Renewable and Sustainable Energy Reviews 74 (2017) 1379–1393

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Revisiting the techno-economic analysis process for building-mounted, grid-connected solar photovoltaic systems: Part one – Review

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ARTICLE INFO

Keywords:
Solar PV
Prosumer
Economics
Investment
Modeling

ABSTRACT

The market for solar photovoltaic systems is growing rapidly into a mature industry, while at the same time policies which have spurred the growth (e.g. feed-in tariffs or net metering) are beginning to fade away. These policies made techno-economic studies relatively simple for engineers, analysts, and owners, however investing in a deregulated market requires more advanced tools than the traditional engineering economics which dominate the literature. The objective of part one in this paper is to catalogue and critique the range of methods and models relevant to techno-economic analysis for PV systems in the context of distributed, grid-connected buildings. This is accomplished by; developing a system modeling framework for prosumer PV investment analysis, reviewing relevant energy, economics, and finance literature to identify mathematical models which can be applied, and cataloging the use of the reviewed techniques in the relevant literature. Also included is a qualitative discussion of the benefits and practicality of the review techniques, where Monte Carlo analysis is highlighted as an exemplary method. This review is useful as a reference for analysts, researchers, and engineers developing PV integration solutions for building energy systems in a post early adopter PV market.

1. Introduction

Solar photovoltaic (PV) systems are being installed at an ever increasing rate globally, and in developed countries the fastest growing sector is distributed, grid-connected, rooftop systems [1–3]. The motivation for individuals to install their own PV system can vary, but much of the exponential growth can be traced back to favorable economic conditions created through government policy [4,5]. To be well understood by the public, support policies are often designed to make investment analysis simple; much more so than the type of analysis required for traditional utility investments [6]. For example; the feed-in tariff (FiT), the most commonly used support mechanism in the world, guarantees a fixed payment for all generated electricity for a pre-determined, usually long-term, period of time [7,8].

The success of these policies are causing many in industry and government to prepare for the time when PV no longer receives dedicated support and participates directly in the open market [9]. In the European Union (EU), increasing electricity rates have led to a directive which “promotes a gradual move to market-based support for renewable energy” [10,11]. In the United States, utilities in several states have begun calling for the removal of net-metering policies and in some cases enacted small fees for grid-connected PV systems [12–14]. This is also within the context of deregulation, while potentially opening the door for new opportunities and innovation in the broader electricity market, adds a layer of complexity and uncertainty that makes long-term investment analysis difficult.

Consumers who become distributed PV system owners, often known as “prosumers”, are a new class of investor in the energy system that have traditionally been the domain of a small number of highly skilled and regulated utilities. There is a well-established toolkit of techno-economic indicators that have guided decision making in profit-maximizing firms and has also been extensively applied to PV systems [15–17]. However in the terms of traditional neo-classic methods, behavioral economics suggest that consumers tend to undervalue energy related investments due to loss aversion and uncertainty [18]. Additionally, social and institutional influences (e.g. altruism, technological lock-in or awareness) can lead to investment decisions considered economically inefficient [19]. Therefore traditional engineering economics may not be the most appropriate tool for analysts, researchers or policy makers interested in describing investment potential for distributed, prosumer oriented technologies.

A majority of PV investment studies use models and methodologies that are an extension of the work that has come before them, with little reflection on the choice of methods or models. Given that the prosumer is a new actor in the energy system, it is useful to identify models, indicators, and methods to determine their appropriateness.

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http://dx.doi.org/10.1016/j.rser.2016.11.232
Received 27 June 2016; Received in revised form 5 August 2016; Accepted 19 November 2016
1364-0321/

Nomenclature

ABM	Agent Based Modeling
ANN	Artificial Neural Network
BCR	Benefit-to-Cost Ratio
CAPM	Capital Asset Pricing Model
DC	Direct Current
DNI	Direct Normal Irradiation
DPB	Discounted Payback Time
DSM	Demand Side Management
EDC	Equivalent Diode Circuit
FiT	Feed-in Tariff
GHI	Global Horizontal Irradiation
IEA	International Energy Agency
IRR	Internal Rate of Return
LCOE	Levelized Cost Of Energy
MCA	Monte Carlo Analysis
NGO	Non-Governmental Organization
NPV	Net Present Value
OECD	Organization for Economic Cooperation and Development
PV	Photovoltaic
PVPS	Photovoltaic Power Systems Program
RMS	Root Mean Square
ROA	Real Options Analysis
SDM	System Dynamics Modeling
SPB	Simple Payback Time
STC	Standard Test Conditions
TLCC	Total Life Cycle Cost
TMY	Typical Meteorological Year
TOU	Time Of Use
WACC	Weighted Average Cost of Capital

Additionally, there is value in collecting a broad set of analysis tools in a single source for reference. The objective of this paper therefore is to catalog the range of tools and models relevant to techno-economic analysis for PV systems in the context of distributed, grid-connected buildings. This will be accomplished by; developing a system modeling framework for prosumer PV investment analysis, reviewing relevant energy, economics, and finance literature to identify mathematical models which can be applied, and cataloging the use of the reviewed techniques in the relevant literature.

