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An Integrated Optimum PV-Based Solution for Urban Households' Energy Autonomy, including Clean Electro-Mobility †

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Abstract: The main focus of this study is to optimize proposed solutions for a residential PV-based net-metering systems with the option of EV adaptation, utilizing a weighted grading system. Technical, environmental and financial parameters are assessed to develop a techno-economic and environmental evaluation model. The proposed analysis investigates the electricity consumption of a typical household and possible energy-saving interventions. Solar PV installation scenarios and their combination with solar water heating and EV adaptation are evaluated in terms of sizing and financial sustainability, as well as CO_2 emissions reduction, along with the net-metering scheme.

Keywords: PV-based net-metering systems; solar water heater; EV adaptation; techno-economic evaluation; environmental footprint

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1. Introduction

According to the International Energy Agency (IEA) [1], worldwide electricity consumption is increasing for all sectors, especially the residential sector. In Greece, domestic-sector electricity consumption is equal to commercial and public sector demand combined.

The PV-based net-metering system is a mature technological application [2], which consist of a PV installation linked to the national energy grid. The system represents an electricity billing mechanism, counterbalancing energy consumption and energy production on an annual basis. However, potential excessive energy production is not compensated [3], leading to consumers limiting their production up to the level of their energy needs. The net-metering scheme is an efficient and sustainable energy investment for domestic RES based systems, especially in cases of increased electricity prices, in contrast to systems built on a Feed-in-Tariff basis, selling electricity at a contractually fixed price [4]. In the meantime, increasing indirect taxes, fuel price ascending fluctuations, and the environmental impacts of CO_2 emissions highlight investment opportunities in electromobility coupled with RES applications.

2. Problem Description and Data

The scenario under examination includes a typical household of four people in Athens, using electricity from a three-phase connection to the national grid in order to cover their energy, heating, cooling and water heating needs, leading to an annual electricity demand of 12,000 kWh_e, which was accompanied by an average annual cost of approximately EUR 2500. The residence of the household possesses an available area of 48 m^2 clear of shading, while the available capital and loan capability of the household is estimated as being flexible for both the PV-based net-metering system and EV adaptation.

2.1. PV System and Net-Metering Parameters

For the current study, three different PV system sizing options are examined, taking into account the small available installation area (~48 m^2) and the possibility of solar water heater and EV adaptation. More specifically, based on a hypothesis of the needed area being 7 m^2/kW_p [5], scenarios of 2.5-, 5.0- and 6.5-kilowatt peak PV systems are examined, and they provide enough electricity supply while allowing the installation of a solar water heater (required area of ~2 m^2).

The solar energy potential of a PV system located in Athens has been calculated via the PVGIS simulation tool [6], leading to a capacity factor of 20% on an annual basis, while the energy losses related to the inverter, wiring, heterogeneity, diodes, shading and temperature are cumulatively calculated as being approximately 15% of the whole system [7]. The installation of the net-metering scheme requires the purchase of an energy production meter, with a cost being EUR 400 for a three-phase meter, along with a connection fee of EUR 500, which is paid to HEDNO, for electricity grid certification purposes, leading to a total cost of EUR 900 [8].

2.2. Solar Water Heater and EV Adaptation

The household's conventional water heating method is a 4 kW electric boiler. Assuming an average daily usage of 30 min leads to an annual energy consumption of 730 kWh, i.e., 6.1% of the total annual household electricity demand. The replacement of this appliance with a 125-liter double-energy solar water heater is taken into consideration, leading to an initial cost of EUR 800 and requiring installation area of 2 m^2. The result of this replacement is expected to be a reduction in the annual domestic water heating energy demand of 90%, namely 660 kWh.

Moreover, the household's current car is an old gasoline-powered city car, which is driven for approximately 15,000 km annually, and it is planned to be replaced by a new conventional or electric car. The annual energy consumption in each scenario is 900 gasoline liters and 2360 kWh_e, respectively. Since the household had already considered buying the replacement car, the techno-economic evaluation of the EV adaptation scenarios only accounted for the excessive forecasted costs linked to an EV car purchase compared to the purchase of a new conventional car.

As a result of the above-mentioned options, annual energy demand for the examined household varies depending on the form of investment used, accounting for 11,200 kWh_e in case of solar water heater installation, and 13,570 kWh_e in the case of its combination with the adaptation of electromobility.

