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Battery energy storage sizing optimisation for different ownership structures in a peer-to-peer energy sharing community[☆]

Daniel L. Rodrigues, Xianming Ye[*], Xiaohua Xia, Bing Zhu

Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria 0002, South Africa

HIGHLIGHTS

- Ownership plays a significant role in battery sizing for P2P energy sharing.
- Three battery ownership structures are analysed for a P2P and P2G network.
- Battery sizes are optimised for a P2P energy sharing network.
- Maximum NPV is obtained when each user owns a battery in the P2P network.

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ABSTRACT

Existing studies have shown the benefits of battery energy storage systems (BESS) inclusion, but do not consider optimal BESS sizing and operation in a peer-to-peer (P2P) energy sharing network under different BESS ownership structures. Under the P2P framework, two different BESS ownership structures, namely the ESP owned structure and the user owned structure are investigated in this study, which are compared to the traditional user owned BESS under the peer-to-grid (P2G) framework. It is found that in campus buildings with a P2P energy sharing network, the user owned BESS exhibits the highest NPV comparing to the other two BESS ownership structures. The ESP owned structure is economically less beneficial, but provided the opportunity for the prosumers to engage in P2P energy sharing and reduce their energy costs without a BESS investment cost.

1. Introduction

The desire to reduce the global carbon footprint while improving electricity affordability and energy security has triggered the on-going energy shift for buildings to become net zero energy buildings (NZEB). NZEBs are highly efficient buildings whose net energy demand is met by local power generation. With the rapid decline in solar photo-voltaic (PV) costs, an increase in the integration of solar PV distributed energy resources (DERs) has grown largely and is continually being promoted [1]. This has led many commercial buildings to become prosumers, who produce electricity with local renewable energy recourses to consume or sell locally. Electricity generation from solar PV is intermittent due to unpredictable solar irradiance. Excess energy from the dynamic mismatch between the local demand and the solar PV generation during peak solar irradiance hours may be either sold back to the grid at the utility feed-in tariff, curtailed, stored in an energy storage system (ESS), or traded with other energy consumers. Simultaneously, increased supply market DERs have caused many countries energy policies to promote self-consumption by diminishing feed-in tariff based incentives because of uncertainty and management pressure that is placed on utility grids [2–4]. As a result, it is essential to develop innovative solutions to improve self-consumption of excess energy to sustain future renewable energy generation installations. Existing buildings in clusters, such as residential complexes, educational campuses, hospital buildings and commercial office parks, manage their renewable energy systems independently to their counter parts. Connecting the individual microgrids enables new opportunities to improve the local generation self-consumption, reduce energy costs, decrease peak community demand, and reduce the size of the ESSs [5–7]. Peer-to-peer (P2P) energy sharing and energy storage sharing [8–11] are two such opportunities.

2. Literature

P2P energy sharing is the energy trade between local prosumers

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* Corresponding author.
E-mail address: xianming.ye@up.ac.za (X. Ye).

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[12] which is an effective solution that allows surplus energy from prosumers DERs to be traded within their local community market, establishing superior advantages in terms of local power self-consumption, self-sufficiency and return on local generation investment than the conventional peer-to-grid (P2G) trading [13,6]. Existing studies show that P2P energy sharing networks with a battery energy storage systems (BESS) can provide significant savings to prosumers within a community [13,3], but do not consider the optimal BESS sizing with different ownership structures and the interaction between P2P energy sharing and energy storage sizing. Although there are extensive optimal energy storage sizing studies [14,15] and improvements to BESS's efficiency and life cycle [16], the high capital investment and operational costs for BESS solutions remains an economic feasibility concern. Therefore, proper power and energy sizing is important such that P2P energy sharing with BESSs are viable considering the life cycle cost, including both the investment and operational costs [14,15]. To this end, a brief up to date review is conducted on P2P energy sharing development, covering the major relevant concepts such as P2P energy sharing frameworks, internal pricing modeling, and optimal BESS sizing determinations.

P2P energy sharing networks can be broadly split into two categories, supervised sharing and autonomous energy sharing. In the autonomous energy sharing mode, a local market is required which allows prosumers to trade energy based on an internal energy price mechanism, with each looking to optimize their own benefits from selling energy locally. This manages DERs in a distributed manner, providing users with the full control of their DERs and requiring no central control system. Most of the existing P2P energy sharing literature focuses on different mechanisms based on this framework for residential communities. The advantage of this framework is that no incentive is usually required to make prosumers participate as it allows them full control of their DER. This framework is established by using a multi-agent system (MAS) [17], analytical [18–22] or auction [23,11] system. A MAS consists of multiple autonomous agents which interact, negotiate and cooperate with each other to achieve their individual objectives. The downfalls of the MAS iterative frameworks are that they are subjected to divergence concerns, consist of designed exit mechanisms to prevent lengthy waiting periods and require intensive computational power and communication systems for energy price bidding [17,6]. In an auction based market for P2P energy trading, the coordinator finalises the market exchange by finding the intersection between the ascending supply and the demand. Auctions are independent with each prosumer, submitting a bid without knowing the bids from the other participants or any other information of the community demand [23,11]. An analytical model bases energy exchange based on a set of rules, calculation methods and game theoretical approaches [21,18]. For an energy sharing network (ESN), a dynamic internal pricing model based on the supply demand ratio (SDR) from economics setup a competitive local market for grid-connected prosumers. The model allows prosumers to carry out internal-based price demand response, which resulted in a community and prosumers electricity cost reduction of between 3.3% and 5% [18]. A study realised a distributed game-based pricing market for solar PV prosumers within a micro-grid to undertake energy sharing using the Stackelberg approach [21]. Another market mechanism that has proved to be eligible for managing P2P energy trading transactions is block-chain [24–27]. A concept of a block-chain based microgrid energy market is one which does not require a central intermediary and is a solution that can address the privacy, cyber-security and mutual-trust concerns, which currently faces P2P energy transactions.

In the supervised energy sharing mode, the energy sharing is coordinated a third-party entity referred to as an energy sharing provider (ESP) based on a community global objective. Frameworks with an ESP require simpler communication systems and utilise less data processing, compared to market related infrastructures, as no bidding is performed. However, benefit equality within the community becomes a concern as well as the requirement of incentives to promote prosumers to join the sharing policy [17]. An analysis of the end-user benefits coupled with the role of energy storage found that the two different local market designs, a distributed and centralised ESS, are both economically viable in a P2P energy sharing community. The results showed that more than half of the savings came from P2P direct trade and the remaining from the BESS added demand and supply flexibility [4]. The distributed design achieved a 31% overall community saving, while the centralised design achieved 24%, but the study does not consider how the ownership of BESS affects the relevant parties interests or the market designs. A proposed aggregated battery control system realised P2P energy sharing within a residential community by controlling the communities distributed energy storage via an ESP. The proposed system realised a cluster level energy cost reduction of 30%, an increase in self-consumption of the solar PV energy by 10–30% and a reduction in the electricity bill of individual consumers by 12.4% from its modified SDR based pricing mechanism [6]. A proposed infrastructure, consisting of an ESP equipped with an ESS, improved solar PV energy sharing within the community and reduced the peak and variation of the communities net load by providing the opportunity of buffered sharing within the ESN [13]. A Stackelberg game provided the dynamic pricing platform bringing economic benefits for the prosumers and the ESP but does not quantify the ESP benefit in relation to energy storage size deployment. A novel P2P energy market, based on a concept of multi-class energy management, achieved, as it describes it, “energy sharing with heterogeneous preferences” [28]. This is being able to share energy with peers based on individual preferences such as generation technology, location in the network and the owner's reputation. The objective is to minimise the costs associated with losses and battery depreciation, while contributing value by accounting for the individual prosumer energy preferences such as financial, social, philanthropic or environmental [28].

