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The Net-Metering Practice in Medium-Voltage PV-BES Prosumers: A Techno-Economic Analysis of the Greek Case

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Abstract

Nowadays, the volatile economic conditions alongside the environmental concerns on using fossil fuels for electricity, necessitate the gradual transition from conventional power plants to distributed photovoltaic (PV) systems. For this reason, various support mechanisms have been introduced to promote PV installations. Net-metering (NEM) is considered as one of the most important alternating pricing policies. Nevertheless, the ever-increasing penetration of PVs and especially their intermittent nature may lead to unprecedented technical issues related to the reliable grid operation. To tackle these challenges, battery energy storage (BES) systems are situated on the premises of PV prosumers. Scope of this paper is the techno-economic evaluation of prospective PV-BES investments of medium-voltage (MV) prosumers operating under the NEM mechanism. The case of university campuses of the Democritus University of Thrace, Greece, are considered. The impact of various parameters on the viability of the NEM investments is investigated under different scenarios.

Keywords: Battery energy storage systems, medium-voltage, net-metering, photovoltaics, techno-economic analysis

1. Introduction

The proliferation of renewable energy sources (RESs) plays a vital role towards the reduction of carbon footprint, fossil fuel dependence, and electricity cost [1]. To this end, several support schemes, e.g., feed-in tariff (FiT), net-metering (NEM), and net-billing (NEB), have been set by local administrations and international organizations to foster the installation of RESs in the electrical grid [2, 3]. Special emphasis was given to the promotion of photovoltaics (PVs) at the distribution level since their modular structure allows the exploitation of the solar potential even under small-scale installations, such as rooftop PVs [4]. However, the widespread deployment of PVs revealed a series of technical challenges, e.g., line overloading, voltage violations, etc., putting in risk the smooth operation of the distribution grid [5]. These issues can be effectively addressed by adding battery energy storage (BES) systems in existing/new PV installations, thus forming PV-BES systems. This way, the impact of the PVs on the distribution grid is mitigated since BES systems can be used to reduce the power exchanged with the grid by storing any power surplus during high generation periods and feeding loads when generation is absent. Nevertheless, since a PV-BES system is characterized by a significantly higher investment cost compared to a standalone PV system [6], an in-depth, techno-economic analysis is needed to assess the viability of this solution in the frame of the various support mechanisms.

Focusing on the NEM mechanism, most of the published works perform an economic assessment assuming standalone PV systems in low-voltage (LV) residential prosumers. Specifically, in [2, 3], the NEM scheme is systematically compared against the FiT and NEB compensation mechanisms in terms of economic viability and levelized cost of energy. The authors in [7, 8] present a framework for the comparative assessment of different NEM compensation mechanisms, providing policy makers with a useful tool towards the determination of the final adopted NEM scheme. Some studies have integrated the BES systems in their analyses. In particular, the authors in [9] introduce the concept of the integrated system efficiency to increase the self-consumption ratio in LV residential prosumers with PV-BES systems. Additionally, a techno-economic sizing process is proposed in [10] to estimate the optimal PV-BES configuration that maximizes the profit of LV prosumers under NEM and NEB compensation mechanisms.

As a common drawback, all the above methods assume LV prosumers in their analyses where a relatively simple electricity billing mechanism is used. Therefore, they cannot be applied in medium-voltage (MV) prosumers, as the complex billing practices, e.g., peak demand tariff, are neglected [11, 12]. An initial attempt is made in [13], where a generic methodology is presented aiming to assess the economic viability of the NEM scheme in MV prosumers,

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considering also the operating properties of the grid via quasi-static simulations. Nevertheless, BES systems are not included in this analysis.

Scope of this paper is to fill this gap by presenting a systematic techno-economic assessment of PV-BES systems in MV prosumers operating under NEM policy. The proposed method consists of two key components, namely a technical and an economic model. The former is used to accurately model the operating properties of the PV-BES system; the latter deals with the economic long-term evaluation of NEM scheme. This paper extends the study of [14] by incorporating an accurate BES degradation mechanism in the technical model and investigating different scenarios regarding the PV capacity and BES costs to determine the optimal investment plan in monetary terms.

The remainder of the paper is organized as follows: Section 2 presents an overview of the NEM compensation mechanism in MV prosumers. The technical as well as the economic models used in the analysis are described in Sections 3 and 4, respectively. In Section 5, the system under study and the different examined scenarios in terms of PV capacity and BES costs are discussed. Section 6 presents the numerical results, and, finally, Section 7 concludes the paper highlighting the most important findings.

2. Overview of NEM Policy

Consider a PV prosumer operating under the NEM program. The prosumer offsets at the end of the billing period the energy consumed within its premises through the use of its privately-owned resources, i.e., PV system. In this sense, the NEM mechanism differs from NEB, where all exchanges with the network are accumulated separately [15] and from self-consumption, where netting process takes place instantaneously [7]. The net energy of the prosumer, E^{net}, is calculated as:

$$E^{\mathrm{net}} = E^{\mathrm{exp}} - E^{\mathrm{imp}} + (RECs^{\mathrm{month}-1}) \qquad (1)$$

where, E^{exp} and E^{imp} is the measured exported and imported energy to/by the grid, respectively.

NEM schemes can be varied according to how E^{net} is charged. If $E^{\mathrm{net}} \geq 0$, i.e., when the exported energy is higher than the imported (positive netting), the prosumer is charged only for E^{net} (full netting) or for a part of it (partial netting) at the retail electricity price, C_{retail} [8]. There are also several other variants; among them the most known includes rolling over the net excess amount at the end of the billing period to the next period in terms of renewable energy credits (RECs). This is denoted in (1) as $RECs^{\mathrm{month}-1}$, i.e., the $RECs$ from the previous billing period. Conversely, in negative netting, the imported energy is larger than the exported ($E^{\mathrm{net}} < 0$) and the prosumer is charged for E^{net}. This NEM policy also applies to Greece [14, 16, 17].

Recent shifts towards alternative retail tariff structures and NEM policy variants are gradually providing incentives for energy users to "store" locally the surplus of their solar energy utilizing on-site BES systems and "consume" it at later times [18]. A widely adopted BES control scheme also in compliance with the Greek legislation [16] is presented the flowchart of Fig. 1. The BES discharges with power $P_{\mathrm{dch}} = P_{\mathrm{load}} - P_{\mathrm{PV}}$, if the prosumer's load, P_{load}, is higher than PV production, P_{PV}. Otherwise, BES charges with $P_{\mathrm{ch}} = P_{\mathrm{PV}} - P_{\mathrm{load}}$. In every case, the constraints regarding the maximum permissible BES charging/discharging power ($P^{\mathrm{max}}_{\mathrm{ch}}/P^{\mathrm{max}}_{\mathrm{dch}}$) and the minimum/maximum state-of-charge, SoC, limits should not be violated.

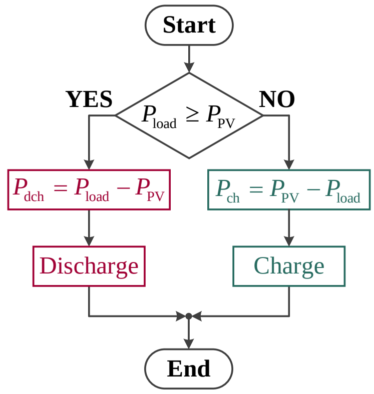

Figure 1: Flowchart of the BES control scheme.

