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Maximizing self-consumption rates and power quality towards two-stage evaluation for solar energy and shared energy storage empowered microgrids

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ABSTRACT

Substantial penetration levels of intermittent and fluctuated renewable energy resources like PV can cause overcapacity and other operational challenges in the grid. Therefore, energy market actors are directed to the feed-in limitations and restrict the installed capacity. Likewise, the declining incentives make energy storage central to increasing self-consumption. However, economic uncertainties arise concerns about the financial feasibility of energy storage investments. This study presents the techno-economic benefits in increasing PV self-consumption using shared energy storage for a prosumer community under various penetration rates. In the first stage, the optimal energy storage allocations were done using the proposed New Best Algorithm and genetic algorithm with Matlab. Then, the technical performance of the proposed method was simulated with year-long using PSS Sincal. In the second stage, the economic feasibility of increasing PV self-consumption using shared energy storage under various penetration rates is evaluated considering residual energy. The effects of incentives are examined in terms of economic indicators such as payback period, net present value, and internal rate of return. The incentives promote prosumers either with or without energy storage to increase self-consumption. As a result, shared energy storage increased self-consumption up to 11% within the prosumer community. Results and sensitivity analysis are given in detail. The proposed method provides significant economic benefits and improved power quality.

1. Introduction

Renewable energy sources (RES) gradually gain importance in sustainable environment and energy economies due to their lower emissions and continuously decreasing specific costs. The increasing popularity of PV generators (PVG) coincides with emerging of numerous decentralized prosumers, which can also produce energy. Advances in smart technologies allow prosumers in various forms to trade their surplus energy with each other and with the grid in energy markets. The results of studies focused on forming an energy community show that the total costs can be reduced significantly compared to the prosumers acting individually [1,2]. However, energy transactions between the prosumers and the distribution systems lead to serious power quality problems due to the intermittent and stochastic generation of RES. PVG cannot generate electricity whenever demanded; instead, the amount and time of generation are determined by weather conditions. Even short-term cloud moves may lead to a significant power variation suddenly. Therefore, unexpected voltage rise that may occur as the penetration rate (PR) of RES increases and reverse power flow (RPF) which happens when PV power is greater than the demand, are such problems. The voltage problem usually is encountered when the generation is less than peak loading or the loading is less than the generation. Namely, keeping the voltage within a specific limit during the peak irradiation or load is essential for grid safety. RPF frequently occurs when the consumption is less than the generation, especially in the summer in the northern hemisphere. RPF raises security and operation problems that disturb energy quality, such as over/under voltage and overcapacity because of an incompatibility of existing grid infrastructure. Increasing the capacity of lines and transformers in network expansion planning is mostly preferred but expensive [3,4].

Power markets are among the most essential and integral elements of the power sector, where electricity is traded as a commodity using

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various methods. Investor or state-owned power generation and delivery had been the main characteristics of the energy markets before the 1990s. Such markets were considered regulated and vertically integrated where the same utility could own the power generation and delivery operations. After the 1990s, the energy sector started to evolve via deregulation and liberalization phases. The main objection of the policymakers was to provide a competitive market environment to enable lower costs towards new retail and wholesale electricity market rules. Furthermore, rapid decarbonization and decentralized power systems with high renewable energy penetration levels are forming next-generation power markets such as innovative local energy markets (LEM). LEM model having shared ESS within microgrid model is shown in Fig. 1. Digitalization technologies such as artificial intelligence, blockchain technology, and advanced information and communication technology enable next-generation LEM and microgrids. Such digitalization infrastructure is based on a robust data flow.

Typical LEM has mainly two types of participants in the core: sellers capable of self-generation using the renewable source, so-called prosumers, and buyers who lean on procurement due to lack of such capabilities. Prosumers want to sell their residual energy in LEM, and consumers are ready to buy this residual energy for consumption. Meanwhile, prosumers seek revenue at a price higher than the feed-in tariff for their surplus energy. Consumers seek a lower price than the grid price. Numerous countries are currently adjusting their energy policies to encourage self-consumption of distributed energy generation on the path of techno-enviro-economic targets. LEMs present the opportunities to balance the energy requirements among the participants, minimize energy loss, reduce energy costs, improve overall reliability [5,6]. Aggregators and any utility agents willing to participate in the LEM can also be considered extended stakeholders of LEM.

Furthermore, the actions in the prosumer pool are determined by the structured markets with a strong relation. The day-ahead market prices are appointed roughly midday before the transaction. However, the intraday and balancing markets complement day-ahead markets in the case of unplanned events and changing weather conditions. In addition, the intraday markets allow purchasing and selling electricity throughout the day, up to a few minutes before the realization of the transaction. System operators preserve the demand-supply balance to secure system stability via the balancing markets. However, some countries use short-term transactions instead of intraday markets. Energy investors, trading companies, transmission, and distribution system operators are conventional stakeholders of today's power markets. Power market liberalization diversified energy market actors. The power market is responsible for simultaneously managing power flow and monetary transactions among prosumers. Competitive and structured markets determine the rules and roles of prosumers with power market regulations. The optimization models are used in numerous recent studies to define demand and supply bids for the day-ahead energy market. The aggregator exploits the flexibility of small prosumers in the energy market, reducing costs [7].

The distribution system operators (DSO) have imposed dynamic or

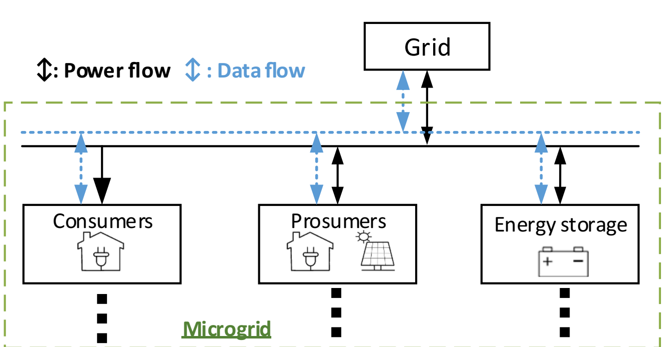

Fig. 1. An illustrative microgrid model having shared energy storage.

fixed feed-in power limitations for RES to prevent such operational problems [8–10]. Injecting power into the grid or the installed power of PVG is limited to reduce the effect of sudden power variations. Prosumers are not be allowed to inject power into the grid greater than a certain percentage of the installed power. For example, in Germany, a prosumer having nominal power up to 30 kW is required to limit the installed power to 70% while injecting power to the grid or allowing DSO to manage this power [10]. Although these limitations help to reach the power quality requests, they decline prosumers' benefits. So, it is departed from the goals of the sustainable environment and energy economy. Incentive packages are needed to encourage consumers to become prosumers due to diminished benefits [11]. In addition, the cost of energy (COE) can be reduced with performance-enhancing methods. Both the increased grid purchase energy price and the decreased grid sold price have triggered significantly self-supplying. Therefore, prosumers have focused on utilizing residual energy (RE), which is excess energy for local demand, locally to increase self-supplying rather than transferring to the grid [12]. The RE arising from the mismatch of loading and RES makes ESS a prior candidate. ESS integration to RES can improve power quality and benefit prosumers economically [13–15].

Selling RE to the grid is not preferred since the COE of RES is higher than the time of use (TOU) tariff due to techno-economic reasons. Thus, RE should be stored using ESS during a larger PV generation period for local evening demand instead of buying from the grid. Moreover, the applicability of ESS has gradually increased because of the reduction in the unit investment cost and increasing efficiency. For example, in Germany, the selling price of solar energy is significantly less than the TOU tariff draws prosumers' attention to ESS for increasing self-consumption to reduce COE. On the other hand, the investment cost of PV-ESS varies by country, city, and even by year for the same investment. For example, due to the lack of government support for PV technologies in the UK, the depreciation periods of investments have increased. However, integrating ESS to PV has significantly increased profitability [12]. Developments and regulations that motivate energy storage for solar and wind energy integration in Europe are of great importance. Consequently, Germany subsidizes up to 30% of the ESS investment cost for domestic solar systems [10]. It has been proven that the energy and power capacity of ESS is an essential factor for integration [16]. According to [17], if the PV power is limited to 30%, only 2/3 of the generated energy can be injected into the grid or used by the consumer for the cases without ESS. The same study stated that determining ESS size according to the energy consumption is more accurate than the PV power. If ESS is sized properly, SCR can be increased by 10–24% depending on regional variables [18]. In Germany, 4906 households with 6.2 kWh ESS and 3–10 kWp PV are selected to analyze the effect of domestic consumption on RE on a regional scale. As a result of the controlling ESS with the daily dynamic feed-in limit strategy, SCR increases by 28%. Even though the grid energy exchange rate is reduced by approximately 20% compared to the without ESS [8]. In addition, assumptions without ESS show that the large PV investments aiming at grid energy exchange are more likely to be deferred. However, the intention to increase self-consumption and exchange inner the prosumer community is realized earlier due to smaller PV needs [19,20]. Thus, prosumers need to scale the PV investment by considering their consumption [21–23]. The proposed model in [24] revealed 84% renewable fraction and 20% annual PV-generated energy sold to the grid. Specifically, prosumers should be charged a fee of around 0.05$/kWh to store PV-generated energy and sell it back to the grid at 0.17$/kWh. Moreover, PV self-consumption levels are more sensitive to the load profile than wind self-consumption levels, although they are relatively homogenous across the UK. Since both PV and UK non-domestic load profiles peak around midday, that shows significantly higher self-consumption levels than domestic loads. SCR is 31–37% for domestic load and 40–50% for non-domestic load, respectively. Prosumers pooling with less fluctuated loads has proven beneficial for increasing the self-consumption levels by as much as 17.6%, thus suggesting that productive collaboration of prosumers can unlock greater economic potential [25]. For example, if prosumers become a community, it encourages a higher solar penetration rate of up to 23% and a slight cost reduction of up to 8% [26]. A local prosumer community can provide approximately a 28–30% share of prosumption depending on the number of prosumers and ESS support via P2P energy trading [27]. In Spain, residential PV self-consumption systems without batteries may compete with other power sources for >1000 kWh/m^2/year. For the three households, high self-consumption was achieved (50–65%), relatively high self-sufficiency reached (37–45%) where the direct self-consumption of PV may supply nearly half the total energy consumption. Moreover, matching the generation and load also required: PV panel orientation, Demand Side Management, and battery energy storage [28]. Residual energy should only be utilized using ESS for such higher irradiations. Minimizing grid purchase is suggested for residential autarky installing an optimized PV-ESS combination instead of leaving the grid. Also, it is recommended that selling residual energy to neighborhoods as an alternative to grid feed-in. It is more economical to waste excess energy than to store on an additional ESS. Getting autarky using PV-ESS is very costly using oversized ESS to meet the demand peaks lasting just a few hours for the year [29]. Many studies recommend using ESS for transferring RE to self-consumption [18,30]. A proper allocation of ESS for evaluating the residual energy is beneficial to minimizing the electricity required from the grid for local prosumers to maintain the connection to the grid. The residual electricity could be sold peer-to-peer (P2P) to other consumers through microgrid [31]. The realization of the ESS benefits depends on the optimal sizing and locating, which is called allocation. There are many metaheuristic approaches for the optimum allocation of ESS in power systems. Complex problems such as planning distributed energy generation (DEG) can be solved efficiently using evolutionary optimization algorithms. An optimum energy management strategy (EMS) with a metaheuristic algorithm has been proposed for households containing PV and ESS [32,33]. Teaching-learning-based optimization was offered for optimal ESS allocation to increase the reliability of microgrid. As a result, the reduction in total operating cost has realized 17% under IEEE 30 and 69 test systems [34]. Optimal sizing PV-ESS considering the annual energy consumption and storage capacity together can minimize the energy exchange with the grid and maximize the self-consumption for some regions in Italy [35]. Moreover, dynamic EMS keeps the grid voltage profile within limits and restricts power exchange with the grid, maximizing the PV-ESS benefits, especially under high PR [36] [37]. Additionally, the annual energy cost can be minimized by increasing self-consumption using shared ESS with the appropriate energy tariff under feed-in power limitation [38]. Therefore, the primary purpose of ESS for prosumers should be to increase SCR rather than reduce the peak load of the network. Other studies considering ESS use to increase PV self-consumption can be found in [39–41]. Due to lower installation and operational costs, chemical batteries such as lead-acid and lithium-ion have been widely used for residential PV-ESS combinations besides EV applications. Although expensive investment costs, hydrogen-based and compressed air-based ESS are investigated in several studies evaluating a significant amount of RE [42–44]. For example, hydrogen-based ESS can be beneficial economically and give flexible usage of hydrogen to diminish emissions [45–47]. Moreover, compressed air-based ESS could maximize the profitability of RES if existing economic incentives [48–52]. Using ESS in microgrids can reduce operating costs by shaving peak loads and minimizing harmonic distortions [53]. In addition, optimally operated ESS reduces undesirable effects of waste energy (WE) on COE because of feed-in power limitations, therefore, utilizing the PV potential at the maximum level [54].

