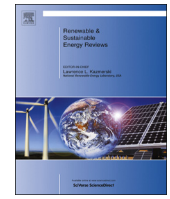
Renewable and Sustainable Energy Reviews 57 (2016) 692–703

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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



Levelized cost of electricity for solar photovoltaic, battery and cogen hybrid systems

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ARTICLE INFO

Article history:
Received 13 May 2015
Received in revised form
12 October 2015
Accepted 17 December 2015

Keywords:
Photovoltaic
Cogeneration
Off-grid
Combined heat and power
Levelized cost of electricity
Battery
Storage

ABSTRACT

The technological development and economic of scale for solar photovoltaic (PV), batteries and combined heat and power (CHP) have led to the technical potential for a mass-scale transition to off-grid home electricity production for a significant number of utility customers. However, economic projections on complex hybrid systems utilizing these three technologies is challenging and no comprehensive method is available for guiding decision makers. This paper provides a new method of quantifying the economic viability of off-grid PV+battery+CHP systems by calculating the levelized cost of electricity (LCOE) of the technology to be compared to centralized grid electricity. The analysis is inherently conservative as it does not include the additional value of the heat form the CHP unit. A case study for residential electricity and thermal demand in an extreme worst case environment (Houghton, Michigan) is provided to demonstrate the methodology. The results of this case study show that with reasonable economic assumptions and current costs, PV+battery+CHP systems already provide a potential source of profit for some consumers to leave the grid. A sensitivity analysis for LCOE of such a hybrid system was then carried out on the capital cost of the three energy sub-systems, capacity factor of PV and CHP, efficiency of the CHP, natural gas rates, and fuel consumption of the CHP. The results of the sensitivity provide decision makers with clear guides to the LCOE of distributed generation with off-grid PV+battery+CHP systems and offer support to preliminary analysis that indicated a potential increase in grid defection in the U.S. in the near future.

Contents

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http://dx.doi.org/10.1016/j.rser.2015.12.084
1364-0321/

1. Introduction

Technical improvements and scaling have resulted in a significant reduction in solar photovoltaic (PV) module costs, which have resulted in PV industry growth both globally as well as in U.S. [1]. In many regions there have been favorable policies for solar energy due to the positive public response and support for growth of solar energy [2–7]. High exergy electricity from PV is not only reliable, safe and sustainable [8–11], but now it has become an economical way of providing global society's energy needs as well [12–13]. As the demand for PV installation continues to increase, the costs continue to decline feeding a virtuous cycle [14–19]. In some regions of U.S. the solar levelized cost of electricity for small-distributed on-grid PV systems is already competitive with conventional utility electrical rates [12,20–21].

This represents an economic threat to conventional electric utility business models and in response utilities are using a number of mechanisms to discourage the distributed renewable energy generation market including: i) revoking or repealing net metering legislation [22–25]; ii) placing caps on distributed generation [27–28]; iii) specifying solar grid charges [29–32]; iv) continuing manipulation of customer charges to act as disincentives of both energy efficiency and distributed renewable energy [33–35]; and v) placing temporary prohibition of activities on state Renewable Portfolio Standards [36].

Many of the arguments (e.g. iii) are framed as costs of an inherently intermittent electrical source such as solar. However, the potential for economic dispatchable distributed power becomes possible with the simultaneous decline of the cost of battery storage. Current battery costs are between $600–1000/kW h. The U.S. DOE expects that this cost will decline further to reach $225/kW h in 2020 and will further drop below $150/kW h in the longer term [37]. Economy of scale will also factor into future battery prices, especially with Tesla's battery GigaFactory, which will shortly have battery packs (Power Wall) available for $350/kW h for home use [38]. However, in many applications (e.g. northern U.S. communities) where a battery bank would need to be prohibitively large to cover the load with PV system alone, such systems can be coupled to a cogeneration or combined heat and power (CHP) system.

