Cost-effective rehabilitation of public buildings into smart and resilient nano-grids using storage

Thematic Objectives: B.4 - Environmental protection, climate change adaptation and mitigation (Address common challenges in environment)
Priority: B.4.3 - Support cost-effective and innovative energy rehabilitations relevant to building types and climatic zones, with a focus on public buildings
Countries: Cyprus, Greece, Israel, Italy

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4 Contents

1 Project summary

In an effort to address high energy consumption in the building sector that is mainly fossil – fuelled, support rural areas and areas powered by weak grids, which are common in the MENA region, and achieve higher grid penetration of renewable energy sources (RES) while maintaining grid stability and power quality, this project aims at the implementation of cross border pilots that will support innovative and cost – effective energy rehabilitation in public buildings based on the nanogrid concept. Thus, BERLIN project focuses on the increase of photovoltaics (PV) penetration, which coupled with energy storage and demand – side management (DSM) will increase the energy efficiency (EE) of the buildings. The implementation of these technologies in a cost – effective way will result in high level of self – resilient public buildings that are green, smart, innovative and sustainable. A total of 6 pilot buildings will be implemented: 1 in Cyprus, 2 in Greece, 2 in Israel and 1 in Italy.

The project has started in September 2019 and is expected to be completed within 48 months.

2 Introduction

The incorporation of renewable energy sources (RES) in the building sector has been a growing trend in recent years. This trend is driven by a variety of factors, including rising energy costs, a growing awareness of climate change issues, and the implementation of government policies and incentives. In this way, governments worldwide have implemented various policies and incentives to promote the integration of renewable energy in the building sector. These measures include tax credits, rebates, and financial incentives provided to building owners who choose to install renewable energy systems. Moreover, many countries have established building codes and regulations that mandate specific energy efficiency and renewable energy standards for new constructions.

In accordance with this approach, the present study evaluates the economic feasibility of integrating PV-battery systems in public buildings, considering the most current financial parameters met in countries of the Mediterranean region, such as systems cost and electricity tariffs. Specifically, a comprehensive techno-economic model that takes into consideration the flexibility of building loads is used to assess the financial viability of PV-battery systems in four countries, i.e., Cyprus, Greece, Italy and Israel. A sensitivity analysis is conducted to study the effect of load flexibility level on the economic profitability of such investments and on the highest energy self-sufficiency that can be reached by the buildings in these countries. Through this approach, a Cost-Benefit analysis for various combinations of PV and battery capacity systems is implemented to provide the most profitable system for each examined building and country.

3 Methodology.

3.1 Mathematical formulation

The main objective of this analysis is to determine the financial cost and benefit resulting from the installation of hybrid PV systems and batteries in public buildings. On one hand, the cost is calculated by the sum of the total extracted cash flows and the investment cost (C_{inv}) as described in (1):

$$Cost = \sum_{n=1}^{N}\left(\frac{C_{out}^{n}}{(1+i)^{n}}\right) + C_{inv} \qquad (1)$$

where C_{out}^{n} is the cash outflow in *n* year, *N* is the analysis period and finally, i is the discount rate, which is used to determine the present and future value. C_{out}^{n} includes the operation and maintenance costs of the investment as presented in (2), where a is the inflation rate. op_{pv}^{n} and op_{ess}^{n} are the operation and maintenance costs of the PV and battery systems, respectively.

$$C_{out}^{n} = \left(op_{pv}^{n} + op_{ess}^{n}\right)\cdot(1+a)^{n-1} \qquad (2)$$

$$C_{inv} = C_{inv,pv} + C_{inv,ess} \qquad (3)$$

Additionally, the investment cost is calculated by (3), where $C_{inv,pv}$ and $C_{inv,ess}$ are the capital investment costs of the PV and battery systems, respectively.

On the other hand, the benefit is the profit that is provided by the investment's contribution to the electricity cost avoidance:

$$Benefit = \sum_{n=1}^{N} \left(\frac{C_{in}^{n}}{(1+i)^{n}} \right) = \sum_{n=1}^{N} \left(\frac{e^{n} - e_{inv}^{n}}{(1+i)^{n}} \right) \quad (4)$$

where C_{out}^{n} is the cash inflow per year, which is calculated for each by the difference between the electricity cost before (e^{n}) and after the installation of the investment (e_{inv}^{n}). Actually, the revenues are calculated as the total electricity cost that is avoided because of the self-generated energy through the PV and the flexibility offered by the battery and the load management.

The electricity cost e^{n} is calculated by (5), where $E_{cons}(t)$ is the load consumption energy within period *t* that is purchased at an electricity price rate of $er(t)$ applied at period *t*. Moreover, *T* corresponds to the last time period of year *n*. On the other side, the electricity cost e_{inv}^{n} is calculated by (6), where $E_{imp}(t)$ is the energy imported from the grid to cover the electricity demand that is not covered by the PV, or the battery.

$$e^{n} = \sum_{t=1}^{T} E_{cons}(t)\, er(t)\, (1+a)^{(n-1)} \quad (5)$$

$$e_{inv}^{n} = \sum_{t=1}^{T} E_{imp}(t)\, er(t)\, (1+a)^{(n-1)} \quad (6)$$

The energy imported from the utility grid varies for different levels of load flexibility. Indeed, the daily energy imported from the grid is lower when load shifting is enabled, as shown in the compared cases of Fig. 1. It is noted that for a building with no PV battery and load flexibility, $E_{imp}(t) = E_{cons}(t)$, i.e., the area below the purple curve in Fig. 1a.

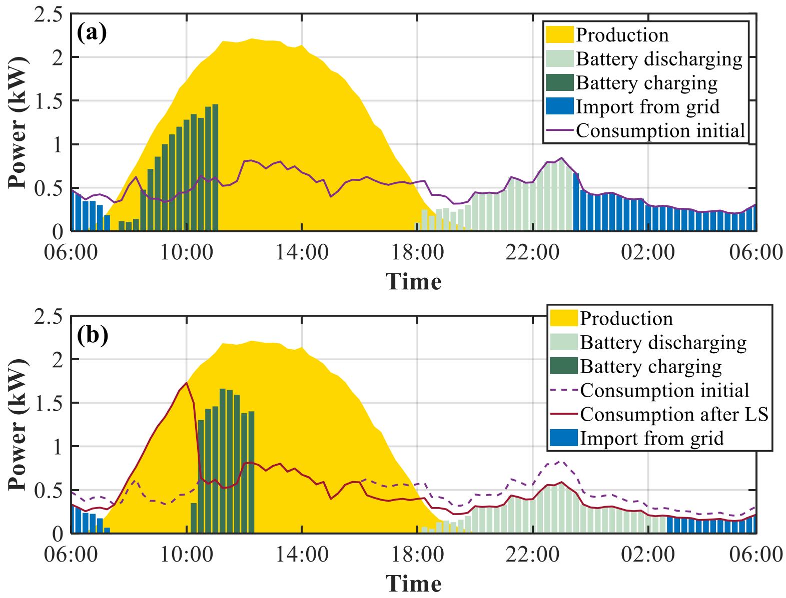

Figure 1 Indicative daily power curves for a building equipped with: (a) PV-battery system, (b) PV-battery system and load shifting (LS) capability.

Finally, the net present value (*NPV*) is a reliable financial criterion for evaluating the financial viability of an investment as shown by [1] and [2], which is calculated considering both the *Benefit* and the *Cost* of each investment. For this reason, the *NPV* is calculated according to (7):

$$NPV = Benefit - Cost = \sum_{n=1}^{N} \left(\frac{C_{in}^{n} - C_{out}^{n}}{(1+i)^{n}} \right) - C_{inv} \qquad (7)$$

Apart from the financial viability, this analysis also assesses the energy self-sufficiency which is provided in the examined building by the installation of the most profitable systems. To this end, the building's self-sufficiency rate (SSR) over period *T* is determined by (8). Here, *T* is considered as an annual period.

$$SSR = \frac{\sum_{t=1}^{T} E_{cons}(t) - \sum_{t=1}^{T} E_{imp}(t)}{\sum_{t=1}^{T} E_{cons}(t)} \qquad (8)$$

3.2 Analysis methodology

The basic concept is to examine several PV's and battery's size combinations by evaluating the economic viability of each investment under different conditions, as presented below:

- The first condition is the location of the examined investment. The production of photovoltaics is completely dependent on the levels of solar radiation and temperature that characterizes the installation area.

- The second one is the consumption profile of the building. The operation type of the examined building affects the energy consumption level and consequently, the result of the dimensioning process.
- Finally, the last condition is the electricity pricing mechanism and the installation cost.

In order to conduct a financial assessment under different conditions, this report examines the installation of hybrid PV and battery systems in public buildings from four different countries (Greece, Cyprus, Italy, and Israel), which are the participating countries in the BERLIN project. In this way, different economic parameters, such as electricity pricing mechanisms and installation costs are considered. Moreover, the actual consumption behavior of the buildings located in the examined countries is considered, based on real electrical consumption measurements of at least one year. The typical PV production curves of the exact location of each building are taken also into account based on the solar irradiance database of PVGIS [3] for all countries except Greece, where real measurements of PV production are utilized.

According to [4], the consideration of demand side management (DSM) in sizing process could, also, increase the benefits of the examined investment. One of the ambitions of this report is to determine the impact of flexibility on the benefits derived by investing in PV-battery systems. To achieve this, we examine different load flexibility levels (0%, 25% and 50%). The DSM strategy implemented in this analysis is based on [4] (see Section III.A in [4]). Specifically, we consider the flexible load consumption as a percentage of the total demand energy that can be shifted towards the PV production time period.

The determination of the financial performance of each investment is a complex process because it requires the consideration of several parameters. Table I presents the parameters considered in this analysis.

Table I: Input parameters

System Parameter	Input Value
PV	Degradation rate [%] Inverter efficiency [%] Minimum size [kWp] Maximum size [kWp] Size step [kWp]
BESS	Usable capacity [%] Maximum charge power [% of rated capacity] Maximum discharge power [% of rated capacity] Lifecycles Round trip efficiency [%] Maximum size [kWh] Size step [kWh]
Flexibility	Load flexibility level within 00:00 – 08:00 [%]

	Load flexibility level within 16:00 – 24:00 [%]
Electricity costs	Number and range of tariff zones Electrical energy cost per tariff zone [€/kWh] Electrical networks cost per tariff zone [€/kWh] Taxes on electrical energy [€/kWh] VAT of electricity prices [%]
Financial	PV system (incl. hybrid inverter) cost [€/kWp] BESS system cost [€/kWh] Annual decrease of BESS cost [%] Annual operation & maintenance cost [% of total cost] Discount rate [%] Inflation rate [%] Inflation rate for electricity costs [%] Subsidy for investment [% of total cost]
RES Policy	Added cost [€/year] Added income [€/year] Compensation for exported PV energy [€/kWh]
Feasibility assessment	Analysis period [years] Time step [min.]

3.3 Input parameters data

The present report considers a range of technical and financial parameters, as indicated in Table I, to accurately assess the performance of the installed PV and battery systems and their impact on the financial evaluation. Parameters such as the degradation of the PV system, the hybrid inverter losses, the battery roundtrip efficiency, and the battery maximum power are taken into account in the financial analysis. For a comprehensive understanding, the detailed parameters and their corresponding values are presented in Table II.

Table II: Input parameters values

Input parameter	**Value**
Annual PV degradation rate	0.2%
Inverter efficiency	95%
BESS usable capacity	80% (i.e., SoC range 10% to 90%)
BESS roundtrip efficiency	80%
BESS maximum charge power	67%
BESS maximum discharge power	67%
BESS lifecycles	8000
Annual decrease of BESS cost	8%
Annual operation & maintenance cost	2%
Discount rate	4%

Inflation rate	2%
Inflation rate for electricity costs	2%
Subsidy	0%
Added cost / added income	0 / 0
Compensation for exported energy	0 €/kWh
Analysis time period	20 years

4 Cost-Benefit analysis in countries of the Mediterranean region considering load flexibility

4.1 Greece

The building of the student dormitories of University of Western Macedonia, which was selected as a pilot site of the BERLIN project, is examined in this section. The examined building is located near Kozani at 40°18'01.85"N 21°47'21.81"E. The weather conditions prevailing in the area determine a typical daily production curve which is taken into account in the analysis. The typical daily production curve for a winter and summer day per 1 kWp is presented in Figure 2a. According to these data, the annual production of 1 kWp PV is determined - excluding the inverter losses - at 1,547 kWh.

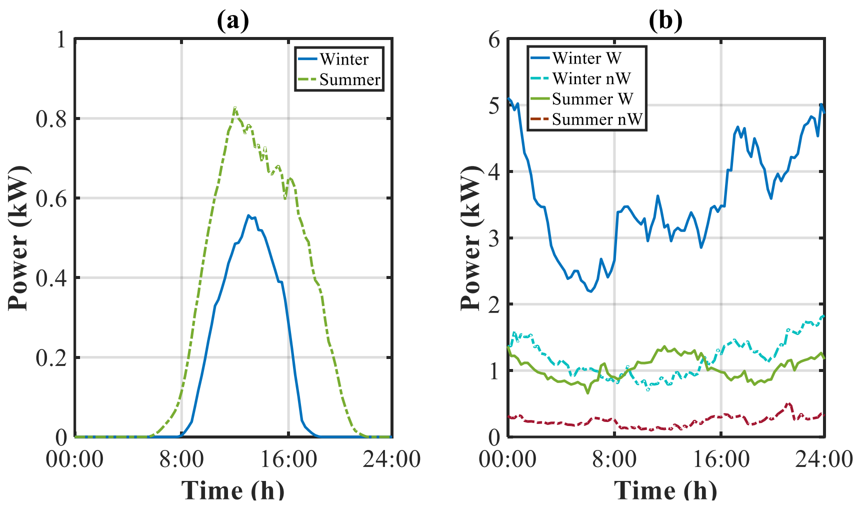

Figure 2 Daily typical (a) production and (b) consumption curves in Greece.