In a P2P ESN, the trading of excess renewable energy amongst prosumers becomes an economic operational problem as it becomes difficult to facilitate energy sharing without an internal pricing mechanism. This makes internal pricing mechanisms an important aspect for the implementation of P2P energy sharing. A Game theory pricing mechanism is one pricing methodology that has been investigated and proposed for an internal pricing mechanism for P2P energy sharing networks [22]. A Stackelberg game realised internal buying and selling prices for an ESN in a distributed method where the Stackelberg equilibrium is the set of internal price decisions and energy sharing profiles. The market co-ordinator acts as a leader maximising its own profit, while the prosumers are followers trying to minimise their costs equally [21,29]. A marginal pricing scheme was used for the pricing of energy exchanges within the community with a social welfare maximisation approach. The mechanism guaranteed all participants achieved energy cost saving between 28% to 74% [30]. A SDR dynamic pricing mechanism provides an internal trading price based on the community's energy supply and demand during specified periods. This ensures competitive internal prices which are bounded by the electricity retailer export and import prices [18]. The mid-market rate (MMR) provides an internal price based on the logic that the internal price is always at the middle of the electricity retailer export and import prices so that prosumers and consumers experience equal energy sharing benefits [31,22]. The bill sharing mechanism distributes the total energy costs and income of the ESN according to the amount of energy consumed and generated by the prosumer [31]. An evaluation of the three mechanisms based on a multi-agent framework found the SDR mechanism to be the best overall, followed by the MMR and then the bill sharing mechanism based on value tapping, participation, equality, energy balance, power flatness and self-sufficiency for different penetration levels of solar PV and electrical vehicle charging. Both the SDR and MMR mechanisms guaranteed increased benefits and harnessed the most cost-saving, but slightly decreased income equality [17]. The SDR mechanism, including a compensating factor, ensured more equal benefits by compensating prosumers when the community SDR is larger than one, not undermining the prosumers who export a large share of their PV generated energy [6].

BESS optimal sizing can be performed based on three types of indicators: financial, technical and hybrid [15]. Financial indicators take into account the financial return on the investment and the operation of the BESS system, and consist of different financial indicators such as the net present value (NPV) [7,32], the market benefit [33] and the levelised cost of electricity [34]. The benefit of financial indicators is the common unit when comparisons are made. The capital investment cost is the important measure in the cost analysis BESSs which considers the payback period and therefore the life cycle of the battery. Technical indicators, otherwise, do not contain the common units for comparison and rely on constraints or achieving an optimisation goal. Technical indicators are separated into two classifications: dynamic and steady-state. Dynamic characteristics consist of time horizons smaller than one minute and revolve around the application of voltage and frequency regulation of a system [35]. Steady-state operation indicators, which include time horizons larger than one minute, consist of energy reliability and curtailment indicators. Examples of reliability indicators are loss of load expectation, renewable energy self-consumption, system peak-demand and other operational parameters such as the depth of discharge (DOD), the battery life cycle and the charge or discharge rates. Battery degradation, which is mostly affected by the number of cycles and the state-of-charge (SOC), affects the life cycle of a battery. For Li-ion batteries excessive temperatures, high charging and discharging rates, cycling and DOD are factors which affect the degradation [36]. Common sizing approaches are hybrid indicators which, simultaneously, consist of financial and technical indicators [14,37,38]. An optimal placement and sizing performed for a network consisting of distributed solar PV used a cost-benefit analysis with the objective of maximising the NPV, improving the load factor and the voltage profile. The results concluded that the amount of PV penetration is insignificant on the optimal placement of the energy storage and that a higher NPV was obtained for energy storage deployments between 2 and 6 compared to a single energy storage [38]. A sizing study for a solar PV system under different tariffs was found not to be affected by the different time-of-use (TOU) and maximum demand tariffs analysed. All solutions favoured large solar PV systems with a smaller sized battery [39].

3. Introduction to BESS ownership and sizing

For a P2P energy sharing community without a prior BESS; sizing, ownership and operation of the BESS are the major concerns for a cost-effective solution. In order to obtain a prioritised BESS in the P2P energy sharing community, this study investigates the following three BESS ownership structures, namely (1) an ESP owned BESS with P2P energy sharing; (2) a user owned BESS with P2P energy sharing; and (3) a user owned BESS with P2G trading. The first two solutions are the potential BESS designs to be deployed in the P2P energy sharing community, while the third option is analysed and compared to justify potential energy and cost savings by adding BESSs to an existing P2P energy sharing network.

3.1. ESP owned BESS with P2P energy sharing

As shown in Fig. 1a, the ESP is the community intermedia who facilitates the P2P energy sharing among the buildings and operates the BESS with communications to each of the buildings' and BESS energy management systems (EMS). In this structure, the required BESS capital investment, operation and maintenance (O&M) costs will be invested by a third-party ESP. The income is generated from the BESS buying and selling of excess energy within the community. This structure removes the investment burden from the building owners but still benefits them with energy cost reduction and a more reliable power supply. The ESP BESS is observed as any other prosumer in the community being able to consume or supply power by charging and discharging the BESS. Energy sharing may take place using two methods, direct or indirect. Direct energy sharing is when PV prosumers share energy among each other when their own demand is met and others require energy in the same time period [13]. Indirect energy sharing is when the BESS buys and stores energy when the communities' energy demand is met, and sells it later when the community requires the energy. This will occur when the communities' SDR is greater than the demand. When the solar PV power fails to meet the demand of buildings, the BESS provides energy to the community [6]. Both types of sharing may be performed simultaneously within the ESN depending on the community energy supply and demand. The ESP BESS may also interact with the grid to charge the BESS during grid off-peak time periods and then sell the energy during peak periods for a profit.

3.2. User owned BESS with P2P energy sharing

In the P2P framework with user owned BESSs, each user deploys its own BESS which is invested and maintained by the user as shown in Fig. 1b. In this structure, supervised P2P energy sharing is performed without the third-party ESP investor. Energy sharing is realised via the internal sharing network, which requires the information and technology network, and communications infrastructure to be setup by the buildings who are willing to engage in the ESN. In the same way as the ESP owned structure, the community is billed from the utility grid as a unit, based on a TOU tariff, as indicated in Fig. 1.

3.3. User owned BESS with P2G energy trading

The user owned BESS with P2G energy trading is the typical independent BESS deployment structure in which battery energy can either supply the building or sell back to the grid. The utility grid bills the building based on the TOU tariff as shown in Fig. 1c. No P2P energy sharing is realised with this structure.

4. ESP owned P2P energy sharing formulation

Considering the ESP owned BESS structure description, an optimal BESS size and power flow are computed based on the following models.

