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DOI
10.1109/ISGTEUROPE56780.2023.10407212

Publication date
2023

Document Version
Final published version

Published in
Proceedings of 2023 IEEE PES Innovative Smart Grid Technologies Europe, ISGT EUROPE 2023

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2023 IEEE PES Innovative Smart Grid Technologies Europe (ISGT EUROPE) | 979-8-3503-9678-2/23/$31.00 ©2023 IEEE | DOI: 10.1109/ISGTEUROPE56780.2023.10407212

***Abstract*—The widespread adoption of solar photovoltaic (PV) technology as a prominent renewable energy source has significant implications for the economy of households and distribution system operators (DSOs). It is crucial to analyse these impacts in light of recent pricing policy changes, including Real-Time Pricing (RTP), Time-of-Use (TOU), and Feed-in Tariffs (FiT). This study analyses the impact of pricing policies based on actual load consumption, pricing rate, and PV generation data. An economic comparison of various scenarios for a typical household in the Netherlands is conducted by determining the optimal values for PV size. The findings suggest that transitioning to RTP policies reduces households' economic advantages. The introduction of FiT further diminishes the financial benefits for households and increases the Payback period (PP). Moreover, the study reveals that imposing an export power limit of less than 3 kW can increase households' energy costs.**

***Index Terms*—Photovoltaic (PV), Real-Time Pricing (RTP), Time-of-Use (TOU), Feed-in Tariff (FiT), Economic comparison**

I. Introduction

Increased household adoption of PV systems in the Netherlands can drive the renewable energy transition. However, high PV penetration can lead to congestion issues in the distribution system. Upgrading the electricity infrastructure by distribution system operators (DSOs) becomes necessary, requiring higher capital investment [1]. To mitigate overload, alternative approaches include incentivizing self-consumption and implementing power limits for selling excess power [2].

To promote the desired outcomes, electricity pricing policies must be revised. Net metering allows solar-equipped households to sell excess power at the purchasing price [3], but this encourages selling during peak hours and exacerbates grid congestion issues [4]. Moreover, reduced taxes on electricity consumption lead to government revenue losses [5], and energy justice concerns arise as households without PV systems face higher taxes. To address these challenges, the Dutch government aims to revise regulations for purchase and sale prices [4].

Regarding the selling price, the Dutch government will implement a Feed-in Tariff (FiT) policy to phase out net metering starting in 2025 [6]. Consequently, end-users will no longer sell excess power at the same price level as their electricity consumption [4]. Regarding import (buying) prices, end-users pay according to time-of-use (TOU) rates, with two predetermined blocks of time prices for peak and off-peak periods. This pricing policy does not accurately reflect the actual cost of electricity generation and, as a result, does not encourage more efficient energy use [5]. In response, the Dutch policy adopts RTP, adjusting electricity prices hourly based on real-time costs and demand [7].

Previous studies have examined the economic effects of PV systems on households, considering both with and without storage. These investigations include determining the optimal size of PV and battery energy storage systems [8] and minimising energy costs for end-users [9]. Additionally, other studies have examined the techno-economic implications of pricing policies for various systems across different countries [10], [11]. However, extending this research by incorporating the effects on the grid and PV sizing in TOU and RTP scenarios can be useful. This study is a continuation of study [12] and aims to compare TOU and RTP policies in conjunction with FiT regulation.

The study is structured as follows. Section II describes the methodology and assumptions. The energy management system and PV sizing optimization are presented in Section III. Economic aspects are explored in Section IV, results are in Section V, and Section VI offers conclusions.

II. Methodology and Assumptions

This study focuses on a PV system installed in a typical household with 30 m^2 rooftop space in Delft, the Netherlands.