On the other hand, Figure 2b shows the typical daily consumption curves for working and non-working winter and summer day (January and July). It is worth noting that the academic period ends at summer, and the students are moving out of the examined building. For this reason, the building's consumption is quite reduced on summer days as shown in Figure 1b. Finally, the annual consumption of the examined building is 15,173 kWh.

Table II shows the financial parameters which are defined in Greece. The total electricity price including the VAT is calculated at 0.25487 €/kWh. In addition, the installation cost of PV and Battery system is defined at 1000 €/kWp and 550 €/kWh, respectively.

Table III: Financial parameters in Greece.

Tariffs	Electrical energy cost [€/kWh]	0.196
	Electrical networks cost [€/kWh]	0.02744
	Taxes on electrical energy [€/kWh]	0.017
VAT	[%]	6
PV installation cost	[€/kWp]	1000
Battery installation cost	[€/kWh]	550

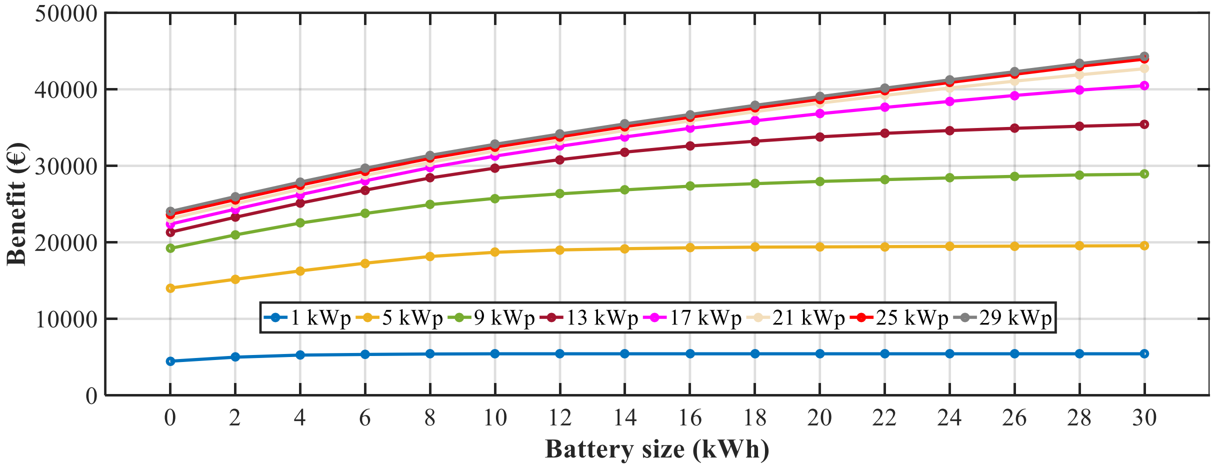

Figure 3 Greece: Benefit for 0% flexibility.

Considering these parameters, a sensitivity analysis with different sizes of hybrid PV and battery systems is performed. In this way, Figure 3 shows the *Benefit* which is calculated by different combinations of PV and battery capacities. According to this figure, increasing the battery capacity in the cases where PV size is between 17 and 29 kWp, the financial benefit is also increased. Although the benefit increases for 5, 9 and 13 kWp PV size, with increasing battery capacity until the 14 kWh, the benefit remains almost constant for further battery increase. Furthermore, none of battery capacities could increase the *Benefit* on PV size at 1 kWp. The reason for this is that the energy produced by the PV system is consumed directly to supply the household's energy demand. As a result, the potential advantages of having a battery system installed are not utilized in the case of such a low PV capacity.

On the other hand, the *Cost* is increased by the installation of larger PV and battery systems as shown in Table III. In more detail, Table III shows the *Cost* of the examined hybrid PV and battery systems. Based on *Benefit* and *Cost* results, we can conclude that different combinations could provide similar *Benefit* with different *Cost*. Specifically, the red and grey lines in Figure 3 are similar, which means that installing a 17 kWp PV in the examined building in Greece, could provide the similar *Benefit* as the installation of a 29 kWp PV. However, the *Cost* of the investment with 29 kWp PV is higher than the other one, reducing thus its economic effectiveness.

Table IV: Greece: Cost defined by the combination of the examined hybrid PV and battery sizes (in €).

BESS size (kWh) \ PV size (kWp)	1	5	9	13	17	21	25	29
0	1,322	6,609	11,896	17,184	22,471	25,758	33,046	38,333
2	2,776	8,063	13,351	18,638	23,925	27,213	34,500	39,787
4	4,230	9,517	14,805	20,092	25,379	28,667	35,954	41,241
6	5,684	10,971	16,259	21,546	26,833	30,121	37,408	42,695
8	7,138	12,425	17,713	23,000	28,287	31,575	38,862	44,149
10	8,592	13,879	19,167	24,454	29,741	33,029	40,316	45,603
12	10,046	15,333	20,621	25,908	31,195	34,483	41,770	47,057
14	11,500	16,787	22,075	27,362	32,649	35,937	43,224	48,511
16	12,954	18,241	23,529	28,816	34,103	37,391	44,678	49,965
18	14,408	19,695	24,983	30,270	35,557	38,845	46,132	51,419
20	15,862	21,149	26,437	31,724	37,011	40,299	47,586	52,873
22	17,316	22,603	27,891	33,178	38,465	41,753	49,040	54,327
24	18,770	24,057	29,345	34,632	39,919	43,207	50,494	55,781
26	20,224	25,511	30,799	36,086	41,373	44,661	51,948	57,235
28	21,678	26,965	32,253	37,540	42,827	46,115	53,402	58,689
30	23,132	28,419	33,707	38,994	44,281	47,569	54,856	60,143

Enabling load shifting, a portion of the total energy demand shifts towards the energy production hours and is covered by own production. Thus, a higher PV capacity and/or a lower BESS capacity may be required when comparing with the case of zero flexibility. In more details, Figures 4 and 5 present the *Benefit* provided by the already examined system capacities, considering now a flexibility level of 25% and 50%, respectively. Upon comparing Figures 3-5, it can be observed that the increase in flexibility contains two important advantages:

a) the *Benefit* of the investment is enhanced, and
b) the necessity for the battery installation is reduced, improving thus the investment's economic viability through the reduction of *Cost*.

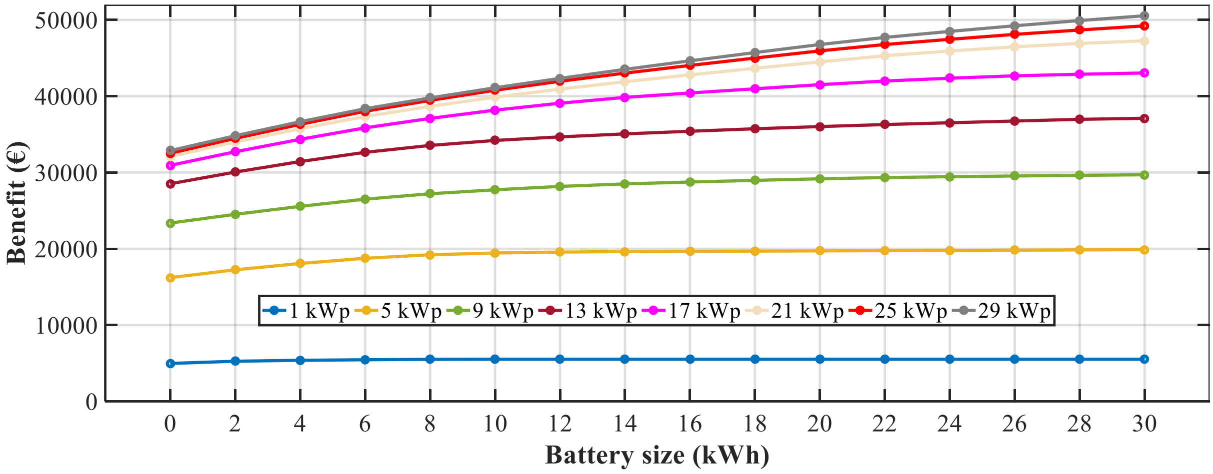

Figure 4 Greece: Benefit for 25% flexibility.

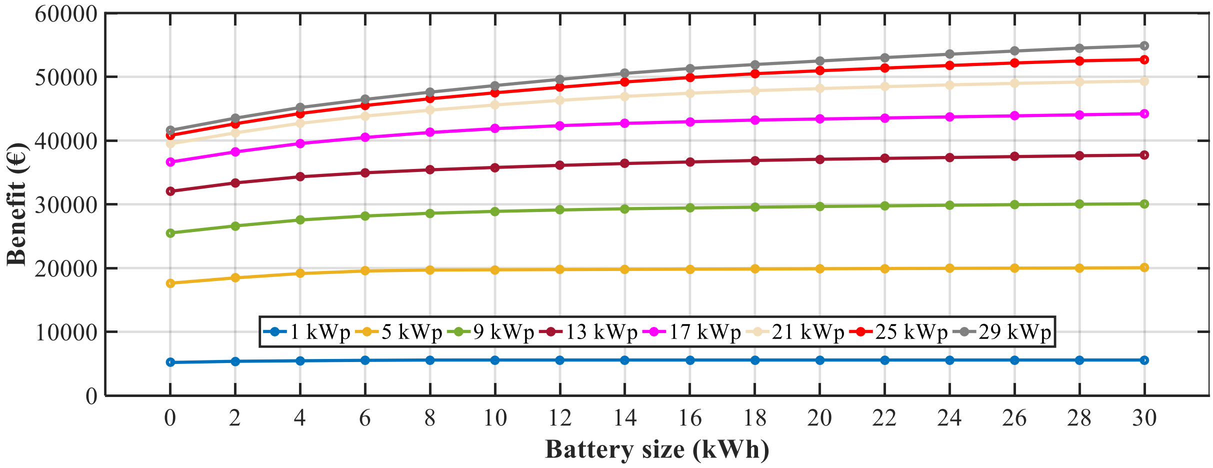

Figure 5 Greece: Benefit for 50% flexibility.

The *NPV* is a reliable financial criterion for the effectiveness of an investment which considers both the *Benefit* and the *Cost* of the investment. The *NPV* of the investment in the building in Greece is depicted in Figure 6 for the different PV and battery sizes examined, when no load shifting is available. The *NPV* rises as the PV size increases up to 9 kWp, while for larger PV capacities it decreases. The most profitable choice is the combination of a 9 kWp PV with a 4 kWh battery, providing 7,710 €. For larger batteries, *NPV* decreases due to the increasing total cost of the battery system. It should be noticed that the 9 kWp–4 kWh PV-battery system differs only by 402€ from the choice to install a 9 kWp PV with no battery system, denoting that battery systems are expensive for integration into buildings in Greece.

When examining a flexibility level of 25%, the most profitable system capacity is 9 kWp–0 kWh, providing *NPV* of 11,473 €, as depicted in Figure 7. It is seen that the ideal PV capacity remains the same while the battery is no longer profitable. In case the load flexibility is even higher, i.e., 50%, more

PV battery size combinations become cost-effective, as demonstrated in Figure 8. Furthermore, *NPV* of the PV-battery solutions is generally increased in comparison with the previous flexibility levels. Here, the most profitable solution is a 13 kWp–0 kWh system with *NPV* =14,844 €.

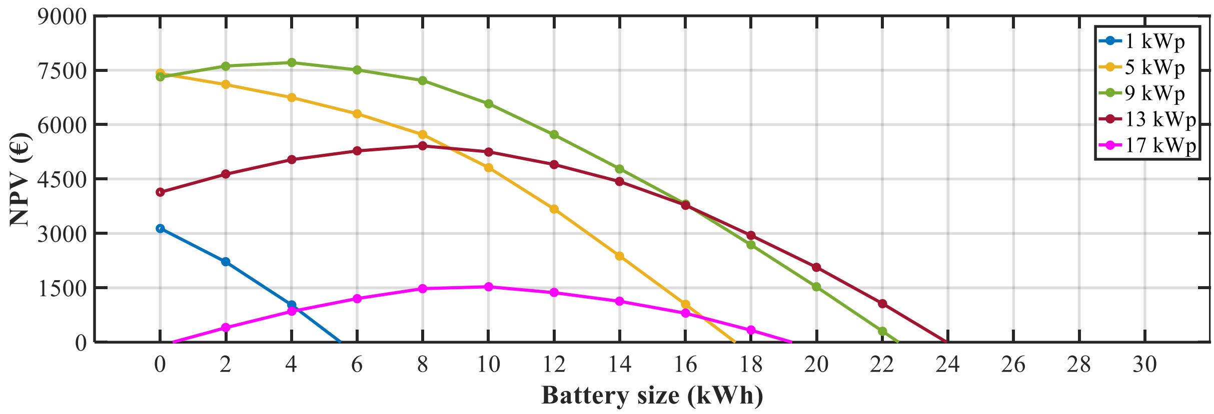

Figure 6 Greece: NPV analysis for 0% flexibility.