4.1. Load and PV system modelling

Without loss of generality, we consider the P2P energy sharing in a community with a number N users. Each of them is equipped with a grid-tied solar PV system. The PV systems are of different sizes, and users also have different energy usage patterns. The power demand of building i is defined as:

$$\mathbf{P_i} = \{P_i(1),\ P_i(2),\ \ldots,\ P_i(T)\}, \quad \forall\ i \in [1,\ N], \tag{1}$$

where T is the total number of time slots t in the operation period. For the prosumers in the ESN, the solar PV power generation for building i at particular time periods which varies with the solar intensity is:

$$\mathbf{P_i^{PV}} = \{P_i^{PV}(1),\ P_i^{PV}(2),\ \ldots,\ P_i^{PV}(T)\}. \tag{2}$$

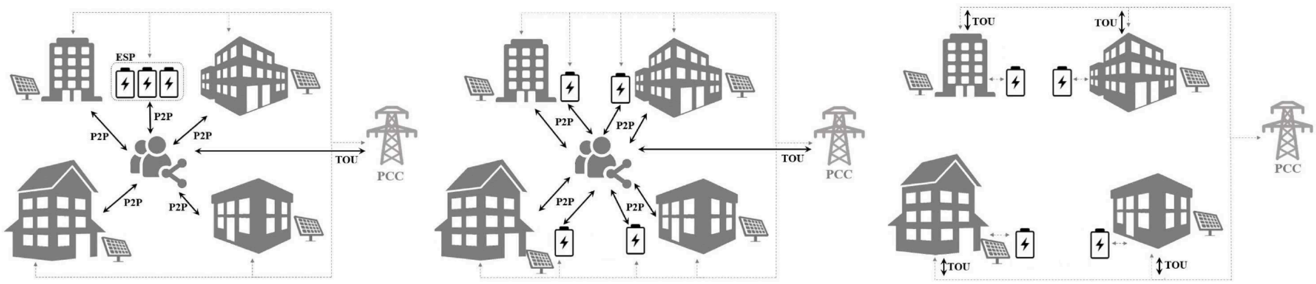
The output power from the buildings' grid-tied solar PV system for building i at time t is

$$P_i^{PV}(t) = A_i \cdot \eta \cdot I_r(t), \quad \forall\ t \in T \tag{3}$$

where A_i is the area in m^2 of solar PV array for building i, η is the solar panel electrical efficiency, and $I_r(t)$ is the global horizontal irradiance for the location of the solar panels at time t in kW/m^2.

4.2. Battery energy storage system

The BESS energy flow model takes into consideration the power charging and discharging, self-discharge losses and charging and



(a) ESP Owned BESS with P2P Energy Sharing (b) User Owned BESS with P2P Energy Sharing (c) User Owned BESS with P2G Energy Trading

Fig. 1. BESS ownership structures; ESP with P2P energy sharing (a), User with P2P energy sharing (b) and User with P2G energy trading (c).

discharging efficiency given by:

$$E^{bat}(t) = \begin{cases} E^{bat}(t-\Delta t)\cdot(1-\sigma_{DC}) - P^{bat}(t)\cdot\eta_b\cdot\Delta t, & P^{bat}(t) \geqslant 0, \\ E^{bat}(t-\Delta t)\cdot(1-\sigma_{DC}) - \frac{P^{bat}(t)}{\eta_b}\cdot\Delta t, & P^{bat}(t) < 0, \end{cases} \tag{4}$$

where $E^{bat}(t)$ is the energy stored in the BESS at time t, Δt is the length of each time step, σ_{DC} is the battery self-discharge rate over Δt, $P^{bat}(t)$ is the charging and discharging power during time interval $[t, t+\Delta t]$ and η_b is the efficiency of the charging and discharging. The BESS receives its optimal charging and discharging schedule control signals from the EPS central EMS.

4.3. Energy sharing power balance

For each building in the ESN, the power flow balance is required amongst the solar PV, the grid and the building power demand as shown in Fig. 2. This is given by:

$$P_i^{net}(t) = P_i^{load}(t) - P_i^{PV}(t), \tag{5}$$

where $P_i^{net}(t)$ is building i's net power and $P_i^{load}(t)$ is the power required by building i at time t. Because of the different building load profiles and output solar PV power, buildings may act as energy suppliers or energy consumers at different times. For the ESN and the ESP BESS, the power flow balance is

$$\sum_{i=1}^{N} P_i^{net}(t) = P^{bat}(t) + P^{grid}(t), \tag{6}$$

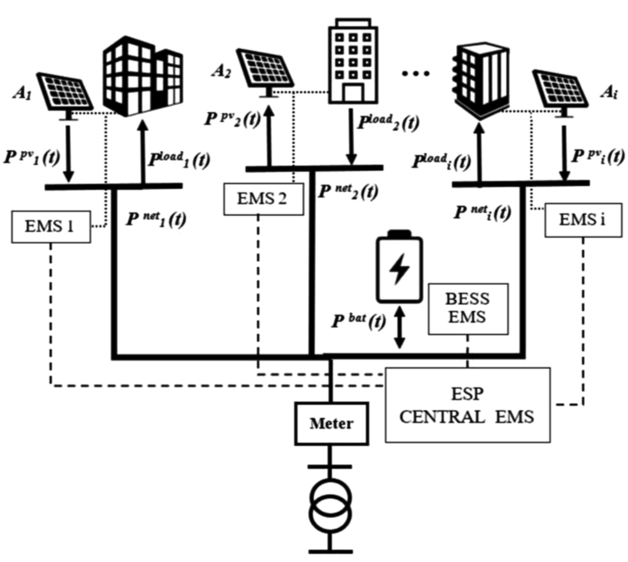


Fig. 2. An illustration of the ESP owned BESS structure with P2P energy sharing.

where $P^{grid}(t)$ is the power flow of the grid supply power to the ESN when positive, and negative when ESN is feeding power into the grid.

4.4. Internal pricing mechanism

An internal P2P dynamic pricing model based on the principle of economic supply and demand [18] with a compensating factor [6] is considered as it was found to have best performance in terms of economic and technical performance indexes for communities of high PV penetration [17]. The P2P buying and selling prices with relation to the SDR are shown in Fig. 3, which is restricted within the utility grid price bounds. The improved model, incorporating a compensating factor after the SDR is larger than one, ensures all prosumers in the ESN are better off [6]. Without the compensation factor, the internal price remains the same after the SDR is larger than one and undermining the prosumers who tend to produce excess power during peak periods and unfairly benefits those who continuously consume the power during those periods (Fig. 4). The SDR for the ESN is denoted as:

$$SDR(t) = \frac{TSP(t)}{TDP(t)}. \tag{7}$$

where $TSP(t)$ is the total supply power (TSP) and $TDP(t)$ total demand power (TDP) at time t, which are calculated using Eqs. (8) and (9),

$$TSP(t) = -\left(\sum_{i=1}^{N} P_i^{net}(t) - P^{bat}(t)\right), \quad P_i^{net}(t) < 0, \quad P^{bat}(t) \geqslant 0, \tag{8}$$

$$TDP(t) = \sum_{i=1}^{N} P_i^{net}(t) - P^{bat}(t), \quad P_i^{net}(t) \geqslant 0, \quad P^{bat}(t) < 0. \tag{9}$$

The TDP refers to the total net power that is required by each building in the ESN and TSP is the net power in excess from each building during time t. By this, all parties within the ESN contribute to the decision of the internal price. The internal selling and buying as a function of time

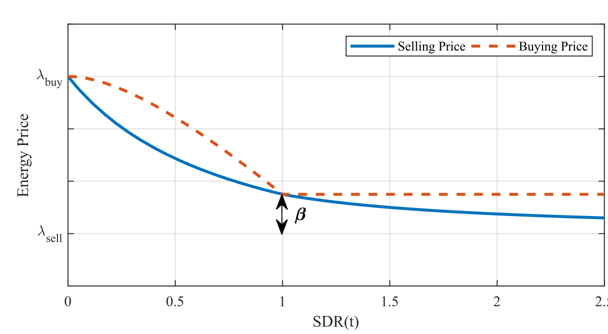


Fig. 3. The internal dynamic pricing with a compensating factor [6] as a function of SDR based from economics for prosumers in a P2P energy sharing community [18].