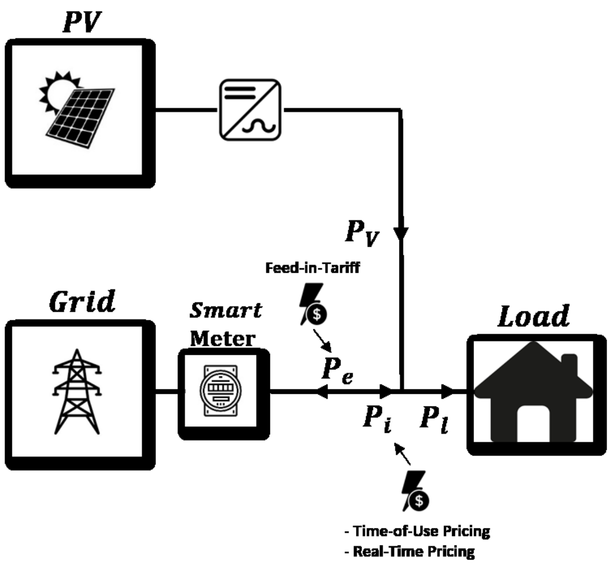

Fig. 1. Household PV system configuration.

As Fig. 1 shows, a household can import power from the grid and export the power when there is excess power. However, the power exported to the grid is subject to limitations [13].

Concerning buying and selling prices, the implementation of FiT sets selling prices considerably lower than the prices for TOU and RTP schemes [4]. The TOU and RTP signals employed in this study are illustrated in Fig. 2. These rates are selected to maintain the same average value of 0.62 €/kWh, ensuring a consistent basis for comparison.

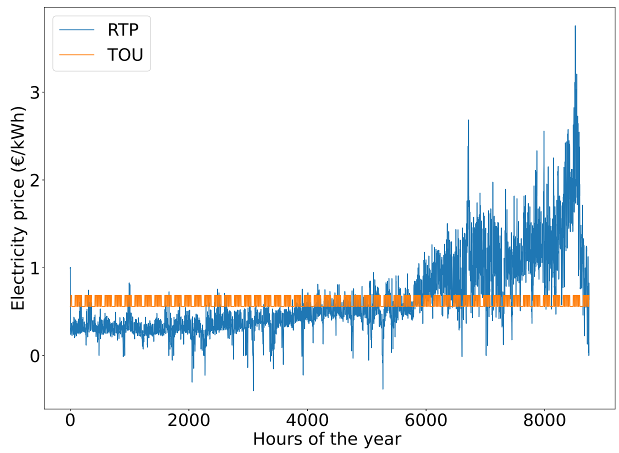

Fig. 2. Hourly TOU and RTP electricity price.

A. Load

Fig. 3 presents the annual load consumption pattern for a typical household in Delft, a city in the Netherlands, in 2021. Over the year, the peak load consumption reached 0.75 kW, with an average value of 0.331 kW. The daily mean energy consumption amounted to 7.94 kWh, leading to an annual total energy consumption of 2899.99 kWh.

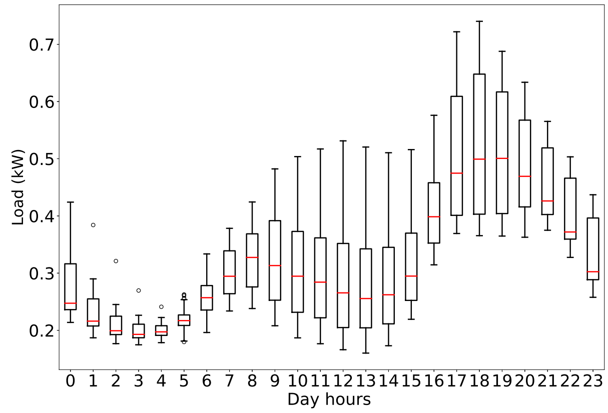

Fig. 3. Daily load consumption Box Plot for a Delft Household, the Netherlands.

