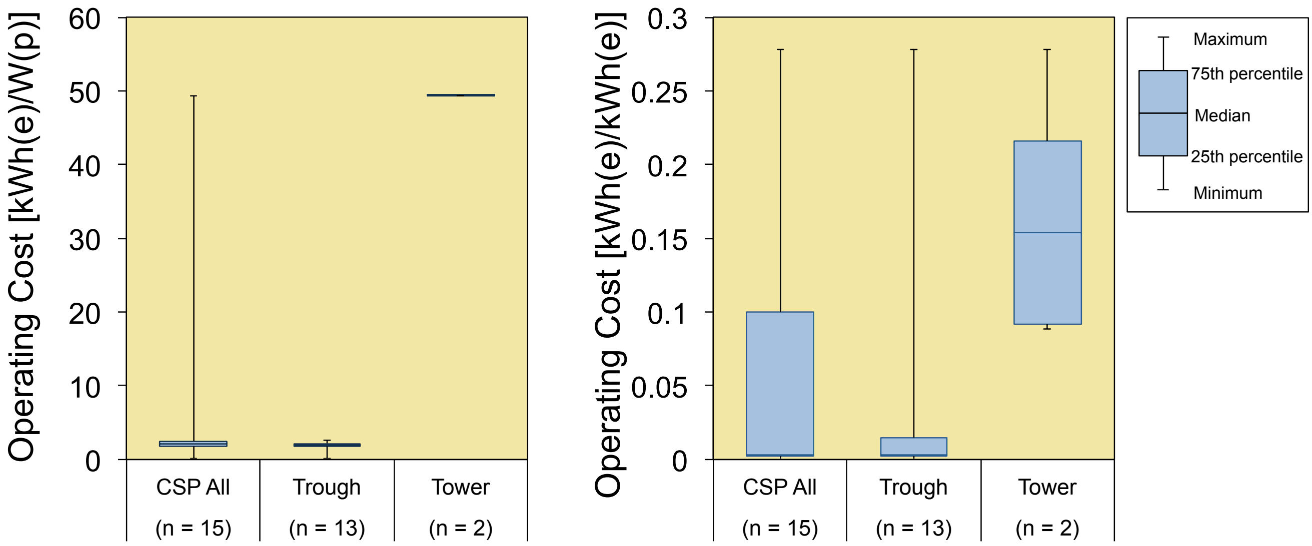
4.2. Operating Energy Costs

Data on operating costs includes energy requirements for maintenance of the system, e.g., washing solar systems, replacing worn parts, including the energy required to build spare parts, energy requirements for operating the systems, such as control systems, or, if necessary, the energy associated with the fuel cycle (including the energy content of any fuel consumed). Such inputs were mainly associated with CSP, where natural gas must sometimes be burned to maintain steam operating temperatures or to restart the steam turbine after an overnight shut-down. Data taken from [39,41–43,45,46].

There was insufficient data to distinguish fixed and variable operating costs, as is done in economic analyses. As such, all operating costs have been aggregated and are displayed in both units of kWh_e/W_p and kWh_e/kWh_e.

Figure 2 shows the distribution of estimates for operating costs. Data could be found only for CSP technologies. As can be seen, tower CSP has higher operating costs than trough. This may be due to natural gas consumption necessary to maintain higher temperatures in the event of cloud cover [69].

Figure 2. Operating cost [kWh_e/kWh_e] of CSP technologies.