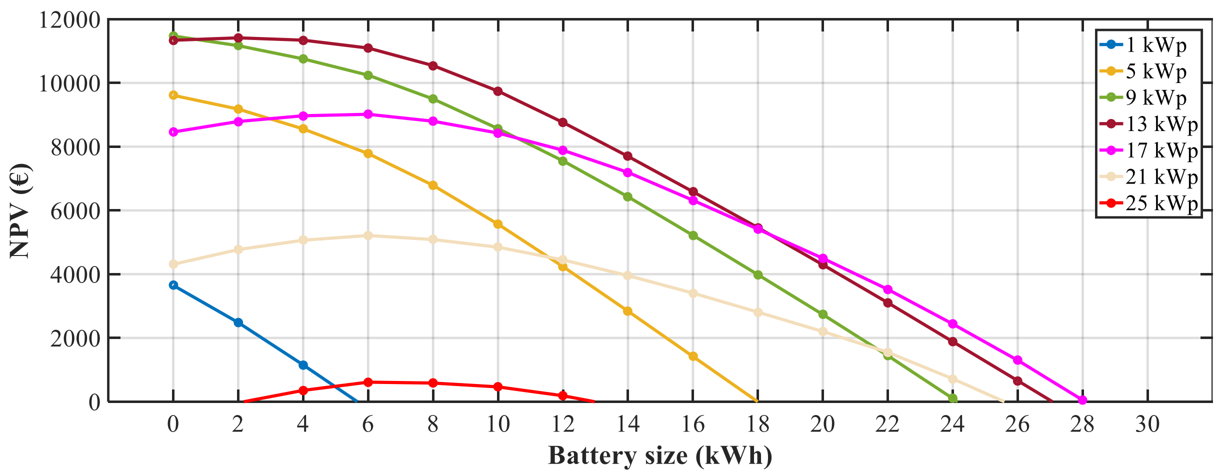

Figure 7 Greece: NPV analysis for 25% flexibility.

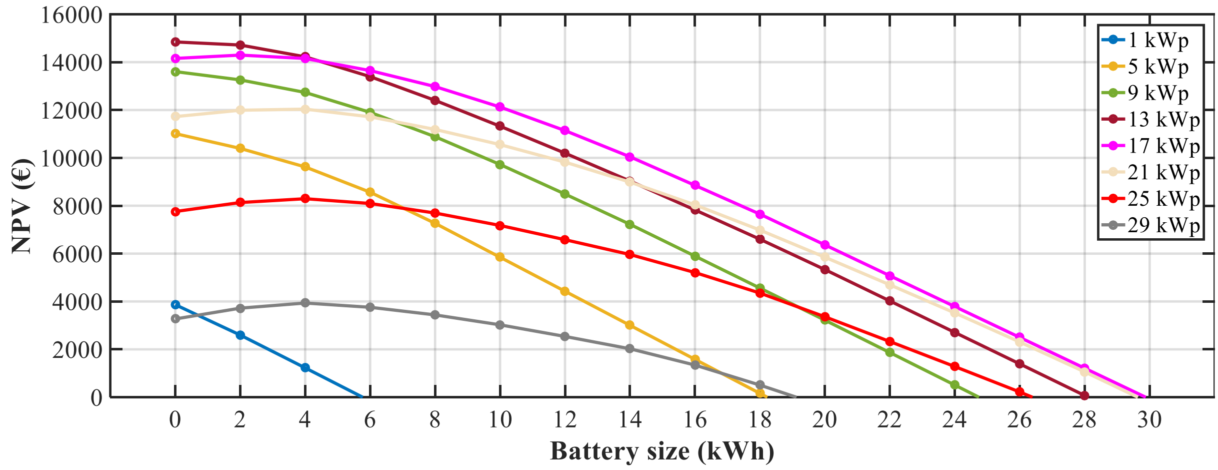

Figure 8 Greece: NPV analysis for 50% flexibility.

Finally, Table IV gathers the most profitable solutions for the examined building under flexibility levels of 0%, 25% and 50%. As already stated, in case where building's consumption is not flexible, the optimal combination of PV-battery to be installed is 9 kWp and 4 kWh, providing 7,710 €. Additionally, this solution reaches the building's SSR at 38%. The investment cost of this solution is determined at 11,200 € and can be paid back in 8.77 years. Considering the flexibility level at 25%, the optimal solution is 9 kWp and 0 kWh, providing *NPV* = 11,475 € and *SSR* = 40%. The consideration of flexibility reduces the need for the installation of battery, but it exploits a higher part of the PV production compared to the optimal solution without load flexibility as observed by the increase in the resulted SSR. Finally, examining a higher flexibility i.e., 50%, the best *NPV* is 14,844 € and is provided by 13 kWp and 0 kWh. This solution could provide a SSR of 54%. The high flexibility level contributes to the further exploitation of PV production, proposing a higher PV size as the optimal one. In this way, the building does not require a battery system to exploit the PV production, thus reducing the total installation cost.

Table V: Greece: Optimal solution based on the maximization of building's NPV.

	flexibility percentage (%)		
	0	**25**	**50**
Optimal PV size [kWp]	9	9	13
Optimal BESS size [kWh]	4	0	0
Optimal NPV [€]	7,710	11,473	14,844
Internal Rate of Return [%]	10.32	14.88	13.89
Simple payback period [years]	8.77	6.62	7.01
Investment cost [€]	11,200	9,000	13,000
SSR (evaluated, not optimized) [%]	38.09	39.67	54.36

4.2 Cyprus

In Cyprus, the examined installation are the buildings that host the PV Lab of the FOSS Research Centre for Sustainable Energy of the University of Cyprus (UCY), situated at coordinates 35°08'45.69"N 33°25'0.43"E. The performance of a PV system is influenced by the prevailing weather conditions in the area. To account for this, a typical daily production curve for each month is determined and used in this analysis. A typical daily production curve for a winter and for a summer day (December and June, respectively) is presented in Figure 9a by the blue solid and green dotted line, respectively. In the same way, the typical daily consumption curves for working and non-working winter and summer day (December and June, respectively) are shown in Figure 9b. Furthermore, the annual production energy per kWp and the annual consumption energy for the examined research center are calculated at 1,916 kWh and 36,526 kWh, respectively.

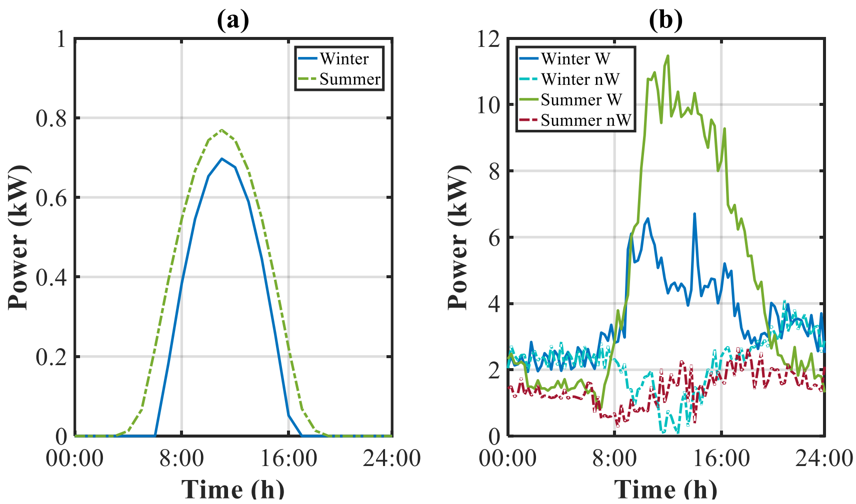

Figure 9 Daily typical (a) production and (b) consumption curves in Cyprus.

Table V shows the financial parameters which are defined in Cyprus. Thus, the total electricity price including the VAT is determined at 0.36849 €/kWh. The installation cost of PV and Battery system in this country is defined at 900 €/kWp and 650 €/kWh, respectively.

Table VI: Financial parameters in Cyprus.

Tariffs	Electrical energy cost [€/kWh]	0.1035
	Electrical networks cost [€/kWh]	0.0302
	Taxes on electrical energy [€/kWh]	0.175954
VAT	[%]	19
PV installation cost	[€/kWp]	900
Battery installation cost	[€/kWh]	650

The profitability of PV and battery systems in the study case in Cyprus differs from the Greek study case since the consumption of the examined building in Cyprus is twice and the electricity tariff is 45% higher. For these reasons, systems with higher PV and BESS size are expected to provide high *Benefit* to the building. In this way, Figure 10 depicts the *Benefit* provided by the most profitable combinations of PV and battery capacities. Indeed, as shown in Figure 10, the *Benefit* in case of Cyprus is significantly increased compared to the Greek one.

One notable observation is that increasing the size of the battery has a significantly positive impact on the *Benefit* for all PV sizes illustrated in Figure 10. However, once the battery size exceeds 96 kWh in the examined PV systems, the *Benefit* seems to level off and remain constant. Enabling the load shifting, the battery usage is decreased, and, thus, the critical battery size, above which the *Benefit* remains constant, is also decreased. Specifically, in the case that the flexibility level is at 25%, the *Benefit* for all considered PV remains unaffected when the battery size exceeds the 60 kWh as shown in Figure 11. In the same way, the *Benefit* remains constant when the battery size exceeds 24 kWh, as depicted in Figure 12 for the case of 50% flexibility.

Although the critical battery size is different for each flexibility level, the maximum *Benefit* at each flexibility level is similar approaching 216,600 €. Therefore, considering the load shifting, the building could achieve the maximum *Benefit* by purchasing lower battery capacities. By purchasing a BESS with reduced capacity, the *Cost* is also reduced as demonstrated in Table VI. This approach allows for a more economically viable investment in the hybrid PV-battery system.

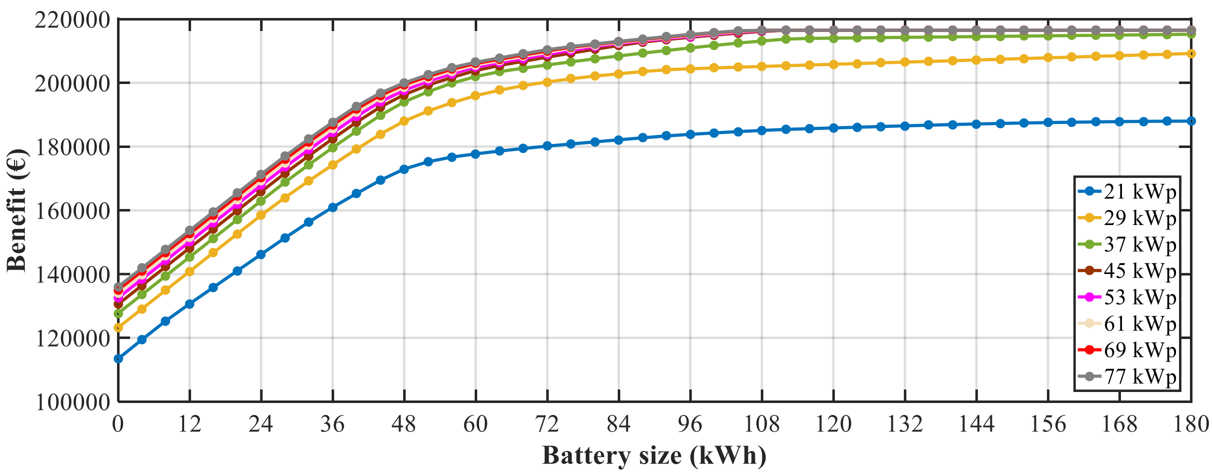

Figure 10 Cyprus: Benefit for 0% flexibility.

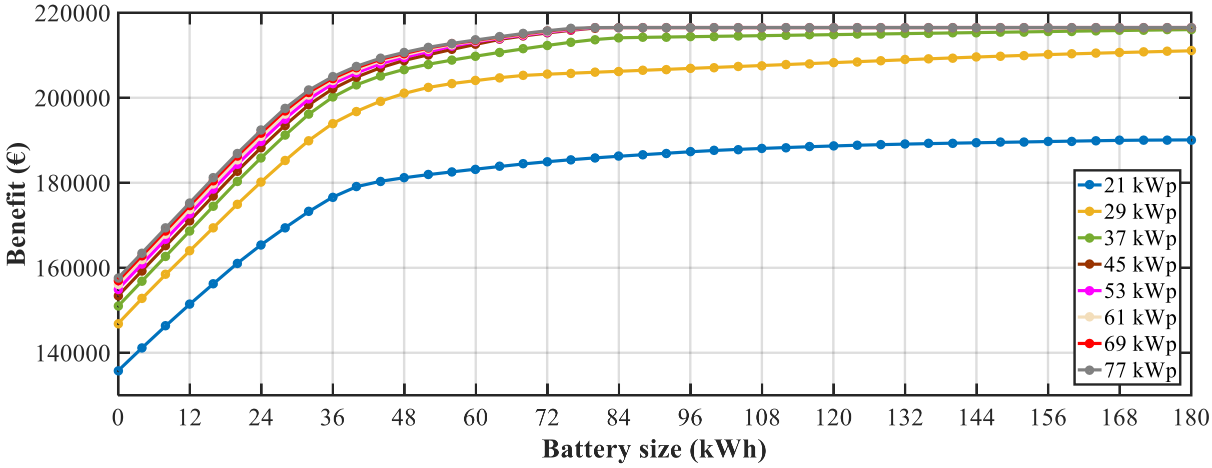

Figure 11 Cyprus: Benefit for 25% flexibility.