B. PV generation

In the present study, the IM72CB-330 photovoltaic module is utilised to simulate power generation from solar energy. The module comprises 72 multi-crystalline solar cells, yielding a maximum power output of 330 Wp [14]. Delft's average daily solar insolation and ambient temperature for 2021 are 2.958 kWh/m^2/day and 10.025 °C, respectively [15]. Considering these parameters, a single array of IM72CB-330 is anticipated to generate approximately 0.96 kWh of electricity per day. This accounts for 12% of the daily energy consumption in a typical household in Delft.

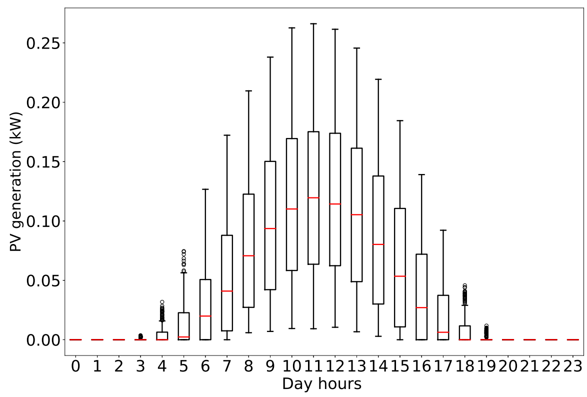

Fig. 4. Daily PV Generation Box Plot for a Delft Household, the Netherlands.

The power output of each photovoltaic system at a specific time step, denoted as t, can be determined by incorporating solar insolation and ambient temperature values using (1)

$$P_{pv}(t) = N_{pv} \times P^{r}_{pv}(G(t)/G^{ref})[1+T^{cof}(T^{c}(t)-T^{ref})] \quad (1)$$

where N_{pv} represents the total number of PV arrays, and P_{pv}^{r} denotes the maximum power of the PV module. The solar irradiance at each time step is given by $G(t)$ and expressed in W/m^2. The reference solar irradiance, G^{ref}, corresponds to a value of 1000 W/m^2. The temperature coefficient for the chosen PV module is represented by T^{cof}, with a value of -3.8×10^{-3} (1/°C). Additionally, under standard test conditions, the reference temperature, T^{ref}, is set at 25 °C [14].

The cell temperature, $T^c(t)$, at a given time step, can be estimated using (2)

$$T^c(t) = T^{amb}(t) + ((T^{noct} - 20)/800 \times G(t)) \tag{2}$$

where $T^{amb}(t)$ denotes the ambient temperature at the given time step and T^{noct} refers to the nominal operating cell temperature. A daily box plot illustrating the PV generation throughout 2021 is presented in Fig. 4.

III. Energy Management System and optimisation

The system maintains a power balance by considering load consumption, PV generation, and the maximum export power limit. When PV generation falls short of consumption, power is purchased from the grid, whereas surplus PV power exceeding household demand is sold back to the grid. To satisfy these conditions, the flowchart in Fig. 5 shows the overview of the control strategy [12]. It is conventionally assumed that imported power from the grid $P_i(t)$ is positive while exported power $P_e(t)$ is negative. Moreover, $P_e(t)$ cannot be more than P_G. Therefore quantities of imported and exported power can be determined using (3) and (4)

$$P_i(t) = \begin{cases} P_l(t) - P_{pv}(t) & \textit{if } P_l(t) > P_{pv}(t) \\ 0 & \textit{if } P_l(t) \le P_{pv}(t) \end{cases} \tag{3}$$

$$P_e(t) = \begin{cases} \min\{P_G, P_{pv}(t) - P_l(t)\} & \textit{if } P_l(t) < P_{pv}(t) \\ 0 & \textit{if } P_l(t) \ge P_{pv}(t) \end{cases} \tag{4}$$

A PV control system manages the excess generation and guarantees that exported power stays within the P_G limit. As a result, the dumped power $P_d(t)$ can be computed using (5)

$$P_d(t) = P_{pv}(t) - P_l(t) - P_G \tag{5}$$

IV. Economical evaluation

An hourly simulation is conducted to assess the PV system's performance. Subsequently, the net present cost is calculated to compare net metering and FiT policies for RTP and TOU pricing schemes.