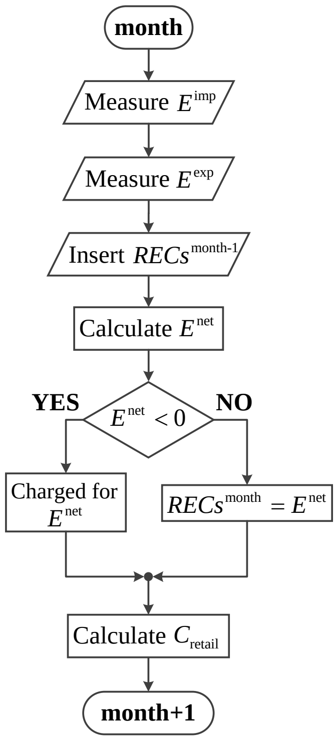

Figure 2: Flowchart of NEM scheme for MV PV-BES prosumers.

The overall algorithm for the billing process of PV-BES MV prosumers under NEM mechanism in Greece is illustrated in Fig. 2. A brief description of the billing policy for MV users in Greece is given in the Appendix.

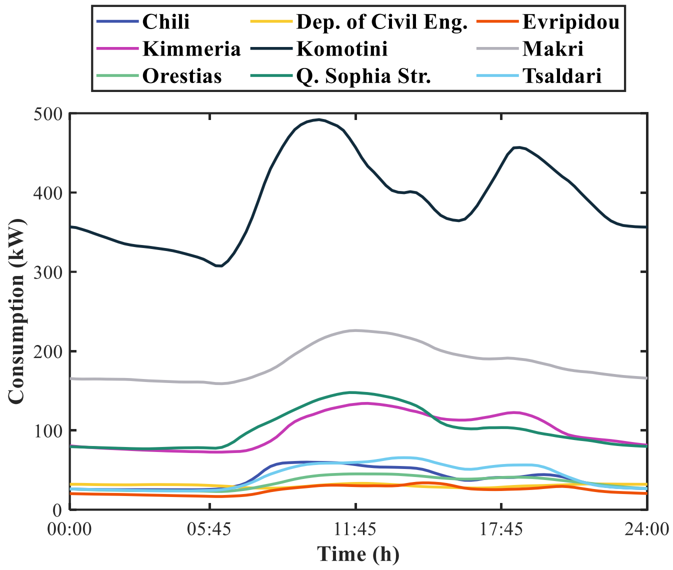

Figure 3: Average daily consumption timeseries of DUTH campuses.

3. Technical Model

To calculate the energy trading between the PV-BES prosumer and the grid, a technical model (TM) is developed. In particular, the TM comprises the required data, i.e., the load timeseries, the annual PV production profiles and the BES operating model, in order to compute the imported/exported energy from/to the grid. The derived energy amounts are used to estimate the electricity bill of the PV-BES prosumer according to the NEM practice. The TM also evaluates the technical performance of the PV-BES prosumer by utilizing the self-sufficiency rate, SSR, index. All data employed by the TM are analytically presented in the following subsections.

3.1. University Campuses Data

The TM uses the annual electricity demand data referring to 2014 for nine MV prosumers, i.e., the nine campuses of Democritus University of Thrace (DUTH) [13]. The examined campuses are situated in different cities within the Thrace region in Greece, as presented in Table 1. Here, the capacity of each university campus is also provided. The average daily consumption timeseries of the university campuses are depicted in Fig. 3. It can be seen that the campuses of Kimmeria, Q. Sophia Str., Makri and Komotini are characterized by significantly higher load demand compared to the rest five campuses, i.e., Evripidou, Orestias, Dep. Of Civil Eng., Tsaldari and Chili.

3.2. PV Production Data

Annual PV production timeseries with 1-h resolution [19] are used for each one of the four cities of DUTH (see Table 1). The normalized average daily demand profiles (scaled to 1 kW, i.e., 1 per unit (pu)) for 2014 are presented in Fig. 4. The PV curves almost overlap as all PV systems are located in the same region.

Table 1: Location and Capacity of University Campuses

City	Name of campus	Capacity (kW)
Alexandroupoli	Makri	1500
	Chili	400
Komotini	Komotini	1500
	Tsaldari	500
Orestiada	Evripidou	1250
	Orestias	650
Xanthi	Q. Sophia Str.	1300
	Dep. of Civil Eng.	1600
	Kimmeria	800

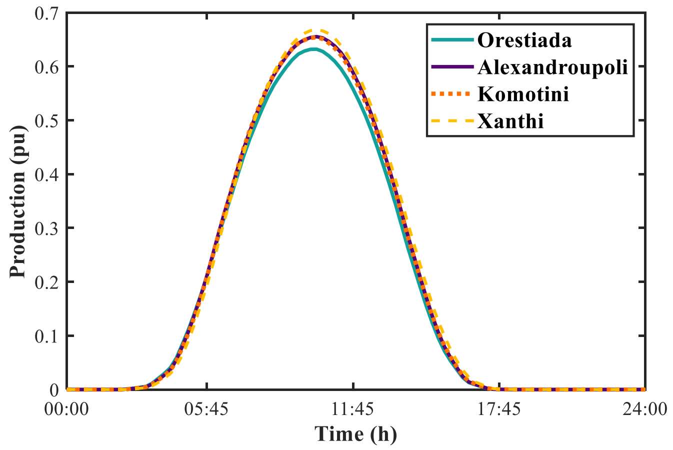

Figure 4: Normalized daily production timeseries for each city of DUTH.

3.3. BES System Model

To simulate the operation of a BES system employed by a MV prosumer, the BES model of (2) is used. In particular, the SoC of a BES unit at each time instant t is estimated as:

$$SoC\,(t) = SoC\,(t-1) + \eta_{\text{ch}} \frac{P_{\text{ch}}\,(t)\,\Delta t}{E_{\text{nom}}} - \frac{P_{\text{dch}}\,(t)\,\Delta t}{\eta_{\text{dch}} E_{\text{nom}}} \quad (2)$$

where E_{nom} is nominal capacity of the BES system, Δt is the analysis time step, η_{dch} and η_{ch} are the corresponding BES discharging and charging efficiencies.

A BES aging model (BAM) [20] is also incorporated in the TM. According to BAM, the BES capacity fading estimation is conducted on an annual basis. At the end of each year n, the updated available BES capacity, E^n_{max}, is derived by:

$$E^n_{\text{max}} = (1 - c^n_{los})E^0_{\text{max}} \quad (3)$$

where E^0_{max} is the initial BES capacity and c^n_{loss} is the capacity loss of lithium-ion BES units till year n. Specifically, c^n_{los} is estimated as:

$$c^n_{los} = 1 - \alpha e^{-\beta f_d} - (1-\alpha)e^{-f_d} \quad (4)$$

where α and β are parameters based on experimental data and f_d is the degradation rate factor for all cycles $CyCs$ till year n, calculated according to (5).

$$f_d = f_{cal} + \sum_{i}^{CyCs} f_{cyc}^{i} \tag{5}$$

Here, f_{cal} stands for the calendar degradation factor and f_{cyc}^{i} denotes the cyclic degradation over the i-th charging-discharging cycle. Specifically, f_{cal} is a function of the average SoC value and the average BES operating temperature till year n. Note that the average SoC value is calculated using the SoC profile obtained by (2). On the other hand, f_{cyc}^{i} depends on the depth of discharge (DoD), the average SoC, and the average BES operating temperature of each cycle i as calculated by the rainflow algorithm [21]. Considering (5), it can be realized that the total BES cyclic aging is calculated as the sum of the capacity degradation caused by all cycles till year n.

