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Original Research Article

Photovoltaics energy: Improved modeling and analysis of the levelized cost of energy (LCOE) and grid parity – Egypt case study

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ABSTRACT

This paper presents improved modeling and analysis of the levelized cost of energy (LCOE) associated with photovoltaic (PV) power plants. The presented model considers the effective lifetime of various PV technologies rather than the usual use of the financial lifetime. The classical use of the solar advisor model (SAM) software is modified for considering the effective and financial lifetimes into consideration. The impact of the effective lifetime on the LCOE and the energy production is clearly presented. In addition, the presented analysis covers a wide range of PV technological characteristics, sun tracking options, and meteorological conditions. Parametric and sensitivity studies are also presented for overcoming the uncertainties in the input data and for searching of the significant options for LCOE reduction. The feasible use of PV energy is analyzed through grid parity analysis. The meteorological conditions of some locations in Egypt and the Egypt's tariff structure are considered in the presented numerical examples. The salient outcome of this paper is that the effective lifetime has a significant impact on both the LCOE and the lifetime energy production. In addition, significant conclusions regarding the effectiveness of various sun tracking options as affected by the PV technological and locational characteristics are derived.

Introduction

Recently, renewable energy technologies have received intense attention. This is due to the energy crisis, increasing requirements of environmental protection, the increased costs associated with the fossil fuels based electrical energy production, and decrement availability of new fossil resources [1,2]. Generally, renewable energy technologies have the advantages of generating electricity with insignificant emission of carbon dioxide (CO_2) or other greenhouse gases (GHG). In addition, they produce insignificant pollutant discharge on water or soil [2].

The sunlight energy is the most abundant renewable energy resource. Therefore solar energy is one of the most promising renewable energy options for large-scale global electricity production [2,3]. In the power and energy discipline, the sunlight energy can be involved in energy conversion processes through three main evolving technological categories. These categories are Photovoltaics (PV), Concentrated Solar Power (CSP), and Solar Heating and Cooling (SHC). This paper focuses on the PV technologies, which generates electricity through direct conversion of sunlight. Photovoltaic (PV) technologies are one of the fastest growing renewable energy technologies in the world [4]. There are three basic technological generations of photovoltaic technologies. The first generation (single-crystalline and poly-crystalline PV cells) represents 85%-90% of the PV market while second generation (thin film PV cells, which include amorphous silicon (a-Si), Cadmium Telluride (CdTe), and Copper-Indium-Selenide (CIS) PV cells) represents 10–15% of the PV market. Thin film cells are less efficient in comparison with the crystalline cells, but they are cheaper [5,6]. The third generation is at the pre-commercial or research and development (R&D) stage. Concentrating PV cells (CPV), dye-sensitized solar cells (DSSC), hetero-junction cells, and organic solar cells are examples of the third generation of photovoltaic cells [6–9].

During its operation, PV technologies are environmental friendly and free of Green House Gases (GHG); however, during its life cycle, there are significant amounts of GHG emissions and energy consumption during, for example, the manufacturing of PV cells and transportation. The environmental impact of PV energy is usually evaluated using the Life Cycle Assessment (LCA). The Energy Payback Time (EPBT) and GHG emission rate are the most widely used indicators to evaluate the sustainability and environmental performance of PV systems [1,2,8–10]. The

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Table 1
LCA summary for various PV technologies and generations [8].

PV technology		EPBT (years)	GHG emission rate (gCO_2-eq/kWh)
First Generation	Mono-Si	1.7–2.7	29–45
	Poly-Si	1.5–2.6	23–44
Second Generation	a-Si	1.4–3.2	15.6–50
	CdTe	0.7–3.2	14–50
	CIS	1.6–2.9	10.5–95
Third Generation	CPV	0.7–2	18–45
	Hetero-junction	1.2	20
	Dye-sensitized	4.92–27.9	84.5–393

EPBT indicator is defined as 'the years required for a PV system to generate a certain amount of energy (converted into equivalent primary energy) for compensation of the energy consumption over its life cycle' [8]. This energy consumption includes the energy requirements in PV modules' manufacturing, assembly, transportation, system installation, operation and maintenance, and system decommissioning or recycling [8]. GHG emission rate indicates the amount of GHG emitted per unit of electrical power generated. In [8], the EPBT and GHG emission rate are estimated considering various PV technologies and generations; a summary of the main results is shown in Table 1. These results indicate the high sustainability of PV technologies. In [9], the analysis shows that the organic PV (OPV) of the future is expected to have significant contribution in the PV market share and very large-scale PV power plants. This expectation is based on the unique techno-economical characteristics of OPV technology in comparison with other PV technologies. OPVs show remarkable low energy payback time and carbon emissions as well as light weight, mechanical flexibility, tunable color, and low-light performance.