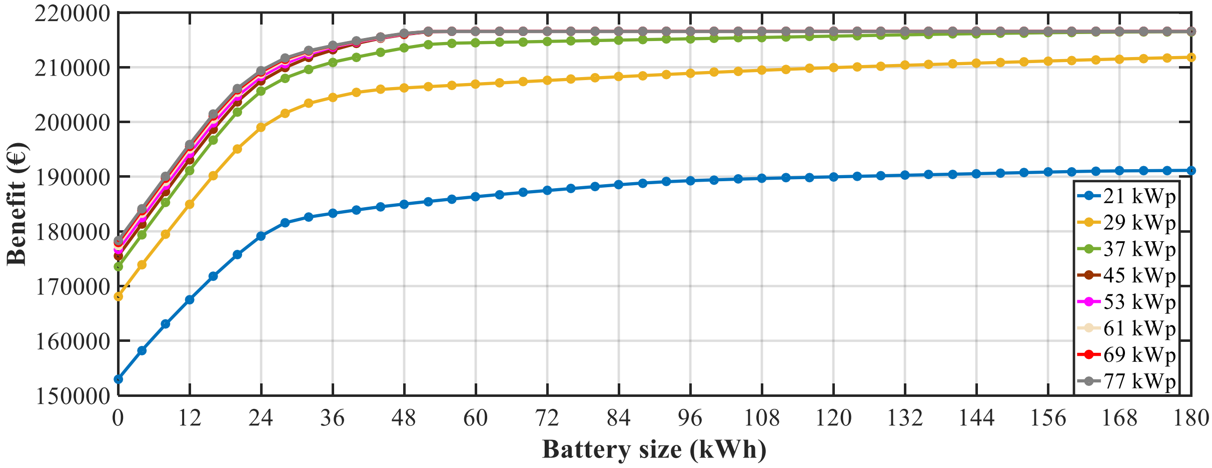

Figure 12 Cyprus: Benefit for 50% flexibility.

Table VII: Cyprus: Cost defined by the combination of the examined hybrid PV and battery sizes (in €).

BESS size (kWh) \ PV size(kWp)	21	29	37	45	53	61	69	77
0	24,983	34,500	44,017	53,534	63,051	72,569	82,086	91,603
12	35,293	44,810	54,327	63,845	73,362	82,879	92,396	101,913
24	45,603	55,120	64,638	74,155	83,672	93,189	102,706	112,224
36	55,914	65,431	74,948	84,465	93,982	103,500	113,017	122,534
48	66,224	75,741	85,258	94,775	104,293	113,810	123,327	132,844
60	76,534	86,051	95,569	105,086	114,603	124,120	133,637	143,155
72	86,844	96,362	105,879	115,396	124,913	134,430	143,948	153,465
84	97,155	106,67	116,189	125,706	135,224	144,741	154,258	163,775
96	107,47	116,98	126,499	136,017	145,534	155,051	164,568	174,085
108	117,78	127,29	136,810	146,327	155,844	165,361	174,879	184,396
120	128,09	137,60	147,120	156,637	166,154	175,672	185,189	194,706
132	138,40	147,91	157,430	166,948	176,465	185,982	195,499	205,016
144	148,71	158,22	167,741	177,258	186,775	196,292	205,809	215,327
156	159,02	168,53	178,051	187,568	197,085	206,602	216,120	225,637
168	169,33	178,84	188,361	197,878	207,396	216,913	226,430	235,947
180	179,64	189,15	198,672	208,189	217,706	227,223	236,740	246,257

As presented in Figure 13, the most profitable solution is a system of 29 kWp–48 kWh where *NPV* = 112,235 €. It is also observed that for each one of the PV sizes illustrated in Figure 13, there is a battery capacity in the range of 44–48 kWh that maximizes the investment profitability. The battery capacity remains almost constant for the various PV sizes, since it is used in all cases to cover almost the same amount of load energy, i.e., the building load demand that does not match with the PV production time period. This characteristic battery size decreases as the load flexibility increases, since a larger portion of demand energy is shifted and supplied directly by the produced energy. Indeed, Figure 14 depicts that this characteristic capacity lies between 32–36 kWh in the case of 25% load flexibility and between 20–24 kWh when the flexibility level is 50%, as seen in Figure 15. However, it should be noted that this characteristic battery capacity depends also on the battery investment cost.

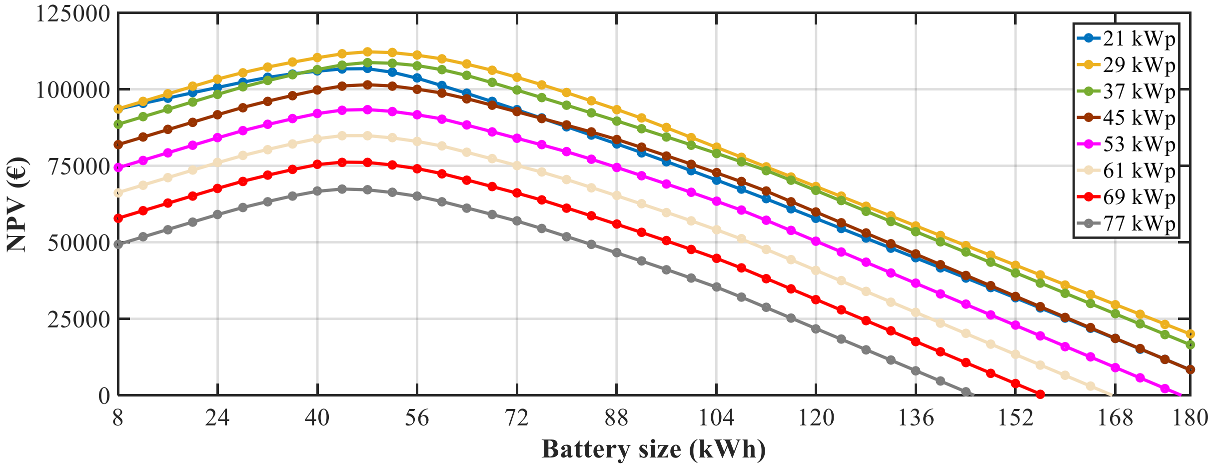

Figure 13 Cyprus: NPV analysis for 0% flexibility.

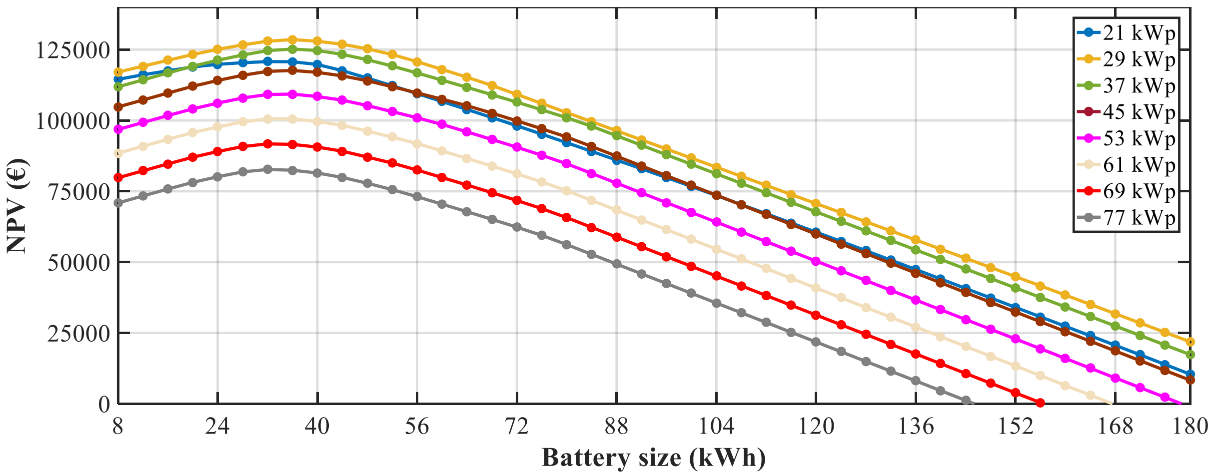

Figure 14 Cyprus: NPV analysis for 25% flexibility.

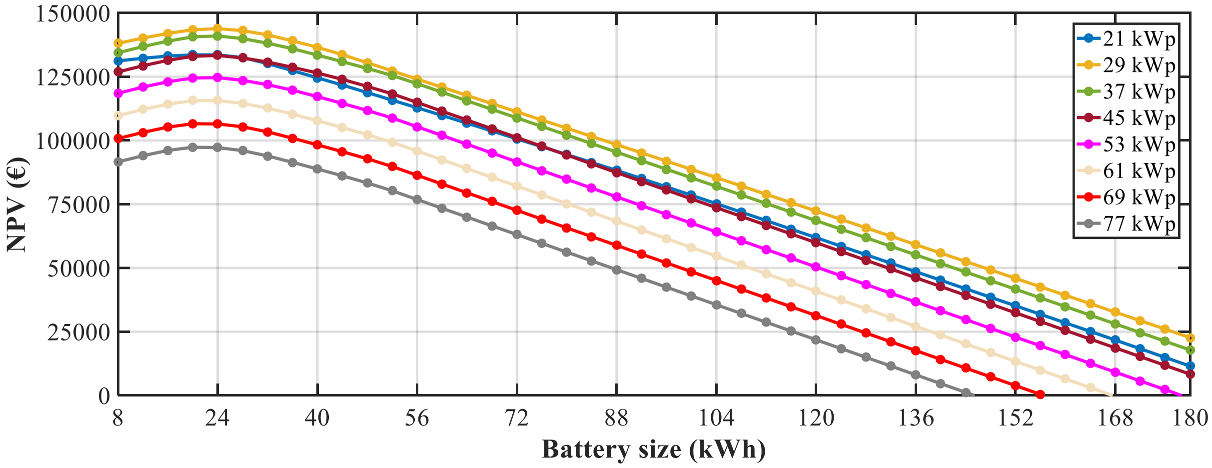

Figure 15 Cyprus: NPV analysis for 50% flexibility.

Examining the PV-battery solution that provides the maximum *NPV*, it is noticed in Table VIII that 29 kWp is the ideal size for all flexibility levels, while the ideal battery size is 48 kWh, 36 kWh, and 24 kWh, for load flexibility equal to 0%, 25%, and 50%, respectively. The self-sufficiency increases as the battery size, or the flexibility level expands. Thus, to achieve *SSR*=87%–92%, the building owner could install lower battery size with lower investment cost and finally greater *NPV*, by adding flexible loads, as highlighted in Table VIII.

Table VIII: Cyprus: Optimal solution based on the maximization of building's NPV.

	flexibility percentage (%)		
	0	**25**	**50**
Optimal PV size [kW]	29	29	29
Optimal BESS size [kWh]	48	36	24
Optimal NPV [€]	112,235	128,521	143,853
Internal Rate of Return [%]	19.67	23.94	29.48
Payback period [years]	5.20	4.31	3.51
Investment cost [€]	57,300	49,500	41,700
SSR (evaluated, not optimized) [%]	87.12	89.87	92.18

4.3 Italy

The building selected as study case in Italy is characterized by high consumption, reaching the annual consumption energy at 343,500 kWh. As a point of comparison, this consumption is almost 10 times higher than the consumption of the building in Cyprus and 22 times higher than the Greek one. In more details, the typical daily consumption curves for working and non-working winter and summer day (January and July) are shown in Figure 16b. On the other hand, the typical daily production curve for a winter and for a summer day per 1 kWp is also illustrated in Figure 16a. According to these data, the annual production of 1 kWp PV is determined - excluding the inverter losses - at 1,909 kWh.

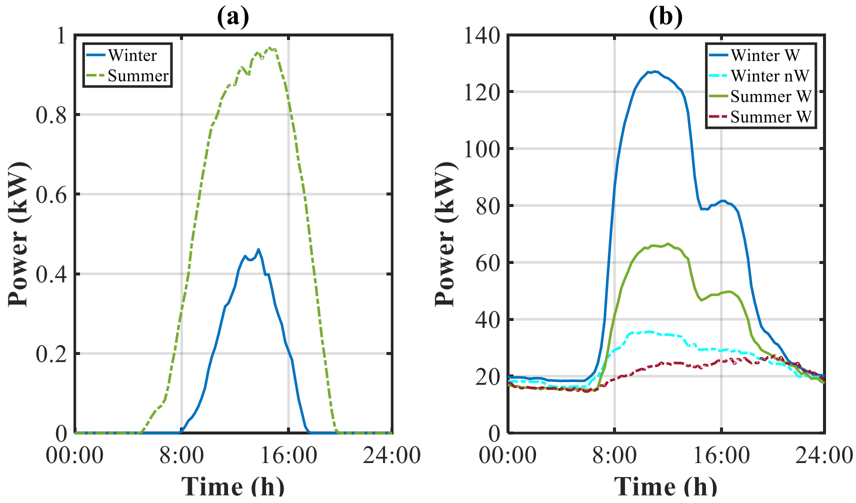

Figure 16 Daily typical (a) production and (b) consumption curves in Italy.

Table IX shows the financial parameters used in the case of Italy. The total electricity price including the VAT is determined at 0.57858 €/kWh which is relatively high. This high electricity cost is expected to encourage the installation of high-capacity PV-battery systems to improve the building's self-sufficiency and consequently, reduce the amount of energy purchased from the grid. On the other side, the installation cost of PV and battery is the highest compared to other cases, thus challenging the financial feasibility of large systems. It is noted that the electricity cost used in this case study corresponds to the electricity tariffs existing in Italy during the first quarter of 2023 and happened to be extremely increased compared to all other periods of the previous years. Since then, the electricity tariffs have been decreased.

Table IX: Financial parameters in Italy.

Tariffs	Electrical energy cost [€/kWh]	0.4349
	Electrical networks cost [€/kWh]	0.0399
	Taxes on electrical energy [€/kWh]	0.05118
VAT	[%]	10
PV installation cost	[€/kWp]	1322
Battery installation cost	[€/kWh]	676

Figures 17-19 present the *Benefit* provided by the most profitable combinations of PV and battery capacities under flexibility levels of 0%, 25% and 50%, respectively. Due to the high electricity price, the *Benefits* are quite higher than these of the other examined countries. According to these figures, it is noteworthy that increasing the size of the battery the *Benefit* rises. However, once the battery size exceeds a limit, the *Benefit* seems to level off and remain constant. Specifically, in the case that the flexibility level is at 25%, the *Benefit* for examined PV sizes becomes constant when the battery size exceeds the 430 kWh as shown in Figure 18. In the same way, the *Benefit* remains constant when the battery size exceeds the 330 kWh as depicted in Figure 19. Consequently, enabling load shifting, the battery utilization is decreased, and the maximum *Benefit* could be achieved employing lower battery capacities. With lower battery sizes, the *Cost* is also reduced as depicted in Table X, thus facilitating the financial feasibility in these systems.