This study presents the techno-economic benefits of PV and ESS for a prosumer community under various penetration rates. The advantages of using ESS inner prosumer community are compared to the base case without storage. Further, ESS units are allocated considering the power distribution quality. The relationship between SCR and the discounted payback period was investigated under various penetration rates. Finally, sensitivity analysis of possible incentives on PV-ESS investment was made according to economic parameters. The main contributions of this paper include the following:

- Maximizing self-consumption rates and power quality within the prosumer community considering shared ESS under various solar energy penetration levels using a two-stage evaluation framework,
- Development of joint framework using genetic and new best algorithms to determine the optimal location of ESS by aiming to increase the power quality as the first stage,
- Optimizing the size of the ESS by considering the techno-economics metrics as the second state,
- Execution of a comprehensive sensitivity analysis supported by a techno-economic evaluation,
- Impact analysis of incentives designed to encourage prosumers to increase self-consumption with shared ESS.

The second part explains the problem's definition and the equations in two-stage evaluation framework calculations. The third part introduces the system modeling, including weather conditions. In the next part, the technical results of the study are given. Then the economic consequences of the cases are provided. Finally, the conclusion follows the discussion part.

2. Methodology

2.1. The description of the problem

Prosumers prefer ESS to increase the self-consumption rate. In this way, the local energy demand in the evening can be delivered from the stored solar energy during sunny hours in the ESS. The capacity of ESS changes the total system cost significantly. Local demand can be supplied by locally generated PV energy using ESS to increase the self-consumption. The net RE is calculated by subtracting demand from the generated PV power. The most suitable ESS capacity is determined by all periods when consumption is lower than the generation ($P_{PVgen} - P_{load} > 0$). Residual power (RP) (P_{RE}) is obtained by subtracting the sum of load power (P_{load}) and total system loss ($P_{totloss}$) from PV power (P_{PVgen}) as expressed in Eq. (1). Waste PV power (P_{WE}) which cannot be used due to the feed-in limitation, is expressed in Eq. (2).

$$P_{RE}(t) = P_{PV_{gen}}(t) - P_{load}(t) - P_{tot_{loss}}(t) \tag{1}$$

$$P_{WE} = P_{RE}(t) - P_{PV_{nom}}.c_{pv}^{limit}, \forall t \in P_{RE}(t). > P_{PV_{nom}}.c_{pv}^{limit} \tag{2}$$

$$0 < c_{pv}^{limit} < 1 \tag{3}$$

In Eq. (3), $c_{pv}{}^{limit}$ is feed-in limitation coefficient changing between zero and one. It limits injected PV power to the grid. It has been taken as 0.5, 0.6, or 0.7 in the related studies [55–59]. In this study $c_{pv}{}^{limit}$ is taken as 0.4. PR is the ratio between PV power and nominal load power in Eq. (4). Eq. (5) describes the power loss reduction of lines after using ESS. $P_{loss,\ PR}$ and $P_{loss,\ PR}{}^{ESS}$ express the power loss related to PR without ESS and with ESS, respectively. $\Delta E_{loss}{}^{PR}$ expresses the difference in the total annual energy loss of the grid for different PR. Alternatively, it is shown that how much the use of ESS could reduce the total loss of the grid.

$$PR = \frac{P_{PV}^{nominal}}{P_{Load}^{nominal}} \tag{4}$$

$$\Delta E_{loss}^{PR} = \sum_{t=1}^{8760} \left(P_{loss,PR}(t) - P_{loss,PR}^{ESS}(t) \right) \tag{5}$$

The discount rate affects the NPV calculation of the PV investment cost, among other parameters in credit payback. A discount rate is generally assumed in the range of 4–6%. However, it is seen that as the discount rate increases, the installable PV size reduces; therefore, the investment of PV is not economical in some regions. Considering the inflation rate (i) as well as the nominal interest rate (n) is necessary for a more realistic calculation of possible revenues from the ESS investment. The real interest rate (r) is determined by the Fisher equation using the probabilistic nominal interest and the inflation rate in Eq. (6). Eq. (7) reduces the calculated costs to the present value. Finally, Eq. (8) shows the calculation for delaying credit payback.

$$r = \frac{(1+n)}{(1+i)} - 1 \tag{6}$$

$$P = A \bullet \left[\frac{(1+\mathrm{r})^{\mathrm{N}} - 1}{\mathrm{r} \bullet (1+\mathrm{r})^{\mathrm{N}}} \right] \tag{7}$$

$$F = B \bullet \left[\frac{\mathrm{r} \bullet (1+\mathrm{r})^{(\mathrm{m}+\mathrm{v})}}{(1+\mathrm{r})^{\mathrm{v}} - 1} \right] \tag{8}$$

Here, P is the present value. A is the annual fixed cost value for N years. F is the present value of the total credit charge, B is the amount of the credit, r is the real interest, m is the year to start payback of the delayed credit payback, and v is the maturity of the loan.

Energy arbitrage revenue is defined as an energy exchange as given in Eqs. (9)–(12). It is taken into consideration for cases that incentive exists or not, where the incentive is shown with the superscript ^{inc}. Moreover, ESS can be charged either from PV or grid. Charging ESS from the PV energy, with/without PV incentive, and charging ESS from the grid with/without ESS incentive is evaluated for showing the difference.

$$p_{sell}^{arb}(h) = p_{sell}^{peak}(h) - p_{sell}^{PV} \tag{9}$$

$$p_{sell}^{inc-arb} = p_{sell}^{inc-bat} - p_{sell}^{inc-PV} \tag{10}$$

$$p_{grid}^{arb}(h) = p_{sell}^{peak}(h) - p_{grid}^{buy}(h) \tag{11}$$

$$p_{grid}^{inc-arb}(h) = p_{sell}^{inc-bat} - p_{grid}^{buy}(h) \tag{12}$$

The maximum profits from energy arbitrage depending on the energy tariff using ESS without incentive is shown in Eq. (9). The daily energy tariff (h) includes three different periods as flat, valley, and peak. Eq. (10) expresses the energy arbitrage profits charging ESS with RE use at other times of day if an incentive exists. Eq. (11) expresses profits from the arbitrage using ESS if an incentive does not exist. Eq. (12) expresses the arbitrage revenue charging ESS with the energy from the grid and selling or using it at the most favorable price while incentive exists. If PR is less than or equal to 50% ($PR \leq$ % 50), PV power is generally smaller than the demand power ($P_{PV} - P_{load} < 0$). A considerable part of ESS capacity is charged from the grid. Therefore, Eqs. (13) and (14) express the objective functions for revenue without incentive ($REV1^{pen}$) and for revenue with incentive ($REV2_{inc}{}^{pen}$), respectively. Here N_{ESS} refers to the number of ESS cycles.

If PR is between 50 and 150% ($50 < PR \leq 150$) objective functions are changed because significant RP is formed. In Eq. (15), PR-depended ESS size equals the daily average energy amount, calculating the reduction in energy loss and the amount of RE and WE together. Revenue objective functions according to PR with and without incentive are given in Eqs. (16) and (17). Arbitrage revenue using RE is calculated according to the TOU tariff. Reduction in energy loss ($\Delta E_{loss}{}^{PR}$) becomes a revenue that can be calculated with the peak tariff price regarding the maximum line losses since it occurs at the peak load time. Additionally, a profit appears in the objective functions instead of transferring WE ($E_{WE}{}^{PR}$) to another prosumer over lines, it can be used locally thanks to ESS. Furthermore, avoiding transferring WE, the line occupation fee (C_{LOF}) turns to a profit.

$$E_{ESS}^{PR} = \left(E_{RE}^{PR} + E_{WE}^{PR} + \Delta E_{loss}^{PR}\right)/365 \tag{15}$$

$$REV^{PR} = \left[\sum\nolimits_{h=1}^{3} E_{RE}^{PR} \bullet \mathrm{p}_{\mathrm{grid}}^{\mathrm{arb}}(\mathrm{h})\right] + \Delta \mathrm{E}_{\mathrm{loss}}^{\mathrm{PR}} \bullet \mathrm{p}_{\mathrm{sell}}^{\mathrm{peak}} + \mathrm{E}_{\mathrm{WE}}^{\mathrm{PR}} \bullet \left(\mathrm{C}_{\mathrm{LOF}} + \mathrm{p}_{\mathrm{sell}}^{\mathrm{peak}}\right) \tag{16}$$

$$REV_{inc}^{PR} = \left[\sum\nolimits_{h=1}^{3} E_{RE}^{PR} \bullet \mathrm{p}_{\mathrm{grid}}^{\mathrm{inc-arb}}(\mathrm{h})\right] + \Delta \mathrm{E}_{\mathrm{loss}}^{\mathrm{PR}} \bullet \mathrm{p}_{\mathrm{sell}}^{\mathrm{inc-bat}} + \mathrm{E}_{\mathrm{WE}}^{\mathrm{PR}} \bullet \left(\mathrm{C}_{\mathrm{LOF}} + \mathrm{p}_{\mathrm{sell}}^{\mathrm{inc-bat}}\right) \tag{17}$$