Currently, the PV market is one of the fastest growing renewable energy technology markets. The global installed PV capacity has multiplied by a factor of 37.44 in 10 years from 1.8 GW in 2000 to 67.4 GW at the end of 2011with a growth rate of 44% per year. In the year 2013, more than 39 GW added. This makes the world wide total capacity to be 139 GW. Despite the rapid growth of the PV market, less than 0.2% of global electricity production is generated by PV. This is because the PV energy costs are typically higher than that from traditional sources such as coal and natural gas power plants [3,5–7,11].

From an economics point of view, PV energy has low marginal cost; only the operational costs are considered in the marginal cost estimation while no fuel costs are considered. As a result, the PV energy production costs are significantly smaller than the energy from conventional fuel such as coal and natural gas. This leads to the merit-order effect [12,13] where the natural gas and coal energy are displaced by PV energy. During 2009–2011, the impact of the implementation of solar power in Germany [13] caused reductions of 7%, 13%, and 23% in the average electricity prices, the average daily maximum price, and the daily price variations.

Egypt is one of the Sunbelt countries and endowed with high intensity of direct solar radiation [14]. The Egyptian solar atlas (issued in 1991) [15] indicated that the average solar radiation ranges between 1970 and 3200 kWh/m^2/year from north to south with very few cloudy days. The average sunshine duration is between 9 and 11 h/day [2,5,15,16]. In the early 1980s, Egypt recognized the fact that the traditional energy resources would be inadequate to meet future needs. The new and renewable energy Authority established in 1986 to be a focal point for renewable energy activities in Egypt. The Egyptian photovoltaic plan, which is approved by the Egyptian Cabinet in July 2012, targets to install 700 MW by 2027 with a private investment share of 67% including enhancement of relevant local industry [16,17].

Generally, the economic feasibility of an energy generation project can be evaluated using various metrics [4,5]. One of these metrics is the cost per watt, but this method does not consider the effects of the lifetime, performance of the energy producing equipment, and the financial policies. The levelized cost of energy is another popular metric which is a cost of generating energy (usually electricity) for a particular system. The Levelized Cost of Energy (LCOE) is an assessment of the economic lifetime energy production and cost. Therefore, it fairly compares the energy costs produced by different means, and it allows alternative technologies to be compared when different scales of operation, investment or operating time periods exist [3–5,18].

The LCOE is sensitive to small changes in the input variables and assumptions. The main input variables are the discount rate, average system cost, financing method and incentives, average system lifetime, and degradation of energy generation over the lifetime [5]. Therefore, accurate values of these input data are essential for reliable results. In addition, the sensitivity of the LCOE to various input data should also be evaluated. This is to overcome the ample uncertainty in the input variables and assumptions.

The breakeven cost of photovoltaic (PV) technology is defined as the point where the cost of PV-generated electricity equals the cost of electricity purchased from the grid. This target has also been referred to as grid parity [5,16]. The tipping point for solar PV adoption is considered to be when the technology achieves grid parity [4]. Grid parity is defined as the threshold at which a grid-connected PV system supplies electricity to the end user at the same price as grid-supplied electricity [19]. Due to the increase of the retail cost of the conventional electricity and the decrease in the costs of photovoltaic electricity, the grid parity concept will be probably achieved in specific situations. These situations depend on the resource availability, the plant scale, and the PV efficiency enhancements as well as PV cost reductions.

The main objectives of this paper include modeling of the PV LCOE and finding possible modeling enhancements for better accuracy. Improved modeling of the LCOE considering the effective lifetime of PV technologies is presented. The paper also presents evaluations of the PV LCOE. These evaluations consider the impact of various input parameters such as the available solar resource, sun tracking method, and PV technological characteristics. The uncertainty associated with various input parameters is assessed through parametric and sensitivity analysis. The System Advisor Model (SAM) [20] is used as a simulation tool while the technological characteristics of various PV technologies are obtained from recent literature and the RETScreen software [6,21]. Grid parity analysis is also demonstrated considering the impact of various input parameters.

Modeling of LCOE and grid parity

The nomenclature used in this paper is listed in the Appendix. Generally, an LCOE model is an assessment of the economic lifetime energy cost and lifetime energy production. Estimation of the LCOE allows alternative technologies to be compared when different scales of operation, investment, or operating time periods exist. The LCOE captures capital costs, ongoing system-related costs and fuel costs – along with the amount of electricity produced – and converts them into a common metric: $/kWh. Simply, the LCOE can be defined by [3,5]:

$$\mathrm{LCOE} = \frac{\text{Total Life Cycle Cost}}{\text{Total Lifetime Energy Production}} \quad (1)$$

From an economic point of view, the LCOE is a representative of the electricity price that would equalize the lifetime cash flows (inflow and outflow) over the economic lifetime of an energy