3.4. Technical Assessment

The TM adopts SSR, i.e., one of the most well-established indices to assess the sizing of PV-BES systems on the basis of prosumer's demand [22, 23]. In general, SSR is used to evaluate the load energy compensated by the PV-BES system and it is calculated according to (6).

$$SSR\,(\%) = \frac{C + E}{A + C + E + F}. \tag{6}$$

From Fig. 5, it can be seen that A and F indicate the total demand covered by the grid, B stands for the excess of the PV produced energy, C is the self-consumed energy, D denotes the excess PV energy stored in the BES system and E is the energy supplied to the load by the BES. Note that, in case of prosumers without BES the corresponding D and E values are zero. Summarizing, the produced PV energy, E_{PV}, and the total load demand, E_{load}, are calculated as $E^{\text{PV}} = B + C + D$ and $E^{\text{load}} = A + C + E + F$, respectively.

4. Economic Model

To evaluate the economic impact of the NEM scheme on the MV PV-BES prosumers, an economic model (EM) is also adopted. The EM employs three economic indices namely, the net present value, NPV, the internal rate of return, IRR, and the discounted payback period, DPP.

NPV is the difference between the present value of revenue and expenditure over the lifetime, N, of an investment and it is calculated as follows [8, 13]:

$$NPV\,(€) = -OC_o + \sum_{n=1}^{N} \frac{(S_n - OM_n)\,(1 + IR)^{n-1}}{(1 + DR)^{n}} \tag{7}$$

where OC_o is the overall capital investment cost, OM_n are the operation–maintenance costs at year n, S_n are the

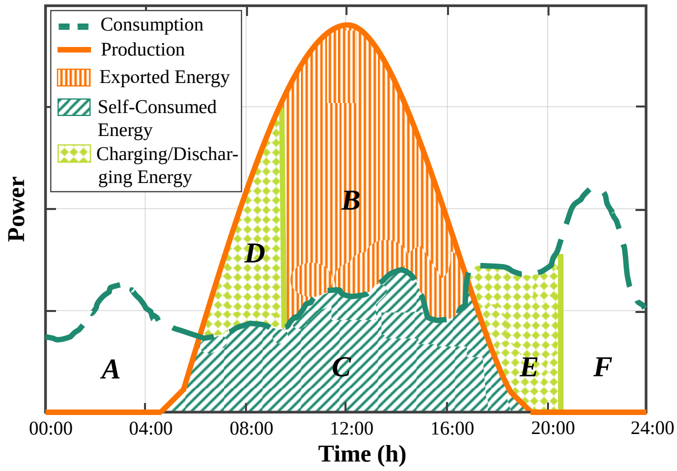

Figure 5: Daily consumption and production timeseries of PV-BES prosumers.

savings in electricity billing due to the NEM policy at year n, IR and DR are the inflation rate and the discount rate, respectively. In general, investments with $NPV > 0$ are worth undertaking while those with $NPV < 0$ are not.

IRR is the annual return that makes $NPV = 0$ and is employed to evaluate the economic performance of a potential investment during its lifetime. IRR is estimated by solving (7) for $NPV = 0$ considering $DR \equiv IRR$ as the unknown variable [8, 13]. In case IRR is higher than DR, the examined investment plan can be accepted. On the contrary, if $IRR \leq DR$, the investment is not profitable.

DPP is defined as the necessary time period for the full repayment of an investment plan and it is calculated by setting (7) equal to zero and solving the corresponding equation for the unknown DPP value of N [8, 13]. This index is used to assess the feasibility of an investment.

5. Examined Scenarios and Analysis Assumptions

A 21-year techno-economic analysis is conducted to assess the profitability of the NEM policy in prospective MV PV-BES prosumers considering three operating scenarios, namely:

- Scenario 1: campuses are PV prosumers (standalone PV systems). The analysis is based on [13].
- Scenario 2: campuses are PV-BES prosumers. The BES system cost is taken assuming current market prices.
- Scenario 3: campuses are PV-BES prosumers. Compared to Scenario 2, a lower BES cost is considered, taking into account current trends in the reduction of the BES cost [6, 24].

In the analysis the PV size, PV_{size}, varies from 50 to 1000 kW, i.e., the maximum permissible PV_{size} for MV prosumers according to the Greek legislation [16, 17]. The

Table 2: PV and BES System Cost Analysis

PV System		**BES System**		
Type of Cost	**€/ kWp**	**Type of Cost**	**€/ kWp**	
PV Module	Equation (8)	Inverter	450	
Inverter	350	BES Replacement	Equation (9)	
Balance of System	65	Operation & Maintenance	2 % (of the overall cost)	
Installation & Administrative	115		**€/ kWh**	
Operation & Maintenance	3 % (of the overall cost)	BES Module	**Scenario 2**	**Scenario 3**
			250	125

annual growth of load demand and the annual PV degradation are assumed equal to 1 % and 2 %, respectively. It is also considered that $DR = 6\%$ and $IR = 7\%$ for all examined test cases. In Scenario 2 and 3, for all examined PV sizes, $P_{\text{ch}}^{\max}$ and $P_{\text{dch}}^{\max}$ are equal to 30 kW, according to the constraints set by the Greek legislation [16, 17]. The BES power to energy ratio is 25 % and $\eta_{\text{ch}} = \eta_{\text{dch}} = 95$ %. In all examined scenarios, prosumers are charged according to a monthly electricity tariff and the NEM compensation mechanism is performed at the end of each billing period, i.e., one month. The corresponding netting period is equal to 3 years [16, 17]. This implies that remaining $RECs$ of previous billing periods are not credited to future electricity bills. Furthermore, the prices of the different electricity cost categories derived from [13] as well as the PV and BES system costs considering 24 % VAT are presented in Table 2. Also, two lump sum costs of 992 € and 400 € are taken into account for the PV and BES connection with the grid [16], respectively.

Regarding the PV module cost (€/kWp), it is calculated as a function of PV_{size} by employing the empirical formula of (8), which has been derived by applying linear interpolation to known PV_{size} – cost data sets, ranging from 300 kWp – 0.6 €/W to 550 kWp – 0.5 €/W, respectively.

$$PV_{cost} = 818.4 - 0.248 PV_{\text{size}} \tag{8}$$

In addition, due to the BES aging mechanism, it might be necessary to replace the BES system during the lifetime of the investment. For this reason the BES replacement cost, BRC, is included in the analysis; BRC is estimated in present value according to (9) [25].

$$BRC\,(€) = \sum_{r=1}^{R} \frac{E_{\text{nom}} BFC_r \,(1 + \text{VAT})}{(1 + DR)^{n_{rep}^{r}}}. \tag{9}$$

Here, R is the total number of replacements during the analysis period, n_{rep}^{r} is the year of the replacement and BFC_r is the BES future cost in €/kWh at the r replacement calculated as [25]:

$$BFC_r = \begin{cases} 0.95 n_{rep}^{r} BMC, & \text{if } n_{rep}^{r} \leq 10 \\ \left(9.5 + 0.975 n_{rep}^{r}\right) BMC, & \text{if } n_{rep}^{r} > 10 \end{cases} \tag{10}$$

where BMC is the BES module cost (See Table 2). Note that, a BES system should be replaced only if the available capacity calculated according to BAM is reduced by 20 % of the nominal BES capacity [26].

