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Community Energy Storage System for Cost Benefits

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***Abstract*—Future low-carbon energy systems will be people-centred. However, optimal utilisation of renewable-based distributed generation in neighbourhood energy market (NEM) remains a limiting factor. This paper investigates a NEM and evaluates the benefits of central energy storage system (ESS) in maximising collective self-consumption and savings, using Sheffield city centre, UK as a case study. The results show that the central ESS has a significant impact on utilization of renewable resources, reduces cost of energy and offers flexibility of the grid through peak reduction. In particular, use of central ESS reduces peak demand by up to 55% while the community's self-consumption and self-sufficiency increased by 28.8% and 32% respectively.**

***Index Terms*—Community Energy Storage system, Energy Cost Optimisation, Low-carbon energy system, Peer-to-Peer Energy Trading, Neighbourhood Area Energy Network.**

I. Introduction

The ongoing decentralisation and decarbonisation of the power grid are transforming traditional energy customers into prosumers. To fully exploit intermittent generation from renewable energy resources (RES) such as wind and solar, this transition is confronted with new challenges, including the coexistence of different agents, network constraint management, uncertainty, privacy, stability, load shifting and energy management [1].

On the positive side, the rapid deployment of distributed energy resources (DERs) in the prosumer domain has enabled a new form of decentralised transactive systems at the edge of the network [2]. Such proliferation of prosumers with different operational schedules and capacities also poses challenges to the energy market and flexibility of the grid [3]. For example, during high production from RES, renewable capacity may not be optimally utilised. Renewable generation can be curtailed according to load or the excess fed to the grid. However, curtailment or export at lower feed-in tariffs may impact profitability. With steadily reducing feed-in tariff, a centralised energy storage system (ESS) provides a way to fully exploit the DER and maximise the utilisation of renewable hosting capacity of the local area. This is even more attractive due to storage-as-a-service now available.

In the current climate of price volatility in the energy market, renewable generation from rooftop photovoltaic (PV) systems and ESS will catalyse the transition to green energy and facilitate more efficient utilisation of DERs. Local trading has the potential to balance local energy supply and demand while also reducing transmission losses, improving power system reliability and deferring infrastructure investment. Since PV and wind energy generation are intermittent and not dispatchable, more flexibility is required on the production and demand sides to maintain grid stability and reliability.

In this regard, peer-to-peer (P2P) energy trading has emerged as one of the innovative ways to respond to some of these challenges by sharing surplus energy from rooftop PV, small-scale wind turbine generation, ESS, etc. Community members (prosumers) in P2P market can directly transact with each other and determine the energy sharing parameters individually, such as the amount and price of energy to share, to whom and when to share the energy [1], [3]. For market agents in the neighbourhood energy markets (NEMs), this ability to independently select trading parameters based on intended objectives can potentially limit the benefits of P2P energy trading [1]. In this study, a local area transactive market is simulated in the D3A grid singularity platform [4] to evaluate the impacts of the central ESS on the community energy trade. The model community comprises households with different generating capacities and demand profiles.

As incentives such as subsidies and favourable feed-in-tariff are diminishing, this may adversely impact the willingness to invest in new small-scale renewable energy assets. This paper explores central ESS as a way to maximally utilise renewable capacity without losing its economic benefits. The contribution of this paper is two-fold; it investigates the

- benefits of centralised ESS on energy balance in a community.
- role of shared ESS in community resilience through self-consumption and self-sufficiency.

II. ESS in Community energy network

Many buildings have turned from passive consumers of electricity into prosumers by being more active in the production, delivery and consumption of electric power. This is leading to a new form of energy market in local areas.

A. Neighbourhood Energy Network

One of the most promising techniques to exploit RES is to empower prosumers through developing NEMs. NEMs allow the dynamic imbalance between local demand and energy generated to be managed locally and reduce its propagation to upstream grid by feeding excess energy to the grid rather than being curtailed. Based on trade and control, NEMs may be broadly classified into two groups; centralised or decentralised.