The result of objective functions are compared using common performance indicators, such as self-consumption rate (SCR), self-supply rate (SSR), peak voltage reduction (PVR), the share of losses rate (SLR), peak power reduction (PPR), curtailment loss reduction (CLR). SCR is defined in Eq. (18) as the ratio between PV-generated energy directly transferred to the load and the total PV generation annually. SSR is defined as the ratio between the total amount of PV generation transferred directly to the load and the total load demand annually. As seen in Eq. (19), if PV share in the load demand increase, SSR value increases. PVR in Eq. (20) expresses the percent reduction of the peak voltage. Peak voltage can be reduced using ESS or active and reactive power control. SLR is expressed as the ratio between total loss in Eq. (21) and the annual total PV generation. PPR in Eq. (22) expresses how much the power peak is reduced thanks to ESS. Finally, CLR in Eq. (23) expresses to what extent the curtailment loss is reduced using ESS as given.

$$SCR = \frac{\sum E_{PV}^{cons}}{\sum E_{PV}^{gen}} \tag{18}$$

$$SSR = \frac{\sum E_{PV}^{cons}}{\sum E_{LOAD}} \tag{19}$$

$$PVR = \frac{U^{peak} - U_{ESS}^{peak}}{U^{peak} - U_n} \tag{20}$$

$$REV1^{PR} = \left[\sum\nolimits_{h=1}^{3} \left(E_{ESS}^{PR} \bullet \mathrm{N}_{\mathrm{ESS}} - \mathrm{E}_{\mathrm{RE}}^{\mathrm{PR}}\right) \bullet \mathrm{p}_{\mathrm{grid}}^{\mathrm{arb}}(\mathrm{h}) + \mathrm{E}_{\mathrm{RE}}^{\mathrm{PR}} \bullet \mathrm{p}_{\mathrm{grid}}^{\mathrm{arb}}(\mathrm{h})\right] + \Delta \mathrm{E}_{\mathrm{loss}}^{\mathrm{PR}} \bullet \mathrm{p}_{\mathrm{sell}}^{\mathrm{peak}} + \mathrm{E}_{\mathrm{WE}}^{\mathrm{PR}} \bullet \left(\mathrm{C}_{\mathrm{LOF}} + \mathrm{p}_{\mathrm{sell}}^{\mathrm{peak}}\right) \tag{13}$$

$$REV2_{inc}^{PR} = \left[\sum\nolimits_{h=1}^{3} \left(E_{ESS}^{PR} \bullet \mathrm{N}_{\mathrm{ESS}} - \mathrm{E}_{\mathrm{RE}}^{\mathrm{PR}}\right) \bullet \mathrm{p}_{\mathrm{grid}}^{\mathrm{inc-arb}}(\mathrm{h}) + \mathrm{E}_{\mathrm{RE}}^{\mathrm{PR}} \bullet \mathrm{p}_{\mathrm{grid}}^{\mathrm{inc-arb}}(\mathrm{h})\right] + \Delta \mathrm{E}_{\mathrm{loss}}^{\mathrm{PR}} \bullet \mathrm{p}_{\mathrm{sell}}^{\mathrm{inc-bat}} + \mathrm{E}_{\mathrm{WE}}^{\mathrm{PR}} \bullet \left(\mathrm{C}_{\mathrm{LOF}} + \mathrm{p}_{\mathrm{sell}}^{\mathrm{inc-bat}}\right) \tag{14}$$

$$SLR = \frac{\sum E_{LOSS}}{\sum E_{PV}^{gen}} \tag{21}$$

$$PPR = \frac{P^{peak} - P_{ESS}^{peak}}{P^{peak}} \tag{22}$$

$$CLR = \frac{\sum E_{CL} - \sum E_{CL}^{ESS}}{\sum E_{PV}^{gen}} \tag{23}$$

$E_{PV}{}^{cons}$ and $E_{PV}{}^{gen}$ are the consumed and the generated PV energy in kWh, respectively. P^{peak} and $P_{ESS}{}^{peak}$ are the observed peak power of the system without and with ESS. E_{LOAD} is the load energy in kWh. U^{peak} and $U_{ESS}{}^{peak}$ are the maximum voltage without and with ESS. U_n is the nominal voltage of the system. E_{LOSS} is the total system loss in kWh. E_{CL} and $E_{CL}{}^{ESS}$ expresses the amount of energy curtailment without and with ESS in kWh. The formulations of three-phase AC power flow analysis (PFA) are given in Eqs. (24)–(28). PFA results are obtained using the following equations.

$$P_{G_{i,t}} - P_{D_{i,t}} - P^{ch}_{ESS_{b,t}} = \sum_{j=1}^{N} V_{i,t} \bullet \mathrm{V}_{j,t} \bullet \mathrm{Y}_{ij} \bullet \cos\left(\theta_{ij} + \delta_{j,t} - \delta_{i,t}\right) \forall \mathrm{i, j, t, b} \tag{24}$$

$$P_{G_{i,t}} - P_{D_{i,t}} + P^{dis}_{ESS_{b,t}} = \sum_{j=1}^{N} V_{i,t} \bullet \mathrm{V}_{j,t} \bullet \mathrm{Y}_{ij} \bullet \cos\left(\theta_{ij} + \delta_{j,t} - \delta_{i,t}\right) \forall \mathrm{i, j, t, b} \tag{25}$$

$$Q_{G_{i,t}} - Q_{D_{i,t}} = -\sum_{j=1}^{N} V_{i,t} \bullet \mathrm{V}_{j,t} \bullet \mathrm{Y}_{ij} \bullet \sin\left(\theta_{ij} + \delta_{j,t} - \delta_{i,t}\right) \forall \mathrm{i, j, t} \tag{26}$$

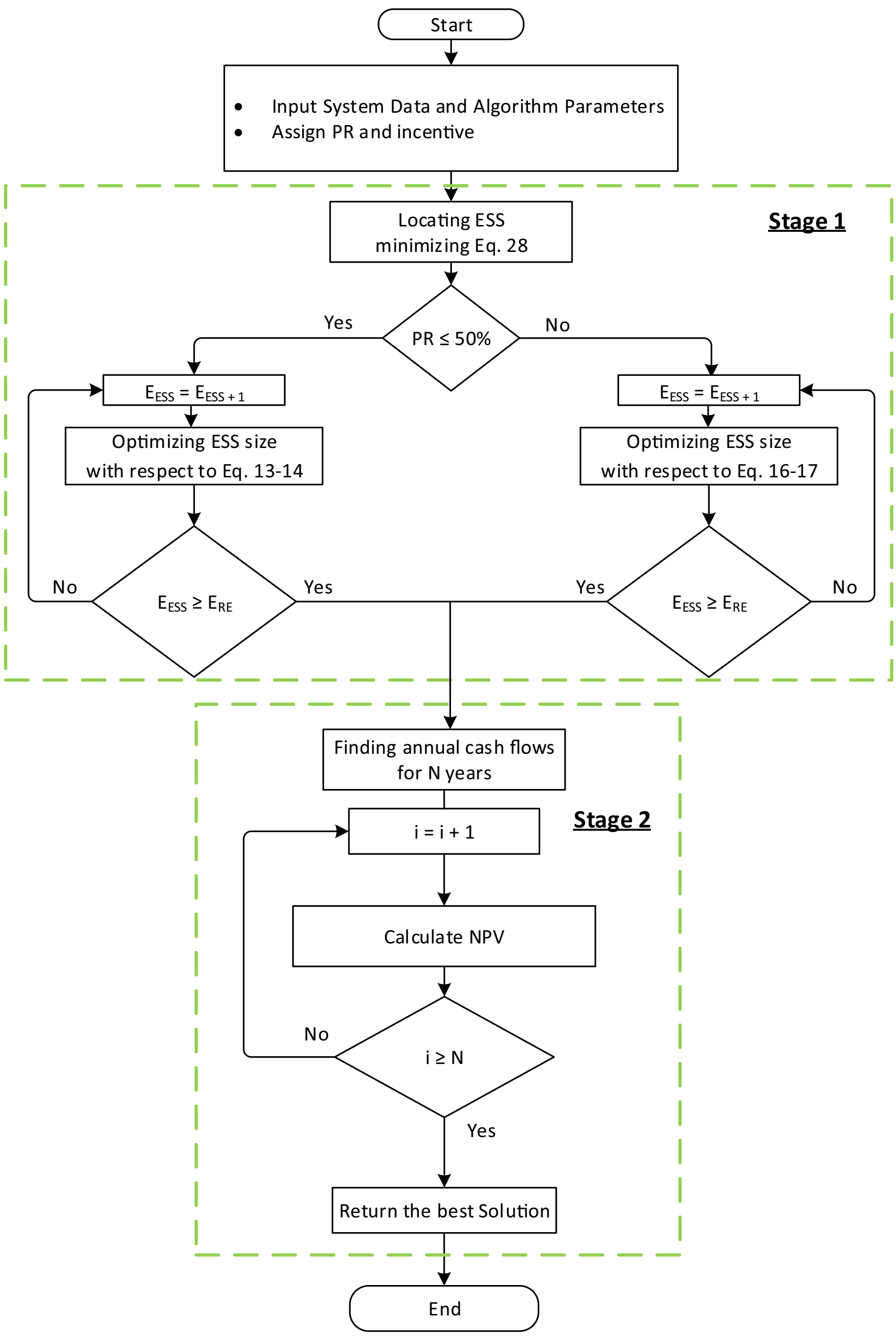

Fig. 2. A two-stage evaluation framework flowchart.

$$I_{ij,t} = |Y_{ij}| \bullet \left[V_{i,t}^2 + V_{j,t}^2 - 2 \bullet V_{i,t} \bullet V_{j,t} \bullet \cos(\delta_{j,t} - \delta_{i,t})\right]^{1/2} \forall i, j, t \quad (27)$$

$$P_{loss} = \sum_{j=1}^{N} I_{ij}^2 \bullet r_{ij} \quad (28)$$

$$V_{\min} \leq V_{i,t} \leq V_{\max} \forall i, t \quad (29)$$

where $P_{Gi,\ t}$ and $P_{Di,\ t}$ are generated and demand active power at bus i, at time t, respectively. $Q_{Gi,\ t}$ and $Q_{Di,\ t}$ are generated and desired reactive power generated at bus i, at time t. $V_{i,\ t}$ and $\delta_{i,\ t}$ are magnitude and angle of the voltage of bus i at time t. Y_{ij} and θ_{ij} are magnitude and angle of the admittance of buses between i and j. Slack bus voltage and angle equal $V_{i,\ t} = 1$, $\delta_{i,\ t} = 0°$. If there is no battery, $P_{ESSb,\ t}{}^{ch}$ and $P_{ESSb,\ t}{}^{dis}$ equal "0" where b denotes the set of ESS units.

