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# A probabilistic portfolio-based model for financial valuation of community solar

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## HIGHLIGHTS

- A probabilistic portfolio-based model is developed for community solar.
- The model incorporates physical, environmental, and financial uncertainties.
- Mean-Variance Portfolio theory is applied for constructing optimized portfolios.
- The model is deployed with an actual residential community consisting of 19 houses.
- A set of investment scenarios are hypothesized, tested, and discussed.

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## ABSTRACT

Community solar has emerged in recent years as an alternative to overcome the limitations of individual rooftop photovoltaic (PV) systems. However, there is no existing model available to support probabilistic valuation and design of community solar based on the uncertain nature of system performance over time. In response, the present study applies the Mean-Variance Portfolio Theory to develop a probabilistic model that can be used to increase electricity generation or reduce volatility in community solar. The study objectives include identifying the sources of uncertainties in PV valuation, developing a probabilistic model that incorporates the identified uncertainties into portfolios, and providing potential investors in community solar with realistic financial indicators. This study focuses on physical, environmental, and financial uncertainties to construct a set of optimized portfolios. Monte Carlo simulation is then performed to calculate the return on investment (ROI) and the payback period of each portfolio. Lastly, inclusion vs. exclusion of generation and export tariffs are compared for each financial indicator. The results show that the portfolio with the maximum output offers the highest ROI and shortest payback period while the portfolio with the minimum risk indicates the lowest ROI and longest payback period. This study also reveals that inclusion of tariffs can significantly influence the financial indicators, even more than the other identified uncertainties.



## 1. Introduction

Community solar has emerged as a viable approach to harnessing solar energy for those who want to overcome the limitations associated with installing photovoltaic (PV) panels on their rooftops [1,2]. It is often the case that an individual property does not meet the required conditions to install a PV system (e.g., improper orientation, not enough roof space, too much shade), which leads to a considerable amount of risk in investment. Instead, a group of homeowners can gather for community solar and invest in a communal PV system and share the benefits of the generated electricity among themselves [3]. According to Campbell et al. [4], from August 2012 to September 2013 community solar had an annual growth rate of 400% reaching the total capacity of 40,000 kW in the U.S.

Different practices of community solar have emerged in recent years. In conventional community solar practice, a PV system is installed off-site in another facility or elsewhere in the community. Then, the customers who subscribe to shared generated electricity receive their portion of benefits based on their share in the PV system [5]. This model is typically implemented when the community location is not favorable to meeting the required conditions of a

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planned PV system. Another practice of community solar is where members of a community share the costs of installing PV systems on the rooftops of the houses that have enough space and proper orientation. Under this practice, the investors receive their share of the profit based on the generated electricity [6].

In either case and in the context of the present study, one significant benefit expected from community solar is reduced volatility in electricity generation, which is achieved by diversifying the risk among the target houses [7,8]. This is analogous to financial investors attempting to hedge the future risk of individual assets by combining them into a portfolio of assets. Therefore, a portfolio of PV systems can be created by applying the Mean-Variance Portfolio (MVP) theory [9]. This approach is expected to lead to minimum volatility for the given level of electricity output, or maximum electricity generation for the given level of volatility [7]. MVP has been widely applied in various fields [10] and proven effective, especially in the energy domain. For example, researchers have applied MVP to identify optimized portfolios that offer the lowest cost of power generation [11–15], highest internal rate of return [16], highest wind capacity factor [17], highest wind speed [18], and highest electricity generation [7,19].

Despite the widespread application of MVP in other fields, there is no model suitable for implementing MVP in community solar. First, the majority of the existing models used to analyze and design a PV system are deterministic. These models do not take into consideration the uncertain nature of a PV system's performance through its service life, which may consequently lead to underestimation or overestimation of the electricity produced. Second, to implement MVP in community solar, it is important for investors to understand the types and magnitudes of uncertainties that are unique to PV investments. However, uncertainties associated with the electricity generation of PV systems have remained largely unmeasured [20]. This is due to the following limitations of the current solar energy audit practice:

- The current practice only targets to provide a per-property estimate of renewable energy offset and potential financial benefit by considering a few variables.
- The current practice precludes potential synergy with adjacent buildings for increasing electricity generation.
- Most existing decision support tools for PV investments are based on financial criteria such as annual electricity generation or return on investment (ROI). They simply do not address the long-term performance of a PV system regarding uncertainties related to the geospatial position, local and regional environment, and energy price trends over the years.