- Centralised: supervised energy trading in which trade is coordinated by a central controller based on a common goal in the community. In this group, no bidding is required. Hence, transaction processing utilises less information. The market operator chooses the optimal dispatch strategy after considering details of the marginal costs and demand for the dispersed units. This has numerous benefits, including improved relationships among residents due to shared goals and aggregate energy needs predictability by grid operators. However, a major challenge its inability to simultaneously meet the energy needs of every member according to their unique preferences. Thus, benefit fairness within the community becomes a concern, as does the need for incentives to encourage prosumers' participation in the sharing policy [5]. For example, an aggregator in a local area makes choices on behalf of the community.

- Decentralised: an autonomous energy market where several prosumers engage and attempt to maximize individual utilities without consideration of others. Within the NEM, pricing mechanisms and strategies are required to maximise revenue or savings from the energy trade. A common example of a decentralised local market is the P2P transactive system [2]. The advantages of a decentralised market include that electricity is traded according to the prosumers' preferences following their ability to choose buyer or seller autonomously. However, the challenges of this scheme include difficulties in reaching a consensus with every trading partner, prediction of system's behaviour due to a lack of centralised knowledge, and minimal quality of service guarantees in terms of safety and quality of supply. This decentralised framework often relies on analytical or multi-agent systems [6]. Prosumers in a multi-agent interaction can negotiate, trade, and cooperate to achieve individual goals. Thus, this multi-agent approach is susceptible to a high churn rate and requires extensive computation and communication resources for bidding [6]. In auction-based P2P markets for instance, prosumers submit bids/offers without knowledge of what other participants sent [7] while analytical models are governed by a collection of rules [6].

P2P trading in communities is becoming a catalyst for decentralising energy production, especially in areas with large residential PV and battery storage applications such as Germany, Australia, the United States, and the United Kingdom [7]. Authors in [8] investigated the viability of EVs trading electricity locally and considered demand response incentives for charging EVs to balance local demand. This is especially important in cases of residential communities and industrial clusters with high peak demand. P2P transactive energy can also save costs by reducing peak demand while increasing the value of flexible assets such as ESS.

Game theory has been widely reported as a promising technique for modelling the decision-making process of market participants, and several approaches have been proposed. For example, in [9], a fully scalable and distributed algorithm to ensure safety and efficient grid operation was proposed to steer the market to a generalised Nash equilibrium as well as trading in the virtual microgrid (VMG). The interactions among prosumers were optimised through the Stackelberg game in which energy producers lead, and consumers follow. According to the findings, P2P energy prosumers gain 47% more benefits from the Stackelberg game.

The simulation in this paper involves a hybrid of P2P and centralised energy exchange through an aggregator. The aggregator locally coordinates the energy transactions and interfaces with the grid on behalf of the community.

B. Storage

Although the use of NEMs in facilitating self-consumption and own storage has been variously reported in the literature, centralised ESS continues to be attractive due to the falling cost of storage systems and advancement in battery chemistry, leading to higher capacity at a reduced cost. Centralised ESS can also douse the distributional effects of renewable uptake in communities as it potentially reduces the upfront investments per household and creates a means to harness the renewable potentials in the local area fully. For example, this allows residents in rented multi-tenant buildings to enjoy low-cost green energy without the burden of ESS ownership.

A P2P market model trialled for a community in London, UK, showed that using private ESS, consumers can save 31% in electricity cost [3]. The project investigated the contribution of consumer-owned battery flexibility to the local energy market. It was observed that more than half of the savings resulted from cooperation and trading in the community, and the rest was due to the battery's flexibility in local balancing services. Our research extends this further by considering a centralised ESS which serves the community. We also investigate the use of central ESS for improving the renewable-hosting capacity of the community.