2.2. A two-stage evaluation framework

New Best Algorithm (NBA) is suggested to allocate increasing SCR for the prosumer community modeled as a microgrid. The flowchart for a two-stage evaluation framework is given in Fig. 2. The first stage begins inputting predefined data and variables related to PV and ESS using Matlab. NBA locate ESS minimizing total system losses. Additionally, the Genetic Algorithm (GA) verifies the ESS locations found by NBA. For optimizing ESS size, Eqs. (13) and (14) are considered as objective functions for $PR \leq 0.5$. If $PR > 0.5$, Eqs. (16) and (17) are valid as objective functions. Then, iterations continue until ESS capacity is greater than or equal to RE. The relevant objective functions calculate the ESS size for each iteration until the maximum ESS capacity. The best result is selected among the calculated candidate solutions in the second stage. Then, NPVs for candidate ESS sizes are calculated for N years. The optimal allocated ESS is returned as the best solution.

3. System modeling and description

The proposed method is applied to a microgrid model shown in Fig. 3 [56]. However, the study did not investigate the islanded mode operation of the microgrid after disconnection from the macro-grid. Therefore, the annual load profile is given in Fig. 4. There are 20 prosumers in the model.

The optimum ESS allocation is given in Table 1. Both algorithms give approximately the same ESS size for increasing PR. Besides, both algorithms shrunk the ESS size to the lower capacity limit of 40 kWh because of the insufficient RE for 50% PR. Both GA and NBA return the largest ESS sizes for 200% PR due to the largest RE.

According to the clearness index, days are clear, partly cloudy, and cloudy. The daily clearness index values in Istanbul are presented in Fig. 5. The maximum clearness index is 0.714, and the minimum is 0.073. The average clearness index is <0.37 on cloudy days, >0.58 on clear days, and between 0.37 and 0.58 on partly cloudy days. Additionally, in April and May, rainy atmospheric conditions are more often observed in Istanbul. The weather data is obtained from [61,62].

The PV and ESS related costs and TOU price are provided in Table 2.

4. Technical results

This section presents the technical results of the proposed methodology and respective case studies. This study uses PSS Sincal for power system modeling and dynamic simulations [60]. Dynamic and year-long PFAs are performed using PSS Sincal. Table 3 shows technical results regarding nominal PV power, annual RE ($E_{RE}{}^{PR}$), reduction in energy loss after ESS ($\Delta E_{loss}{}^{PR}$), WE ($E_{WE}{}^{PR}$).

For 50% PR, RP cannot exceed 11 kW, and RE cannot exceed 111 kWh/year. Thus, there is not enough RE for an evaluation. In other words, a total amount of PV-generated energy is almost transferred to the load. However, if ESS is used, total system loss could be reduced by only 130 kWh/year. For 100% PR, the maximum RP is 36.5 kW, and RE is over 18 MWh/year. If ESS is used, total system loss could be reduced by 352 kWh/year. Since RP does not exceed the network constraint in Eq. (2) for 50% and 100% PR, there is no wasted energy, and WE equals zero. For 150% PR, RP exceeds the network constraint for 66 h. The total RE is almost 70 MWh/year, and WE is 110 kWh/year. Thanks to ESS, total system loss can be reduced by 594 kWh/year. For 200% PR, RP exceeds the network constraint for 320 h; thus, there is plenty of time for using RE. A >130 MWh RE is evaluated for self-consumption, and nearly 2 MWh/year WE is prevented from waste. Using ESS can reduce the losses by 805 kWh in a year. If ESS is not used, WE could be 1.6 MWh during RE generation every year. Therefore, all WE in 150% and 200% PR can be transferred to the load thanks to ESS.

The SCR, SSR, SLR, PRR, and CLR are given in Table 4 for comparison with or without ESS. Since the load almost consumes PV generation for 50% PR, SCR is nearly 100%. Therefore, ESS is unnecessary for 50% PR. Solar energy has a different profile than the load. An advantage of ESS is eliminating dissimilarity between load and generation. The contribution of ESS for increasing SCR is significant for larger PR than 50%. SCR is increased 8.18, 10.78, 10.97%, in turn. SCR is trending downward, although PR increases. SSR tends to rise as PR increases. SSR can be improved by 7.7, 9.7, 10.3, and 10.6%. The highest SSR is obtained for 200% PR. SLR decreases as PR increases since providing a part of load demand locally by PV-ESS decreases current on the lines. However, if PR

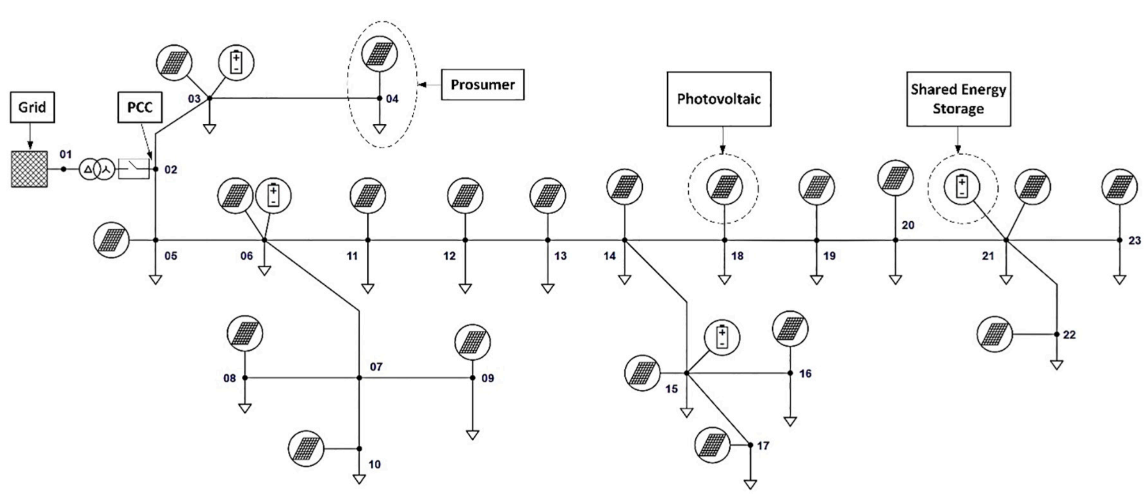

Fig. 3. The evaluated microgrid model.

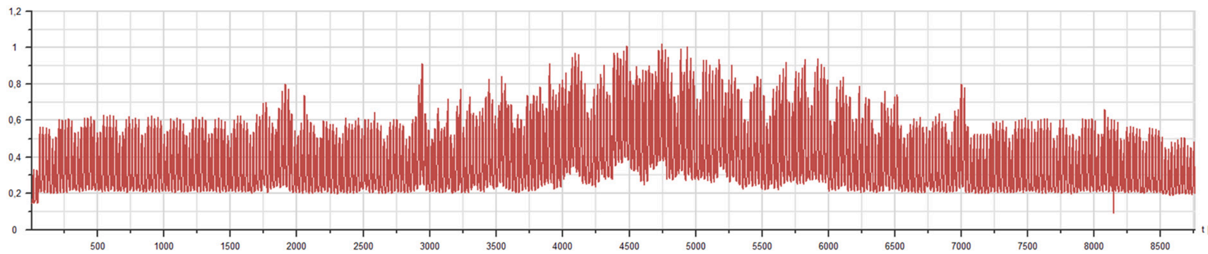

Fig. 4. Residential load profile.

Table 1
ESS allocation.

Algorithm	ESS locations	PR [%]	ESS size [kWh]
GA	6 or 7, 14, 21	50	40
		100	52
		150	193
		200	265
NBA	3, 6, 15, 21	50	40
		100	52
		150	193
		200	265

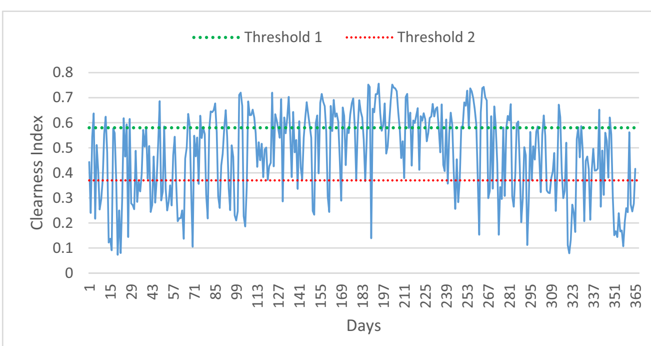

Fig. 5. Weather conditions categorized according to the clearness index of Istanbul.

Table 2
Price and costs values.

Component	Price/cost
Battery cost (lead-acid)	250 \$/kWh
PV cost	1050 \$/kW
Solar feed-in tariff	0.05 \$/kWh
Solar feed-in tariff with incentive	0.13 \$/kWh
TOU price-flat (06.00–17.00)	0.07 \$/kWh
TOU price-peak (17.00–22.00)	0.09 \$/kWh
TOU price-valley (22.00–06.00)	0.04 \$/kWh

Table 3
Annual energy values according to PR.

PR	$P_{PV_{nom}}$ [kW]	RE [kWh/year]	$\Delta E_{loss}{}^{PR}$ [kWh/year]	WE [kWh/year]
50%	50	111	130	0
100%	100	18,591	352	0
150%	150	69,639	594	110
200%	200	130,433	805	1652

is larger than 150%, SLR increases due to RPF. SLR is reduced thank to ESS by 4.8%, 30.6%, 32.8%, and 30.2% for PR is 50%, 100%, 150%, and 200%, respectively. The best SLR is obtained for 150% PR.

Furthermore, PRR shows the peak reduction using ESS. Peaks are reduced by 26% for 50% PR and 32% for 100% PR, especially the evening peaks are observed more. However, the observed peaks for 150% and 200% PR are during the peak generation (noon hours), not during the peak demand (evening hours). Additionally, PRR is improved 44% and 49%, respectively, for 150% and 200% PR. Moreover, CLR is not available since it is not expected to exceed the feed-in limit for lower PR. Therefore, curtailment losses may be encountered when PR is higher than 150%. Moreover, CLR is 100%, which can be reduced thanks to ESS completely. Therefore, it is an advantage of ESS use in technical and economic improvement.

The daily power variations of the sample days depending on PR are given in Fig. 6. The simulation results are divided into weather conditions such as clear/partly cloudy/cloudy days relative to PR. Fig. 6.a1–2–3 points out that almost all PV generation is transferred to the load even on clear days for 50% PR. Thus, it is observed that almost no RP is formed throughout the year. However, the power is supplied by the grid during the daily peak loading is reduced with PV generation. For 100% PR, It can be seen that PV generation exceeds the load demand; RP is transferred to the grid in Fig. 6.b1. Besides, the feed-in limitation (dashed green line) is not exceeded. Therefore, the overall power from the grid decreases. Therefore, RPF is prevented during partly cloudy and cloudy days. Even the shading effect reduces PV generation; the power from the grid is slightly reduced. For 150% PR, Fig. 6.c1 illustrated that RP, which is excessive, exceeds the feed-in limit on certain clear days only. Therefore, forming due to feed-in limitation waste power (WP) can be stored in ESS to use during intense demand of the prosumer. Besides, small and short RP and RPF are observed on partly cloudy days. Thus, the grid is occupied in a minimal time in Fig. 6.c2. On cloudy days, RP is not observed in Fig. 6.c3. For 200% PR, RP lasts longer and becomes more significant than any PR, especially on clear days. Thus, WP is seen as the most significant amount in Fig. 6.d1. ESS size is optimized techno-economically to evaluate WP for the local demand of prosumers. Therefore, WP cannot be stored entirely because of economic constraints. Thus, a small part of WP is curtailed. Fig. 6.d2–3 has similarities to 150% PR on partly cloudy and cloudy days. The SOC of ESS and voltage graphs for the sample days are given in Fig. 7. The most violated voltage profiles (bus 21) are pointed out with V0 and V1 to compare voltage violations without and with ESS, respectively. SOC changes of ESS are given for evaluating the system performance for each PR on clear and cloudy days separately.

