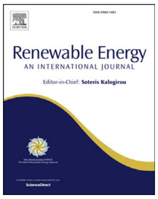
Renewable Energy 87 (2016) 77–87

Contents lists available at ScienceDirect

Renewable Energy

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



Profitability in absence of subsidies: A techno-economic analysis of rooftop photovoltaic self-consumption in residential and commercial buildings

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ARTICLE INFO

Article history:
Received 1 April 2015
Received in revised form
14 August 2015
Accepted 27 September 2015
Available online xxx

Keywords:
Photovoltaics
Buildings
Self-consumption
Economic performance
Energy policy

ABSTRACT

In the face of fading regulatory support for the deployment of photovoltaics (PV), self-consumption models for photovoltaics on buildings present an option to decouple economic performance from policy support such as feed-in tariffs. Through a techno-economic analysis we analyze the potential of PV self-consumption for four different building types (residential and commercial, each large and small) in Germany, Switzerland and Austria. We find that with self-consumption rooftop PV can be attractive for many buildings in central Europe already today, even in the absence of regulatory support. Main profitability drivers include electricity prices and the achievable self-consumption share of a building (driven, in turn, by the building-specific ratio of PV power production and electricity demand, and the timely overlap of production and the consumption curve). We complement our techno-economic analysis of rooftop PV with a discussion of diffusion barriers, i.e., mechanisms that hinder market adoption despite cost-effectiveness, such as split incentives and risk and uncertainty. We formulate recommendations for the deployment of rooftop PV for business and policy makers.

1. Introduction

The building sector presents a priority for efforts to confront climate change, accounting for one third of total global final energy use and one fifth of global greenhouse gas (GHG) emissions [1,2]. To be consistent with a 2° pathway [3,4], the GHG intensity of buildings must be reduced five-fold by 2050 [5]. Photovoltaics (PV) present a promising technology for achieving this goal given their clear environmental advantages as a low-carbon energy source and their considerable economic potential [6–9].

Following large reductions in PV manufacturing costs due to massive deployment, PV is reaching economic competitiveness with other energy sources in more and more parts of the world [10–14]. When deployed on buildings, PV's electricity generation cost competes with electricity retail prices rather than with generation cost of other electricity sources. Grid prices are typically substantially higher, as they include trading and grid operation costs, taxes, margins and other cost components. Electricity from a rooftop PV system can directly fuel the building's electricity demand, a process which we refer to as PV self-consumption. When the generation cost of PV electricity is below grid prices, self-consumption lowers a building's electricity bill, creating monetary value without the support of subsidies. Self-consumption has begun to evolve into a core driver of rooftop PV's economic performance, presenting a promising alternative to subsidized feed-in tariffs [11,15].

While many studies have investigated the economic or technological potential of PV in general [10,16–21], the potential for and drivers of self-consumption performance have not been comprehensively assessed. Studies that have investigated PV self-consumption have focused their analysis on case-specific building types, e.g., single family houses [11,15,20,22,23], large office buildings [24] or university campuses [25] or on aggregations of buildings on district level [26]. Moreover, PV self-consumption assessments have typically focused solely on technological aspects, such as optimization of self-consumption shares with battery storage [22,27]. The small number of studies that assess investment attractiveness has focused on single family houses [15,23] or agricultural buildings [28]. While these studies indicate the high economic potential of self-consumption, a comprehensive assessment of the underlying performance drivers and their corresponding sensitivity is still missing. This seems striking given that demand

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http://dx.doi.org/10.1016/j.renene.2015.09.059
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patterns, electricity prices, and consequentially self-consumption potentials are highly building-specific [29–31]. In this manuscript, we address this gap by investigating how technological and economic factors determine the economic performance of rooftop PV self-consumption for different building types in the absence of policy support.

We address this question through a granular techno-economic analysis of rooftop PV systems on grid-connected buildings (small residential, large residential, small office building, large office building). To account for the influence of economic factors, we assess performance for buildings in Berlin (Germany), Bern (Switzerland), and Vienna (Austria) by simulating electricity production and loads in a quarterly-hour resolution. We evaluate economic potential in terms of the system's internal rate of return (IRR), which allows us to combine all economic indicators in a single, easily interpreted figure [32]. To our knowledge, our study is the first to comprehensively assess investment attractiveness of self-consumption in the absence of policy support, accounting for both supply and consumption, based on granular and realistic yet generalizable building parameterizations. Moreover, for large buildings we assess not only the potential for energy savings, but also for capacity savings (demand charge savings), which are of increasing importance for the energy financing structures of such buildings.