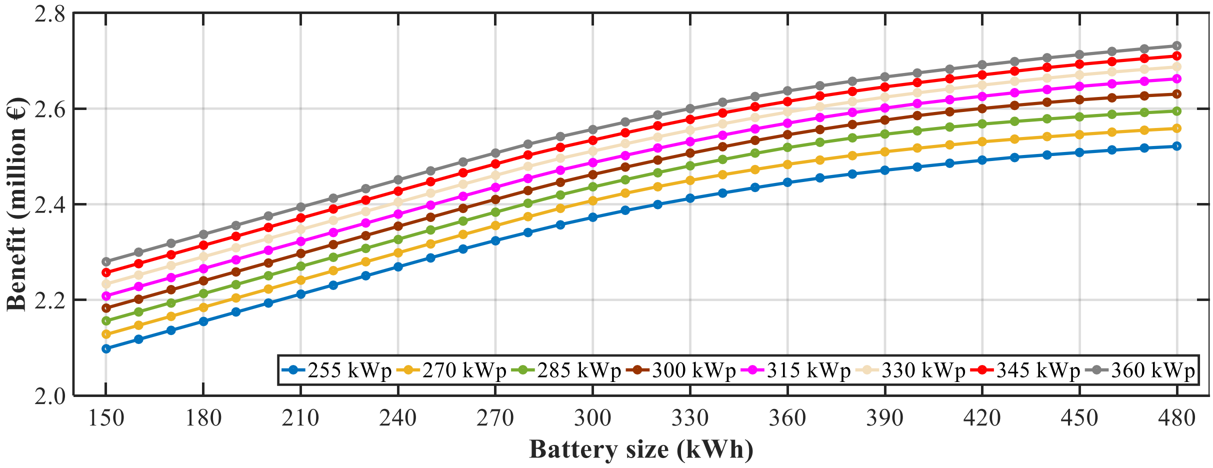

Figure 17 Italy: Benefit for 0% flexibility.

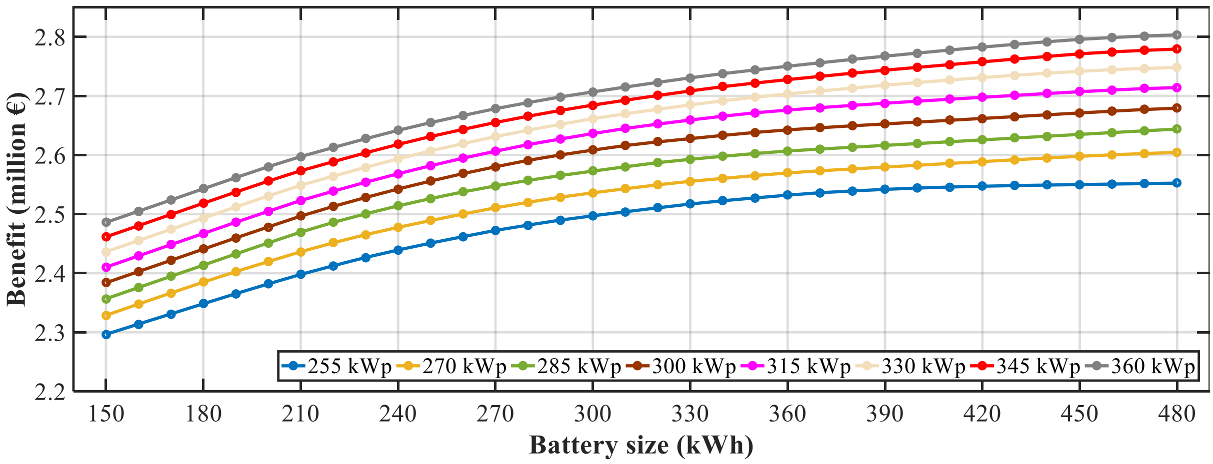

Figure 18 Italy: Benefit for 25% flexibility.

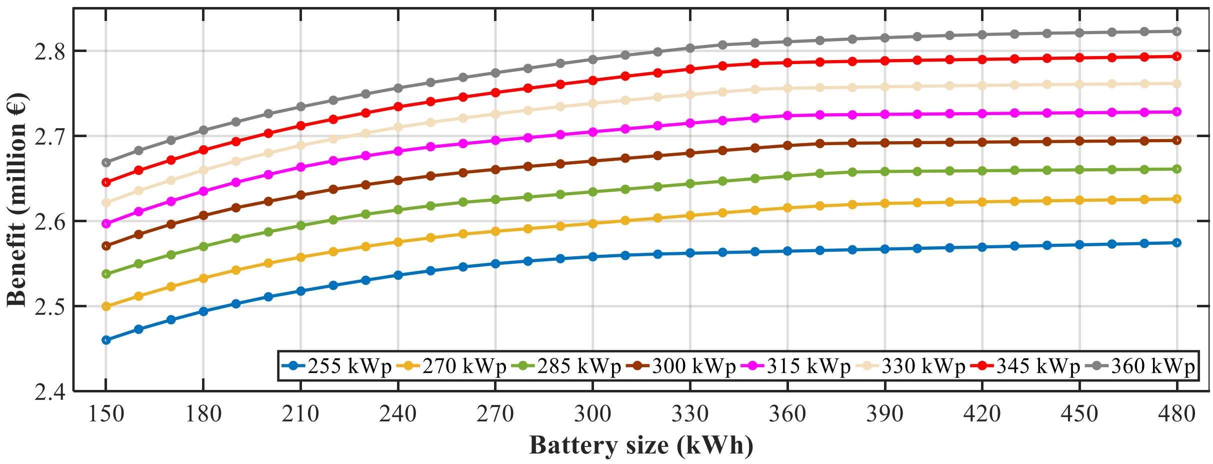

Figure 19 Italy: Benefit for 50% flexibility.

Table X: Italy: Cost defined by the combination of the examined hybrid PV and battery sizes (in €).

Battery size (kWh)	PV size (kWp)							
	255	270	285	300	315	330	345	360
150	579,637	605,849	632,061	658,273	684,485	710,697	736,909	763,121
160	588,573	614,785	640,996	667,208	693,420	719,632	745,844	772,056
170	597,508	623,720	649,932	676,144	702,356	728,568	754,780	780,992
180	606,444	632,656	658,868	685,080	711,292	737,504	763,715	789,927
190	615,379	641,591	667,803	694,015	720,227	746,439	772,651	798,863
200	624,315	650,527	676,739	702,951	729,163	755,375	781,587	807,799
210	633,251	659,462	685,674	711,886	738,098	764,310	790,522	816,734
220	642,186	668,398	694,610	720,822	747,034	773,246	799,458	825,670
230	651,122	677,334	703,546	729,758	755,970	782,181	808,393	834,605
240	660,057	686,269	712,481	738,693	764,905	791,117	817,329	843,541
250	668,993	695,205	721,417	747,629	773,841	800,053	826,265	852,477
260	677,928	704,140	730,352	756,564	782,776	808,988	835,200	861,412
270	686,864	713,076	739,288	765,500	791,712	817,924	844,136	870,348
280	695,800	722,012	748,224	774,436	800,647	826,859	853,071	879,283
290	704,735	730,947	757,159	783,371	809,583	835,795	862,007	888,219
300	713,671	739,883	766,095	792,307	818,519	844,731	870,943	897,154
310	722,606	748,818	775,030	801,242	827,454	853,666	879,878	906,090
320	731,542	757,754	783,966	810,178	836,390	862,602	888,814	915,026
330	740,478	766,690	792,902	819,113	845,325	871,537	897,749	923,961
340	749,413	775,625	801,837	828,049	854,261	880,473	906,685	932,897
350	758,349	784,561	810,773	836,985	863,197	889,409	915,621	941,832
360	767,284	793,496	819,708	845,920	872,132	898,344	924,556	950,768
370	776,220	802,432	828,644	854,856	881,068	907,280	933,492	959,704
380	785,156	811,368	837,579	863,791	890,003	916,215	942,427	968,639
390	794,091	820,303	846,515	872,727	898,939	925,151	951,363	977,575
400	803,027	829,239	855,451	881,663	907,875	934,087	960,298	986,510
410	811,962	838,174	864,386	890,598	916,810	943,022	969,234	995,446
420	820,898	847,110	873,322	899,534	925,746	951,958	978,170	1,004,382
430	829,834	856,045	882,257	908,469	934,681	960,893	987,105	1,013,317
440	838,769	864,981	891,193	917,405	943,617	969,829	996,041	1,022,253
450	847,705	873,917	900,129	926,341	952,553	978,764	1,004,976	1,031,188
460	856,640	882,852	909,064	935,276	961,488	987,700	1,013,912	1,040,124
470	865,576	891,788	918,000	944,212	970,424	996,636	1,022,848	1,049,060
480	874,511	900,723	926,935	953,147	979,359	1,005,571	1,031,783	1,057,995

The most cost-effective solution is a 300 kWp-400 kWh system when no load flexibility is considered, as illustrated in Figure 20. It is noted that each of the depicted PV sizes over 270 kWp offers a maximum *NPV* around 1.69M €. In such cases, the safest option is to choose the PV-battery system that provides the maximum *SSR*. Actually, a high self-sufficiency means low E_{imp} and thus ensures that the electricity bill will remain low even in cases of future tariffs rise. In the examined building, this system would be the 360 kWp-390 kWh that offers an *NPV* lower than the most profitable solution by only 0.8%.

Furthermore, considering a flexibility level of 25% increases the profit as illustrated in Figure 21 with the most cost-effective solution being a system of 315 kWp-300 kWh. Doubling the flexibility level, a higher *NPV* can be acquired with the same PV size and smaller BESS capacity, as depicted in Figure 22. In general, it is observed that as the flexibility level rises, the most profitable solutions require lower battery size.

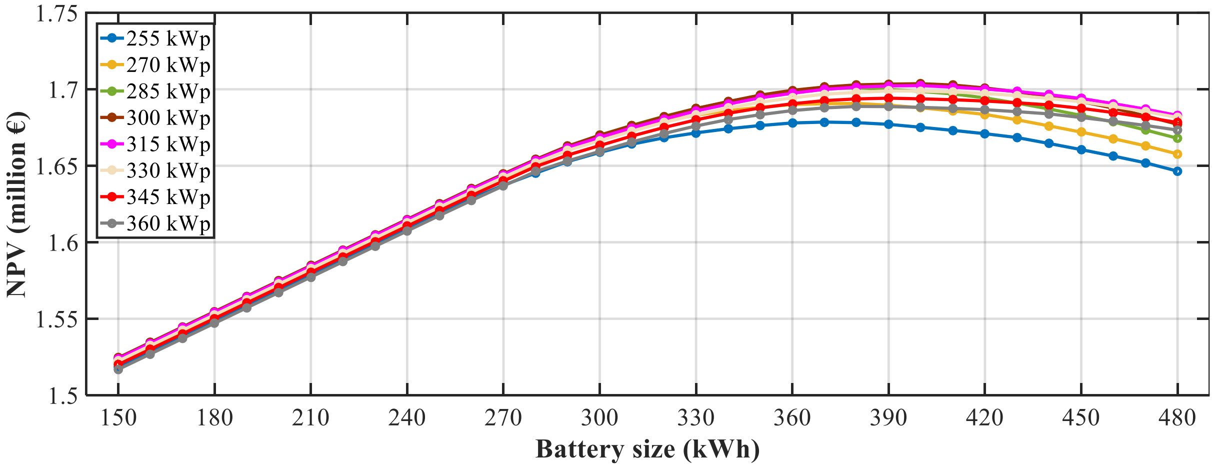

Figure 20 Italy: NPV analysis for 0% flexibility.

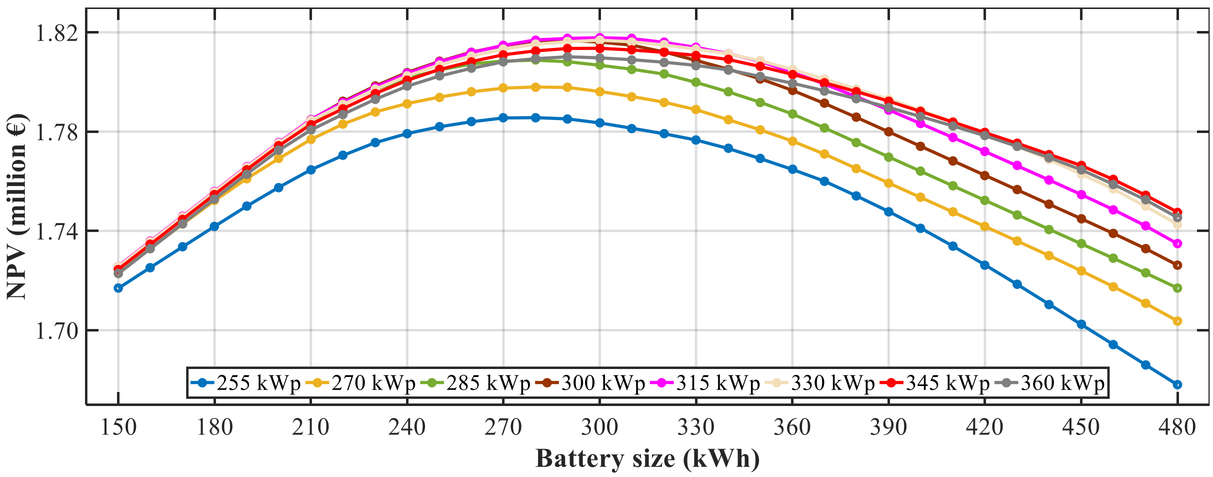

Figure 21 Italy: NPV analysis for 25% flexibility.