6. Numerical Results

In this section, the techno-economic assessment results of NEM policy for the DUTH campuses are discussed. A parametric analysis is conducted to evaluate the effect of the annual load demand growth, the annual PV degradation, IR and DR on the viability of the investments.

6.1. Techno-economic Assessment

By using the simulation parameters of Section 5, the impact of PV_{size} on the performance of the campuses is assessed for the different scenarios. Initially, the SSR variation for Scenario 1 and 2 with respect to the PV_{size} for the 1st and 21st (last) year of the analysis is illustrated in Figs. 6a and 6b, respectively. It should be indicated that SSR results for Scenario 3 are identical to those of Scenario 2; thus, are not presented. In all cases the SSR increases with PV_{size}. Higher SSR values are obtained for both scenarios considering campuses presenting low load demand, i.e., Chili, Evripidou, etc. On the other hand, for campuses with high demand, the SSR is lower than 50 % for all examined PV_{size} values. Comparing Figs. 6a and 6b, it can be realized that the SSR for the 1st year of the investment is higher than the SSR of the 21st year. This is owed to the lower rate of annual load demand growth than the PV-BES degradation. Furthermore, by comparing the SSR results for Scenario 1 and 2, it can be deduced that the use of BES leads to increased SSR indicating that the grid dependence level of the PV-BES prosumers is decreased. This increase is more pronounced in campuses with lower load demand.

The economic viability of the investments is discussed in terms of NPV, IRR and DPP. In Fig. 7, the NPV variation with respect to PV_{size} is illustrated for the campuses of Orestias, Chili, Q. Sophia Str. and Makri. It can be seen that Scenario 2 and 3 lead to decreased NPV

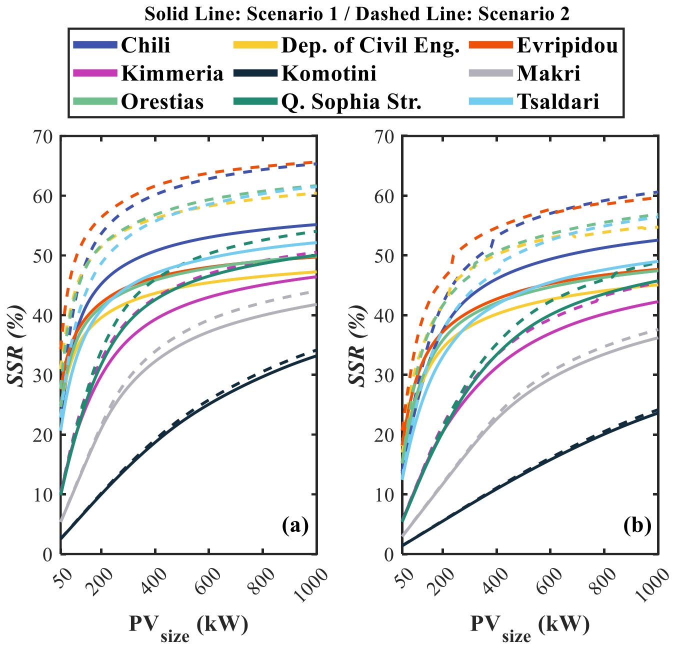

Figure 6: SSR with respect to PV_{size}. (a) 1st and (b) 21st year of the analysis.

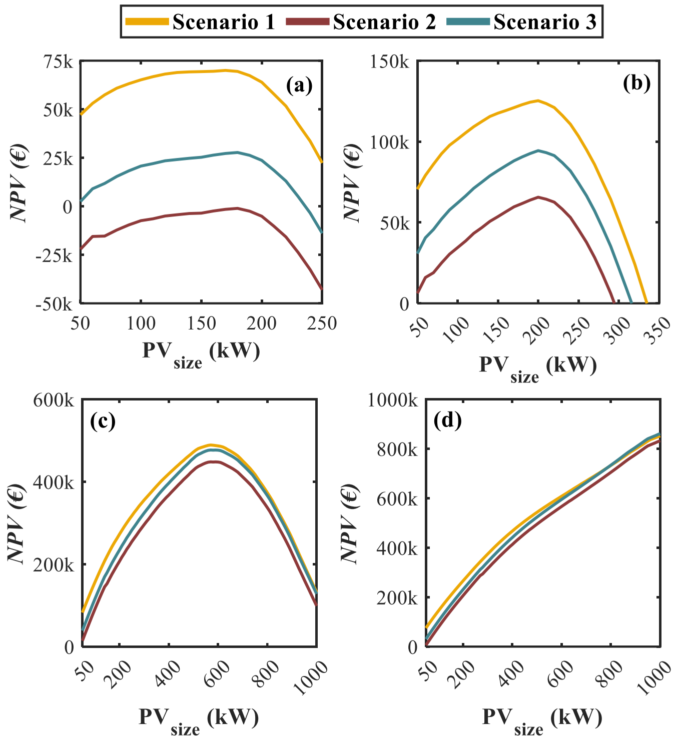

Figure 7: NPV with respect to PV_{size} for Scenario 1, 2 and 3 for the campus of (a) Orestias, (b) Chili, (c) Q. Sophia Str. and (d) Makri.

compared to Scenario 1, due to the increased capital costs (purchase and replacement) of the BES systems that cannot be recuperated. This is more noticeable in the results of Orestias (Fig. 7a), where the NPV of Scenario 2 is negative for all examined PV_{size} values. Results for the campuses of Chili and Q. Sophia Str. (Figs. 7b and 7c) reveal that NPV increases with PV_{size} up to a certain value; for higher PV_{size} values, the NPV starts decreasing. This is mostly because of the Greek NEM legislation, where the excess amount of the produced energy is not credited or compensated to the prosumer's profits at the end of the netting period. Therefore, the additional costs of the PV-BES system cannot be depreciated and this entails reduced NPV. Regarding the NPV of Makri (Fig. 7d), it can be realized that for $PV_{\text{size}} > 780$ kW, Scenario 1 and 2 present a similar NPV and Scenario 3 results into the highest NPV. This is ascribed to the even lower costs, i.e., the regulated charges, $C_{\text{regulated}}$, and the cost of power, $C_{\text{supply}}^{\text{power}}$, (See Appendix), of the electricity bill due to the BES employment, leading to increased savings for the campus and consequently to higher profits during the lifetime of the investment [16]. Here, it should be also stressed out that the reduced $C_{\text{supply}}^{\text{power}}$ is owed to the peak shaving achieved by the BES operation. Moreover, the increased SSR of the PV-BES prosumers leads to lower amounts of energy imported by the grid and consequently to decreased $C_{\text{regulated}}$.