2.3. Financial and Systemic Charasteristics and Assumptions

In this study, systemic variables needed for the proper implementation of the model have been considered based on their price at the time of this research. More specifically, the electricity price has been set at 0.13 EUR/kWh, while the annual price volatility has been forecasted at 3%. Moreover, the gasoline price and its annual average increase have been set to 1.90 EUR/l and 3% per year, respectively, while the discount rate of the investment was set to 5%, with an annual inflation rate of 1%. Finally, the case study assumed that the examined system is totally free of annual maintenance and operation or severe repair costs, and the investment will not be burdened by taxes due to its non-profit character.

The examined case study consists of nine different scenarios devised via a 3×3 rectangular matrix, which is a combination of three types of installations shown in rows (a: standalone PV; b: PV and SWH; and c: PV and SWH and EV adaptation) and three different PV system sizes shown in columns (2.5 kWp, 5.0 kWp and 6.5 kWp), as depicted in Table 1.

Table 1. Matrix representation of combinations leading to examined scenarios.

	2.5 kWp	5 kWp	6.5 kWp
Solar PV (standalone)	M[1,1]	M[1,2]	M[1,3]
Solar PV and SWH (standalone)	M[2,1]	M[2,2]	M[2,3]
Solar PV and SWH and EV (standalone)	M[3,1]	M[3,2]	M[3,3]

For the proper calculation of the critical values of the study, a series of variables was introduced into the model, being mainly derived from data collected or assumed, as previously stated. Some of the input variables were linearly connected to the size of the PV system, as shown in Table 2.

Table 2. Input variables for different PV system sizes.

	2.5 kW_p	5 kW_p	6.5 kW_p
Annual solar PV system production	3745 kWh	7490 kWh	9740 kWh
Solar PV turnkey cost	1700 EUR/kW_p	1300 EUR/kW_p	1150 EUR/kW_p
Non-fixed solar PV M&O costs [1]	EUR 1250	EUR 1500	EUR 1800
Solar PV CapEx	EUR 4250	EUR 6500	EUR 7500

[1] Inverter replacement in the 12th year.

Furthermore, other variables were common in every type of installation, as shown in Table 3.

Table 3. Common input variables for all PV system sizes for a 20-year period operation.

Input Data	Values	Comments
Annual energy demand	12,000 kWh 11,200 kWh 13,570 kWh	Solar PV scenario Solar PV and SWH scenario Solar PV and SWH and EV scenario
Capacity factor of PV system	20%	average
Overall system loss	15%	-
Annual (fixed) PV M&O cost	2%	Percentage of initial capital
Total net-metering cost	EUR 900	-
Adjusted electricity price	0.13 EUR/kWh	-
Electricity price annual escalation	3%	Per year
Solar water heater turnkey cost	EUR 800	-
Solar water heater M&O cost	EUR 25	Every 4 years
Energy saving via SWH usage	660 kWh/year	-
EV price	EUR 25,500	After state subsidy
EV excess price	EUR 10,000	Compared to conventional car
Household EV charger price	EUR 500	After state subsidy
EV excess adaptation CapEx	EUR 10,500	Compared to conventional car
Decrease in EV and battery price	−3%	Per year (technological maturity)
Fuel savings	900 l/year	-
Fuel price	1.90 EUR/l	-

Table 3. *Cont.*

Input Data	Values	Comments
Fuel price variation	3%	Per year
Annual M&O/severe repair cost of EV	EUR 0	Assumption
Discount rate	5%	-
M&O costs inflation	1%	Per year
Taxes	0%	-

3. Scenarios' Evaluation Criteria

The nine examined scenarios were evaluated with respect to both their techno-economic efficiency and environmental impact. Regarding this scope, a series of critical variables were defined, and a grading system was established, in order to provide an efficient sorting mechanism that compared weighted averages.

The selected criteria for use in this study included techno-economic aspects (IRR, NPV and PI), along with environmental aspects (CDES). These criteria had to be weighted according to the scope of this specific study, balancing its financial and environmental effects. For this reason, a 50–50 approach between the two main aspects was embraced, while financial criteria weights were purposefully chosen in order to obtain a global perspective regarding the investment. The distribution of evaluation weights is presented in Figure 1.

Evaluation Criteria			
100%			
Environmental Criteria	Financial Criteria		
50%	50%		
CDES	IRR	NPV	PI
50%	25%	12.5%	12.5%

Figure 1. Multi-level distribution of critical values' evaluation weights.

The grading mechanism used in every criterion was represented by a numerical value from 0 to 100, awarding a grade of 100 to the maximum value for each criterion "max (C_k)", while the grades of all other values were calculated as follows:

$$G_k[i,j] = \frac{C_k[i,j]}{\max\,(C_k)} \cdot 100 \quad (1)$$

where "k" represents each of the 4 selected criteria (IRR, NPV, PI and CDES), "$G_k[i,j]$" represents the matrix of grades for the k-th criterion, "$C_k[i,j]$" represents the matrix of values for the k-th criterion, "i" represents the 3 types of installation (matrices rows) and "j" represents the 3 different PV system sizes (matrices columns).