III. System Model

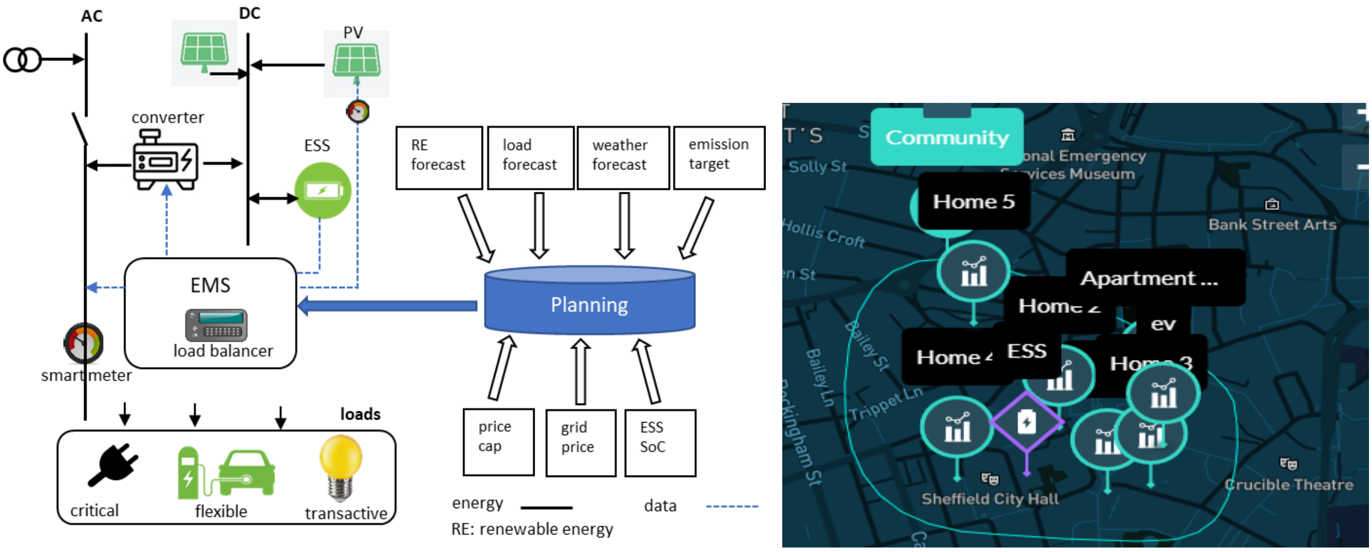
Consider a community, $\mathcal{C}$, with N homes denoted as $h_1, h_2, \ldots, h_z, \ldots, h_N$. To study the local transactive energy system, $\mathcal{C}$ is modeled as a NEM comprising prosumers with renewable generating assets, a central ESS and consumers with different load profiles as show in Figure 1.

For planning purposes, the local aggregator considers key parameters such as load forecast, weather forecast and state-of-charge (SoC) of central ESS, as shown in Fig. 1. These, combined with data from PV and energy market, help the community to minimise cost and maximise the utilisation of locally generated green energy. This paper uses the solar energy profile of Sheffield city centre (Figure 1b). Each h_z in the community generates $E_r(h_z, t)$ amount of energy from RES at time t, imports $E_g(h_z, t)$ from the grid and directly purchases $P_p(h_z, t)$ via P2P energy trading. The effective energy available in the community can be expressed as:

$$E_{\mathcal{C}}(t) = \sum_{z=1}^{N} E_g(h_z, t) + \sum_{z=1}^{N} E_\pi(h_z, t) \tag{1a}$$

$$E_\pi(h_z, t) = E_r(h_z, t) + P_p(h_z, t) + B_d(h_z, t) \tag{1b}$$

where $B_d(\cdot)$ is the energy drawn from central ESS per h_z. We assume that the energy transceived with the ESS are from RES only so that $E_\pi(\cdot)$ is from RES only. Each h_z is equipped with



(a) A community energy network with different characteristics

(b) Local community in Sheffield, UK case study

Figure 1: Model of transactive community energy network illustrating neighbourhood energy market.

a local storage system from which it engages in P2P energy trading. Each h_z contributes $B_c(h_z, t)$ energy to recharge the community ESS from RES. The total energy the community contributes to the ESS is:

$$E_b(t) = E_b(t-1) + \sum_{z=1}^{N} B_c(h_z, t) \tag{2}$$

where $E_b(t)$ is the energy remaining the ESS at time t. Each household demands $d(h_z, t)$ amount of energy at a time, t, so that the total energy required by the community becomes:

$$D_{\mathcal{C}}(t) = \sum_{z=1}^{N} d(h_z, t). \tag{3}$$

The demand includes energy for flexible and non-flexible loads (home appliances, EV charging, etc.). Let $P_s(h_z, t)$ be the P2P energy sales in the community. The daily energy mix is obtained from a variety of sources and satisfies

$$E_{\mathcal{C}}(t) \geq D_{\mathcal{C}}(t) \tag{4a}$$
$$P_s(h_z, t) \leq d(h_z, t) \tag{4b}$$
$$P_s(h_z, t) \leq P_p(h_z, t). \tag{4c}$$