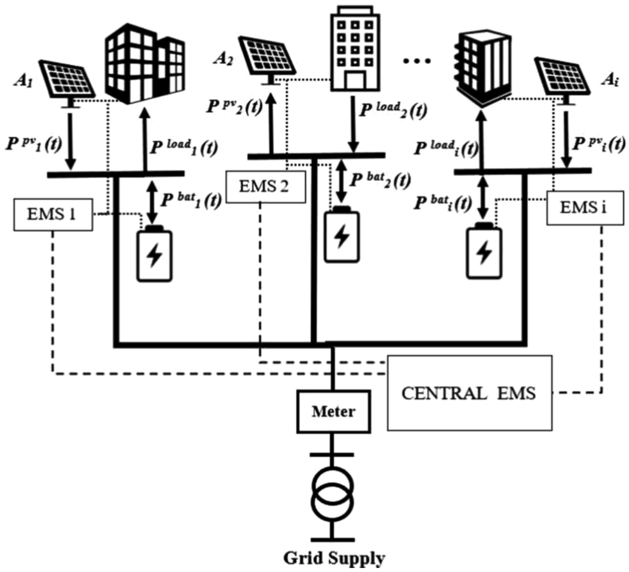


Fig. 4. An illustration of the user owned BESS with P2P energy sharing structure realisation.

is represented as a set as follows:

$$\mathbf{Pr^{sell}} = \{Pr^{sell}(1),\ Pr^{sell}(2),\ \ldots,\ Pr^{sell}(T)\}, \tag{10}$$

$$\mathbf{Pr^{buy}} = \{Pr^{buy}(1),\ Pr^{buy}(2),\ \ldots,\ Pr^{buy}(T)\}. \tag{11}$$

The internal prices from Eqs. (10) and (11) for the prosumers at a particular period depends on the buildings demand and solar PV power generation, as a prosumer may be buying or selling power in a single time interval. Therefore, building i internal energy price at time t is described as follows:

$$Pr_i(t) = f(P_i^{net}(t)) = \begin{cases} Pr^{sell}(t), & P_i^{net}(t) < 0 \\ Pr^{buy}(t), & P_i^{net}(t) \geqslant 0. \end{cases} \tag{12}$$

The internal selling and buying price is given respectively:

$$Pr^{sell}(t) = \begin{cases} \frac{(\lambda^{sell}(t)+\beta(t))\cdot\lambda^{buy}(t)}{(\lambda^{buy}(t)-\lambda^{sell}(t)-\beta(t))\cdot SDR(t)+\lambda^{sell}(t)+\beta(t)}, & 0 \leqslant SDR(t) \leqslant 1 \\ \lambda^{sell}(t) + \beta(t)/SDR(t), & SDR(t) > 1 \end{cases} \tag{13}$$

$$Pr^{buy}(t) = \begin{cases} Pr^{sell}(t)\cdot SDR(t) + \lambda^{buy}(t)\cdot(1 - SDR(t)), & 0 \leqslant SDR(t) \leqslant 1 \\ \lambda^{sell}(t) + \beta(t), & SDR(t) > 1 \end{cases} \tag{14}$$

where $\lambda^{sell}(t)$ is the grid feed-in tariff energy price, $\lambda^{buy}(t)$ is the grid TOU supply energy price and $\beta(t)$ is the compensating factor restricted by:

$$0 \leqslant \beta(t) \leqslant \lambda^{buy}(t) - \lambda^{sell}(t). \tag{15}$$

4.5. *ESP owned BESS P2P objective function*

The optimal sizing and energy sharing problem can be formulated into a constrained non-linear programming multi-objective model, with one objective Eq. (16), maximising the BESS NPV over its life span and the other Eq. (17), minimising the community energy costs. The BESS NPV consists of the income and investment costs, which are split up into the capital investment and the monthly O&M costs. The capital investment cost of the BESS contains a power conversion rating cost in $/kW, incorporating all inverters and power management equipment, and an energy rating cost C_{cap} in $/kWh for the energy storage cost. The community grid cost consists of the energy cost $\lambda^{grid}(t)$ and the maximum demand charge C_{md}. The decision variables in the following optimisation are the BESS size E^b, the power conversion rating E^{con}, the discharging and charging schedule $P^{bat}(t)$ and the internal energy sharing prices, which contain variable constraints Eqs. (18)–(23).

$$\max_{Pr_b E^b E^{con}} BESS_{NPV} = \sum (Income_{NPV},\ Costs_{NPV}) = \left(\sum_{t=1}^{T} Pr_b(t)\cdot P^{bat}(t) - E^{con}\cdot P_{OM} - E^b\cdot E_{OM}\right) \cdot PVF - C_{cap}\cdot E^b - C_{con}\cdot E^{con}, \tag{16}$$

$$\min_{Pr_b E^b E^{con}} Com_{grid} = P^{grid}(t)\cdot\lambda^{grid}(t) + P_{max}^{grid}\cdot C_{md}, \tag{17}$$

s.t

$$\lambda^{grid}(t) = \begin{cases} \lambda^{buy}(t), & P^{grid}(t) \geqslant 0 \\ \lambda^{sell}, & P^{grid}(t) < 0 \end{cases} \tag{18}$$

$$Pr_b(t) = \begin{cases} Pr^{sell}(t), & P^{bat}(t) \geqslant 0 \\ Pr^{buy}(t), & P^{bat}(t) < 0 \end{cases} \tag{19}$$

$$P_{min}^{bat} \leqslant P^{bat}(t) \leqslant P_{max}^{bat}, \tag{20}$$

$$E_{min}^{bat} \leqslant E^{bat}(t) \leqslant E_{max}^{bat}, \tag{21}$$

$$E^{bat}(T) = E^{bat}(0), \tag{22}$$

$$BESS_{NPV} > 0. \tag{23}$$

The P_{OM} and E_{OM} are the power conversion and energy rating monthly O&M costs, $Pr_b(t)$ is the BESS energy price for either charging or discharging given by Eq. (12), and PVF is the present value factor defined as:

$$PVF = \frac{(1 + d')^n - 1}{d'(1 + d')^n}, \tag{24}$$

where n is the number of years and d' is the equivalent discount rate taking into consideration future energy escalation given by:

$$d' = \frac{d - e}{1 + e} \tag{25}$$

where d is the discount rate and e is the energy escalation rate per year.

5. User owned P2P energy sharing formulation

The user owned BESS with P2P energy sharing is derived using the same load, solar PV, BESS and internal pricing policy described in Eqs. (3)–(16), (24) and (25) as the ESP owned structure formulation but with a different energy balance equation, optimisation objective function and constraints. All BESS parameters ($P_i^{bat}(t)$, $E_i^{bat}(t)$) also obtain a building index i as there are now multiple BESS deployed within the ESN. The ESN energy balance model is given by:

$$\sum_{i=1}^{N} P_i^{net}(t) = \sum_{i=1}^{N} P_i^{bat}(t) + P^{grid}(t), \tag{26}$$

where P_i^{bat} now becomes a sum for all BESSs deployed within the ESN.