In Figs. 8a, 8b and 8c the IRR of Scenario 1, 2 and 3 is presented, respectively. In these figures DR, i.e., the discount rate limit, is also plotted. Results of Scenario 1 show that IRR decreases as PV_{size} increases (See Fig. 8a); the IRR of Scenario 2 and 3 increases up to a certain value, and then starts decreasing (See Figs. 8b and 8c). Comparing Figs. 8a-8c, it can be observed that Scenario 1 and 2 present the highest and the lowest IRR, respectively. For $IRR > DR$, NPV is positive and thus, the investment is considered profitable. On the other hand, for cases where $IRR \leq DR$, a negative NPV is acquired and consequently the investment is not viable. This is mainly observed for Scenario 2 and 3 for campuses presenting low load demand.

In Fig. 9 the variation of DPP with respect to PV_{size} is presented for Scenario 1 to 3. Note that, the plotted DPP curves refer to investments that can be depreciated in the analysis period of 21 years. For all plotted cases DPP is higher than 8 years. Regarding Scenario 1, the DPP increases with PV_{size} (Fig. 9a); for Scenario 2 and 3 (Figs. 9b and 9c) the DPP decreases with the PV_{size} up to a certain value and for higher PV_{size} values, the DPP increases. This is not the case for Komotini, where the DPP of Scenario 1 remains relatively constant to 9.5 years and the corresponding DPP of Scenario 2 and 3 decreases with PV_{size}.

In Table 3 different parameters are summarized, i.e., the $PV_{\text{size}}^{NPV_{\max}}$ that pertains to the maximum NPV, NPV_{max}, and the corresponding DPP for all examined cases. It can be deduced that Scenario 1 results into the most profitable investments in both terms of revenues and payback period for the majority of the examined cases. These investments present an average repayment period of $\sim$ 13.5 years, i.e., an acceptable time period for MV asset investment. Nevertheless, significant profits can be

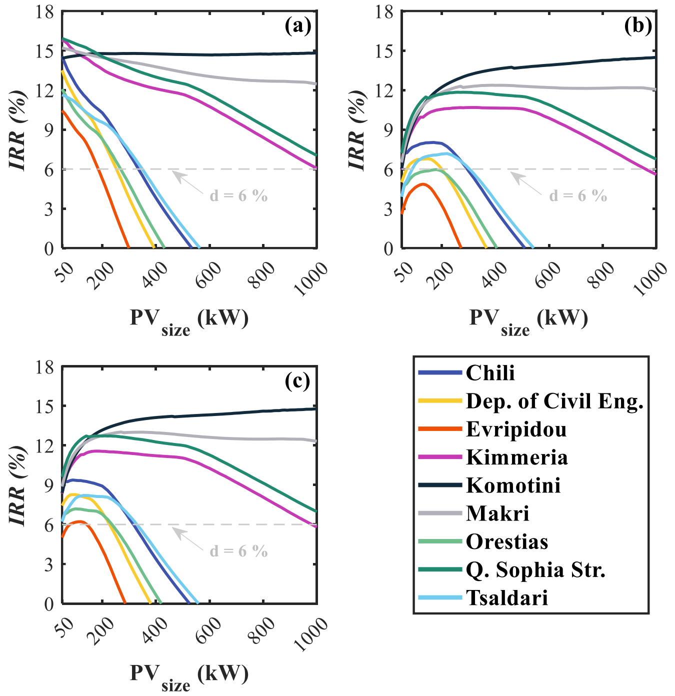

Figure 8: IRR with respect to PV_{size} for (a) Scenario 1, (b) Scenario 2, and (c) Scenario 3.

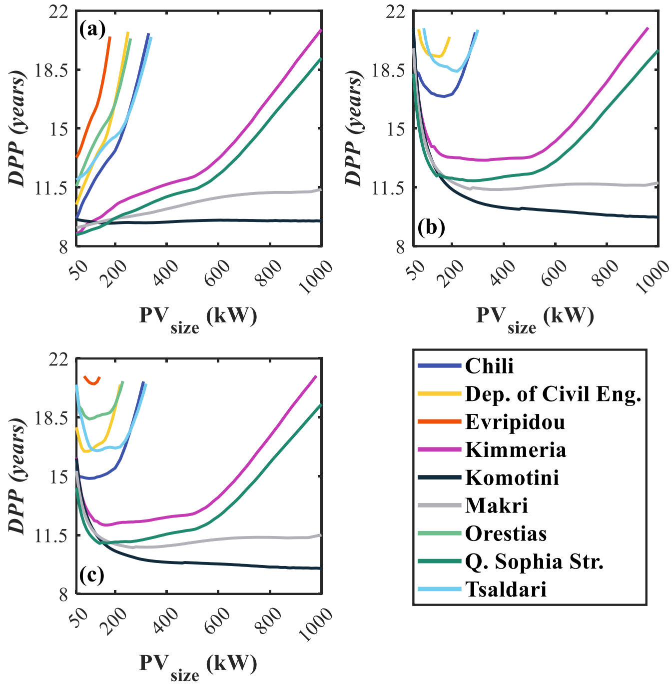

Figure 9: DPP with respect to PV_{size} for (a) Scenario 1, (b) Scenario 2, and (c) Scenario 3.

also reaped by PV-BES prosumers with high demand. For example, by comparing the calculated NPV for Scenario 1, 2 and 3, it can be deduced that the BES employment in Komotini campus results into higher NPV by 0.42 % and 2.76 % for Scenario 2 and 3, respectively. In addition, if future predictions of reduced BES costs are accurate (Scenario 3) [24], also the profits of Makri are anticipated to increase by 1.09 % compared to Scenario 1. On the contrary, PV-BES systems operating under the NEM scheme cannot be considered as a profitable investment for campuses with low demand, e.g., Chili, Tsaldari, Evripidou, etc., since NPV acquires significant lower or even negative values for the examined PV_{size} cases. This is attributed to the fact that prosumer's savings during the investment lifetime cannot fully compensate the initial investment cost.

6.2. Effect of Load Demand Growth

The effect of the annual load demand growth on the techno-economic assessment of NEM is investigated, considering also 2 % and 3 % values. To evaluate the SSR' and NPV' indices for the varied model parameters, e.g., demand growth load, the difference in SSR and NPV, defined in (11) and (12), respectively, are calculated with respect to indices SSR_{original} and NPV_{original} of the original test case (see Section 6.1).

$$Diff_{\text{SSR}}(\%) = SSR'(\%) - SSR_{\text{original}}(\%), \qquad (11)$$

$$Diff_{\text{NPV}}(€) = NPV'(€) - NPV_{\text{original.}}(€). \qquad (12)$$

In Fig. 10, $Diff_{\text{SSR}}$ is presented for the 21$^{\text{st}}$ year of the analysis for the campuses of Dep. of Civil Eng., Kimmeria, Makri and Komotini for Scenario 1 and 2; Scenario 3 calculations are similar to those of Scenario 2 (see Section 6.1). In general, results show that SSR decreases ($Diff_{\text{SSR}} < 0$) for increasing load demand growth, as the additional load energy cannot be fully compensated by the PV or the PV-BES system. The variation of $Diff_{\text{SSR}}$ for Scenario 2 denoted within red circles is due to the BES replacement as determined by BAM. This is more marked for campuses with lower load demand, i.e., Dep. of Civil Eng. (See Fig. 10a).