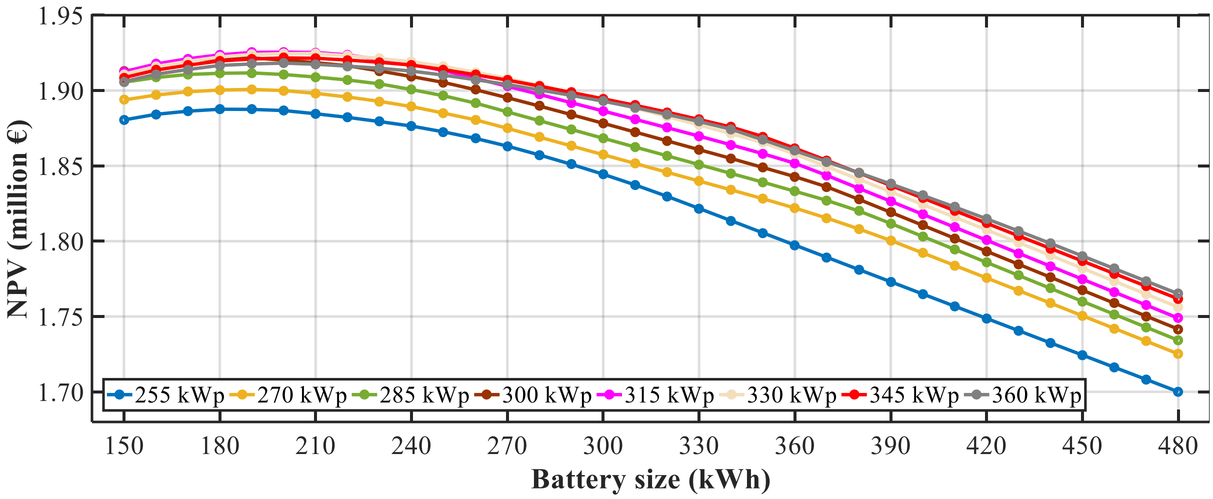

Figure 22 Italy: NPV analysis for 50% flexibility.

Table XI gathers the PV-battery solution that provides the maximum *NPV*. According to these results, it is noteworthy in that the ideal PV size is similar for all flexibility level (300 kWp for 0% flexibility level and 315 kWp for 25% and 50% flexibility level), while the ideal battery size is 400 kWh, 305 kWh, and 200 kWh, for load flexibility equal to 0%, 25%, and 50%, respectively. The self-sufficiency increases as the battery size or the flexibility level. Thus, to achieve *SSR*=81%–93%, the building owner could install lower battery size with lower investment cost and finally higher *NPV*, by adding flexible loads, as highlighted in Table XI.

Table XI: Italy: Optimal solution based on the maximization of building's NPV.

	flexibility percentage (%)		
	0	**25**	**50**
Optimal PV size [kW]	300	315	315
Optimal BESS size [kWh]	400	305	200
Optimal NPV [€]	1,703,625	1,817,913	1,925,506
Internal Rate of Return [%]	23.66	26.06	29.74
Payback period [years]	4.36	3.97	3.48
Investment cost [€]	667,000	622,610	551,163
SSR (evaluated, not optimized) [%]	81.12	82.88	83.31

4.4 Israel

The study case selected for Israel is a building that serves as a school. The annual consumption energy of the examined building amounts to 303,010 kWh which means that it is almost 9 times higher than the building in Cyprus and 20 times higher than the building in Greece. Furthermore, the expected annual production energy for each installed kWp of PV is determined to be 1,909 kWh. In more details, the typical daily production and consumption curves for working and non-working winter and summer day (January and June) are shown in Figure 23.

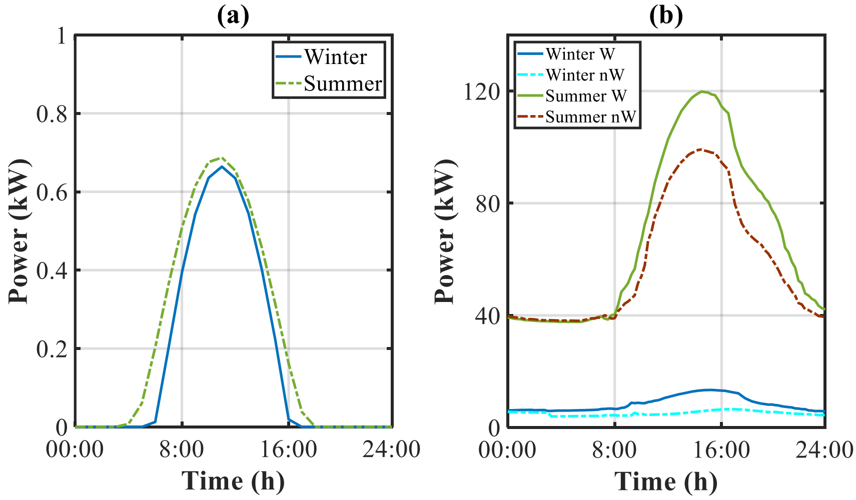

Figure 23 Daily typical (a) production and (b) consumption curves in Israel.

The financial parameters used in the case of Israel are depicted in Table XII. According to these data, the total electricity price including the VAT is determined to be 0.15239 €/kWh. In contrast to the other countries, the electricity pricing policy does not impose additional taxes, making it the lowest of all study cases. In addition, Table XII also presents the installation cost of PV and battery system which are defined at 924 €/kWp and 540 €/kWh, respectively.

Table XII: Financial parameters in Israel.

Tariffs	Electrical energy cost [€/kWh]	0.13025
	Electrical networks cost [€/kWh]	0.0
	Taxes on electrical energy [€/kWh]	0.0
VAT	[%]	17
PV installation cost	[€/kWp]	924
Battery installation cost	[€/kWh]	540

On one hand, the building's high energy consumption necessitates the installation of high-capacity PV-battery systems to enhance self-sufficiency and reduce reliance on grid energy. On the other hand, the low electricity price diminishes the need for such high-capacity systems to make a profitable investment. To examine this further, Figures 24-26 present the *Benefit* offered by the most profitable combinations of PV and battery capacities under flexibility levels of 0%, 25% and 50%, respectively.

Remarkably, the *Benefits* are comparatively lower in the study case of Israel. Specifically, the Israeli and Italian cases show buildings with similar annual consumption energy requirements. However, we observe two noticeable differences in the *Benefits* comparing Figures 25 and 18. The first one is that the most profitable solutions come with larger PV and battery capacities in the case of Italy than Israel. It is important to note that this happens despite the significantly higher installation costs in Italy. In this way, we conclude that the higher electricity price creates an opportunity for installing larger PV and battery systems. The second one is that the *Benefit* in Israel is extremely lower than in Italy for the same reason. Finally, examining exclusively the *Benefit* presented in Figures 24-26, it is observed that increasing the battery capacity and the flexibility level, the *Benefit* is also increasing. The *Cost* provided by each PV-battery system is shown in Table XIII.

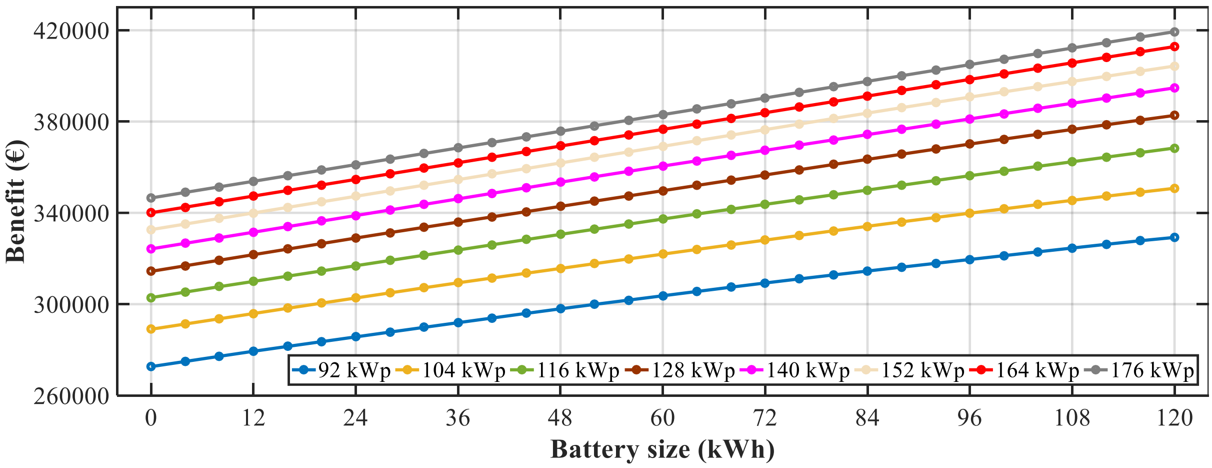

Figure 24 Israel: Benefit for 0% flexibility.

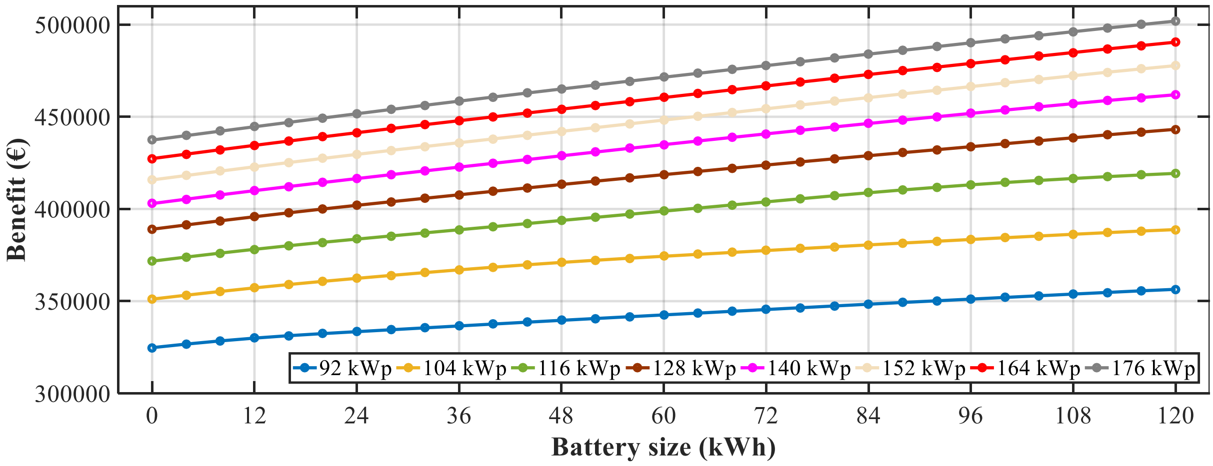

Figure 25 Israel: Benefit for 25% flexibility.

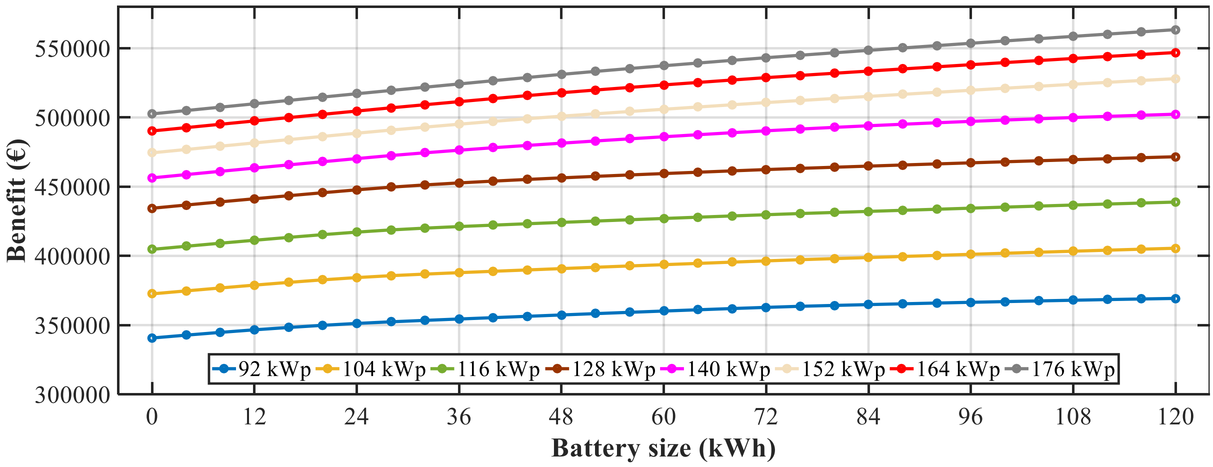

Figure 26 Israel: Benefit for 50% flexibility.

Table XIII: Israel: Cost defined by the combination of the examined hybrid PV and battery sizes (in €).