For each scenario, the grades' weighted averages were equal to the following equation:

$$G[i,j] = 0.5(0.5G_{IRR}[i,j] + 0.25G_{NPV}[i,j] + 0.25G_{PI}[i,j]) + 0.5G_{CDES}[i,j] \quad (2)$$

4. Results and Discussion

4.1. Numberical Results for Critical Values

By inserting the relevant data, the model calculated the critical values for the nine scenarios under evaluation (Figure 2).

IRR (%)	2.5 kWp	5.0 kWp	6.5 kWp
PV standalone	6.8%	13.7%	16.9%
PV + SWH	7.7%	13.6%	16.5%
PV + SHW + EV	15.2%	17.0%	18.3%

(**a**)

NPV (€)	2.5 kWp	5.0 kWp	6.5 kWp
PV standalone	688	5297	8434
PV + SWH	1250	5859	8996
PV + SHW + EV	11496	16105	19242

(**b**)

Profitability Index (%)	2.5 kWp	5.0 kWp	6.5 kWp
PV standalone	13.4%	71.6%	100.6%
PV + SWH	21.0%	71.5%	97.9%
PV + SHW + EV	69.9%	86.1%	97.7%

(**c**)

Savings in $kgCO_2$/year	2.5 kWp	5.0 kWp	6.5 kWp
PV standalone	1754	3507	4559
PV + SWH	2061	3815	4867
PV + SHW + EV	2913	4971	6206

(**d**)

Figure 2. Combined numerical and graphical comparison of the results of the nine examined scenarios related to the four critical variables: (**a**) IRR comparison for a 20-year investment; (**b**) NPV (in EUR) for a 20-year investment; (**c**) profitability index (NPV/CapEx) for a 20-year investment; (**d**) yearly savings of $kgCO_2$ for each scenario (CDES).

4.2. Graphic Respesentation of Critical Values

The numerical results of the four critical values for the nine scenarios can be graphically visualized in the four graphs shown in Figure 3.

4.3. Assignment of Grades to Critical Values and Evaluation

The results derived from the model can be used as inputs to the before-mentioned grading mechanism (Equations (1) and (2)), allowing the evaluation and sorting of the nine suggested scenarios presented in Table 4.

Table 4. Examined scenarios under study and corresponding grades.

Element	Scenario	IRR	NPV	PI	CDES	Total
M[3,3]	6.5 kWp PV with SWH and EV	100	100	97	100	**100**
M[3,2]	5.0 kWp PV with SWH and EV	93	84	86	80	**84**
M[2,3]	6.5 kWp PV with SWH	90	47	97	78	**80**
M[1,3]	6.5 kWp PV (standalone)	92	44	100	73	**78**
M[2,2]	5.0 kWp PV with SWH	74	30	71	61	**62**
M[3,1]	2.5 kWp PV with SWH and EV	83	60	69	47	**60**
M[1,2]	5.0 kWp PV (standalone)	75	28	71	57	**59**
M[2,1]	2.5 kWp PV with SWH	42	6	21	33	**31**
M[1,1]	2.5 kWp PV (standalone)	37	4	13	28	**25**

A more concentrated and comparative depiction of the total grading values for each scenario is presented below, providing investors with the overview needed to complete the decision-making process.

As shown in Figure 4, the optimal scenario for the case study under examination is the 6.5-kilowatt peak PV system coupled with solar water heater and EV adaptation under the net-metering mechanism, as it offers the best techno-economic and environmental protection results. Except the optimal solution, three other scenarios seem to provide investors with significant advantages, offering IRR of 16.5–17% and similar carbon dioxide emission savings (approximately 4500–5000 $kgCO_2$ annually).