For a comprehensive economic evaluation, it is essential to determine the optimal value for the PV size. This is achieved by defining an objective function that encompasses both the net present cost of electricity (NPC_e) and the net present cost of system components (NPC_j). The total net present cost (NPC_t) is then computed using (6)

$$NPC_t = NPC_e + NPC_j \tag{6}$$

To compute NPC_e, it is necessary to determine the annual cost of electricity ($Cost_e$) under both time-of-use (TOU) and real-time pricing (RTP) rates, as described by (7) and (8), respectively

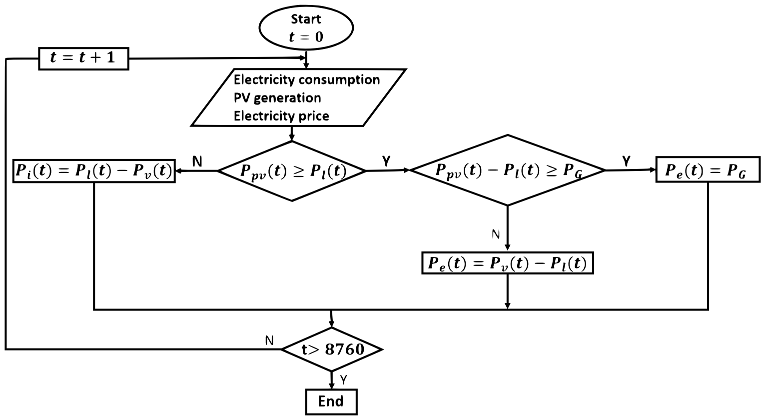

Fig. 5. Rule-based energy management system.

$$Cost_{e_{RTP}} = \sum_{t=0}^{8759} RTP(t).P_i(t) - \sum_{t=0}^{8759} RTP(t).P_e(t) \tag{7}$$

$$Cost_{e_{TOU}} = \sum_{t=0}^{8759} TOU(t).P_i(t) - \sum_{t=0}^{8759} TOU(t).P_e(t) \tag{8}$$

Therefore, the NPC for different RTP and TOU policies is calculated using (9) and (10)

$$NPC_{e_{RTP}} = Cost_{e_{RTP}} . \frac{(1 + i_{elec})^y - 1}{i_{elec}(1 + i_{elec})^y} \tag{9}$$

$$NPC_{e_{TOU}} = Cost_{e_{TOU}} . \frac{(1 + i_{elec})^y - 1}{i_{elec}(1 + i_{elec})^y} \tag{10}$$

where i_{elec} represents electricity interest rate and y is project lifetime.

The components' NPC encompasses capital, maintenance, and replacement costs as (11)

$$NPC_j = NPC_{cap_j} + NPC_{main_j} + NPC_{rep_j} \tag{11}$$

In (11), cap_j refers to capital cost of the jth component. The maintenance cost is represented by $main_j$, and the replacement cost is represented by rep_j. Maintenance and replacement costs depend on the individual component lifetimes and the overall project lifetime as (12) and (13)

$$NPC_{main_j} = Cost_{main_j} . \frac{(1 + i)^{(life_j)} - 1}{i(1 + i)^{(life_j)}} \tag{12}$$

$$NPC_{rep_j} = Cost_{rep_j} . \sum_{t=0}^{N_{rep_j}} \frac{1}{(1 + i)^{t.life_j}} \tag{13}$$

In (13), N_{rep_j} is defined as the number of times each component j is replaced during the system's lifetime, and $life_j$ represents the lifetime of component j. The calculation for N_{rep_j} can be expressed as (14)

$$N_{rep_j} = Integer(\frac{y}{life_j}) \tag{14}$$

To determine the optimal size of the PV system, (6) should be minimised, while considering the relevant design constraints.

$$P_{pv}(t) + P_i(t) - P_e(t) \geq P_l(t) \tag{15}$$

$$0 \leq P_e(t) \leq P_G \tag{16}$$

$$0 \leq P_{pv}(t) \leq P_{pv,max} \tag{17}$$

Equation (15) ensures that the power balance is maintained at each time instance. Furthermore, the export power constraint is articulated by (16), while the photovoltaic (PV) output power constraint is represented by (17).