Battery size (kWh)	PV size (kWp)							
	92	104	116	128	140	152	164	176
0	112,366	127,023	141,679	156,336	170,992	185,649	200,305	214,962
4	115,222	129,878	144,535	159,191	173,847	188,504	203,160	217,817
8	118,077	132,733	147,390	162,046	176,703	191,359	206,016	220,672
12	120,932	135,588	150,245	164,901	179,558	194,214	208,871	223,527
16	123,787	138,444	153,100	167,756	182,413	197,069	211,726	226,382
20	126,642	141,299	155,955	170,612	185,268	199,925	214,581	229,238
24	129,497	144,154	158,810	173,467	188,123	202,780	217,436	232,093
28	132,352	147,009	161,665	176,322	190,978	205,635	220,291	234,948
32	135,208	149,864	164,521	179,177	193,834	208,490	223,147	237,803
36	138,063	152,719	167,376	182,032	196,689	211,345	226,002	240,658
40	140,918	155,574	170,231	184,887	199,544	214,200	228,857	243,513
44	143,773	158,430	173,086	187,743	202,399	217,056	231,712	246,369
48	146,628	161,285	175,941	190,598	205,254	219,911	234,567	249,224
52	149,483	164,140	178,796	193,453	208,109	222,766	237,422	252,079
56	152,339	166,995	181,652	196,308	210,965	225,621	240,278	254,934
60	155,194	169,850	184,507	199,163	213,820	228,476	243,133	257,789
64	158,049	172,705	187,362	202,018	216,675	231,331	245,988	260,644
68	160,904	175,561	190,217	204,874	219,530	234,187	248,843	263,499
72	163,759	178,416	193,072	207,729	222,385	237,042	251,698	266,355
76	166,614	181,271	195,927	210,584	225,240	239,897	254,553	269,210
80	169,470	184,126	198,783	213,439	228,096	242,752	257,408	272,065
84	172,325	186,981	201,638	216,294	230,951	245,607	260,264	274,920
88	175,180	189,836	204,493	219,149	233,806	248,462	263,119	277,775
92	178,035	192,692	207,348	222,004	236,661	251,317	265,974	280,630
96	180,890	195,547	210,203	224,860	239,516	254,173	268,829	283,486
100	183,745	198,402	213,058	227,715	242,371	257,028	271,684	286,341
104	186,601	201,257	215,913	230,570	245,226	259,883	274,539	289,196
108	189,456	204,112	218,769	233,425	248,082	262,738	277,395	292,051
112	192,311	206,967	221,624	236,280	250,937	265,593	280,250	294,906
116	195,166	209,822	224,479	239,135	253,792	268,448	283,105	297,761
120	198,021	212,678	227,334	241,991	256,647	271,304	285,960	300,617

As shown in Figures 24-26, increasing the battery capacity under the same PV size, the *Benefit* is also increasing. In the same way, the *Cost* is increasing too, as illustrated in Table XIII and raises concerns about the cost-effectiveness of these solutions. On contrast, enabling the load shifting, the *Benefit* could also be increased, maintaining *Cost* unaffected. The *NPV* considers both the *Benefit* and the *Cost* of each investment, thus providing a clearer view of its financial viability. To this end, the *NPV* of the most profitable combinations of PV and battery capacities under flexibility levels of 0%, 25% and 50% are presented in Figures 27-29, respectively. As depicted in Figure 27, when the flexibility is no available, the *NPV* rises as the PV size increases up to 104 kWp, while for larger PV capacities it decreases. In this way, the most profitable choice is the combination of a 104 kWp PV with no battery system, providing 161,986 €. Enabling a flexibility level of 25%, the building could further exploit the PV production. In this way, the *NPV* rises as the PV size increases up to 128 kWp as shown in Figure 28. Consequently, the most profitable system capacity is selected at 128 kWp-0 kWh, providing 232,690 €. In case the load flexibility is even higher, i.e., 50%, larger PV capacity systems could enhance the *NPV*, as demonstrated in Figure 29. In this case the *NPV* rises as the PV size increases up to 164 kWp and the optimal *NPV* is calculated at 289,934 € and is provided by the installation of 164 kWp PV without battery system. Finally, it is worth to note that although the integration of battery system could increase the *Benefit*, it decreases the NPV either the load shifting is available or not, denoting that the battery systems are expensive for integration into buildings in Israel.

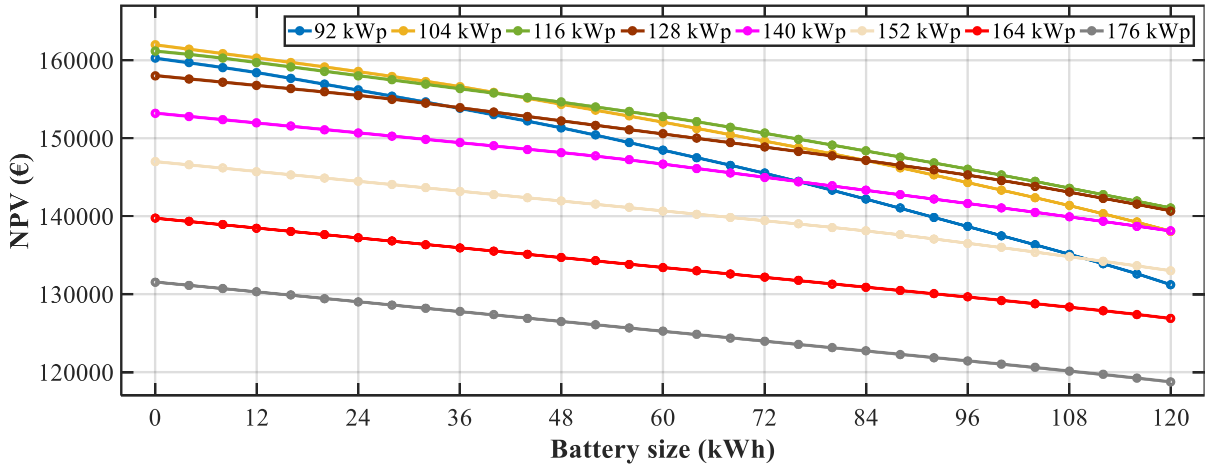

Figure 27 Israel: NPV analysis for 0% flexibility.

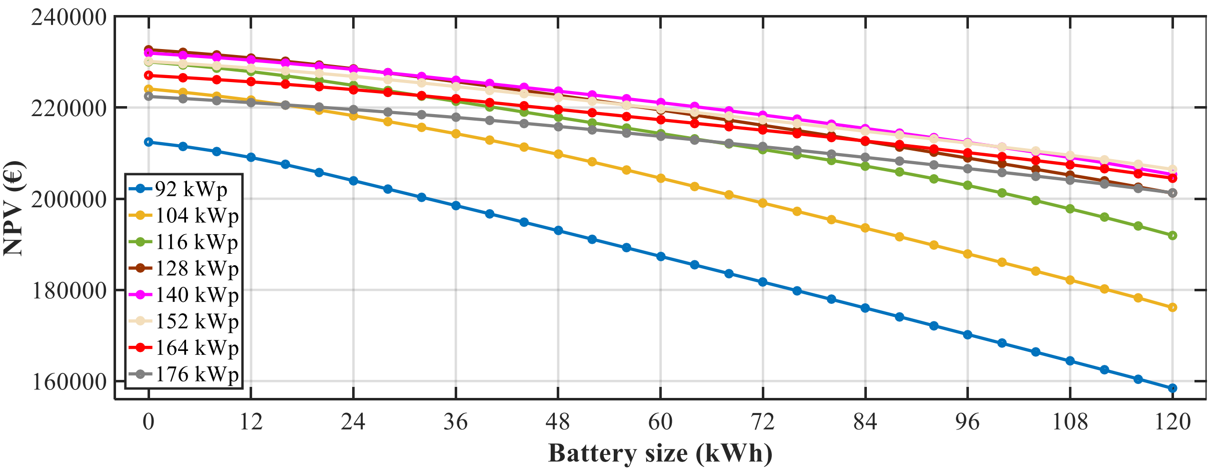

Figure 28 Israel: NPV analysis for 25% flexibility.

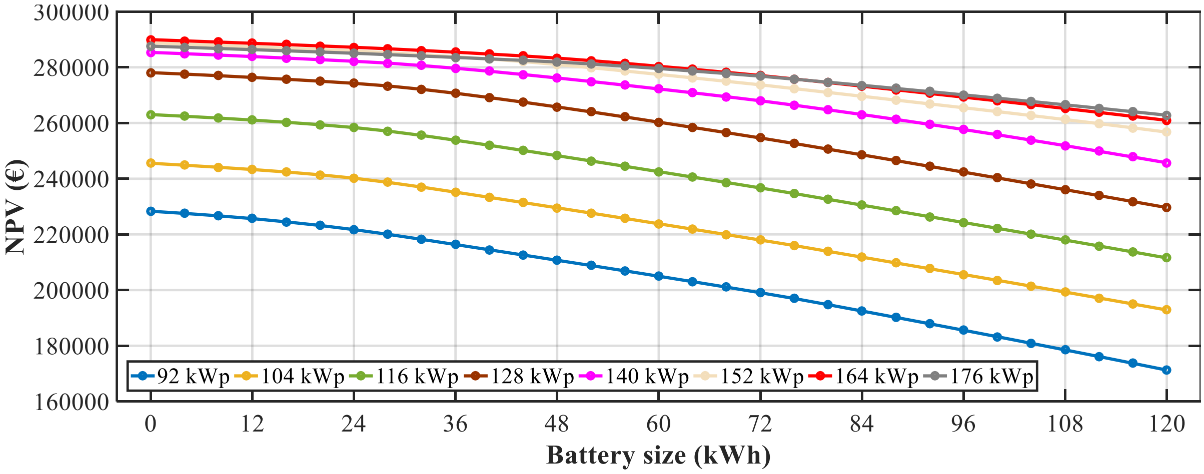

Figure 29 Israel: NPV analysis for 50% flexibility.

Table XIV gathers the optimal solutions based on the maximization of the examined building's *NPV* under flexibility levels of 0%, 25% and 50%. As already stated, due to high installation cost, none of these solutions propose the integration of a battery system. In case without load flexibility, the optimal combination of PV-battery to be installed is 104 kWp and 0 kWh, providing 161,986 €. This solution reaches the building's SSR at 39%. The investment cost is determined at 96,096 € and can be paid back in 5.68 years. Considering the flexibility level at 25%, the optimal solution is 128 kWp and 0 kWh, providing *NPV* = 232,690 € and *SSR* = 53%. The consideration of flexibility contributes to the further exploitation of PV production, facilitating the installation of a higher PV size compared to the case without load flexibility. To this end, the investment cost of this solution is calculated at 118,272 € and can be paid back in 5.17 years. According to this, although the investment cost is higher than the case without flexibility, the payback period is lower. Finally, examining a higher flexibility, i.e., 50%, the optimal *NPV* is 289,934 € and is provided by 164 kWp and 0 kWh. As expected, the high flexibility level contributes to the further exploitation of PV production, proposing a higher PV size as the optimal one. In this way, the building's SSR is increased at 66% and the investment cost is also increased at 151,536 €. However, the payback period is determined at 5.26 years.

Table XIV: Israel: Optimal solution based on the maximization of building's NPV.

	flexibility percentage (%)		
	0	**25**	**50**
Optimal PV size [kW]	104	128	164
Optimal BESS size [kWh]	0	0	0
Optimal NPV [€]	161,986	232,690	289,934
Internal Rate of Return [%]	17.81	19.76	19.39
Payback period [years]	5.68	5.17	5.26
Investment cost [€]	96,096	118,272	151,536
SSR (evaluated, not optimized) [%]	39.21	52.74	66.47

5 Cost-effective System Design for Maximum Possible Self-sufficiency

In addition to the cost and benefit analysis, the self-sufficiency level of the buildings is assessed for the various cases of PV and battery sizes examined. It is observed that the value of *SSR* of a building increases up to a certain maximum and then saturates as the PV and battery size gets higher. This saturated maximum value may be reached by PV-battery solutions that are not economically viable. It is thus crucial to explore the solution that provides the maximum possible energy self-sufficiency that is still cost-effective. Figures 30 and 31 demonstrate how the *NPV* and *SSR* varies for different PV and BESS capacities in the case of Greece in the form of a heatmap. Note that, the economically viable PV-battery solutions are these located at the yellow part of the *NPV* graph. Comparing the two figures, it is deduced that cost-effective PV-battery solutions reach *SSR* values below 80%, while for *SSR* > 80% the PV-battery systems are not economically feasible.

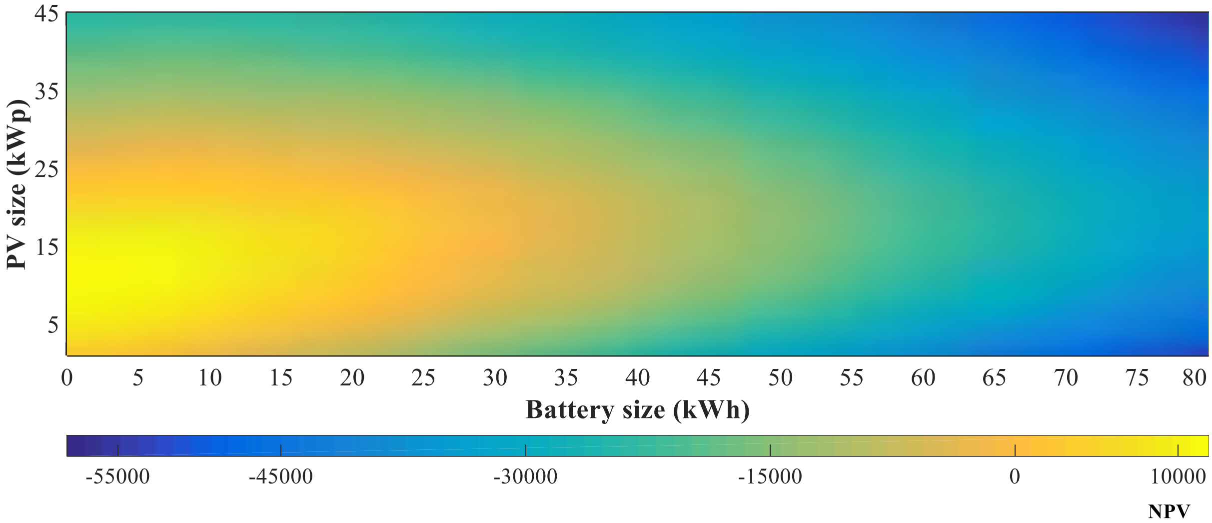

Figure 30 Impact of hybrid PV and battery size on NPV (in €).

