Cost-effectiveness of virtual power plants based on residential aggregators

COST-EFFECTIVENESS OF VIRTUAL POWER PLANTS BASED ON RESIDENTIAL AGGREGATORS

Mousa Zerai[1*], Desen Kirli[1], John Calautit[2],
Hafiz Wasif[3], Thomas Morstyn[1], Aristides Kiprakis[1].

[1]Institute for Energy Systems, School of Engineering, University of Edinburgh, Edinburgh, UK
[2]Department of Architecture and Built Environment, Faculty of Engineering, University of Nottingham, UK
[3]Principal Consultant, Keyup Technology Limited, Loughborough, UK
** email address of corresponding author: M.Zerai@sms.ed.ac.uk*

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Abstract

The domestic sector accounts for a third of the UK's energy consumption and with increasing pressure from net-zero targets, the potential of residential flexibility is more widely recognised by consumers, aggregators and governments. The development in near real-time metering systems and home energy management technologies provide new possibilities for residential demand-side control. Due to the increase in energy prices and government schemes for improving residential energy efficiency and flexibility, domestic consumers are more aware and willing to participate in balancing services. The aggregator business model is previously proven to be successful for commercial-scale markets, due to the adequate amount of flexibility during peak hours and the corresponding financial incentives. Similarly, the domestic aggregation market is expected to grow and there has been a few feasibility studies that demonstrate the benefits to the grid and economy. However, there is a need for a further in-depth study of the cost-effectiveness of residential aggregation to provide virtual power plant (VPP) actions to encourage the development of residential demand response (DR). Here, we model and compare profitable cost-effective VPP methods using residential aggregation through the integration of a novel market entity called the residential aggregator.

1 Introduction

The domestic sector accounts for approximately a third of the UK's energy consumption, with an annual consumption of 3,729kWh per metering point and energy from natural gas covers most of this load [1]. In response to the Paris agreement targets for 2050 and the increases in energy prices worldwide, renewable energy technologies such as photovoltaic (PV) solar systems, batteries and heat pumps are becoming more attractive to homeowners which achieve an estimated payback period of around 10 years [2], subject to the system's type and efficiency. To decrease the payback period, homeowners are more interested to use their renewable energy sources, energy storage technology, and advanced automated systems for demand-side response and local energy trading as a part of a virtual power plant (VPP) [3].

VPPs accelerate the decentralisation of energy from a single supply system to a variety of diverse and distributed supply based on numerous sources [4]. By its arrangement, VPP offers a business ecosystem with a high degree of communication and interdependency between all stakeholders. Its success in the residential domain mainly depends on the economic benefit of contributing investors (Utility and prosumers) [3]. Due to the market de-regulation in Western countries, aggregators are allowed to group generation units in a VPP and participate in the market as a single generator [5]. Aggregators are also able to offer demand response (DR) services by altering the electricity usage pattern of the subscribers in the VPP based on signals from the system operator [6]. Faruque et al. [3] studied "residential aggregators" that coordinate several domestic prosumers with on-site renewable generation and energy storage. Residential aggregators may combine energy storage (including electric vehicles and batteries), flexible demand to achieve aggregated residential DR participation. Currently, the aggregation market for domestic customers is scarce and needs highlighting the economic benefits of domestic participation to the users and the system. The local flexibility markets are emerging and starting to commission smaller scale products [7, 8]. The residential aggregator is given greater control such as DR decisions, domestic generation control and load shifting using storage. Consequently, this brings economic value to all stakeholders, namely, prosumers, utility and aggregators.

This paper presents a novel use-case of a residential microgrid that is economically beneficial for all stakeholders due to its business model and policy design. We compare three scenarios focusing on aggregator, community (i.e. prosumers) and shared ownership of solar energy and storage systems. The first scenario is more representative of the UK as the prosumers invest in roof-top solar PV panels and the aggregator owns and controls the battery energy storage systems which has a higher capital cost. In the second scenario, aggregator owns all assets including solar panels, inverters and centralised battery energy storage systems. Therefore, the aggregator does not purchase any energy from the prosumers, but the users get discounts for consuming local energy and increasing self-sufficiency. The last scenario mimics the second, but the prosumers own all assets, and the role of the aggregator is restricted to control and scheduling only.