The passage of the Public Utility Regulatory Policies Act (PURPA) in November 1978 [39], created the impetus for a resurgence of co-generation and significant growth in CHP capacity. Conventional generation is inherently inefficient, only converting on average about a third of the input fuel's potential energy into usable energy. When comparing overall CHP system efficiency to the typical central power station (for electricity) and boiler system (for steam) scenario, CHP offers reductions in total primary fuel consumption on the order of 30–35%, which results in a similar CO_2 emissions reduction, consuming the same fuels [40]. However, if coal-fired electric generation is compared to natural-gas fired CHP systems the result is CO_2 emission reductions approaching 60% and even greater reductions in pollutants such as SO_2, NO_X and mercury [41]. More than two-thirds of the CHPs in the U.S. are fueled with natural gas, but renewable biomass and process wastes are also potential fuel sources [41]. According to a 2012 joint report by U.S. D.O.E. and U.S. E.P.A., CHP makes up about 8% of U.S. total generating capacity with an installed capacity of about 82 GW (2012) [42]. The CHP technologies have also improved and are now available at a household scale. In a review comparing various CHP technologies depending on size, cost, efficiency and performance parameters for residential use, CHP modules with internal combustion engine technology were found to be more efficient [43–45]. Finally, the development of shale gas has had a significant moderating effect on natural gas prices [40]. For example, average residential natural gas rates for Michigan in 2009 were $11.30/MMBTU and in 2014 they were $8.99/MMBTU [46]. This has assisted in the economic viability of small-scale CHP units.

Hence, these three technological developments in PV, batteries and CHP have led to the possibility of grid defection (moving completely off-grid) for a significant number of utility customers and is projected to increase in the future [47]. However, economic projections on such complex systems utilizing multiple technologies and fuel sources is challenging and no comprehensive review is available for guiding decision makers. This paper provides such a means by quantifying the economic viability of off-grid PV+battery+CHP systems by calculating the levelized cost of electricity (LCOE) of the technology and a case study for residential electricity and thermal demand in Houghton, Michigan is provided to demonstrate the methodology. A sensitivity analysis for LCOE of such a hybrid system is then carried out on the following factors: capital cost of the three components, capacity factor of PV and CHP, efficiency of the CHP, natural gas rates, and fuel consumption of the CHP. The results enable the cost of distributed generation with off-grid PV+battery+CHP systems to be compared to the cost of electricity with the conventional grid. The results for potential grid defection are discussed.

2. Background

The simplified block diagram of the modeled PV+CHP+battery hybrid system considers only AC loads [48] and is depicted in Fig. 1. Such a hybrid system is used to satisfy electrical as well as thermal load demand for a residential single-family detached homes. The hybrid system consists of PV and CHP unit, which are both used to generate electricity. Also the waste heat from co-generation units can be used primarily for space heating and cooling and domestic water heating. The use of co-generation units in this way is optimal for energy management [49–51]. Moreover the CHP unit also generates thermal energy, which it uses to partially fulfill thermal load demand and thus offsets the primary furnace and fuel source (e.g. natural gas furnace). The output of PV and the energy stored in the battery is DC, which necessitates a DC–AC inverter to supply the AC load. Moreover, as the output of CHP unit is AC, any excess AC output has to be converted into DC form before storing it in the battery unit. Thus, an AC to DC rectifier is incorporated for this purpose. It should be noted, the dispatch strategy of the system will be reliant on both the load data and the fuel economics for a given region. Parallel topology is employed for the electrical component of the system [52]. Here, the priority given to fulfill the electrical demand will be solar PV followed by the storage battery and finally the CHP unit, in order to minimize fuel use and greenhouse gas emissions. Thus, the PV unit will try to satisfy the AC load demand. If it is incapable of satisfying, then PV and the battery unit will fulfill the load demand, which will help to increase system efficiency. If still the AC load demand is not satisfied the remaining load demand will be served by the CHP unit [53].