For 50% PR, there is no excessive power for RP since the PV power is less than the load demand ($P_{PV} - P_{load} \leq 0$). Even on some clear days, it seems that charging cannot be completed. However, the voltage drop due to the high load demand is limited for clear and cloudy days at the end of the day. For 100% PR, Fig. 7.b1–2 shows that ESS can be fully charged on and off days. The difference in the charging time of the ESS is

Table 4
Comparison of performance indicators for the investigated scenarios.

PR	Without ESS				With ESS			
	50%	100%	150%	200%	50%	100%	150%	200%
SCR	99.85	87.37	68.46	55.13	99.97	95.55	79.24	66.10
SSR	22.22	44.45	66.67	88.90	29.93	54.11	76.94	99.50
SLR	3.73	1.57	1.19	1.26	3.55	1.09	0.80	0.88
PRR	–	–	–	–	26	32	44	49
CLR	–	–	–	–	–	–	100	100

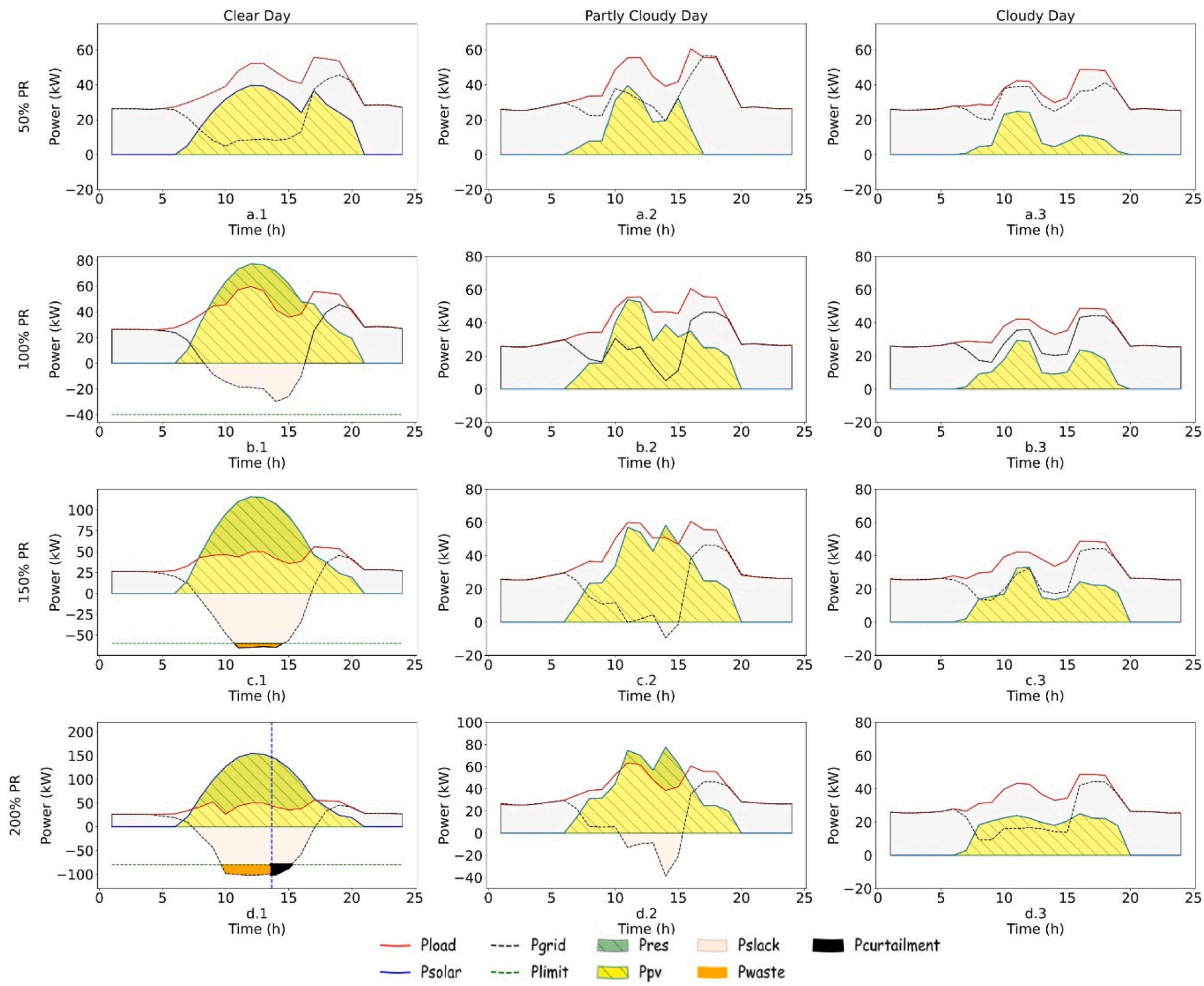

Fig. 6. Power variations depending on PR for sample days.

due to the lower RP formation on clear and cloudy days. Improving the voltage rise and drop caused by the PV generation and the peak load demand in the evening, respectively, is shown by before and after ESS use. Thus, using ESS for 100% PR is technically practical. For 150% PR, the voltage profiles in Fig. 7.c1–2 increase due to a large RP, especially on a clear day. Because the existing RE is smaller than clear days, the voltage variation is kept within the range thanks to the ESS. However, the voltage drop caused by the evening load peak on clear and cloudy days is prevented for the voltage stability. For 200% PR, it is seen in Fig. 7.d1–2 that charging ESS is completed earlier, especially on clear days, because of the most significant amount of RP for all weather conditions. Moreover, it is possible to prevent the voltage rise using a larger ESS. However, curtailing excessive energy is an economical solution for eliminating occasional voltage rise on a few days of the studied region throughout a year instead of increasing ESS size resulting in additional cost.

Voltage stability problems are more rarely encountered, especially for higher PR. Feed-in power limitation reduces voltage variation, especially when low load demand and high PV generation coincide. Thus, RE may be limited or stored and curtailed to regulate the voltages [64]. Restricting PV generation for grid relief, the voltage of point of common coupling (PCC) is prevented from exceeding 1.1 per unit by inverters. When feed-in limitation increases, the total system cost increases. Fixed feed-in limitation reduces energy curtailment, especially for regions where PV generation and load profiles are similar [8]. However, the fixed feed-in limitation may prevent only a part of energy curtailment loss, especially where PV generation and load profiles are highly variated.

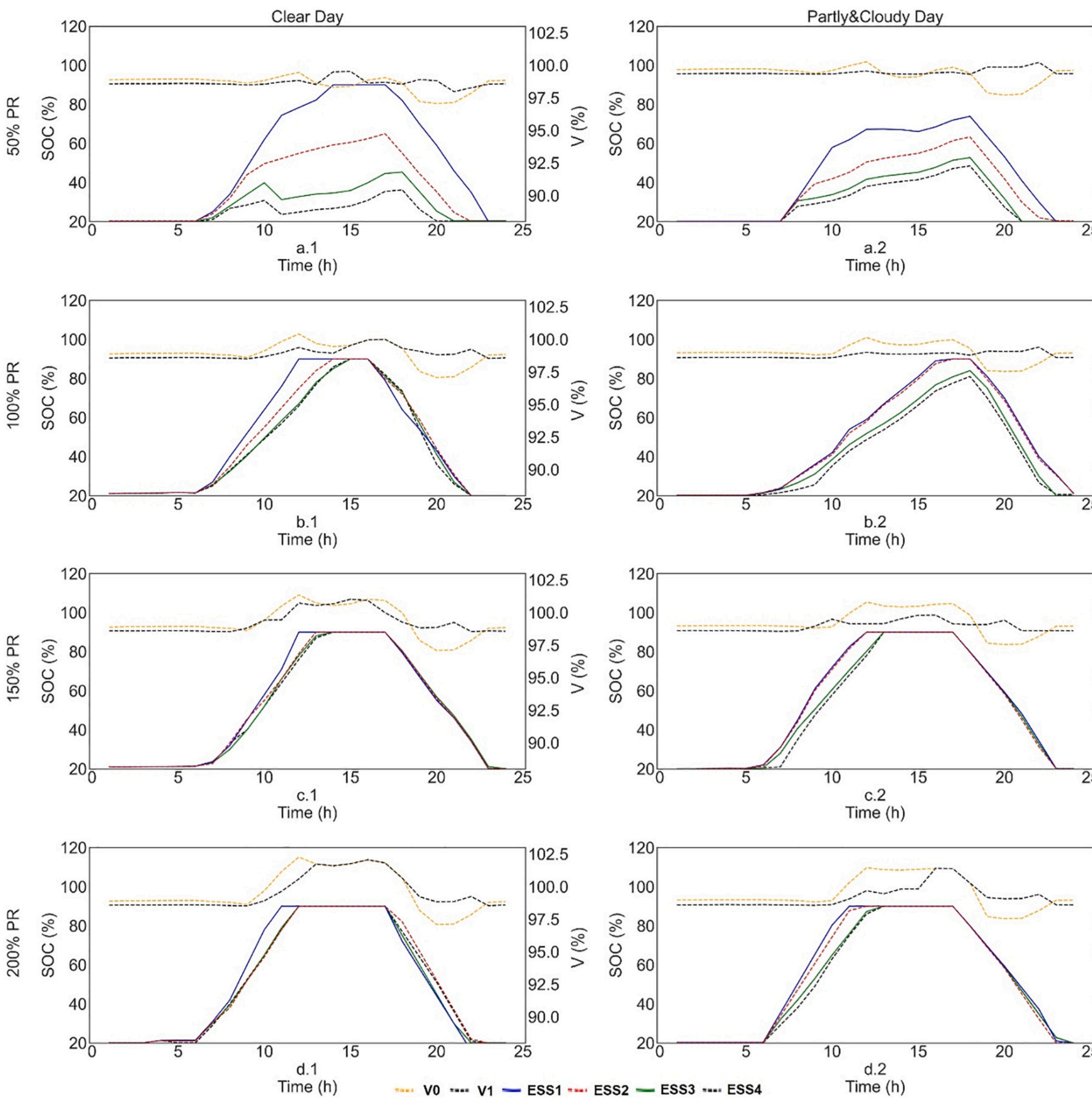

Fig. 7. SOC of ESS units and voltage profiles under various PR.

Table 5
Economic indicators comparing incentive.