2. Methodology

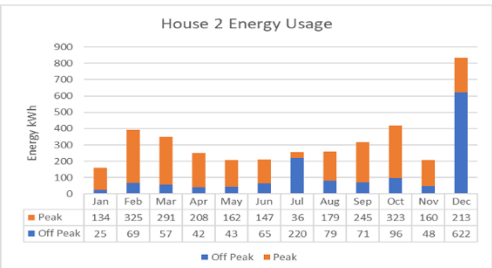
To study the economic effect of residential aggregator business models and VPPs, four different house types located in the South of England with real electrical demand data were used. The data is sampled at one minute for whole of year 2019 [9]. Using the demand profile of each house type, a PV solar generator and battery storage system was designed. The PV system is designed such that it meets the demand of the house. The battery storage system was designed to ensure uninterrupted energy at times when there is less solar generation (typically in winter). The model was developed to sell energy to the grid when the selling price is high at peak time and buy the energy from the grid in case there is less energy available in the battery storage system. The sharing of the storage system between houses is also investigated in the paper. The demand analysis which leads to the VPP design is described in this section.

2.1 Demand Data Analysis

The electricity demand was measured for 4 dwellings (2x detached and 1x semi-detached and terraced) over the whole year of 2009. Every dwelling was fitted with a single meter monitoring the electricity use of the whole dwelling where the one-minute resolution allowed switching of individual domestic appliances to be observed. This data was used to investigate the potential of participating in the domestic VPP, as well as to assess profitable scenarios for all stakeholders (aggregators, prosumers, and utilities).

Figure (1) represents the electricity consumption for a terraced house with 4 residents, participating in the *Economy7* program which offers a reduced tariff for consumption during off-peak hours. The participants have a higher off-peak consumption by scheduling their appliances such as the washing machine and dishwasher using timers [10]. Figure (1) shows the monthly consumption of the electricity during day and night-time of the year 2009. Each house consumes a different amount of electricity throughout the whole year, the changes mainly occur based on the number of occupancies and different weather condition for example in winter seasons additional heating and lighting are required, whereas cooling demand increases within summer seasons.

Figure 1: Monthly Energy Used for House 2

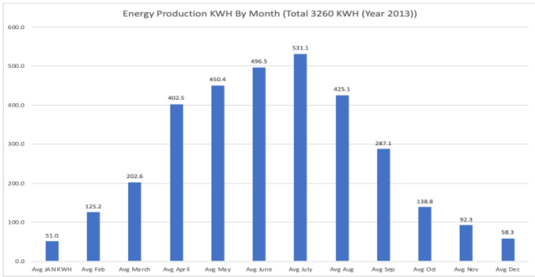


Electricity consumption could be different from one house to the other because of different consumer's behaviour. For example, the electric usage remains stable through weekdays for consumers who have a daily routine such as going to work from 9:00 am to 5:00 pm. Finally, the time-of-use tariff such as Economy7 affect consumption behaviour. The energy consumption among the 4 houses of the study varies between 3370 kWh and 4133 kWh, with the average at 3800 kWh. The average yearly power demand is 0.4 kW.

2.2 Solar energy generator

The solar energy generator is designed by analysing the average summer and winter temperature range between 13 and 23ºC, and 4 to 8ºC respectively [11], and with an average of 7 sunshine hours daily in summer months, and 4-5 hours in winter. A 5 kW PV solar panel was used where estimated energy production is summarised by month in Figure (2). The maximum electrical power obtained from the solar system is in the month of July is peaked at 2500 W during the mid-day. The cost of the array, based on 16 typical 315 W PV modules is around £7300.

Figure 2: Solar Energy Production



2.3 Design of the Storage System for a Single House

The battery should be capable to store the maximum energy production. For 5 kW system, the energy production is peaked in July, the energy production is 531 kWh. To meet the daily demand of the summer, the average energy production during three months of summer period is 15 kWh. For costing purposes, a Tesla Powerwall battery was chosen which has a battery size of 13.3 kWh which is closed to the required level. To keep the batteries in a good health, the algorithm will not discharge the battery below 20% of their total capacity. Furthermore, the energy storage capacity of the Li-Ion battery reduces over the time. Therefore, yearly reduction of its capacity also considered, and one percent drop in available capacity is assume for the total lifetime of the battery.