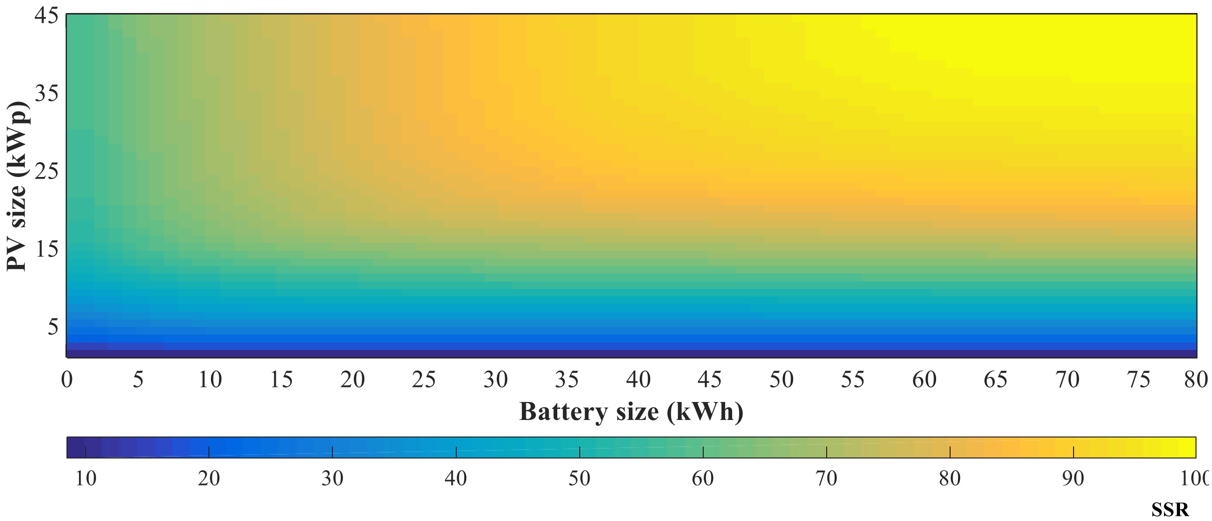

Figure 31 Impact of hybrid PV and battery size on SSR (in %).

Furthermore, Figure 31 shows that the PV capacity plays a key role at the maximum *SSR* that can be achieved. Actually, the highest values of *SSR* are provided by the largest PV-battery systems as shown by the lightest yellow colour in Figure 31. On the other hand, due to the high installation cost, the largest PV-battery systems provide the lowest *NPV* according to the deep blue colour in Figure 30. To examine this further, Figures 32 and 33 are a replicate of Figures 31 and 30, respectively, focusing on the area with the largest PV-battery systems. As presented in Figure 32, the examined building could achieve $SSR \geq 92\%$ by installing a PV-battery system equal or larger to 35 kWp-40 kWh. Additionally, the building could achieve a *SSR* of 100% by the installation of a 45 kWp-76 kWh PV-battery system. The installation of such systems is not cost-effective solutions as shown in Figure 33. Specifically, the systems with $SSR \geq 92\%$ provide negative *NPV*.

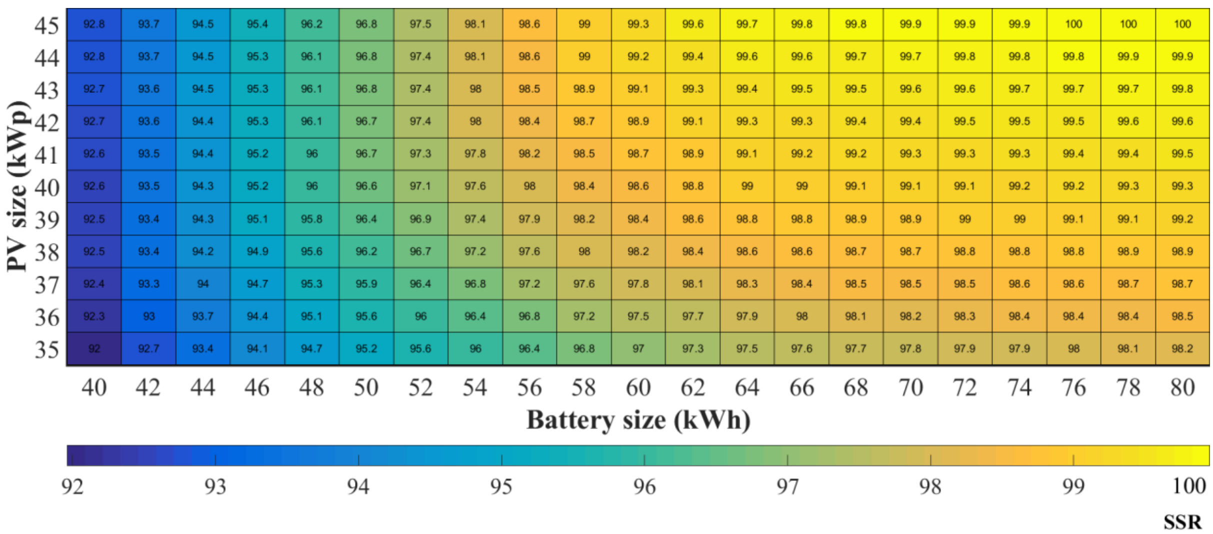

Figure 32 Sensitivity analysis to define the combination with the SSR at 100%: examination of SSR (in %).

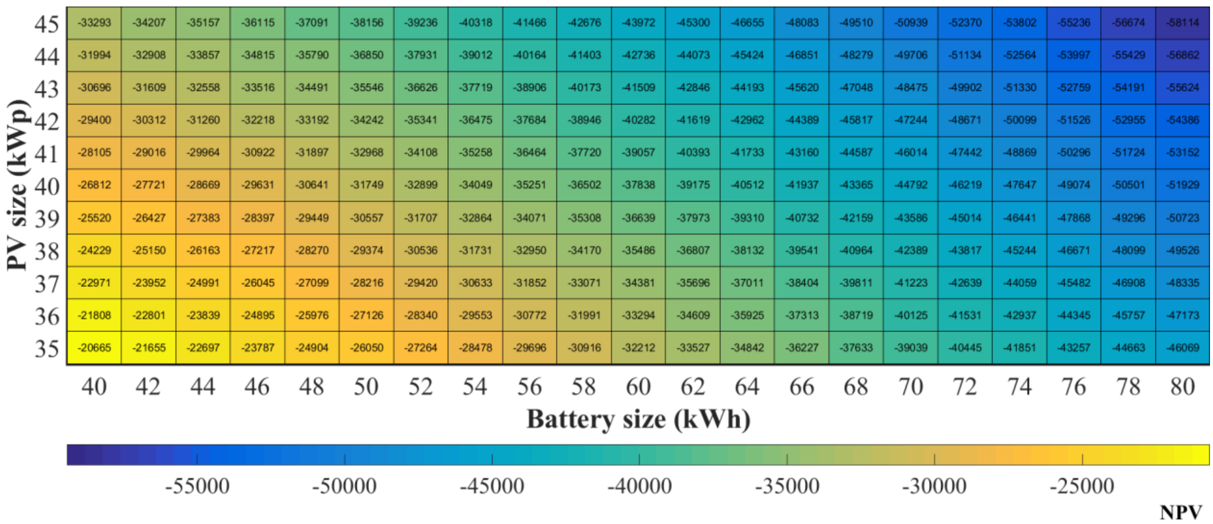

Figure 33 Sensitivity analysis to define the combination with the SSR at 100%: examination of NPV (in €)

In contrast to the *SSR*, the highest values of the *NPV* are provided by the lower capacity systems, that avoid the high installation cost. For this reason, to find the highest possible *SSR* that can be reached with cost-effective solution, one has to explore solutions with high enough PV capacity. Figures 34 and 35 are a replicate of Figures 30 and 31, respectively, focusing on the area of interest. Comparing these figures, it is seen that the maximum *SSR* for non-negative *NPV* equals to 77.9% and is provided specifically by the 21 kWp-25 kWh system with *NPV*=265 €. Offering financial incentives to promote the battery system, such as subsidies for the purchase of battery systems, or adopting time-of-use tariffs, would increase the profitability of the investment and thus lead the building owner to purchase the specific PV-battery system that offers high self-sufficiency.

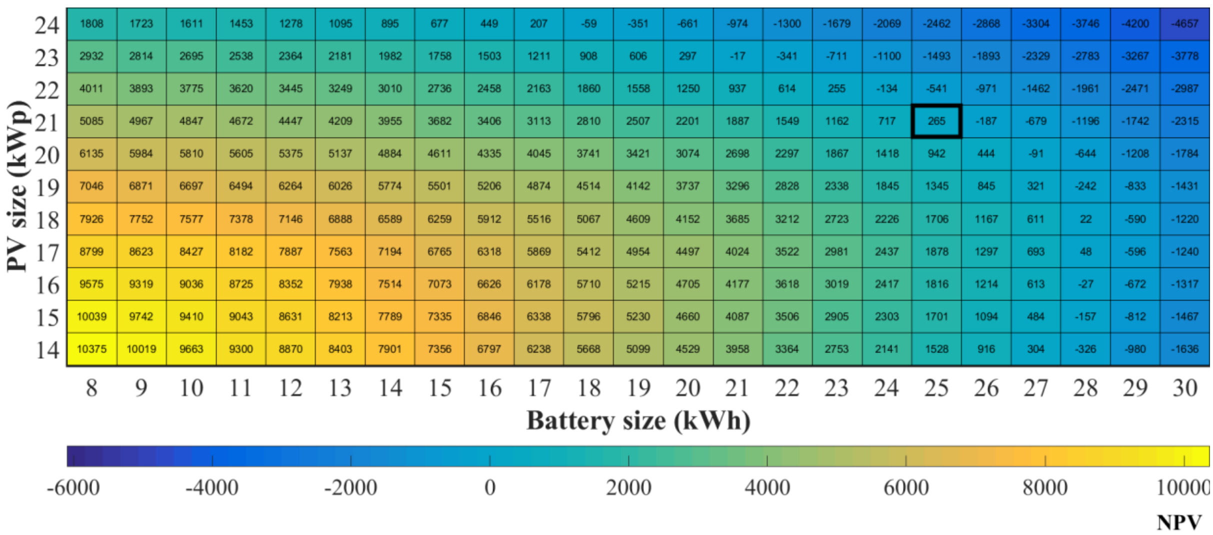

Figure 34 Sensitivity analysis to define the combination with the highest SSR and positive NPV: examination of NPV (in €).

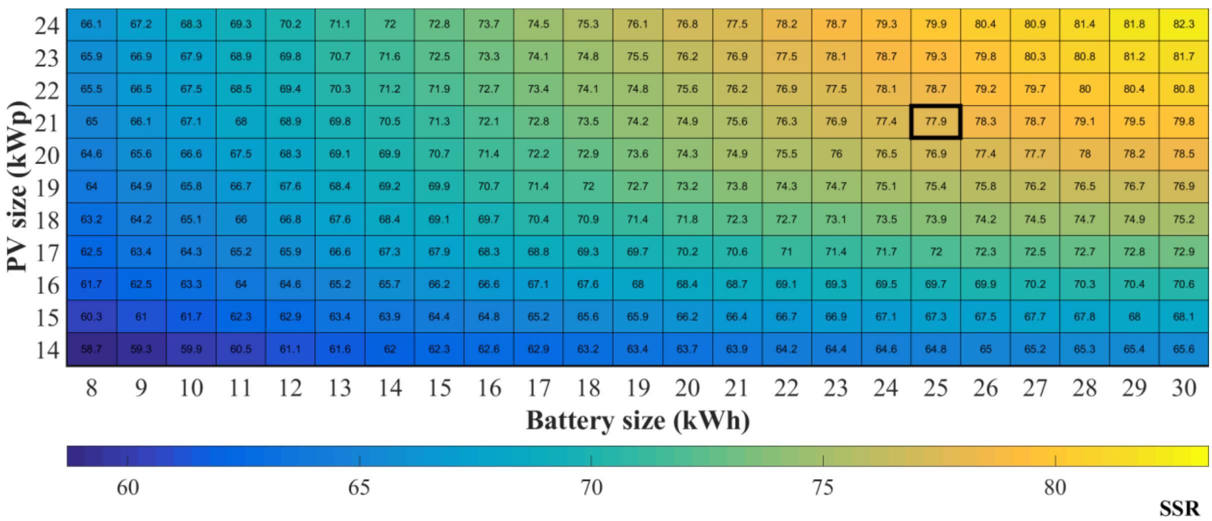

Figure 35 Sensitivity analysis to define the combination with the highest SSR and positive NPV: examination of SSR (%).

6 Conclusions

This analysis evaluates the financial benefits, the costs, and the economic feasibility of PV-battery systems integrated in buildings considering the effect of load flexibility. Study cases from four different public buildings are examined in Cyprus, Greece, Italy, and Israel. The results show that when load shifting is available due to flexible loads, the profitability of the investment increases for solutions with larger PV and lower battery capacity. It is also deduced that for each flexibility level, there is a battery capacity that maximizes the investment profitability. This characteristic capacity remains almost constant for the various PV sizes and depends on the building's consumption and the battery system cost. Moreover, the results demonstrate that the solutions providing the maximum possible self-sufficiency are not yet cost-effective in the absence of financial incentives.

7 References

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