The optimisation process is conducted utilising a Genetic Algorithm (GA) solver, using the economic parameters outlined in Table I to minimise the objective function as expressed in (6). A population of 300 and 1000 generations are used in the GA algorithm to reach optimal solutions.

To compare the cost of the system under different scenarios, Levelised Cost of Electricity (LCOE) can be calculated for the lifetime of the system using (18)

$$LCOE = \frac{NPC_t}{(\sum_{t=0}^{8759} P_l(t)).y} \tag{18}$$

Moreover, the Payback period (PP) is a useful metric for analysing end-user motivation to invest in PV under different pricing scenarios. It can be calculated using (19).

$$PP = \frac{Capital\ cost}{Average\ annual\ saving} \tag{19}$$

In (19), the difference between the yearly costs of the system with PV and the base system without PV determines annual savings.

TABLE I
PV SYSTEM COSTS AND ECONOMIC PARAMETERS [14], [16]

PV	Installation cost = 1000 €/kW Replacement cost = 230 €/kW Maintenance cost = 40 €/kW/year PV lifetime and Project lifetime (y) = 20 years Inverter lifetime = 8 years
Electricity economics	TOU (average) = 0.62 €/kWh TOU (peak,off) = 0.69 €/kWh, 0.56 €/kWh RTP (average) = 0.62 €/kWh RTP (max,min) = 3.75 €/kWh, -0.4 €/kWh FiT= 0.2 €/kWh Electricity interest rate (i_{elec}) = 22.2% Annual interest rate (i) = 2.7%

V. RESULT

During optimisation, the photovoltaic (PV) size is within 1 kW to 10 kW. Although increasing the PV size further could yield additional economic benefits, a 3.3 kW capacity corresponds to installing ten IM72CB-330 module arrays. Considering the physical size of PV arrays, householders usually install up to ten arrays. The results demonstrate that a power limit of less than 3 kW diminishes homeowners' economic benefits, as illustrated in Fig. 6. This observation suggests that the influence of the power export limit on the overall system cost becomes negligible as the allowable power export increases beyond 3kW.

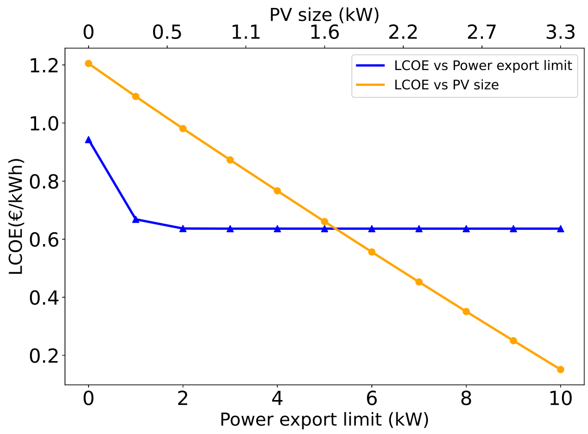

Fig. 6. Impact of power export limit and PV size on the LCOE.

Consequently, for the economic analysis, a 3.3 kW PV system size was chosen along with a power export limit of 4 kW, which is commonly used in most regions of the Dutch distribution system. Total NPC and LCOE are computed for all policy scenarios. Table II summarises the economic evaluation results. The currently implemented net metering policy offers the most significant financial advantages for households employing PV systems. A key observation is that RTP results in lower economic advantages under both net metering and FiT policies. The elevated electricity prices can explain this phenomenon during winter when demand peaks (Fig. 2). Moreover, the increased PV generation in summer contributes to decreased electricity prices during periods of lower load demand throughout the year.