For these reasons, there is a need for a probabilistic model that can support the design of community solar by taking into consideration the uncertain nature of system performance over time. In response, the objectives of this study are to (1) identify the sources of uncertainties in PV investments, (2) develop a probabilistic model that incorporates the identified uncertainties into a set of portfolios, and (3) provide potential investors in community solar with realistic financial indicators. By integrating the MVP theory and accounting for the sources of unique uncertainties in PV investments, the developed model will support PV system designers to develop optimized portfolios of community solar that lead to a higher electricity output and a lower level of volatility.

## 2. Sources of uncertainties in PV investments

Badescu and Iacobescu [21] identified physical, environmental, and financial factors as decision-making criteria that potential investors must consider when evaluating different PV investment options. By adapting Badescu and Iacobescu [21], the present study focuses on incorporating physical, environmental, and financial sources of uncertainties that affect the investment in PV systems. In this context, physical uncertainties refer to physical properties that influence the performance of a PV system (e.g., availability and maintenance, inverter efficiency). Environmental uncertainties refer to climatic and geographic parameters that influence electricity generation, including shading, solar radiation, and temperature. Financial uncertainties refer to financial parameters (such as energy price) that directly affect the potential profit projection of the system. The following sections are intended to provide background information about the three types of uncertainties considered for the present study.

### *2.1. Physical uncertainties*

#### *2.1.1. Availability and maintenance*

The reliability of PV modules has significantly improved in recent years [22,23], and most PV manufacturers provide warranties for up to 25 years. However, users still observe occasional failures in PV systems. These failures can be attributed to different uncertainties including inverter failure, human error, or inclement weather [24]. Some studies investigated the reliability of PV systems regarding long-term degradation of performance in the field [25], time to failure [26], and power warranty [27]. In particular, Japanese researchers analyzed the data from PV systems in field tests between 1992 and 2005, reporting that 20% of the studied PV systems required maintenance or component replacement within the first four years of operation [28]. Similarly, Kato et al. [29] reported that 14% of 257 studied residential PV systems had inverter problems, which resulted in replacement. Both studies reported that the downtime due to replacements or repairs impaired the efficient energy generation of PV systems. Therefore, an accurate prediction of system outputs requires incorporating the availability of the target system, and likelihood and duration of any downtime.

#### *2.1.2. Inverter efficiency*

An inverter is a critical component of any PV system because it converts the direct current (DC) output from PV panels to alternating current (AC) for end users. Three types of inverters are commonly used in the PV systems, namely, string inverters, micro-inventers, and power optimizers. Among the three types, string inverters are most widely used because they are the least expensive. However, the efficiency of string inverters is known to drop significantly if panels are shaded at any point during the day. One essential function of inverters is to vary the resistance in the system to track and find the maximum power point (MPP) that results in the highest power output from a panel. String inverters treat a group of panels as a single large panel. Therefore, if the performance of one panel is affected (e.g., due to the shade), the inverter is unable to determine the MPP of other individual panels and therefore the performance of all panels will suffer respectively [30]. This problem can be solved by using a micro-inverter or a power optimizer for each panel. Micro-inventers and power optimizers are often referred to as module-level power electronic (MLPEs) and are more suitable for cases in which some of the panels may be shaded or have different orientations. As opposed to string inverters, microinverters are installed on each PV panel and control the performance of panels individually. Therefore, the poor performance of one panel will not affect the rest of the panels [31]. Similar to micro-inverters, power optimizers are installed on each panel and monitor the performance of panels independently. The difference between micro-inverters and power optimizers is that the former converts DC to AC directly whereas the latter optimizes the output power mismatch between PV mod-