5.1. *User owned P2P energy sharing objective function*

In this structure all the buildings deploy their own BESS without an incentive. Ideally they would deploy a BESS size that maximises the NPV of their investment that does not consider an ESP's income. However, because the buildings will be engaging in P2P energy sharing, the other community prosumers should be considered and a combined NPV for all the BESSs and their individual savings NPV are formulated into a constrained non-linear programming model given by:

$$\max_{Pr_b E^b E^{con}} NPV = \sum (Income_{NPV}, Costs_{NPV}, Savings_{NPV}) = \left(\sum_{i=1}^{N}\sum_{t=1}^{T} Pr_{b-i}(t)\cdot P_i^{bat}(t) - \sum_{i=1}^{N} E_i^{con}\cdot P_{OM} - \sum_{i=1}^{N} E_i^{b}\cdot E_{OM} + (E_i^{cost} - (Pr_i(t)\cdot P_i^{net}(t)))\right)\cdot PVF - C_{cap}\cdot \sum_{i=1}^{N} E_i^{b} - C_{con}\cdot \sum_{i=1}^{N} E_i^{con}, \quad (27)$$

s.t

$$\lambda^{grid}(t) = \begin{cases}\lambda^{buy}(t), & P^{grid}(t) \geqslant 0\\ \lambda^{sell}, & P^{grid}(t) < 0\end{cases} \quad (28)$$

$$Pr_i^{bat}(t) = \begin{cases}Pr^{sell}(t), & P_i^{bat}(t) \geqslant 0\\ Pr^{buy}(t), & P_i^{bat}(t) < 0\end{cases} \quad (29)$$

$$P_{min}^{bat_i} \leqslant P_i^{bat}(t) \leqslant P_{max}^{bat_i}, \quad (30)$$

$$E_{min}^{bat_i} \leqslant E_i^{bat}(t) \leqslant E_{max}^{bat_i}, \quad (31)$$

$$E_i^{bat}(T) = E_i^{bat}(0), \quad (32)$$

$$BESS_i^{NPV} > 0, \quad (33)$$

where E_i^{cost} is the building's existing P2G energy cost. For this structure it is assumed all buildings are willing and financially able to invest in a BESS. “”

6. User owned P2G energy trading formulation

The user owned BESS with P2G energy trading, shown in Fig. 1c, is derived using the same load, BESS and solar PV models Eqs. (3)–(5), (12), (20), (21), (24) and (25) as the ESP owned structure formulation but is charged simply from the grid utility TOU price and contains a different optimisation objective function and constraints. The individual P2G energy balance model is given by:

$$P_i^{net}(t) = P_i^{bat}(t) + P_i^{grid}(t), \quad (34)$$

where P_i^{net}, is the individual building net power, P_i^{bat} is the building energy storage internal power exchange and P_i^{grid} is the building grid power. Note that the grid power is a function of i because of the P2G framework.

6.1. User owned P2G energy trading objective function

The constrained non-linear programming optimisation objective function, with constraints Eqs. (36)–(39), is the individual building project BESS deployment NPV which takes into account the BESS costs and the building's savings NPV given by:

$$\max_{Pr_b E^b E^{con}} Project_{NPV} = \sum (Savings_{NPV}, Costs_{NPV}) = \left(\sum_{t=1}^{T} ((P_i^{bat}(t) + P_i^{net}(t))\cdot\lambda^{grid}(t)) - E^{con}\cdot P_{OM} - E^{b}\cdot E_{OM}\right)\cdot PVF - C_{cap}\cdot E^{b} - C_{con}\cdot E^{con}. \quad (35)$$

s.t

$$\lambda^{grid}(t) = \begin{cases}\lambda^{buy}(t), & P_i^{grid}(t) \geqslant 0\\ \lambda^{sell}, & P_i^{grid}(t) < 0\end{cases} \quad (36)$$

$$P_{min}^{bat_i} \leqslant P_i^{bat}(t) \leqslant P_{max}^{bat_i}, \quad (37)$$

$$E_{min}^{bat_i} \leqslant E_i^{bat}(t) \leqslant E_{max}^{bat_i}, \quad (38)$$

$$E_i^{bat}(T) = E_i^{bat}(0). \quad (39)$$

7. Case study

In order to investigate the performance of our proposed BESS ownership structures, we conducted some feasibility studies on some campus buildings whose historical energy usage data were continuously monitored at half-hourly interval over multiple years [40]. Previously the campus electricity was paid directly from the university account. In order to boost energy efficiency, the campus has taken many energy efficiency measures to reduce the campus building energy consumptions identified by its facility management department. For instance, (1) each faculty must be responsible for their own electricity; and (2) grid-tied solar PV systems are installed for many buildings, etc. In addition, as P2P energy sharing is quite a new energy efficiency strategy [6], the facility management is indeed looking forward to a feasibility report for a possible adoption of the P2P energy sharing scheme. For this purpose, six buildings are properly selected from each faculty in this case study, where each building contains a grid-tied solar PV system with no BESS. Since a P2P energy sharing network will be established amongst the six buildings, each building is referred to as a “prosumer”. The effective solar PV areas, and a half-hourly measured peak demand is provided in Table 1. In the following analyses, historical records of the solar irradiance and buildings' energy usage data are obtained over a calendar year. The data records are screened and processed to obtain a daily average solar irradiance profile and demand profile at one-hour sampling interval.

7.1. Load and solar PV profiles

Each selected building possesses different activities and different physical characteristics with regard to size, design and age, which leads to different demand profiles. The buildings' load, solar PV and net power profiles are shown in Figs. 5 and 6, which are averaged from the annual quarter-hourly sampled demand data in 2017. The solar irradiance data used in the solar irradiance Eq. (3) was obtained from the weather station database [41]. The grid electricity is charged under the TOU tariff. The peak, standard and off-peak energy prices are $ 0.31, $ 0.2 and $ 0.17 per kWh, respectively and a maximum demand price of $ 6 and $ 4 per kVA during peak and standard hours [42]. A power factor of unity was assumed for all the buildings. The utility feed-in tariff agreement was at a fixed price of $ 0.1688 per kWh [43] and the compensating factor $\beta(t)$ was ¢ 0.096, ¢ 2.496 and ¢ 14.12 for peak, standard and off-peak periods, respectively. Table 2 shows the technical equipment parameters used in the case study, with li-ion batteries being the choice for the energy storage and the life cycle of the li-ion batteries being 8 years based on a full charge cycle and 80% DOD per day [16]. For the energy storage and power conversion costs, 15% accounts for the procurement and construction costs [16]. The technical and economic BESS equipment parameters used for the P2P BESS sizing and energy management models are provided in Table 2 [16]. An additional 15% was added to the energy storage and power conversion costs to account for engineering, procurement and construction costs. The DOD selected in Table 2 corresponds to the li-ion battery's life cycle for a full

Table 1
Sharing community prosumer PV capacity and peak demand.

Prosumer	Solar array area (m^2)	Peak demand (kW)
Building 1	16000	847.34
Building 2	2800	148.53
Building 3	750	68.11
Building 4	1400	96.52
Building 5	1000	97.14
Building 6	5250	303.71

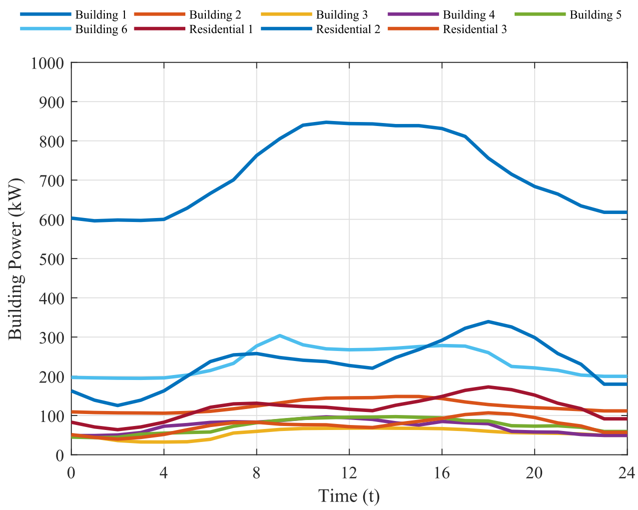


Fig. 5. Building's daily averaged demand profiles over a calendar year [40].