	PR (%)	Without incentive (WOI)				With incentive (WI)			
		50	100	150	200	50	100	150	200
Case 1	DPP (year)	16	16	15	13	7	7	7	6
Grid + PV	IRR (%)	6.32	6.89	7.50	9.05	15.72	16.58	17.49	19.88
Case 2	DPP (years)	17	17	16	14	7	7	7	6
Grid + PV + ESS	IRR (%)	6.28	6.68	6.93	8.13	17.00	17.66	17.42	19.45
	ΔNPV	−5.42%	−5.99%	−11.93%	−8.25%	13.36%	14.51%	12.68%	15.03%

5. Economic results

This study makes economic improvement by evaluating RE and energy curtailment under various PR, minimizing the total cost. In this analysis, considering incentives for PV and ESS in different configurations for varying PR are evaluated. PV is operated with the grid in case 1, PV and ESS are operated together with the grid in case 2. It is assumed without incentive (WOI) that the investment is funded by self-capital. At the same time, energy sales from PV are calculated at the regular tariff price. Furthermore, it is assumed with an incentive (WI) that 40% of the investment cost is credited, and the credit payback is postponed for two years. Investment is decided by technical and economic analysis considering many parameters. The success of an investment is directly related to the experience, capacity, and soundness of the financing structure of a project and the profitability of the DPP process [65]. Significantly prolonging the project realization, technical errors and changes that may occur, administrative deficiencies, economic, financial, political, and legal uncertainties increase the risk factor significantly. Inferences are made based on specific indices in determining and analyzing investment projects and making the most appropriate investment decision. Internal rate of return (IRR), discounted payback period (DPP), net present value (NPV), and levelized COE (LCOE) are among the techno-economic metrics actively used to show the best possible decisions of projects. Performance of these indicators are determined generally according to these followings: easy to understand and calculate; measure profitability, making sure for liquidity, adjusting for risks, considering all cash flows, adjust for the time value of money, consistent with the wealth maximization goal, assume realistic reinvestment of intermediate cash inflow. None of these indicators has barely answered these uncertainties at a time. However, evaluating an investment considering NPV and DPP is more accurate than other indicators. The economic feasibility is analyzed considering NPV, DPP, and IRR in Table 5.

The IRR, also called the marginal efficiency of the investment, is the ratio that sets the NPV to zero. The project investments are decided by comparing profitability rates. Although the project acceptability varies according to technical and economic risk factors and the profitability expectation of the investor, if IRR is greater than the expected rate of profitability, the relevant project is considered acceptable. It is shown that in Table 5, IRR increase under all PRs. However, IRR is decreased in case 2 compared to case 1 due to the low return on ESS investment. Therefore, ESS integration led to the completion of DPP for all PRs one year later without incentive. Considering that the effective operating period is 20 years, investments in both cases are not economically viable without incentive. Therefore, DPP shortened approximately ten years, and IRR also increased with the incentive. However, DPP remains the same duration, though the ESS investment with incentive. In this respect, it is seen that ESS investment is applicable, mainly if an incentive exists. In case 2, ΔNPVs were reduced by 5–8% without incentive. Therefore, it seems that the ESS investment is not applicable. On the other hand, the ESS investment is feasible since ΔNPV increased by 12–15% due to the incentive. Namely, the incentive improved the ΔNPV average by 20%.

One of the most critical parameters affecting investment acceptability is the discount rate changes, as shown in Fig. 8. In the case of WI, it is observed that IRR gives good results in all PRs for both cases. However, if the discount rate exceeds 16–17%, NPV turns negative, indicating the investment is not profitable even with an incentive. On the other hand, the investment is not profitable without incentive if the discount rate is <6–7%. The payback period of both cases and IRR values calculated for ESS are given in Fig. 9. While bar graphs show only NPV values of the ESS investment, the red line shows case 1, and the blue line shows the payback period of case 2. In Fig. 9.a.1–b.1–c.1–d.1, it is seen that the IRR is negative for all PR without incentives. It seems clear that IRRs are much lower than the 6% discount rate, so they are not economical. The ESS investment adversely affects the DPP of PV because the investment is covered entirely from self-capital without incentives. For 50% PR, the adverse effect of ESS is more significant without incentive because of the insufficient RE. for example, IRR is reduced by 6.17% under 50% PR. However, IRR is reduced only by 2.76, 0.93, 0.11% under >50% PRs. It can be seen in Fig. 9.a.2–b.2–c.2–d.2 that ESS investments are amortized for all PR with incentives. Nevertheless, DPP

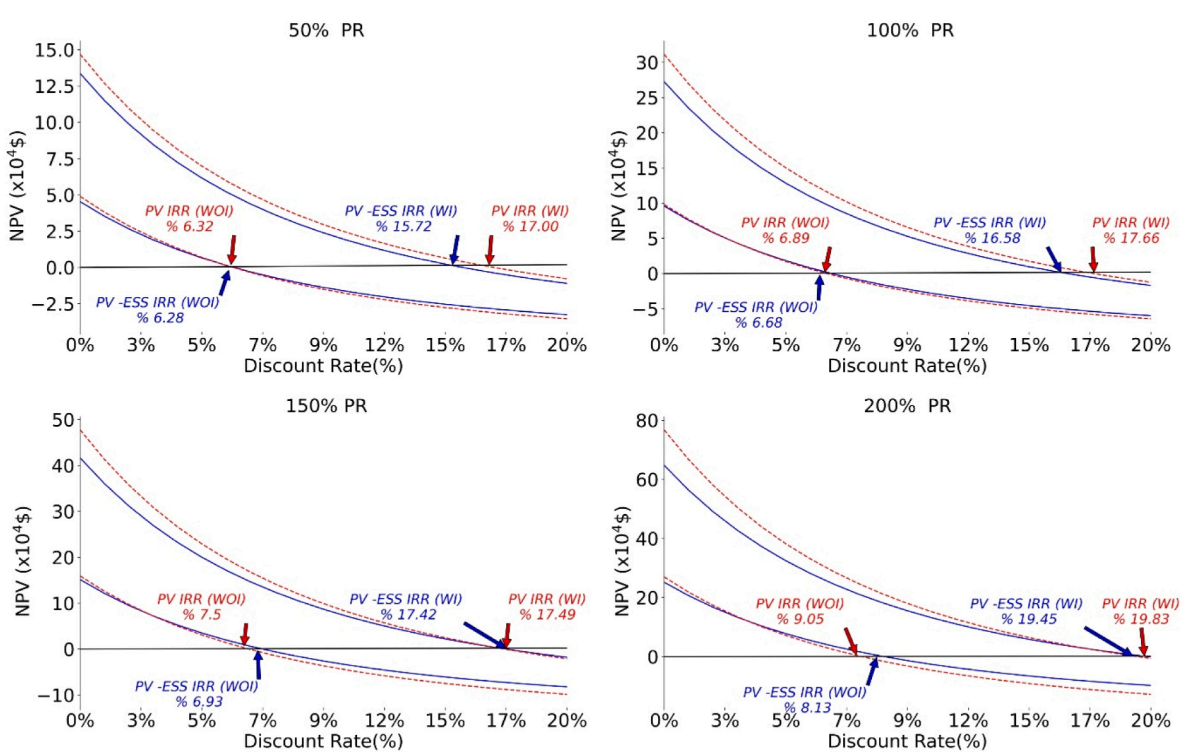

Fig. 8. NPV variations depending on the discount rate of cases.

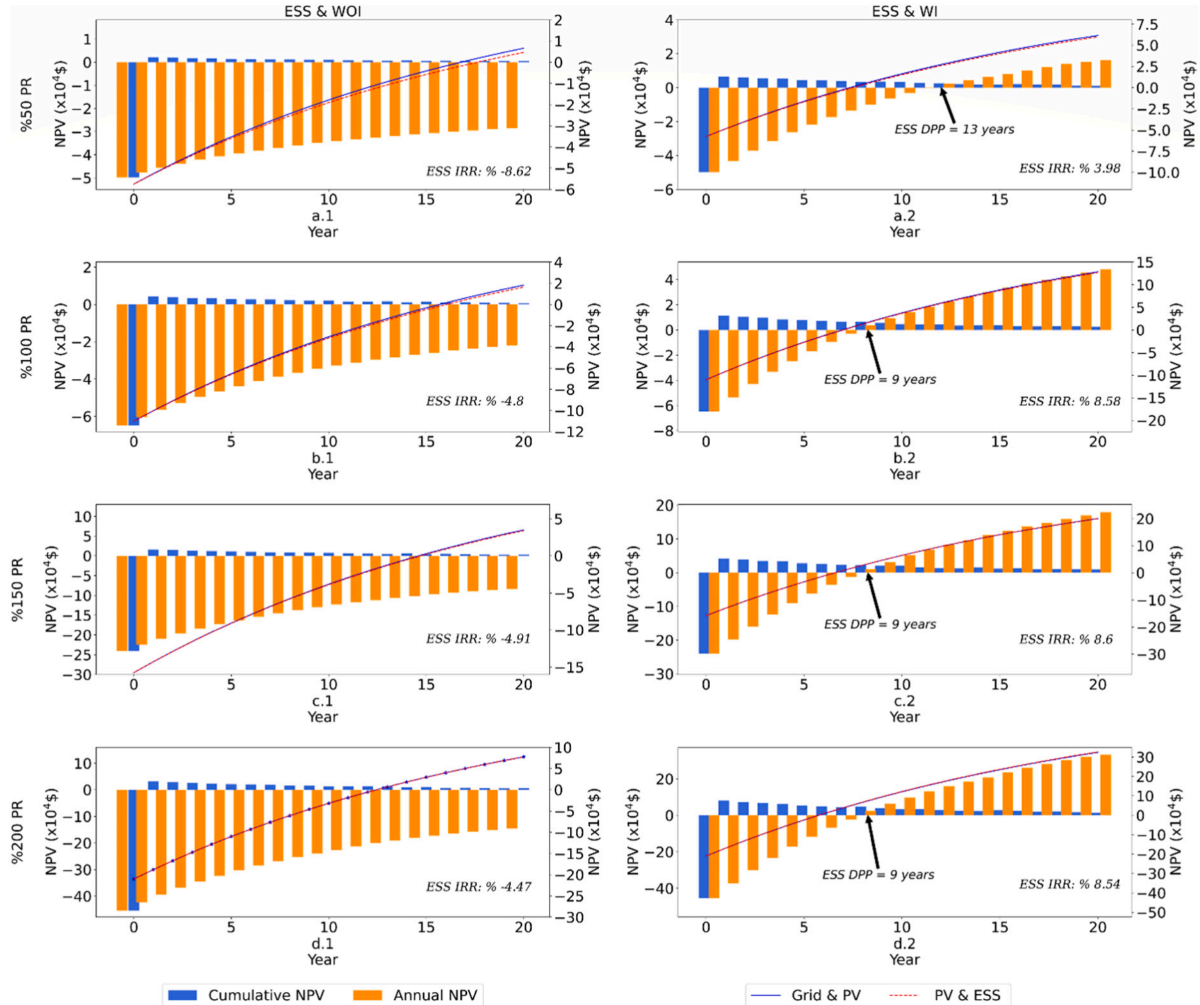

Fig. 9. DPP and NPV related to various ESS investment options. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

is 13 years under 50% PR due to insufficient RE; DPPs reduce to 9 years if PR is >50%.