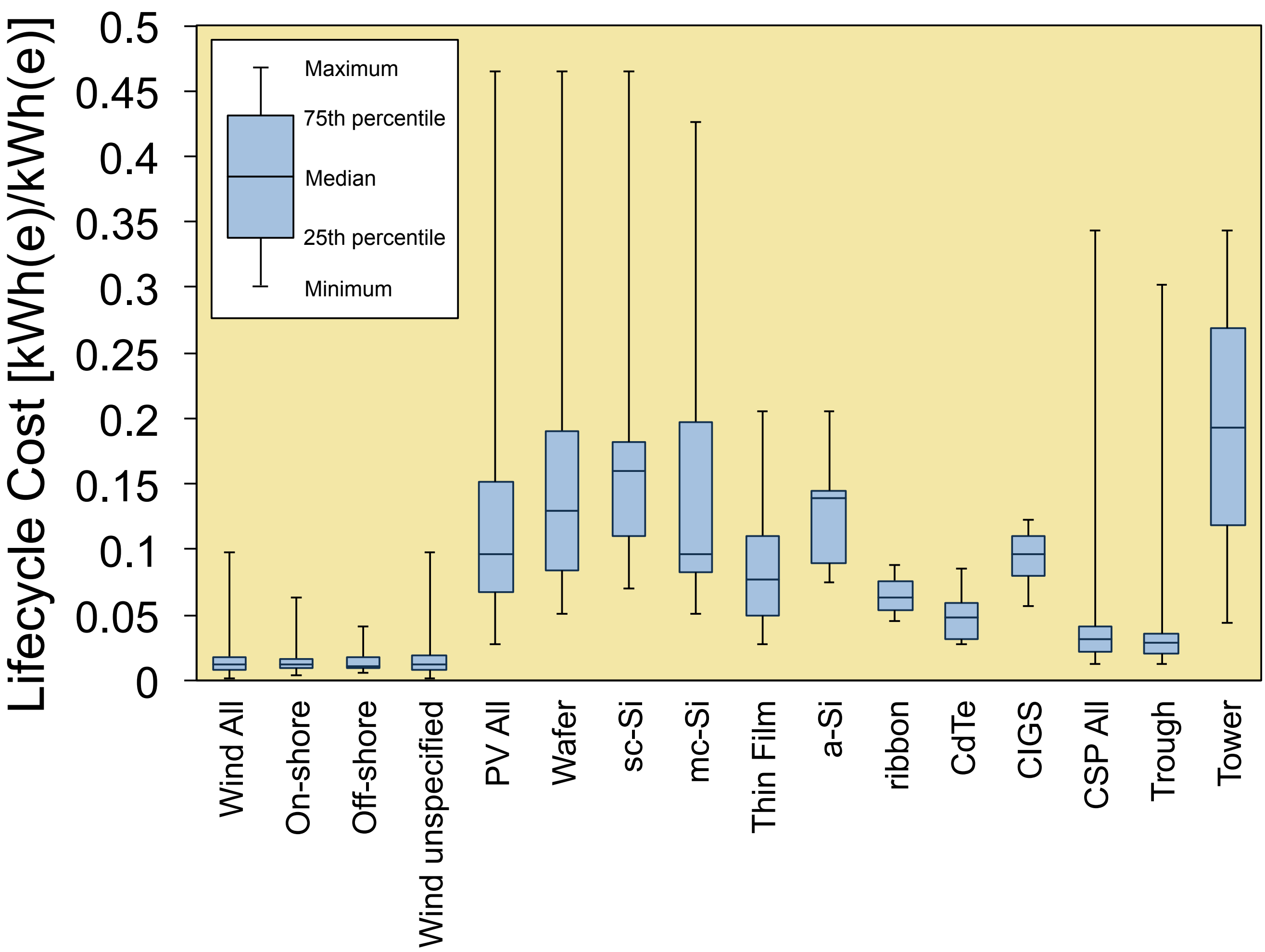
4.3. Life-Cycle Energy Costs (LCEC)

Life-cycle costs include all of the energy inputs over the full life-cycle of the system, including end-of-life, normalized by the total lifetime electricity output from the system. The unit of measurement is kWh_e/kWh_e. Unlike the financial metric LCOE, no discounting of inputs and outputs has been made. Data taken from [6,7,11–66].

Figure 3 shows the life-cycle energy requirements for a number of the renewable technologies. Similarly to capital costs, wind power has the lowest LCEC, followed by CSP and then PV. Ranking specific technology types by median LCEC we find:

1. off-shore wind
2. on-shore wind
3. CdTe PV
4. trough CSP
5. ribbon PV
6. CIGS PV
7. a-Si PV
8. mc-Si PV
9. sc-Si PV
10. tower CSP

Figure 3. Life-cycle cost [kWh_e/kWh_e] of various wind, PV and CSP technologies.



5. Conclusions

The results of a meta-analysis of energy requirements for three renewable electricity production technologies—wind, PV and CSP—has been presented. To facilitate the utility of this information, the metrics presented are direct analogies of financial metrics commonly used to characterize electricity production technologies: overnight capital cost, operating costs and LCOE. The author recommends the use of these metrics to enable more interaction between researchers in the field of LCA with policy makers and advisers. The analysis has found that there is a wide range in energy requirements for producing electricity from different renewable resources. Wind was found to have the lowest capital costs, followed by CSP and then PV. The LCEC followed a similar pattern, though tower CSP was found to have the highest LCEC due mainly to consumption of natural gas during operation.

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