2. Modeling framework

Techno-economic analysis can take a wide array of forms depending on motivation, audience, market, owner, scale, and location. This review is focused on the needs and motivations of a prosumer in a deregulated electricity market, which comes with specific concerns separate from those of traditional actors in the energy market. When compared to a traditional electricity supplier who is primarily concerned with supplying the market, the prosumer is usually concerned with supplying themselves first, then the market when there is oversupply. When compared to storable fuels which can be converted into electricity on demand, solar PV generation is by-in-large dictated by the weather. When compared to steam or gas turbines, solar PV (and supporting building energy equipment) is a young technology in a landscape where dramatic changes are commonplace.

Given the widely varying state of electricity markets around the world, it is important to identify the difference between a regulated and deregulated market in the context of this review. A regulated market is one in which there is a single, vertical utility supplying electricity to a region. In this case, the utility and regulators are in control of nearly all aspects of the rates and structure. In a deregulated market, there are many actors supplying and demanding electricity and it is assumed that access is equally available to anyone. The latter is in focus here due to the increasing move to reform or deregulate markets around the world, even though many may not have the same structure as the one used here.

This section seeks to define the techno-economic analysis framework as a system model (different from the PV system), defined using the principles outlined by Churchman [20], which can be used for mathematical simulation. The objective of the model is to produce descriptive PV investment information to the prosumer within the context of a deregulated electricity market, which could then be used as a component of the decision making process. It is important to state that this system does not have the objective of prescribing an action or predicting the decision making behavior of prosumers, which is the domain of technology diffusion analysis [21,22].

2.1. Components

Model construction begins by identifying the components that impact the objective of the model. The basic physical components

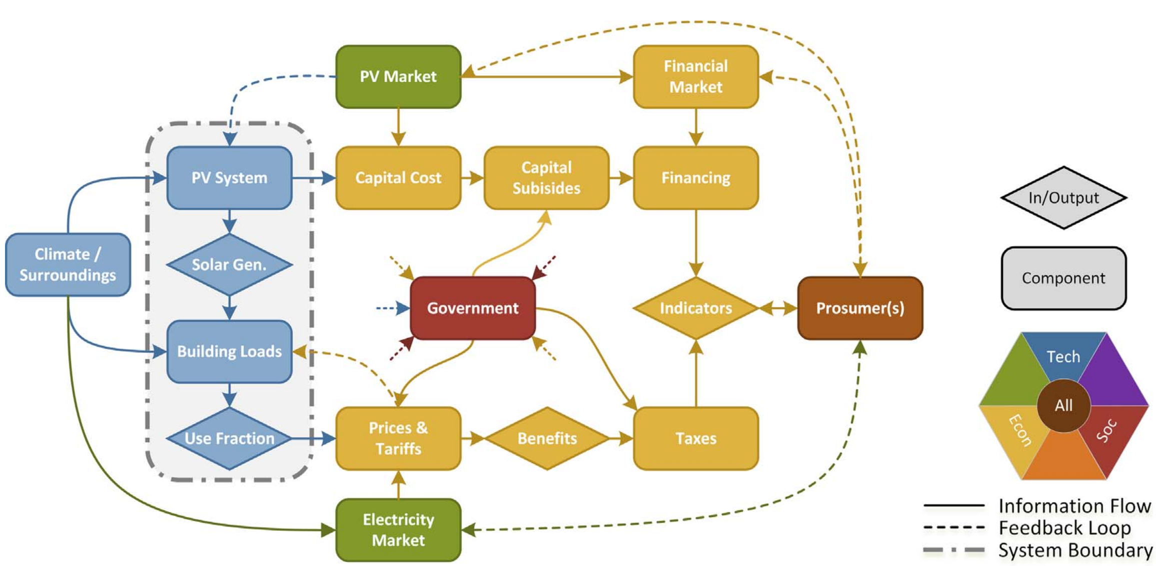

Fig. 1. – Techno-economic PV modeling framework from the prosumer's viewpoint.