6. Discussion

The distorting effects of higher solar penetrations on the energy supply-demand balance cause the feed-in limitation. Therefore, an important implication of the feed-in limitation is a decline or restriction in the incentives and installation of PVG. This study maximizes self-consumption rates for increasing penetration of solar energy and using shared energy storage. These results agree with other studies showing that ESS improves SCR and SSR, ensuring power balance and reducing capacity problems. Thus, the economic benefits of the prosumers are increased by utilizing RE using ESS. This paper presents a pilot study to find how the main factors drive the shared ESS benefits. Economic outputs vary depending on RE and PR. The first finding related to 50% PR is that ESS use does not seem to benefit significantly, neither technically nor economically. Secondly, even though there is no significant energy waste because the feed-in limit is not exceeded under 100% PR, the ESS provides technical benefits. Further, ESS recovers the curtailment losses and reduces energy losses under higher PR than 150%. Although the technical results are favorable, the financial results differ up to various PR. In the absence of incentives, it is not economically viable to support PV with ESS. Our observations that the incentives increased the benefits under all PRs depending on RE are not new. However, the sensitivity analysis of the benefits using the commonly used investment economic indicators such as DPP, NPV, and IRR has revealed a strong relationship between the incentive and the DPP. Thus, the findings suggest that this approach could also be helpful for a more realistic evaluation of the ESS investment considering DPP durations and IRR values. As a result, any PV-ESS configuration is not economical for the non-incentive situation considering the obtained DPP and IRR values. If the incentive exists, DPP durations are reduced to an acceptable level, less than ten years when NPV increases 15%. The profitability of the investment is extremely sensitive to the discount rate. As the discount rate increases, the profitability of the investment decreases, even if there are incentives. Since the profitability of ESS investments is directly related to RE, the climatic characteristics of the region can give very different economic results under the same PR. The study shows that ESS reduces power peaks in generation and load by 26–49%, especially in the evening. A decrease in SLR and elimination of curtailed energy leads to an increase in SCR and NPV. The obtained results can be expanded to different prosumer communities, considering the regional weather and economic conditions. The performed financial analysis proves the economic viability of these systems under the current energy market and economic conditions in Turkey. However, the economic benefits defer depending on the weather conditions, such as the number of clear, partly cloudy, and cloudy days. Due to economic concerns, there is an important opportunity for the power system and prosumers to increase the SCR with a shared ESS. Therefore, it is seen that sustainable energy and environmental targets can be achieved in reducing CO_2 emissions and the cost of energy.

7. Conclusion

Decarbonization of the energy sector is becoming one of the emerging trends for investors and governments, aiming to increase the share of renewable; energy resources by reducing the dependency on fossil fuel-based energy resources. This transition requires deploying advanced solutions that focus on integrating higher amounts of renewable energy resources such as PV solar energy into the power system. Arising technical issues due to the large penetration of PV panels imposes certain limitations and challenges for network operators regarding capacity and power quality-related issues. This study aimed to maximize self-consumption rates and power quality for a prosumer community under various penetration levels. The advantages of using shared ESS within the prosumer community are compared to the base case without storage. Further, ESS units are allocated considering the power distribution quality. The relationship between SCR and the discounted payback period was investigated under various penetration rates. Sensitivity analysis of possible incentives on PV-ESS investment was made according to economic parameters. Optimal allocation of ESS units was done using the genetic and new best algorithm. The effects of incentives that encourage prosumers to increase self-consumption and use ESS were examined. The use of ESS reduces the peak power up to 49% resulting in grid relief for the investigated cases. Moreover, converting residual energy to self-consumption to avoid curtailment applies to higher penetration levels. Furthermore, economic parameters affect all scenarios significantly evaluated in sensitivity analyses. High penetration of renewables causes power quality degradation. Voltage fluctuations decrease with energy storage unless penetration reaches 200%. As a result, shared energy storage increased self-consumption rates up to 11% within the prosumer community. The proposed method provides significant economic benefits and improved power quality. Additionally, prosumers need an ESS to improve self-consumption, especially as renewable penetration levels increase in the power grid. Furthermore, economic parameters affect all scenarios significantly evaluated in sensitivity analyses. ESS integration led to the completion of DPP for all PRs one year later without incentive. DPP shortened approximately ten years, and IRR also increased with the incentive. More precisely, the incentive improved the ΔNPV average by 20%. If the discount rate exceeds 16% even with incentives, the investment can be considered economically infeasible. Nevertheless, DPP is 13 years under 50% PR conditions due to scarce of RE. With this regard, DPP figures reduce to 9 years where PRs are >50%. The adverse effect of ESS is significant for 50% PR due to lack of RE. However, this impact is limited for higher PRs. The proposed approach provided considerable benefits in terms of power quality and improved self-consumption rates for a prosumer community under various penetration levels. It is recommended that the policymakers shall design new push-policy instruments such as innovative support mechanisms to promote ESS for the LEM and microgrids. Further research is needed to prove additional extensions to investigate the decarbonization impacts by quantifying environmental benefits where next generation digital technologies such as blockchain and AI will be used as enabler of new business plans.

CRediT authorship contribution statement

Said Mirza Tercan: Conceptualization, Methodology, Writing-Reviewing and editing, Visualization, Writing-Original draft preparation
Alpaslan Demirci: Conceptualization, Methodology, Visualization, Software, Data curation
Erdin Gokalp: Conceptualization, Methodology, Validation, Supervision
Ümit Cali: Investigation, Resources, Writing-Reviewing and editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] M. Kühnbach, A. Bekk, A. Weidlich, Towards improved prosumer participation: electricity trading in local markets, Energy 239 (2022), 122445, https://doi.org/10.1016/j.energy.2021.122445.
[2] A.D. Mustika, R. Rigo-Mariani, V. Debusschere, A. Pachurka, A two-stage management strategy for the optimal operation and billing in an energy community with collective self-consumption, Appl. Energy 310 (2022), 118484, https://doi.org/10.1016/j.apenergy.2021.118484.
[3] D. Zarrilli, A. Giannitrapani, S. Paoletti, A. Vicino, Energy storage operation for voltage control in distribution networks: a receding horizon approach, IEEE Trans. Control Syst. Technol. 26 (2018) 599–609, https://doi.org/10.1109/TCST.2017.2692719.
[4] S.M. Tercan, O. Elma, E. Gokalp, U. Cali, An expansion planning method for extending distributed energy system lifespan with energy storage systems, Energy Explor. Exploit. 40 (2022) 599–618, https://doi.org/10.1177/01445987211058304.
[5] U. Halden, U. Cali, M.F. Dynge, J. Stekli, L. Bai, DLT-based equity crowdfunding on the techno-economic feasibility of solar energy investments, Sol. Energy 227 (2021) 137–150, https://doi.org/10.1016/j.solener.2021.08.067.
[6] U. Cali, O. Cakir, Novel donation sharing mechanisms under smart energy cyber-physical-social system and DLT to contend the energy poverty problem, IEEE Access 9 (2021) 127037–127053, https://doi.org/10.1109/ACCESS.2021.3106833.
[7] U. Cali, O. Cakir, Energy policy instruments for distributed ledger technology empowered peer-to-peer local energy markets, IEEE Access 7 (2019) 82888–82900, https://doi.org/10.1109/ACCESS.2019.2923906.
[8] A. Reimuth, M. Prasch, V. Locherer, M. Danner, W. Mauser, Influence of different battery charging strategies on residual grid power flows and self-consumption rates at regional scale, Appl. Energy 238 (2019) 572–581, https://doi.org/10.1016/j.apenergy.2019.01.112.
[9] M. Ragwitz, J. Winkler, C. Klessmann, M. Gephart, G. Resch, Recent developments of feed-in systems in the EU – a research paper for the International Feed-In Cooperation, in: A Rep Comm by Minist Environ Nat Conserv Nucl Saf, 2012, pp. 1–16.
[10] H. Ruf, Limitations for the feed-in power of residential photovoltaic systems in Germany – an overview of the regulatory framework, Sol. Energy 159 (2018) 588–600, https://doi.org/10.1016/j.solener.2017.10.072.
[11] R. Espinoza, E. Muñoz-Cerón, J. Aguilera, J. de la Casa, Feasibility evaluation of residential photovoltaic self-consumption projects in Peru, Renew. Energy 136 (2019) 414–427, https://doi.org/10.1016/j.renene.2019.01.003.
[12] Y. Wang, R. Das, G. Putrus, R. Kotter, Economic evaluation of photovoltaic and energy storage technologies for future domestic energy systems – a case study of the UK, Energy 203 (2020), 117826, https://doi.org/10.1016/j.energy.2020.117826.
[13] A. Zeh, R. Witzmann, Operational strategies for battery storage systems in low-voltage distribution grids to limit the feed-in power of roof-mounted solar power systems, Energy Procedia 46 (2014) 114–123, https://doi.org/10.1016/j.egypro.2014.01.164.
[14] M. Brenna, A. Corradi, F. Foiadelli, M. Longo, W. Yaici, Numerical simulation analysis of the impact of photovoltaic systems and energy storage technologies on centralised generation: a case study for Australia, Int. J. Energy Environ. Eng. 11 (2020) 9–31, https://doi.org/10.1007/s40095-019-00330-3.
[15] M. Zeraati, M.E. Hamedani Golshan, J.M. Guerrero, Distributed control of battery energy storage Systems for Voltage Regulation in distribution networks with high PV penetration, IEEE Trans Smart Grid 9 (2018) 3582–3593, https://doi.org/10.1109/TSG.2016.2636217.
[16] J. Morales, A. Conejo, H. Madsen, P. Pinson, M. Zugno, Handbook on Data Envelopment Analysis 164, Springer US, Boston, MA, 2011, https://doi.org/10.1007/978-1-4419-6151-8.
[17] E. Waffenschmidt, Dimensioning of decentralized photovoltaic storages with limited feed-in power and their impact on the distribution grid, Energy Procedia 46 (2014) 88–97, https://doi.org/10.1016/j.egypro.2014.01.161.
[18] R. Luthander, J. Widén, D. Nilsson, J. Palm, Photovoltaic self-consumption in buildings: a review, Appl. Energy 142 (2015) 80–94, https://doi.org/10.1016/j.apenergy.2014.12.028.
[19] M. Castellini, F. Menoncin, M. Moretto, S. Vergalli, Photovoltaic smart grids in the prosumers investment decisions: a real option model, J. Econ. Dyn. Control. 126 (2021), 103988, https://doi.org/10.1016/j.jedc.2020.103988.
[20] M. Castellini, L. Di Corato, M. Moretto, S. Vergalli, Energy exchange among heterogeneous prosumers under price uncertainty, SSRN Electron. J. (2021), https://doi.org/10.2139/ssrn.3970630.