The P2P energy trade is represented as

$$P_s(h_z, t) = \sum_{j \neq z} E_{ps}(h_z \to h_j, t) \tag{5a}$$
$$P_p(h_z, t) = \sum_{j \neq z} E_{pp}(h_z \to h_j, t) \tag{5b}$$

where $E_{ps}(\cdot)$ is the energy in P2P sales, $E_{pp}(\cdot)$ is the energy in P2P purchase, $h_z \to h_j$ denotes prosumer h_z trades with h_j. To ensure a balanced market where demand matches supply in $\mathcal{C}$, then the amount of energy involved in P2P trade among prosumers in the community suffices in the following energy balance:

$$\sum_{z=1}^{N} P_s(h_z, t) = \sum_{z=1}^{N} P_p(h_z, t). \tag{6}$$

The effective energy cost for the Sheffield community is:

$$\alpha(t, \lambda) = \lambda(t)[E_{\mathcal{C}}(t) - D_{\mathcal{C}}(t))] \tag{7a}$$
$$= \lambda_g(t)\mathcal{E}_g(t) + \lambda_c(t)E_\pi(t) - \lambda_d(t)D_{\mathcal{C}}(t)) \tag{7b}$$

where $\mathcal{E}_g(t) = \sum_z E_g(h_z, t)$, λ_d is energy selling price, $\lambda_c(t)$ is energy production cost and satisfies $\lambda_c(t) < \lambda_g(t)$ with $\lambda_g(t)$ as the grid price and $\lambda_c(t) \leq \lambda_d(t) \leq \lambda_g(t)$. The energy prices in the UK change with time, hence the notations $\lambda_c(t)$ and $\lambda_g(t)$. A self-sufficient community will not buy energy from the grid (i.e., $\mathcal{E}_g(t) = 0$), thus $\alpha(\cdot)$ in (7) reduces to:

$$\alpha(t, \lambda) = \lambda_c(t)E_\pi(t) - \lambda_d(t)D_{\mathcal{C}}(t)). \tag{8}$$

The goal of the community is to minimise energy costs by centrally storing some energy in an ESS; that is,

$$\min_{\lambda_c, \lambda_d, \lambda_g} \quad \alpha(t, \lambda) \tag{9a}$$
$$\text{subject to: } E_b(t) > 0. \tag{9b}$$

Practically, it is difficult to minimise energy prices, instead increase energy production (i.e., $E_b(\cdot)$ and $E_\pi(\cdot)$). For a community without central ESS $B_d(\cdot) = B_c(\cdot) = 0$. Rather than curtail generation from PV due to its intermittent nature, the excess energy can be stored. Given the charging efficiency, η_c of the battery, the projected reserve in ESS is described as

$$E_b(t) = E_b(t-1) + \eta_c \sum_{z=1}^{N} B_c(h_z, t). \qquad \forall t \in T \tag{10}$$

The central ESS can be charged by the grid or RES produced within the community. The SoC at any time is given by [10]

$$SOC(k) = SOC(k-1) + \frac{\eta \times \Delta_k \times i(k)}{3600 \times C_{batt}} \tag{11}$$

where $i(k)$ is the current flowing through the battery at time k, Δ_k is the sampling time (in seconds), C_{batt} is capacity of the ESS and η is the Coulomb counting efficiency defined as

$$\eta = \begin{cases} \eta_c & i(t) > 0 \\ \eta_d & i(t) < 0 \end{cases} \tag{12}$$