The corresponding $Diff_{\text{NPV}}$ is plotted in Fig 11. Similar differences in NPV are calculated for the three scenarios per load demand growth, as the corresponding curves overlap. Prosumers revenue increases with load demand growth and PV_{size} ($Diff_{\text{NPV}} > 0$) by virtue of the PV production being used to fully compensate the prosumers' load demand, instead of being exported to the grid as REC that might not be remunerated at the end of the netting period. In other words, the increase of load demand, and most importantly for high load demand prosumers, results into full exploitation of E^{PV} and consequently into higher NPV values. This is also compliant with the remark that NEM is profitable for prosumers with high demand (See Table 3). Similar remarks can be also drawn for the rest campuses; thus, the results are not presented.

6.3. Effect of PV Degradation

The impact of the annual PV degradation rate on the viability of the investments is also examined, assuming 1 % and 3 % values.

The $Diff_{\text{SSR}}$ is calculated via (11) and is presented for the 21$^{\text{st}}$ year of the analysis indicatively for the campuses

Table 3: NPV and DPP for DUTH Campuses.

Campus	Scenario 1			Scenario 2			Scenario 3		
	$PV_{\text{size}}^{NPV_{\max}}$ (kW)	$NPV_{\max}$ (€)	DPP (years)	$PV_{\text{size}}^{NPV_{\max}}$ (kW)	$NPV_{\max}$ (€)	DPP (years)	$PV_{\text{size}}^{NPV_{\max}}$ (kW)	$NPV_{\max}$ (€)	DPP (years)
Chili	200	125,257	13.67	200	65,603	17.03	200	94,383	15.48
Dep. of Civil Eng.	150	89,227	13.99	160	20,252	19.34	160	49,033	17.15
Evripidou	100	43,373	15.31	120	-24,586	21+	120	4,194	20.49
Kimmeria	550	411,296	12.55	550	355,043	13.63	550	383,824	13.12
Komotini	1000	1,199,570	9.49	1000	1,204,587	9.72	1000	1,232,720	9.51
Makri	1000	851.669	11.37	1000	832,224	11.76	1000	861,005	11.50
Orestias	170	69,984	15.48	180	-1,077	21+	180	27,703	18.78
Q. Sophia Str.	570	488,816	11.88	570	447,907	12.73	570	476,688	12.28
Tsaldari	220	103,010	14.80	220	41,116	18.40	220	69,896	16.74

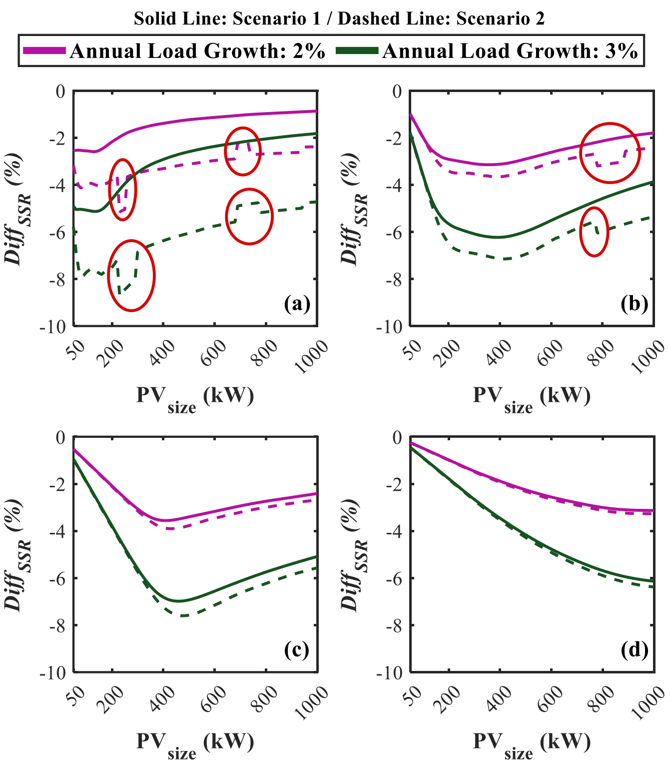

Figure 10: $Diff_{\text{SSR}}$ as a function of PV_{size} for the campuses of (a) Dep. of Civil Eng., (b) Kimmeria, (c) Makri and (d) Komotini.

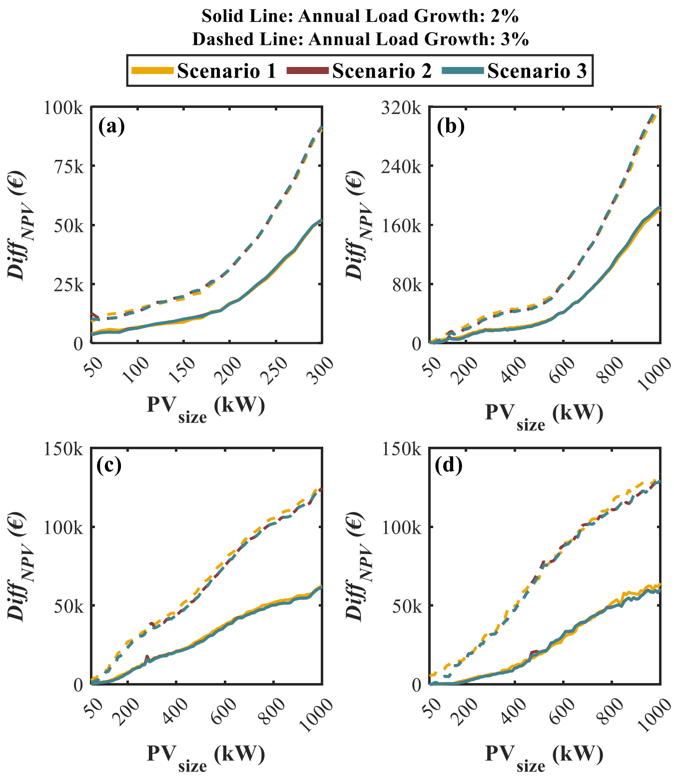

Figure 11: $Diff_{\text{NPV}}$ as a function of PV_{size} for the campuses of (a) Dep. of Civil Eng., (b) Kimmeria, (c) Makri and (d) Komotini.