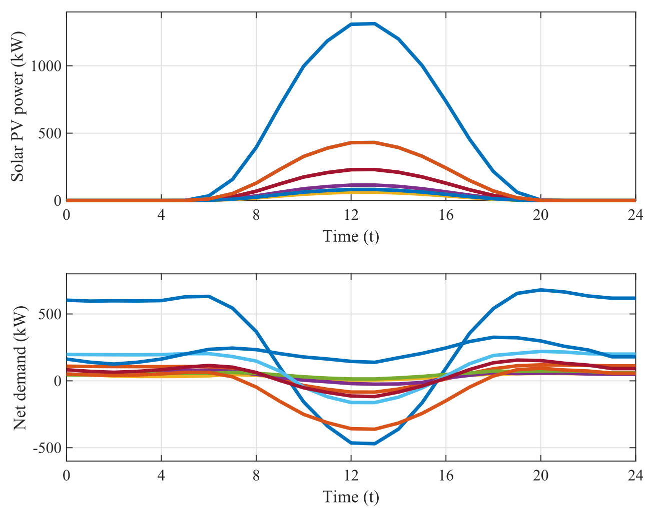


Fig. 6. Buildings solar PV power [41] and net demand.

Table 2
Input simulation parameters [16].

Parameter	Value	Unit
Li-ion storage cost	250	\$/kWh
Power conversion cost	300	\$/kW
Li-ion storage O&M cost	7.5	\$/(kWh·year)
Power conversion O&M cost	6	\$/(kW·year)
Li-ion storage life cycle	8	year
Maximum depth of discharge	80	%
Self discharge rate	0.1	%/day
Round trip efficiency	95	%
Solar PV panel efficiency	18	%
Discount rate	6	%
Energy escalation rate	3.5	%/year

charge cycle per day.

8. Results

Results for the case study shown in Figs. 7–13 and Tables 3 and 4 was obtained using the *gamultiobj* function from the MATLAB optimisation [44] with a constraint and function tolerance of 10^{-6}, the crossover function "crossoverintermediate" and fraction of 0.8. The Pareto front from *gamultiobj* function is vital to observe interactions between the objective functions such that a consensus can be met between the ESP and the prosumers. The baseline is the original state of the campus in a P2G setup with no BESSs. Fig. 7 shows the ESP BESS SOC and hourly charge and discharge power time slots throughout the

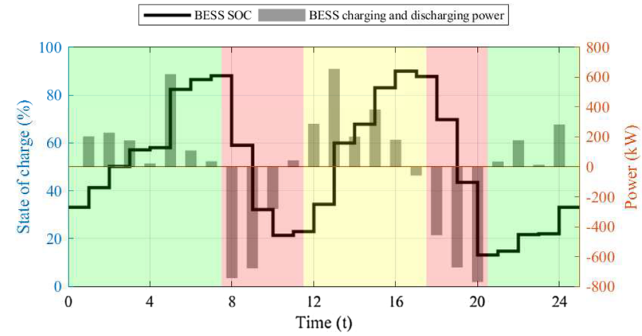


Fig. 7. BESS SOC, charging and discharging power.

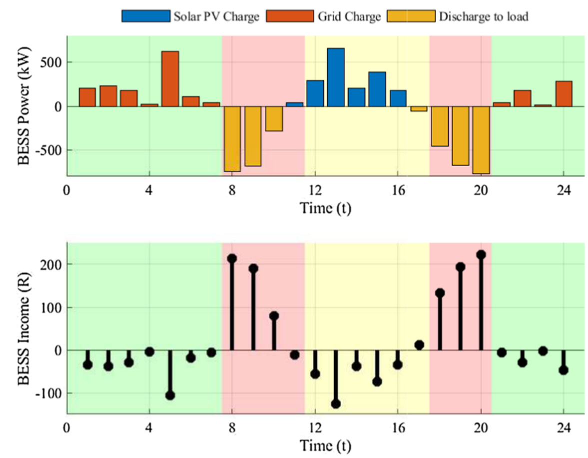


Fig. 8. BESS operation and income.

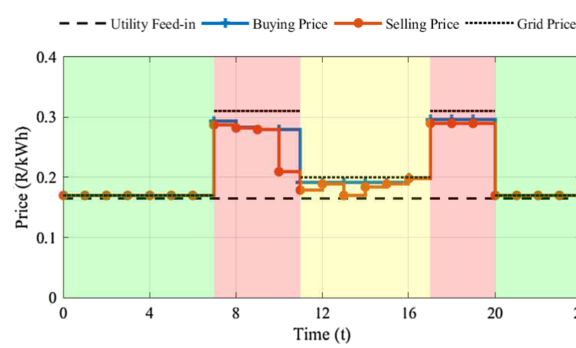


Fig. 9. Energy sharing network internal electricity prices.

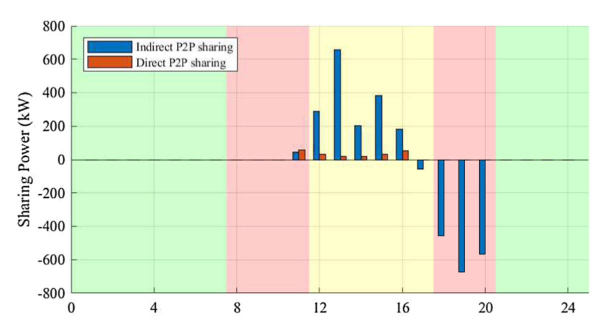


Fig. 10. Direct versus indirect power sharing.

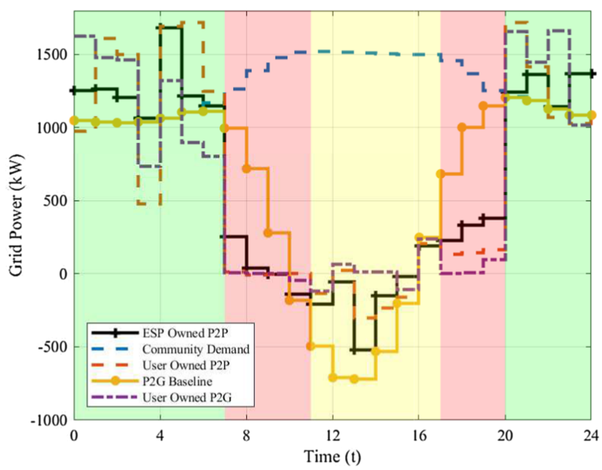


Fig. 11. Comparison of power flows for different BESS ownership structures.

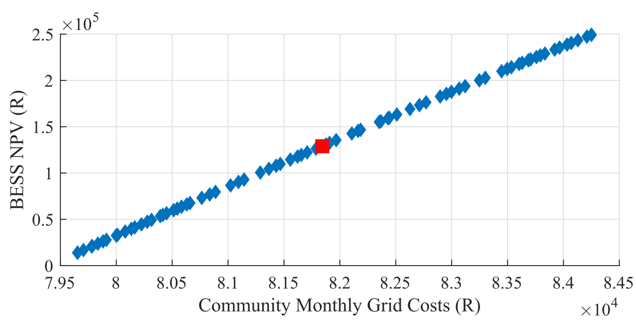


Fig. 12. Plot showing the simulation Pareto front for the community energy costs versus BESS NPV. The red square is the median point.