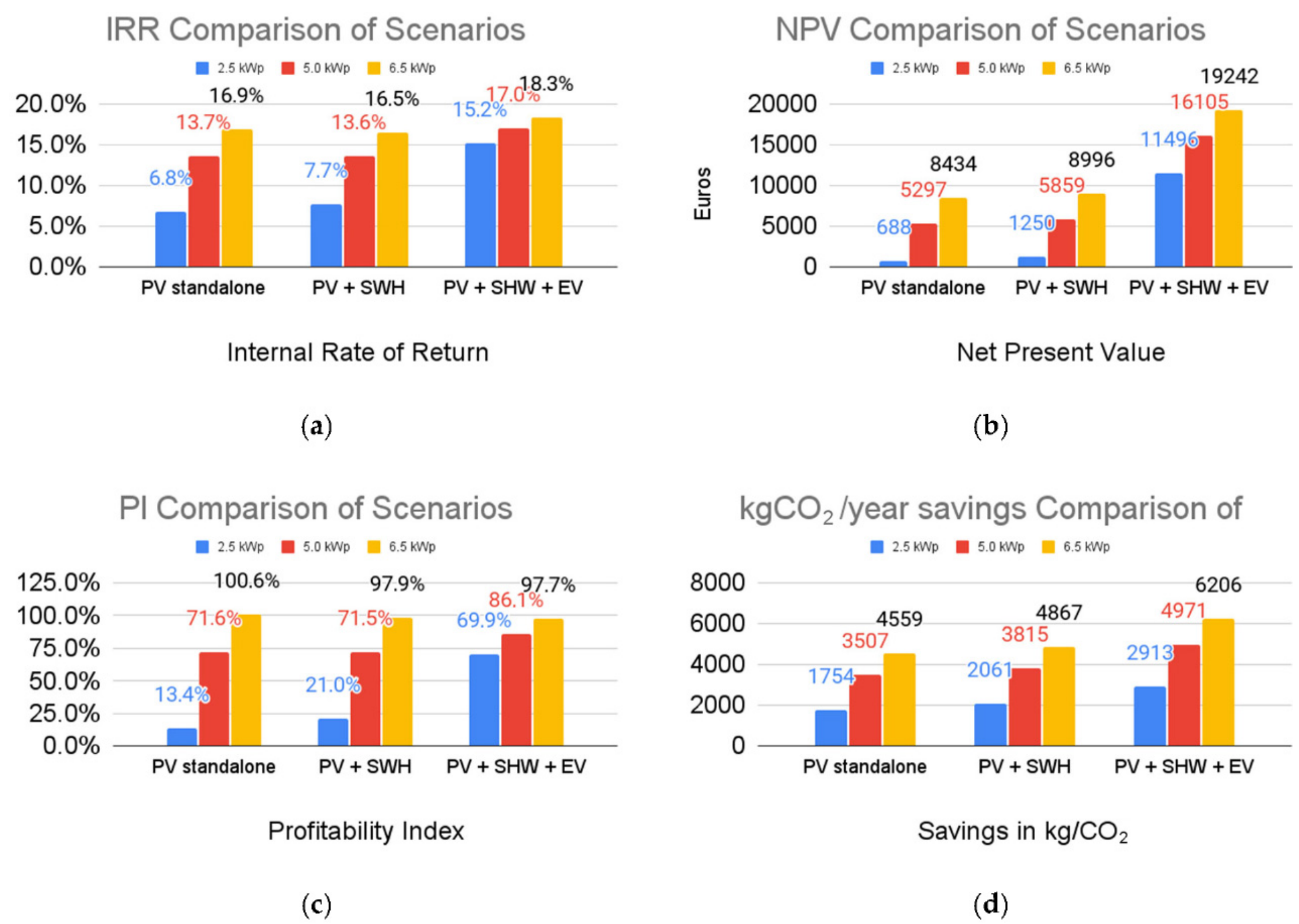

Figure 3. Graphic representation of calculated data for the nine examined scenarios related to the four critical variables: (**a**) IRR comparison for a 20-year investment; (**b**) NPV (in EUR) for a 20-year investment; (**c**) profitability index (PI = NPV/CapEx) for a 20-year investment; (**d**) yearly savings of $kgCO_2$ for each scenario.

Grade Value	2.5 kWp	5.0 kWp	6.5 kWp
PV standalone	**25**	**59**	**78**
PV + SWH	**31**	**62**	**80**
PV + SHW + EV	**60**	**84**	**100**

Figure 4. Hybrid visualization of the final grades of the nine proposed scenarios.

5. Conclusions and Proposals

According to results presented, the maximization of PV installation improves the techno-economic efficiency to the greatest extent, since solar PV installation is the most efficient studied technology in terms of net metering scheme. Moreover, the solar water heater seems to slightly reduce the techno-economic efficiency (IRR) of the PV installation (especially for larger-sized installations) while improving the NPV index, supporting energy-saving and the rational use of energy, especially concerning the primary energy consumption and environmental protection.

In parallel, EV adaption proves to be a very efficient alternative due to the Greek national subsidy policy. However, electro-mobility adaptation requires an extra initial investment capital that is more relevant to consumers who are already considering purchasing a new car.

Finally, the available household area is fully exploited, leaving enough space for the installation of a solar water heater, allowing the consumer to maximize their energy independence, while eliminating their environmental impact and investing in an efficient optimized energy system.

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