[21] A. Shivakumar, A. Dobbins, U. Fahl, A. Singh, Drivers of renewable energy deployment in the EU: an analysis of past trends and projections, Energy Strateg. Rev. 26 (2019), 100402, https://doi.org/10.1016/j.esr.2019.100402.
[22] A. Clerjon, F. Perdu, Matching intermittency and electricity storage characteristics through time scale analysis: an energy return on investment comparison, Energy Environ. Sci. 12 (2019) 693–705, https://doi.org/10.1039/c8ee01940a.
[23] W.-G. Früh, The residual load duration curve (rLDC) to model an energy system, Renew Energy Power Qual. J. (2019) 500–505, https://doi.org/10.24084/repqj17.357.
[24] N. Mukisa, R. Zamora, Lie T. Tjing, Store-on grid scheme model for grid-tied solar photovoltaic systems for industrial sector application: costs analysis, Sustain. Energy Technol. Assess. 41 (2020), 100797, https://doi.org/10.1016/j.seta.2020.100797.
[25] P. Kästel, B. Gilroy-Scott, Economics of pooling small local electricity prosumers - LCOE & self-consumption, Renew. Sust. Energ. Rev. 51 (2015) 718–729, https://doi.org/10.1016/j.rser.2015.06.057.
[26] G.P. Luz, E. Silva, RA., Modeling energy communities with collective photovoltaic self-consumption: synergies between a small city and a winery in Portugal, Energies 14 (2021), https://doi.org/10.3390/en14020323.
[27] S. Bellekom, M. Arentsen, K. van Gorkum, Prosumption and the distribution and supply of electricity, Energy Sustain. Soc. 6 (2016) 1–17, https://doi.org/10.1186/s13705-016-0087-7.
[28] D.L. Talavera, F.J. Muñoz-Rodriguez, G. Jimenez-Castillo, C. Rus-Casas, A new approach to sizing the photovoltaic generator in self-consumption systems based on cost–competitiveness, maximizing direct self-consumption, Renew. Energy 130 (2019) 1021–1035, https://doi.org/10.1016/j.renene.2018.06.088.
[29] F. Sabadini, R. Madlener, The economic potential of grid defection of energy prosumer households in Germany, Adv. Appl. Energy 4 (2021), 100075, https://doi.org/10.1016/j.adapen.2021.100075.
[30] J. Struth, M. Leuthold, A. Aretz, M. Bost, PV-benefit: a critical review of the effect of grid integrated PV-storage-systems, in: 8th Int Renew Energy Storage Conf Exhib, 2013, pp. 1–10.
[31] S. Englberger, A.C. Chapman, W. Tushar, T. Almomani, S. Snow, R. Witzmann, et al., Evaluating the interdependency between peer-to-peer networks and energy storages: a techno-economic proof for prosumers, Adv. Appl. Energy 3 (2021), 100059, https://doi.org/10.1016/j.adapen.2021.100059.
[32] Y. Zhu, Q. Zhang, K. Liu, M. Han, Q. Chen, Y. Liu, Optimized capacity configuration of photovoltaic generation and energy storage for residential microgrid, in: 2019 IEEE PES Innov Smart Grid Technol Asia, ISGT, 2019, pp. 1751–1755, https://doi.org/10.1109/ISGT-Asia.2019.8881525.
[33] A.S.A. Awad, T.H.M. El-Fouly, M.M.A. Salama, Optimal ESS allocation for load management application, IEEE Trans. Power Syst. 30 (2015) 327–336, https://doi.org/10.1109/TPWRS.2014.2326044.
[34] P. Lata, S. Vadhera, TLBO-based approach to optimally place and sizing of energy storage system for reliability enhancement of radial distribution system, Int. Trans. Electr. Energy Syst. 30 (2020) 1–20, https://doi.org/10.1002/2050-7038.12334.
[35] A. Gagliano, F. Nocera, G. Tina, Performances and economic analysis of small photovoltaic–electricity energy storage system for residential applications, Energy Environ. 31 (2020) 155–175, https://doi.org/10.1177/0958305X18787313.
[36] B. Mukhopadhyay, D. Das, Multi-objective dynamic and static reconfiguration with optimized allocation of PV-DG and battery energy storage system, Renew. Sust. Energ. Rev. 124 (2020), 109777, https://doi.org/10.1016/j.rser.2020.109777.
[37] I. Ranaweera, O.-M. Midtgård, Optimization of operational cost for a grid-supporting PV system with battery storage, Renew. Energy 88 (2016) 262–272, https://doi.org/10.1016/j.renene.2015.11.044.
[38] P. Sharma, M. Kolhe, A. Sharma, Economic performance assessment of building integrated photovoltaic system with battery energy storage under grid constraints, Renew. Energy 145 (2020) 1901–1909, https://doi.org/10.1016/j.renene.2019.07.099.
[39] J. Struth, K.-P. Kairies, M. Leuthold, A. Aretz, M. Bost, S. Gährs, et al., A critical review of the effect of grid integrated PV-storage-systems self-consumption, Ires 2013 (2013) 54.
[40] M.U. Hashmi, J. Cavaleiro, L. Pereira, A. Busic, in: Sizing and Profitability of Energy Storage for Prosumers in Madeira, Portugal. 2020 IEEE Power Energy Soc. Innov. Smart Grid Technol. Conf, IEEE, 2020, pp. 1–5, https://doi.org/10.1109/ISGT45199.2020.9087772.
[41] M. Pierro, M. De Felice, E. Maggioni, D. Moser, A. Perotto, F. Spada, et al., Residual load probabilistic forecast for reserve assessment: a real case study, Renew. Energy 149 (2020) 508–522, https://doi.org/10.1016/j.renene.2019.12.056.
[42] J. Liu, Z. Xu, J. Wu, K. Liu, X. Guan, Optimal planning of distributed hydrogen-based multi-energy systems, Appl. Energy 281 (2021), https://doi.org/10.1016/j.apenergy.2020.116107.
[43] S. Peláez-Peláez, A. Colmenar-Santos, C. Pérez-Molina, A.E. Rosales, E. Rosales-Asensio, Techno-economic analysis of a heat and power combination system based on hybrid photovoltaic-fuel cell systems using hydrogen as an energy vector, Energy 224 (2021), https://doi.org/10.1016/j.energy.2021.120110.
[44] J. Tariq, Energy management using storage to facilitate high shares of variable renewable energy, Int. J. Sustain. Energy Plan. Manag. 25 (2020) 61–76, https://doi.org/10.5278/ijsepm.3453.
[45] P. Colbertaldo, S.B. Agustin, S. Campanari, J. Brouwer, Impact of hydrogen energy storage on California electric power system: towards 100% renewable electricity, Int. J. Hydrog. Energy 44 (2019) 9558–9576, https://doi.org/10.1016/j.ijhydene.2018.11.062.
[46] P. Colombo, A. Saeedmanesh, M. Santarelli, J. Brouwer, Dynamic dispatch of solid oxide electrolysis system for high renewable energy penetration in a microgrid, Energy Convers. Manag. 204 (2020), 112322, https://doi.org/10.1016/j.enconman.2019.112322.
[47] Y. Matsuo, S. Endo, Y. Nagatomi, Y. Shibata, R. Komiyama, Y. Fujii, Investigating the economics of the power sector under high penetration of variable renewable energies, Appl. Energy 267 (2020), 113956, https://doi.org/10.1016/j.apenergy.2019.113956.
[48] P. Lombardi, C. Röhrig, K. Rudion, R. Marquardt, M. Müler-Mienack, A. S. Estermann, et al., An A-CAES pilot installation in the distribution system: a technical study for RES integration, Energy Sci. Eng. 2 (2014) 116–127, https://doi.org/10.1002/ese3.38.
[49] Q. Zhou, D. Du, C. Lu, Q. He, W. Liu, A review of thermal energy storage in compressed air energy storage system, Energy 188 (2019), 115993, https://doi.org/10.1016/j.energy.2019.115993.
[50] M. Budt, D. Wolf, R. Span, J. Yan, A review on compressed air energy storage: basic principles, past milestones and recent developments, Appl. Energy 170 (2016) 250–268, https://doi.org/10.1016/j.apenergy.2016.02.108.
[51] A.G. Olabi, T. Wilberforce, M. Ramadan, M.A. Abdelkareem, A.H. Alami, Compressed air energy storage systems: components and operating parameters – a review, J. Energy Storage 34 (2020), 102000, https://doi.org/10.1016/j.est.2020.102000.
[52] M. Jabbari Ghadi, A. Azizivahed, A. Rajabi, S. Ghavidel, L. Li, J. Zhang, et al., Day-ahead market participation of an active distribution network equipped with small-scale CAES systems, IEEE Trans. Smart Grid 11 (2020) 2966–2979, https://doi.org/10.1109/TSG.2020.2967937.
[53] H. Ebrahimi, S.R. Marjani, V. Talavat, Optimal planning in active distribution networks considering nonlinear loads using the MOPSO algorithm in the TOPSIS framework, Int. Trans. Electr. Energy Syst. 30 (2020) 1–17, https://doi.org/10.1002/2050-7038.12244.
[54] X. Yao, B. Yi, Y. Yu, Y. Fan, L. Zhu, Economic analysis of grid integration of variable solar and wind power with conventional power system, Appl. Energy 264 (2020), 114706, https://doi.org/10.1016/j.apenergy.2020.114706.
[55] J. Weniger, T. Tjaden, V. Quaschning, Sizing of residential PV battery systems, Energy Procedia 46 (2014) 78–87, https://doi.org/10.1016/j.egypro.2014.01.160.
[56] M. Resch, B. Ramadhani, J. Bühler, A. Sumper, Comparison of control strategies of residential PV storage systems, in: 9th Int Renew Energy Storage Conf (IRES 2015) 18, 2015, https://doi.org/10.13140/RG.2.1.3668.2084.
[57] J. von Appen, T. Stetz, M. Braun, A. Schmiegel, Local voltage control strategies for PV storage systems in distribution grids, IEEE Trans. Smart Grid 5 (2014) 1002–1009, https://doi.org/10.1109/TSG.2013.2291116.
[58] G. Angenendt, S. Zurmühlen, H. Axelsen, D.U. Sauer, Comparison of different operation strategies for PV battery home storage systems including forecast-based operation strategies, Appl. Energy 229 (2018) 884–899, https://doi.org/10.1016/j.apenergy.2018.08.058.
[59] G. Litjens, W. Van Sark, E. Worrell, On the influence of electricity demand patterns, battery storage and PV system design on PV self-consumption and grid interaction, in: 2017 IEEE 44th Photovolt Spec Conf PVSC 2017, 2017, pp. 1–4, https://doi.org/10.1109/PVSC.2017.8366453.
[60] Siemens. PSS®SINCAL n.d.
[61] Joint Research Centre. Hourly radiation data of İstanbul, Photovoltaic Geographical information system. EU Sci HUB n.d. ec.europa.eu/jrc/en/PVGIS/tools/hourly-radiation.
[62] Turkish State Meteorological Service n.d. www.mgm.gov.tr/eng/forecast-cities.aspx.
[64] R. Luthander, D. Lingfors, J. Widén, Large-scale integration of photovoltaic power in a distribution grid using power curtailment and energy storage, Sol. Energy 155 (2017) 1319–1325, https://doi.org/10.1016/j.solener.2017.07.083.
[65] S.B. Bhandari, Discounted Payback Period-SOME. Proc. ASBBS 16, 2009.