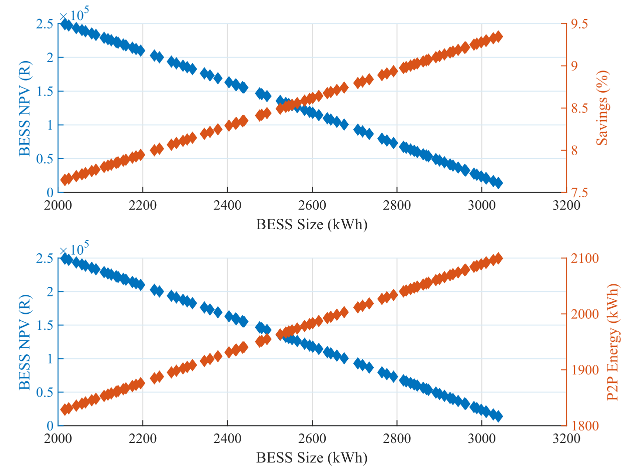


Fig. 13. BESS NPV, community savings and P2P energy sharing against BESS size.

day. Grid charging takes place during the off-peak grid demand periods when energy prices are low, seen within the green regions of the plot. Discharging occurs during peak grid demand periods when prices are high, seen within the red regions of the plot when the solar PV output power is low. The BESS completes one full DOD cycle per day from its maximum SOC to the minimum. Fig. 8 shows the BESS's daily power exchange with the ESN and its corresponding income generated. It can be seen that no power is exported to the grid from the BESS and is only imported during the off-peak periods. The BESS makes its income from purchasing power during off-peak grid periods and during excess PV power periods, and then sells this power to the ESN during the peak grid periods. This helps reduce the ESN costs during the peak-periods by using the power from the peak solar PV power periods. The internal ESN buying and selling energy price is shown in Fig. 9. During peak periods the internal price is much lower compared to the grid because of the ESP BESS discharge power and slightly reduced during standard energy price periods.

The amount of P2P energy sharing is shown in Fig. 10. It can be seen that the indirect P2P energy sharing accounts for a larger portion than the direct sharing. Fig. 11 shows a plot of the community energy demand, P2G baseline, ESP owned BESS, user owned BESS with P2P energy sharing and the user owned BESS with P2G trading profiles. During the peak periods when the grid is under strain, the power drawn from grid for the BESS structures is reduced, as seen within the red regions, because of the BESS discharging power. However, during the off-peak periods the peak grid power increased because of the BESS charging. This does not affect the maximum demand charge because it falls out of the peak and standard periods. Overall the user owned BESS structure with P2G trading exports the least amount of power into the grid. The ESP owned structure exports the most amount of power. This corresponds to the net BESS sizes of the structures. The user owned BESS with P2P energy sharing has the highest peak demand followed by the user owned with P2G energy trading. Fig. 12 shows the plot of the Pareto front with an indication of the median point.The optimal results are from the median point of the multi-objective function Pareto front, giving equal benefits to the prosumers and the ESP. Other points on the Pareto front may be considered based on the negotiations between the third-party ESP investor and the ESN prosumers.

Table 3 shows the three BESS structures li-ion: sizes, investment costs, and net energy savings. The structures achieved an average saving of 23.26%, 8.50% and 24.58% for the ESP owned with P2P sharing, the user owned with P2P sharing and the user owned with P2G trading, respectively. The ESP owned structure's savings is a lot lower than the others however, there is no investment cost required by the buildings as observed in Table 3. The prosumers that benefit the least for the P2P structures, building 3 and 5, are the ones that contributed the least relative to their size to the ESN. The most beneficial buildings, building 4 for the user owned P2P structure and building 2 for the ESP owned P2P structure, contributed the most power relative to their

Table 3
Building's optimal li-ion sizes, costs and savings.

	ESP owned P2P			User owned P2P			User owned P2G		
	Li-ion size (kWh)	Investment ($)	Saving (%)	Li-ion size (kWh)	Investment ($)	Saving (%)	Li-ion size (kWh)	Investment ($)	Saving (%)
Building 1	–	–	9.86	1700	$553 050.38	26.91	1860	$642 145.23	26.82
Building 2	–	–	10.06	232	$85 938.73	26.12	311	$108 631.52	26.19
Building 3	–	–	6.62	100	$36 999.94	15.11	176	$58 712.57	20.54
Building 4	–	–	8.07	464	$171 500.63	31.32	207	$70 695.56	25.69
Building 5	–	–	6.63	200	$74 001.10	16.79	242	$80 922.11	20.16
Building 6	–	–	9.79	400	$148 000.02	23.35	651	$219 626.80	28.10
ESP	2552	$886 458.93	–	–	–	–	–	–	–
Community	2552	$886 458.93	8.50	3096	$1 069 490.76	23.26	3447	$1 180 733.80	24.58

Table 4
BESS structures li-ion sizes with corresponding conversion equipment and costs.

Structure	Li-ion size (kWh)	Conversion rating (kW)	Li-ion cost ($)	Conversion cost ($)	BESS cost ($)	Project NPV ($)	Self-sufficiency (%)	Self-consumption (%)
ESP owned P2P	2552	828	$638 076.09	$248 382.84	$886 458.93	$1 149 307.33	50.24	93.44
User owned P2P	3096	985	$773 945.88	$295 544.91	$1 069 490.76	$1 397 770.04	51.03	94.92
User owned P2G	3447	1063	$861 770.33	$318 963.45	$1 180 733.80	$1 386 078.58	51.45	95.70
P2G baseline	–	–	–	–	–	–	43.86	81.58

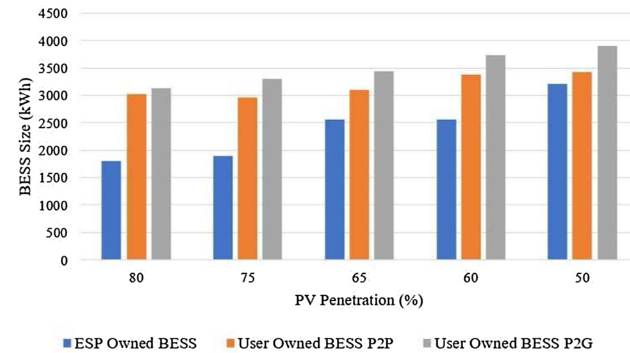


Fig. 14. BESS size against PV penetration percentage of the community base demand.

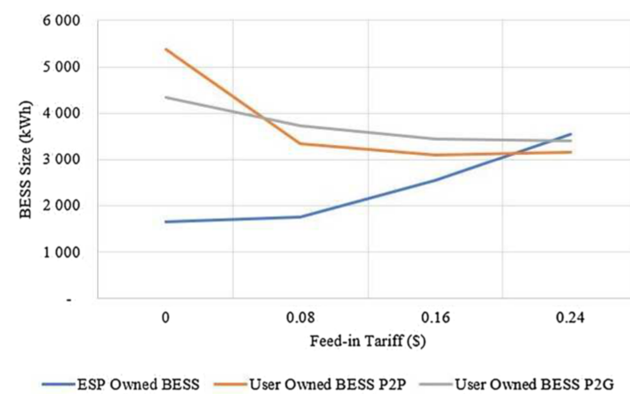


Fig. 15. BESS size versus feed-in price.

