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On the use of hourly pricing in techno-economic analyses for solar photovoltaic systems ☆

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ABSTRACT

The use of hourly prices in distributed photovoltaic (PV) techno-economic analysis is rare, but may become necessary as time-of-day retail pricing becomes more common. A methodology is presented for selecting an hourly price curve suitable for long-term analysis, called the typical price year (TPY), which is based on the methodology for TMY weather data. Using a techno-economic analysis with annual revenues and net present value as indicators, a TPY curve for the Swedish market is validated and then compared to 18 price simplification methods to determine the error introduced by the use of non-hourly prices. Results show that the TPY method produces a curve which accurately represents long term pricing trends, but using a static annual mean introduces minor revenue errors of 1.3%. This suggests the TPY may not be necessary in the Swedish market, but further analysis of the method is suggested for other markets.

1. Introduction

Solar photovoltaic (PV) systems are being installed at an ever increasing rate globally, and in developed regions the fastest growing sector is distributed rooftop systems [1–3]. For building owners considering a renewable energy installation, investment analysis requires predicting future electricity prices. A common method for pricing is to assume the most recent retail electricity price and apply it to all hours of the year [4–21]. This is usually a reasonable assumption given that in many places where grid connected PV is installed, owners are given a fixed feed-in tariff (FiT), power purchase agreement (PPA) or have net metering based on a static retail price [22]. However, in the E.U. and U.S., there is interest in shifting retail customers to fluctuating hourly pricing based on wholesale electricity markets [23–27]. This could lead to increased error in existing techno-economic PV analysis methods if the variable prices deviate significantly from the mean.

While it has been discussed for decades [28,29], hourly or dynamic pricing has only recently begun retail market acceptance with the advent of smart meters, demand response programs and distributed renewable energy [30,31]. In regards to solar PV systems, Perez et al. [32] highlighted the need to consider hourly instead of static retail prices because of solar energy's generation during higher loads and prices in the United States. This notion is not lost on utilities, and has been one factor in the rapid installation of solar PV in cooling driven climates [33]. Conversely, the relatively high amount of non-dispatchable renewable generation in the German grid has even caused negative wholesale prices, highlighting the value of generation timing [34,35].

The relatively recent adjustments to PV and time-of-use (TOU) pricing policy mean few techno-economic studies have considered separate purchase and selling prices or hourly pricing. A step beyond single prices, Cucchiella et al. [36] and Colmenar-Santos et al. [20] have considered separate prices for deferred grid purchases and excess sold back to the utility, but use a static price for each. Ren et al. [37] considered tiered TOU pricing in their PV system sizing optimization model. Batman et al. [38] considered tiered TOU pricing for Turkish residential electricity costs with and without solar PV. Kwan and Kwan [39] used TOU pricing for an analysis of a college campus in Los Angeles, CA to match the owner's actual purchasing conditions.

The lack of hourly, dynamic pricing in the literature represents a gap between the future evolution of electricity markets and the current methods of assessing the economic performance of solar PV systems. At the same time, determining appropriate long-term prices for every single hour, particularly in a system with a high proportion of renewables, is a considerable burden on the modeling process. Hourly pricing also opens the door to several new

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Nomenclature

Variables

E_{PV}	PV generated electricity (kW h)
E_d	portion of PV generated electricity used directly (kW h)
E_s	portion of PV generated electricity sold to network (kW h)
P_r	retail price of electricity (EUR/kW h)
P_w	wholesale price of electricity (EUR/kW h)
R_y	annual revenues (EUR)
C_{OM}	annual operations and maintenance cost (EUR)
d_r	real discount rate (%)
I_{PV}	total investment cost of PV system (EUR)
NPV	net present value (EUR)
l	lifetime of analysis (years)

Subscripts

y	year
h	hour

questions, such as; what are the appropriate hourly prices for long-term analysis? How can these prices be determined? Are hourly prices necessary or can a simplified price work? This study introduces a price selection methodology that creates an annual price curve for long-term analysis, called the typical price year (TPY). The objective is to assess the validity of the methodology and the sensitivity of pricing models on solar PV techno-economic analyses.