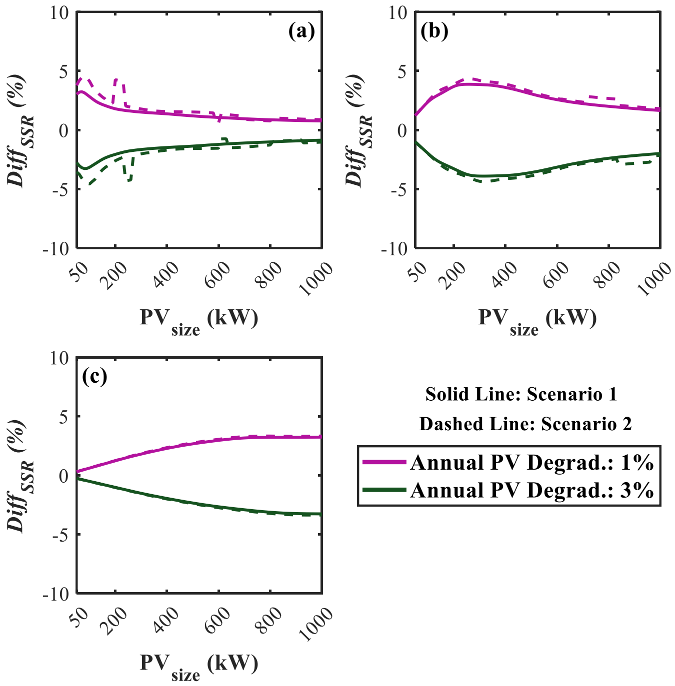

Figure 12: $Diff_{\text{SSR}}$ as a function of PV_{size} for the campuses of (a) Evripidou, (b) Q. Sophia Str. and (c) Komotini.

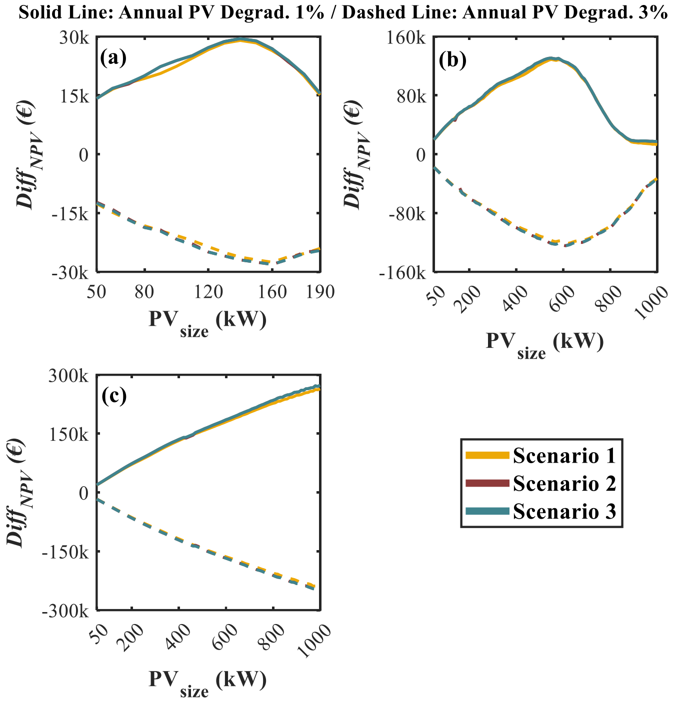

Figure 13: $Diff_{\text{NPV}}$ as a function of PV_{size} for the campuses of (a) Evripidou, (b) Q. Sophia Str. and (c) Komotini.

of Evripidou, Q. Sophia Str. and Komotini in Figs. 12a - 12c, respectively. In addition, the differences in the profits (in terms of $Diff_{\text{NPV}}$ as calculated via (12)) are also demonstrated in Fig. 13. A decrease of PV degradation rate yields an increase to the total E^{PV} during the lifetime of the investment and consequently to a reduction of the total E^{imp} from the grid. Therefore, for the reduced PV degradation rate of 1 %, the SSR as well as the profitability of the NEM investment increases ($Diff_{\text{SSR}} > 0$ and $Diff_{\text{NPV}} > 0$) as shown in Figs. 12 and 13, respectively. On the contrary, as PV degradation increases (3 %), lower SSR and NPV values are acquired compared to the original test case ($Diff_{\text{SSR}} < 0$ and $Diff_{\text{NPV}} < 0$) for all scenarios.

For low PV degradation values, 1 %, it is shown that the $Diff_{\text{NPV}}$ curves for the campuses of Evripidou (See Figs. 13a) and Q. Sophia (13b) increase up to a certain PV_{size} value and subsequently start decrease as the excess of E^{PV} cannot be fully exploited (see similar remarks in the previous sub-sections). However, this is not the case for the Komotini campus (Fig. 13c), where $Diff_{\text{NPV}}$ is an increasing function of PV_{size}.

6.4. Effect of Inflation Rate

The economic viability of an investment is also influenced by IR. Therefore, simulations are conducted assuming IR varying from 3 % to 9 %.

The $PV_{\text{size}}^{NPV_{\max}}$, $NPV_{\max}$ and the corresponding IRR and DPP are depicted in the bar graphs of Figs. 14a - 14d, respectively, for the different IR values; the case of Chili campus is examined. In general, results reveal that the $PV_{\text{size}}^{NPV_{\max}}$, $NPV_{\max}$ and the IRR increase with IR for all scenarios (Figs. 14a-c). Consequently, DPP (Fig. 14d) decreases, as IR increases.

In particular, for low inflation rate values, i.e., $IR =$ 3 %, non-viable investment plans are observed ($NPV < 0$ in Fig. 14b) for Scenario 2 and 3. This is also substantiated by the IRR results, being lower than $DR = 6$ %, as well as $DPP > 21$ years, revealing that the overall investment costs cannot be recuperated during the project lifetime.

Moreover, it can be deduced that the profitability of the investment plans for Scenario 2 and 3 are more sensitive to IR variations compared to those of Scenario 1. For example, the IRR for Scenario 1 varies within the range of 9.11 % to 11.58 %, while for Scenario 2 within 3.57 %, 9.51 %. This is attributed to the increased capital costs of these projects. Similar remarks are also applied to the rest DUTH campuses.

6.5. Effect of Discount Rate

The impact of the DR on the economic viability of the PV-BES systems is investigated by assuming different DR values ranging form 3 % to 9 %. Focusing on Chili campus, the corresponding results, i.e., $PV_{\text{size}}^{NPV_{\max}}$, $NPV_{\max}$, IRR and DPP for Scenario 1 to 3, are presented in Fig. 15.

According to Fig. 15, it can be observed that DR has a noticeable impact on the economic viability in all the examined scenarios, since the $NPV_{\max}$ is reduced as the DR increases reaching also negative values, as shown in Fig. 15b. This can be justified using (7), where it can be deduced that for a given PV_{size}, an increase of the DR

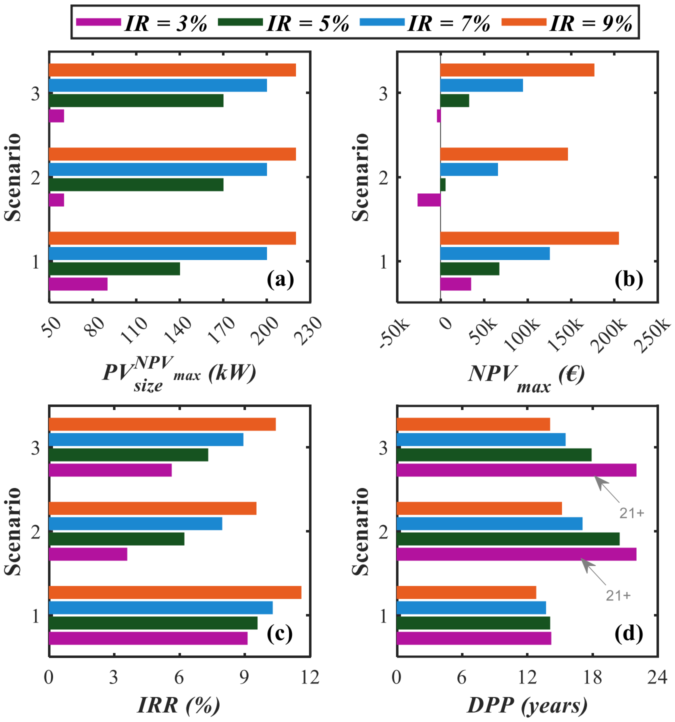

Figure 14: Results for the campus of Chili considering different IR values. (a) $PV_{\text{size}}^{NPV_{\max}}$, (b) $NPV_{\max}$, (c) IRR and (d) DPP.