η_d is the discharging efficiency. We remark that $\Delta_k i(k) \approx \int_{t(k-1)}^{t(k)} i(\tau) d\tau$, where $i(\tau)$ is the current at time instant τ and $\Delta_k = k(t) - k(t-1)$. For planning purposes, the quarter-hourly PV production and load are described as [11]

$$E_{\frac{1}{4}h}^{PV} = \int_{t_0+nT}^{t_0+(n+1)T} \bar{P}_{24h}^{PV}(t)dt = T.\bar{P}_{24h}^{PV}(t_0 + n.T) \quad (13)$$

where $T = 15$ min, $n \in [0, 95]$, $\overline{P}^{PV}$ is the average output power of PV and t_0 is the start time of the observation. Correspondingly, the energy required by the load is given by

$$E_{\frac{1}{4}h}^{Load} = \int_{t_0+nT}^{t_0+(n+1)T} \bar{P}_{24h}(t)dt = T.\bar{P}_{24h}^{Load}(t_0 + n.T) \quad (14)$$

where the average load is $\overline{P} = 1/N. \sum_{z=1}^{N} P(h_z)$. The net energy balance at the start of each day is

$$E^{Net}(t) = E_b(t) + \sum_{z=1}^{N} \left(E_\pi(h_z, t) - d(h_z, t) \right) \quad (15)$$

where $d(h_z, t) \approx E^{load}(h_z, t)$. The load of the EV charging station is

$$L = \sum_{t=1}^{24} \sum_{m=1}^{M} Q_m^j.h_t[Wh] \quad (16)$$

where M is the number of chargers and each charger's power rating is Q^j, while the letters h_t is the charging duration.

A. Transactive Energy Market

In this study, the community comprises prosumers who generate electricity from PV, EV stations and a central ESS. The NEM is connected to the grid, allowing it to export and import energy. The target of the community is to maximise the use of renewable sources within to achieve self-sufficiency and minimise the cost of electricity in each household. The constraint $\lambda_c(t) \leq \lambda_d(t) \leq \lambda_g(t)$ motivates consumers to prefer locally sourced green energy and only import from the grid in the event of deficit. The grid also wishes to be stable and flexible. The prosumers can trade locally at the agreed price. The profiles of agents in the NEM were composed from:

- the D3A, using the consumption profiles templates (D3A Grid Singularity)
- Low Carbon London project10, which captured energy consumption profiles of 5567 houses in the Greater London area, from November 2011 to February 2014.
- load profiles in Table 1 are assigned based on average of 2.4 people per British household and consumption of 2,900 kWh of electricity and 12,000 kWh of gas annually [12]. The charging stations in the table are assigned 21kWh, 189kWh, 41kWh of PV.
- the PV generation profiles were obtained from D3A template generated from Energy Data Map with Sheffield as the geographical area of interest.

B. Community Energy Network Simulation using D3A

As a flexibility enabler, the central ESS can only charge from RES within the community alone. The price rule is designed in a way to also discourage charging the ESS from the grid, except if $\lambda_g < \lambda_p$, where $\lambda_p \in [\lambda_c \ \lambda_d]$ is the unit cost of energy in P2P trade. At $0 \leq \lambda_g \leq \lambda_p$, more $E_g(\cdot)$ can be purchased and stored for later use. Therefore, storing excess green energy from the grid at low price for later use will increase renewable energy consumption and improve the sustainability credentials of the community. The following market operations were considered in the model:

- households prosumers buy/ sell energy to/ from the grid,
- trading energy within the communities between prosumers and consumers,
- ESS for load balancing and maximisation of renewable generation.

  A critical aspect of local electricity market is defining characteristics which are closely linked to the players market. As primary contributors to market activities, prosumers are connected to the NEM through bidirectional energy and information transfer. The P2P trading adopts a two-sided strong balanced budget (SBB) auction approach for market clearing in which buyers and sellers follow specific rules which allow them to maximise savings and revenue, respectively.

Table I: Simulation Parameters

Participant	Characteristics	Load/wk (kWh)	PV Gen (kWh)
Home1	Family (3 children)[a]	110	41
Home2	Family(2 children)[a]	99	41
Home3	1 Parent, 2 children[b]	94	207
Home4	Family(3 children)	110	207
Home5	1 Parent, 1 child [a]	45	62
EV station		17	21,189 41, 21
Apt Complex	1 Parent, 2 children	94	
Community	ESS capacity 30kWh		

a: both parents work in office; b: 1 parent work from home

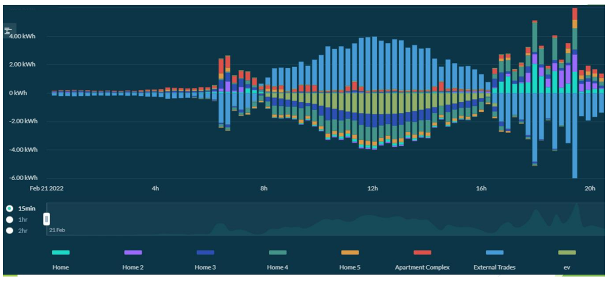
IV. Results and Discussion

This section presents and analyses the simulation results, starting with the performance of the transactive network components and the impact of the centralised ESS on flexibility.