2. Methodology

The procedure for creating a TPY is based on an existing method used for weather data, the typical meteorological year (TMY), and is presented in detail below. The resulting price curve is used to calculate revenues of a PV installation in central Sweden, and then to calculate net present value (NPV). First year revenues and NPV are used as the basis of comparison. Test cases are based on hourly prices from the TPY as well as each calendar year between 1996 and 2013. The study can be broken into two sections; first a test of the performance of the TPY, and second, a test of simplification methods for hourly prices.

In the first test, only hourly prices are used and the results for the TPY are compared against the real prices in all other years. Next, all prices are scaled such that the mean annual price for all years is equal to 2010, the year with the highest annual mean. This test is meant to show the significance of the profile of hourly prices by removing the difference in overall scale between years. Prices are scaled to the most expensive year to avoid any negative values.

In the second test, the hourly prices are simplified across three dimensions; price source, statistical reduction methods, and pricing schemes; for a total of 18 models. Price source refers to the hourly prices used to create the static values, which come from two data sets; all prices during the time frame, and only those during PV production hours excluding the standby period. The static prices are calculated using three statistical methods; arithmetic mean, median and geometric mean. The price schemes tested include; static annual, static monthly, and a hybrid using a static annual retail rate with hourly spot selling price (currently the dominant pricing model in Sweden). A summary of the simplification models and their ID number is presented in Table 1. Hourly prices are the highest available resolution. Therefore they are assumed to be the most accurate and the basis for comparison. All years of data are tested so that a wide variety of pricing patterns and scales are considered.

All prices are inflation adjusted to 2013 SEK and converted into Euros using the 2013 average rate of 1 SEK = 0.1156 EUR [40].

2.1. Scope

Sweden is the area of interest where the wholesale spot market, Nord Pool Spot (NPS), has been operating since 1996, providing 18 complete years of unregulated hourly clearing prices [41]. The volumes and timing of deferred and sold of electricity are highly dependent on the building and PV installation. This study is limited to multi-family housing, however three buildings with varying sizes and orientations are considered. Each building is tested with two PV system sizes for a total of six cases.

Inputs and assumptions made for this study are based on current Swedish PV market conditions [42], however; the focus is on the effect of the pricing models, not the actual techno-economic performance of the system. Therefore, detailed inputs (such as shading, soiling, and wiring losses) and a detailed discussion and sensitivity analysis of input assumptions are omitted.

2.2. Building inputs and assumptions

Electric load data with hourly resolution from actual meters is used and provided by the network utility in Linköping, Sweden [43]. It includes all electricity used in the apartments and common areas. Roof space for PV is based on the buildings where the demand data is sourced. Commonly found in Sweden, these buildings are relatively long and narrow with two/three stories and pitched roofs. The geometries do not match the metered buildings exactly and are not meant to represent a case study. A simple description of each building's geometry is reported in Table 2 and a one week sample of the demand curves is depicted in Fig. 1.

2.3. PV system inputs and assumptions

Typically a PV installation would be optimally sized for the best economic performance. For this study, the sizing is arbitrarily

Table 1
Summary of the price simplification models and their respective numbers.

Number	Price source	Statistical reduction	Price scheme
1	All	Mean	Annual
2	All	Mean	Monthly
3	All	Mean	Hybrid
4	All	Median	Annual
5	All	Median	Monthly
6	All	Median	Hybrid
7	All	Geometric mean	Annual
8	All	Geometric mean	Monthly
9	All	Geometric mean	Hybrid
10	PV	Mean	Annual
11	PV	Mean	Monthly
12	PV	Mean	Hybrid
13	PV	Median	Annual
14	PV	Median	Monthly
15	PV	Median	Hybrid
16	PV	Geometric Mean	Annual
17	PV	Geometric mean	Monthly
18	PV	Geometric mean	Hybrid