Building on the insight that an attractive economic potential of a technology might be a necessary but insufficient condition for market success [33], we complement our techno-economic analysis with a discussion of the most important diffusion barriers for rooftop PV and self-consumption. We then formulate implications for business and policy practitioners, as well as scholars, with regard to how the diffusion of clean technology can be promoted.

The remainder of this article is structured as follows: Section 2 describes our methodology. We present our results in section 3 and discuss them in section 4. In section 5 we elaborate on limitations and areas for future research. Section 6 concludes.

2. Methods and materials

2.1. Design of analysis

We assess economic performance of rooftop PV self-consumption in terms of investment attractiveness, measured in IRR [11]. This allows to account for the time value of money, which is crucial for long-time investments such as PV. Furthermore, the IRR enables comparability of different projects.

We modeled the economic performance of rooftop PV for a differentiated sample of building types, namely a small residential building (SR), housing a single-family, a large residential building (LR), representing a multi-family house, as well as a small office (SO) and a large office (LO) building as commercial buildings. All buildings are modeled with the HOMIE model (see next section), and include the same set of technologies (e.g., same PV system). Each building type was defined through building-specific dimensions, demand patterns, and electricity prices.

Based on this model, we assessed the IRR and its dynamics in two steps. First, we investigated the breakdown of the IRR for each building type and compared it to the other building types. By doing so, we isolated the main performance dynamics. In a second step, we assessed the relative importance of these determining factors of economic performance through a range of sensitivity analyses.

2.2. HOMIE model

Our techno-economic analysis is based on the Matlab-based HOMIE model (HOusehold Model for Intelligent Energy supply and use) [34]. The structural overview of the HOMIE model workflow is shown in Fig. 1.

We limit our presentation here to a description of the building model and the economic model. A comprehensive and detailed description of the modeling logic is available online [34,35]. The exact parameterization for all modeled technology and each building type will be introduced in section 2.3.

2.2.1. Building model: simulating and matching power supply and demand

HOMIE calculates a building's electricity flows and corresponding economic performance derived from region- and building-specific input parameters. It details a comprehensive set of building energy sinks related to the activities and needs of building occupants. Moreover, it entails a detailed thermal model, which simulates the occurring heat flows in the building, taking building and outside temperatures, as well as specific heat capacities and heat transfer coefficients (U-values), into account.

The building's total electricity demand is calculated as the sum of demand of each individual energy service (cf. Table 1). Power supply is available from PV power generation and from the grid. PV generation P_{PV} is computed as

$$P_{PV} = \mathrm{G} \cdot \eta \cdot PR \cdot \beta \cdot A \tag{1}$$

where G refers to horizontal irradiance in Watt per square meter, η denotes module efficiency, PR denotes the performance ratio of the complete system before temperature effects, β denotes the correction factor compared to a horizontal panel and A denotes total panel area (refer to section 2.3 for parameterization per building type). Power from the PV system has priority in meeting the building's electricity demand. Remaining power needs are fueled from the grid. When PV power generation exceeds demand, excess power is fed into the grid. Grid usage, that is power demand fueled from the grid, is thus calculated as follows:

$$Grid\ usage = \begin{matrix} 0; \quad if\ P_{PV} > PowerDemand \\ PowerDemand - P_{PV}; \quad otherwise \end{matrix} \tag{2}$$

2.2.2. Economic model: calculation of economic performance

Fig. 2 provides a schematic presentation of all cash flow dynamics. From the individual cash-flows, internal rate of return is calculated as the solution of the following equation:

$$0 = -I_1 + \sum_{t=1}^{T} \frac{FeedInCashFlow_t + SelfConsumptionCashFlow_t - O\&Mcost_t}{(1 + IRR)^t} \tag{3}$$

I_1 describes the initial investment, $FeedInCashFlow_t$ describes the revenues from feed-in in year t, $SelfConsumptionCashFlow_t$