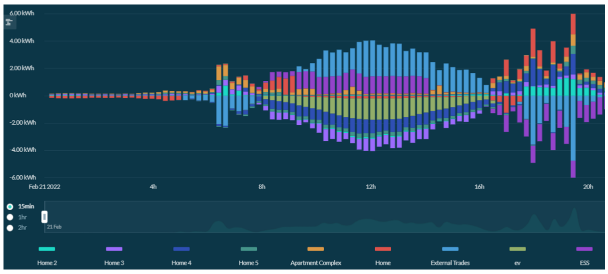
A. Contribution of renewable utilisation to net energy

The net energy traded in the community and the grid is presented in Fig 2 with 15 minutes resolution. It shows that the community with central ESS exhibits a better utilisation of locally produced renewable than without ESS. Exporting the excess energy at peak periods could yield revenue since the community without ESS is forced to export excess energy at relatively lower tariffs and import at higher prices.

An example of an energy mix including 3.263kWh imported from the grid and various amounts consumed in the homes in 15-minute market slots is shown in Fig. 2. High generation, low price on the grid arises when there is excess production of renewable on the grid (e.g grid congestion on a sunny, windy afternoon). For example, in UK, wind power output is strongest in January and February than remaining months. As seen in Fig 2a, although the buildings contributed different amounts to the energy export during the day, without ESS the community imports all the energy during peak demand e.g at 19:45 in Fig 2a. The figure also shows that in some cases, the ESS can reduce energy import from the grid by up to 63% in the evening around 20:15 - 20:45 (Fig 2b).



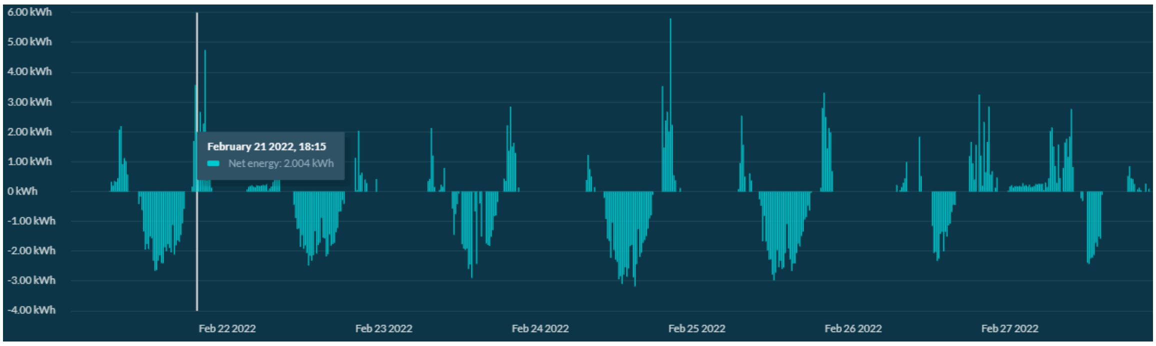
(a) Without ESS



(b) With ESS

Figure 2: Daily energy trade profile for the community showing results with ESS and without ESS.

(a) Without ESS



(b) With ESS

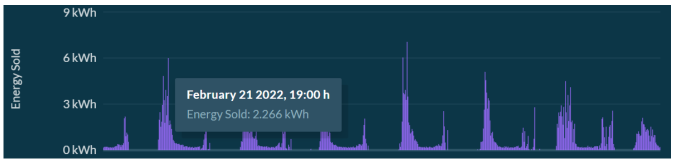
Figure 3: Reduction of peak load in community.