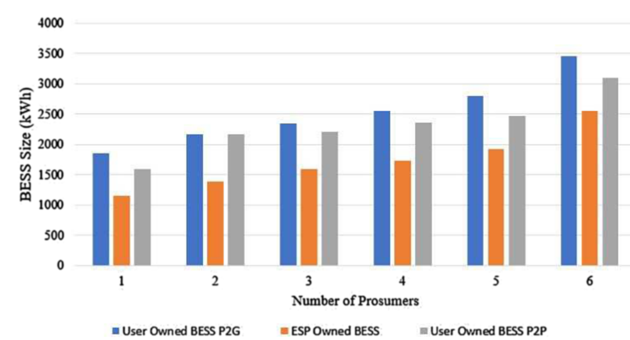


Fig. 16. BESS size versus number of prosumers within a community.

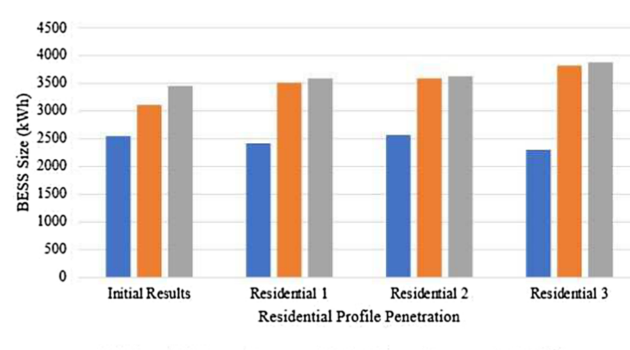


Fig. 17. BESS size against residential profile penetration.

demand.

The overall li-ion energy storage reduced by 26% and 10% for the ESP owned and the user owned BESS with P2P energy sharing structures respectively, compared to the user owned P2G structure. Building 4's li-ion size increased for user owned P2P structure, giving it a larger saving, because no specific constraint was implemented on the individual building li-ion sizes. For the realisation of the user owned P2P structure, the ESN building owners could engage amongst themselves their desired li-ion size investments based on their financial capacity and interests. A consensus can then be reached based on the individual maximum desired li-ion sizes, which would be a constraint when maximising the ESN BESS deployment NPV. Table 4 shows the optimal BESS parameters for the three structures, the ESN BESS project NPV and the ESN self-sufficiency and self-consumption. The ESN self-sufficiency measures the share of the community demand that is supplied by the communities local solar PV generation, which increases by 6.38%, 7.17% and 7.59% for the ESP owned, user owned P2P and the user owned P2G structures respectively. The ESN self-consumption is the ratio between the net local solar PV energy consumed and the total amount of local solar PV power generated by the prosumers. This improved with the optimal BESS by 11.86%, 13.34% and 14.12% for the three structures. The project NPV in Table 4 accounts for the total savings, benefits and costs associated with the deployment of BESSs with the P2P energy sharing for the respective structures.

9. Discussion

9.1. ESP owned BESS with P2P energy sharing structure

With an average saving of 8.50% for the ESN prosumers and a NPV of $129 078.77 for the ESP, the proposed ESP owned BESS model realises a self-sufficient BESS that significantly benefits both parties. The community savings are lower than the two other structures and other similar studies [3,6], one saving as much as 31% [4], because of the benefits being split between the ESN prosumers and the third-party ESP. However, the benefit of the split structure is that prosumers require no investment cost to achieve their savings and the simpler BESS operation control. The distribution of benefits amongst the prosumers within the ESN may still be further improved with the difference of only 3.44% between the highest contributor and the lowest. This may be achieved by finding an optimal compensating factor that would provide a better distribution based on the prosumers contribution towards the P2P energy sharing. However, this compensating factor should pay particular attention in finding a balance between benefitting those who contribute with excess power and at the same time keeping the low contributing prosumers interested in joining the ESN.

9.2. P2P energy sharing and optimal sizing interaction

The interaction between the ESP BESS optimal sizing with the BESS NPV, the community savings and the total P2P energy sharing are shown in Fig. 13. An approximate linear relationship is observed showing that the larger the BESS, the more P2P energy sharing flexibility is available, increasing the prosumer's operational energy benefits. However, increasing the BESS size, decreases the BESS NPV and could possibly make it infeasible. Therefore a trade off exists between a larger and more P2P flexible BESS, and a smaller, more economically feasible BESS. Of the three BESS structures, the user owned BESS with P2G trading achieved the most energy savings with an average of 24.58%, but requires the largest li-ion energy storage, therefore requiring a larger upfront investment cost. However, when comparing the size of the li-ion energy storage in comparison to the NPV in Table 4, the user owned structure with P2P energy sharing is most desirable. This shows that for a smaller li-ion energy storage, a higher NPV is achievable with P2P energy sharing, making this structure more desirable. The BESS structures achieved self-consumption improvements of almost double that compared to self-sufficiency as shown in Table 4. This shows that the BESS deployment along with the P2P energy sharing is a larger contributor to consuming excess solar PV power from the ESN than decreasing the ESN's dependence on the grid. The self-sufficiency does not improve as much because of the BESS grid charging and discharging demand response that takes place.

9.3. Sensitivity analysis

A sensitivity analysis is performed to investigate the influence of PV penetration, feed-in tariff, number of prosumers, and demand profile on the optimal BESS sizing models. In Fig. 14, it shows that the BESS size is decreased when the PV penetration is increased as a percentage of the community base demand for the three different BESS ownership structures. It is more cost-effective to apply larger batteries to store the PV generated power during the morning off-peak period when the PV penetration is relatively low. The demand profiles of building 2, 5 and 6 are iteratively changed to the residential profiles, as shown in Fig. 5, to investigate the influence of the demand profile patterns on the optimal BESS sizes. The results in Fig. 17 show that both the user owned BESS sizes are increased because of the peak demands falling outside the peak solar PV generation periods. The ESP owned BESS is reduced in size because more direct P2P energy sharing is happening with increased variations in load profiles. Fig. 15 shows the BESS size against feed-in tariff. The ESP owned BESS is increased in size with an increase in the feed-in tariff. This makes it viable for the ESP to sell electricity back to grid during standard periods using the stored energy from off-peak periods. Fig. 16 shows that the more prosumers within the community the larger the li-ion battery size. Comparing the three battery ownership structures, the user owned BESS with P2G trading has a larger increase in size because it does not take advantage of P2P energy sharing.

10. Conclusion and future work

This study investigates the optimal BESS sizing problem in a P2P energy sharing network considering different ownership structures, namely the user owned and a third-party ESP owned battery structures. It is found that the user owned BESS ownership model has the greatest NPV. Contrary to that, the ESP owned BESS model exhibits a relatively smaller NPV but provides the opportunity for prosumers to engage in P2P energy sharing and reduce their energy costs without a BESS investment. In the sensitivity analysis, some scalability analysis has been conducted to investigate the impact of number of prosumers on the optimal BESS sizes of different ownerships. The presented results demonstrate that the proposed model is scalable. However, due to limit data availability, this study does not include a scale up experiments to include larger number of prosumers in the P2P energy sharing network. It is worthy of further investigations to apply the multi-agent based stochastic simulations to quantify the influences on the optimal BESS sizing in the P2P energy sharing networks with large number of prosumers. Future work could also include improvements to a fair distribution of benefits for the proposed ESP owned model and the influence of BESS location on the sizing and BESS ownership in the P2P energy sharing networks [45].

Acknowledgement

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