Furthermore, results indicate that moving to FiT policy significantly increases the payback period (PP) for both RTP and TOU. As a payback period of more than six years is not encouraging for adopting the PV systems [4], policymakers should ensure that the PV penetration rate is high enough when total FiT is introduced in 2031.

To examine the system's operation, Fig. 7 and 8 display the power flow within the system. The fluctuations in power exchange with the grid, PV generation, and load consumption are illustrated for two consecutive summer and winter days in 2021. During the two sample winter days, PV generation reaches a maximum of 0.65 kW, providing power for a limited number of hours (i.e., between 7:00 A.M. and 3:00 P.M.). Most of the power demand is met by imports from the grid. The maximum generated power reaches 2.3 kW on the two sample summer days. PV generation occurs between 5:00 A.M. and 7:00 P.M., with excess power being exported between 6:00 A.M. and 5:00 P.M. Notably, the dumped power remains consistently zero, even during high PV generation in the summer.

TABLE II
ECONOMIC EVALUATION RESULTS FOR VARIOUS POLICY SCENARIOS

Scenario	NPC (€)	LCOE (€/kWh)	PP (year)
Without PV with TOU	26474	0.45	-
Without PV with RTP	27956	0.48	-
Net metering with TOU	1118	0.019	2.6
Net metering with RTP	8561	0.157	3.5
FiT with TOU	16384	0.18	6.5
FiT with RTP	19096	0.22	7.5

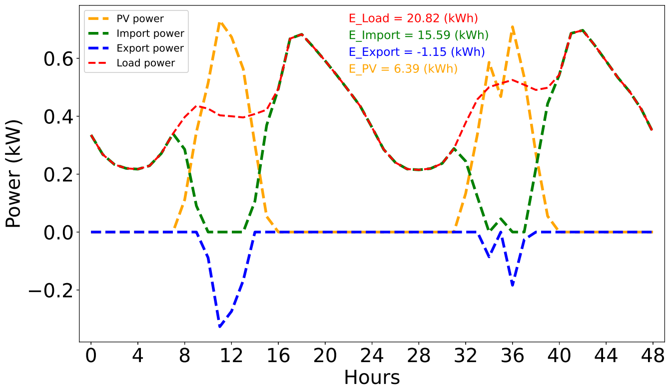

Fig. 8. PV system power flow for two winter days in 2021.

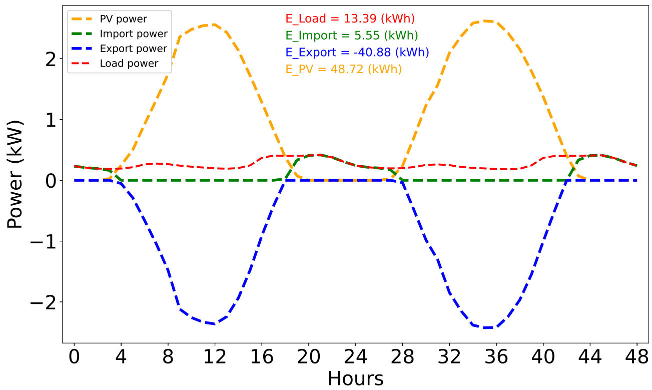

Fig. 7. PV system power flow for two summer days in 2021.

VI. CONCLUSIONS AND FUTURE WORK

This research evaluates the economic implications of implementing TOU, RTP, and FiT policies on a PV system installed in a typical household in Delft, the Netherlands. Using an actual case study and determining an optimal PV size of 3.3 kW, the net present cost of a PV system is computed for 20 years. The findings suggest that RTP reduces homeowners' economic benefits, and removing the net metering policy may discourage PV system adoption. Increasing self-consumption and utilizing storage devices could enhance homeowners' economic gains. However, replacement costs may rise under RTP due to increased charging cycles. Further investigation and updated energy management strategies are necessary to mitigate these expenses.

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