B. Peak Management

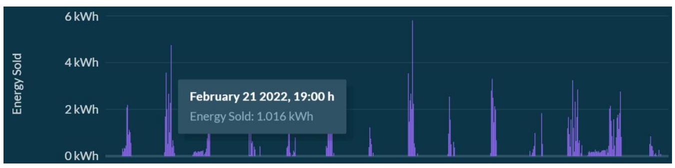
The peak energy demand differs across the days of the week. Figure 3 shows the peak values for the week for of 21st February 2022. As seen in Fig 3b, the ESS not only reduces the demand peaks but also dampens its spread on each day. For the network operator, the reduced peak-to-average load ratio can lower the cost of short and medium-term planning.

At peak period, some loads are supplied by the central ESS which reduces the peak demand on the main grid. This also contributes to flexibility potentials of the grid.

The results in Figs 4a and 4b show that the use of ESS can reduce peak demand from the grid by about 55%. This has many practical implications for the prosumers, such as reduced cost of energy, resilience of the communities against price volatility and disruptions as well as access to low-carbon

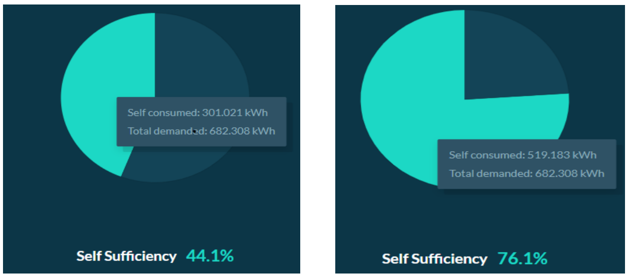


(a) Without ESS



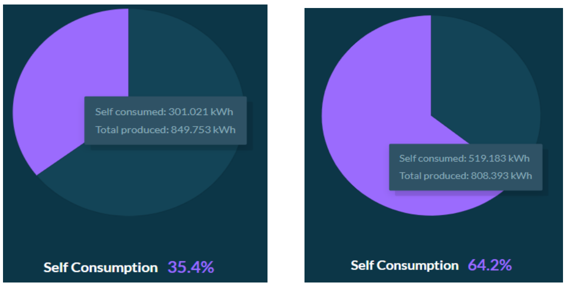
(b) With ESS

Figure 4: Grid export profile



(a) Without ESS (b) With ESS

Figure 5: Self sufficiency



(a) Without ESS (b) With ESS

Figure 6: Self consumption

energy. For the network operator this offers potential for flexibility services.

C. Self-sufficiency and self-consumption

Here, self-consumption refers to the proportion of energy in kWh consumed by the community from its own generation while self-sufficiency is a measure of the locally produced renewable energy relative to the total energy consumed. According to Figs 5 and 6, with the aid of the central ESS, sufficiency and self- consumption improved by 32% and 28.8% respectively.
These improvements are enabled by the fact that rather than export all excess energy, the central ESS allows the community to store surplus energy from PV and only export when the ESS is fully charged. On the other hand, the community imports when ESS is discharged. The benefits follows from Fig. 3b.
In particular, the 28.8% improvement in self-consumption arise from better utilisation of the renewable energy. Thus, with ESS, the community utilised the stored energy to locally balance the demand as well as maximise the economic benefits for the community. These results are in tandem with the outcomes reported in [3] which previously reported a cost-saving of 31% when private storage was combined with P2P. The additional benefit of central ESS as proposed here is the relief from cost of battery ownership, maintenance and replacement which can now be overcome through a storage-as-a-service subscription.

V. Conclusion

This paper investigates the benefits of central ESS by maximising collective self-consumption of energy and cost in a NEM. The proposed design for the community energy network includes a central ESS. The transactive market was simulated on the D3A grid singularity platform to understand the impacts of the ESS on the community in terms of renewable energy utilisation through deferred collective consumption, cost of energy of the community, flexibility of the market, and peak load management. First, it is observed that the peak import from the grid can be reduced by about 55%, using ESS. The results also show 28.8% and 32% improvements in community self-consumption and self-sufficiency, respectively. These indicate optimised use of renewable generation potentials of the community. Future research would consider the willingness to invest in the ESS and the effects on existing operating models.

VI. Acknowledgments

For the purpose of open access, the author has applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising from this submission.

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