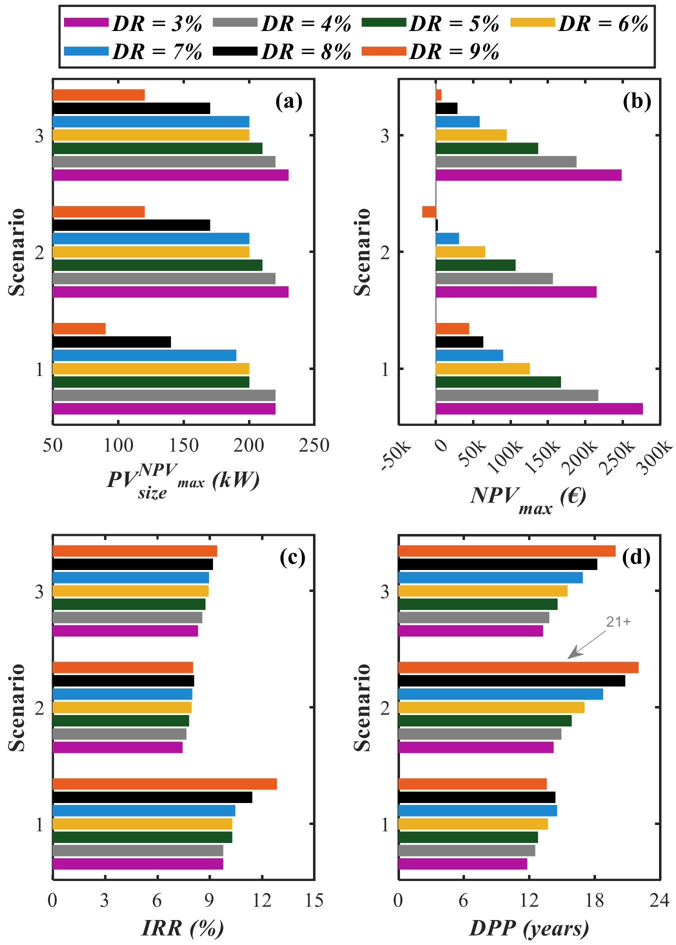

Figure 15: Results for the campus of Chili considering different DR values. (a) $PV_{\text{size}}^{NPV_{\max}}$, (b) $NPV_{\max}$, (c) IRR and (d) DPP.

leads to decreased discounted cash flows, and thus NPV. This also affects the $PV_{\text{size}}^{NPV_{\max}}$ which is reduced as the DR increases, as shown in Fig. 15a. Following a similar rationale, it can be shown that as the DR increases, higher DPP values occur as observed in Fig. 15d, since more years are needed to recover the initial investment cost due to the decreased discounted cash flows. On the contrary, the IRR is by definition not related to the DR, since this economic index is calculated by replacing DR with IRR in (7) and setting NPV equal to zero (see Section 4). However, an indirect relation exists, since the DR changes lead to different $PV_{\text{size}}^{NPV_{\max}}$, which, in turn, affects the IRR, as shown in Figs. 15a and 15c. It is worth mentioning that similar conclusions can be drawn for the rest DUTH campuses.

7. Conclusion

In this paper, a systematic techno-economic analysis is conducted to assess the viability of PV-BES investement plans of MV prosumers operating under the NEM compensation mechanism. In the study, nine university campuses are considered as the prospective PV-BES prosumers and different parameters influencing the profitability of investments are examined.

By analysing the calculated techno-economic indices it can be inferred that the NEM practice is a profitable policy that can lead to significant energy savings and revenues to prosumers with high load demand.

Results also reveal that the profitability of the investment is significantly determined by the BES cost. Presently, standalone PV systems result into higher revenues compared to PV-BES systems, as substantiated by the higher NPV calculations. Although, BES units alongside PVs result in increased SSR values, as the prosumer's grid dependence is limited, the viability of such systems cannot be guaranteed. This is attributed to the current market prices and the present Greek legislation regarding the NEM mechanism which cannot ensure the full recuperation of the capital PV-BES investment costs. Nevertheless, by shifting towards low-carbon energy systems, in the future significant BES cost reductions are expected. By examining such a scenario, results have shown that PV-BES MV prosumers can become cost-competitive with standalone PV systems. In particular, when electricity charging tariffs on the basis of both energy and power, i.e., MV prosumers, are considered, BES can be utilized to provide peak shaving ancillary services. This entails reduced energy imports from the grid, and in essence increased overall profits at the end of the lifetime of the investment.

In this context, as future investments are highly dependent on the existing economic conditions the effect of the inflation and discount rate has been also examined. It has been demonstrated that increasing inflation rates and decreasing discount rates result into increasing revenues for the prosumer and eventually render the NEM mechanism a viable support scheme.

Finally, the effect of prosumer's load demand growth and PV degradation on the techno-economic performance of the system have been also examined. Evidently, PV degradation is an important parameter that reduces the efficiency of the PV system. In line with the fact that the NEM is more profitable for prosumers with high demand, it can be also deduced that the load demand growth has a beneficial effect on NEM as the produced PV energy is exploited locally to cover the demand instead of being exported to the grid.

The proposed methodology and findings can be a useful tool and guide for interested parties, e.g., prosumers, PV ownwers, policy makers and market regulators.

8. Appendix

The general billing policy for MV users in Greece, depends on the MV end-users' needs. Therefore, several electricity tariffs are provided. Nevertheless, in general the total electricity charging, C_{retail}, is described by:

$$C_{\text{retail}} = C_{\text{supply}} + C_{\text{regulated}} + C_{\text{municipal}} \tag{13}$$

Here, C_{supply} is the supply charges and are calculated considering the cost of power, $C^{\text{power}}_{\text{supply}}$, and the cost of energy, $C^{\text{energy}}_{\text{supply}}$. $C^{\text{energy}}_{\text{supply}}$ is calculated by dividing the end-user's consumed energy, E^{load}, into the the base and peak load time zones; each of them with different prices.

Regulated charges, $C_{\text{regulated}}$, consist of the transmission network charges, distribution network charges, services of general interest, greenhouse taxes and other charges. Finally, $C_{\text{municipal}}$ refer to the municipal fees and taxes.

It must be indicated that the supply, regulated charges (apart from greenhouse taxes and other charges) and municipal fees and taxes are estimated in terms of E^{imp}. Greenhouse taxes and other charges are determined by using E^{load}. More information for the different types of costs is provided in [13].

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