2.4.1 Business Model

This section demonstrates the method for profitable and cost-effective ways to implement a residential microgrid, integrating a novel market entity "residential aggregator" among the stakeholders (prosumers and the utility) [3]. The residential aggregator is assumed to have the capability to negotiate in the electricity market such as, in the demand response (DR) and household renewables generation and fixable electricity consumption (shifting the load through storage). Consequently, this brings an economic benefit to all participating stakeholders (prosumers, utility and aggregator).

The aggregator business model previously has been successfully implemented for both commercial and industrial markets, due to the appropriate amount of electricity that can be saved through DR during peak time and its financial advantages. On the other hand, to implement such a microgrid in the domestic sector, numerous regulations and rules respecting electricity prices will need to be established. To the best of our knowledge, there is no record of implementing a residential microgrid that is economically beneficial for all stakeholders because of non-existent applicable business rules and policies established in place. This section presents the rules and their impacts, and different scenarios are used to illustrate that solar distributed energy resource is vital to beneficial residential microgrid operation [3].

Three scenarios are applied on the business model: shared ownership, aggregator-owned and user-owned systems. To build the models, the following parameters are also optimised: installed solar and storage capacity, their location in the residential area, number of houses taking part in the proposed schemes, UK utility prices and government incentives for the renewable industry.

We first define a set of rules that may immediately benefit all stakeholders of the residential microgrid based on up-to-the-minute prices of electricity, renewable energy, and power elections such as batteries, solar panels and inverters. We consider the following factors to assist modelling and simulating a residential microgrid: (i) houses with a different pattern usage, (ii) real weather data of Milton Keynes, UK, (iii) PV panels, (iv) inverters and centralised batteries, (v) real electrical data consumption, (vi) distribution lines, and (vii) transformer to be connected with the grid nodes.

A proposed set of **business rules** by Faruque et al in [3], that may allow all participating stakeholders of a residential microgrid (prosumers, aggregator and the utility) to generate profit: Rule (1): The aggregator pays higher price to prosumers for their renewable electricity compared to the price the utility does. Rule (2): Prosumers cannot receive higher price from aggregator compared to what aggregator gets paid for selling renewable electricity to the utility. Rule (3): Prosumers receive cheaper electricity price from aggregator than utility does. Rule (4): The electricity price that the aggregator sell to the utility during the peak load time must increase compared to normal flat price. Rule (5): The electricity price is fixed for all prosumers in the microgrid. Rule (6): Energy storage may also include EV batteries as a backup to accommodate intermittency of the renewables. Rule (7): Trading electricity between neighbours participating in the residential aggregators may also be possible.

2.4.2 Profitability Evaluation Method

The fixed capital cost including (2%) interest rate due per period (of 10 years), as a proportion of the amount could be lent or borrowed from the bank to set up the residential aggregator business in cases (3) and (4) in scenarios (1) and (2). Simple interest equation (Principle +Interest) is formulated as follows [12]: $A = P (1+rt)$
Where: A = Total Accrued Amount (principal + interest), P = Principal Amount, I = Interest Amount, r = Rate of Interest per year in decimal; r = R/100, R = Rate of Interest per year as a percent; R = r * 100, t = Time Period involved in months or years. From the base formula, $A = P (1 + rt)$ derived from $A = P + I$ and $I = Prt$ so $A = P + I = P + Prt = P (1 + rt)$

Fixed term repayments [13]:

$$A = Vp^r \ 1-(1+r)-n$$

Where: A is the amount to be repaid, Vp is the amount borrowed, r is the discount rate, n is the number of payments.

When buying a large quantity of hardware such as batteries and inverters residential aggregator will get bulk buying discount from the manufacturer which could be assumed 5 to 10% in most cases. Considering the different components parts of the capital cost related to the microgrid project design, return on invested capital of the aggregator investment can be formulated as follow: Breakeven Point = Fixed cost + Variable cost / yearly net profit. Yearly Profit= Standing charge rate + Consumption cost + Selling Utility – Buying from Utility – Cost of Equipment Per year.

3 Results

This section presents the results and discusses three scenarios. First scenario (3.1) is shared ownership of power generation between prosumers and aggregator; in this scenario prosumers will have PV installed on their properties and they will own the system; the aggregator will invest in centralised battery storage and inverters to enable operation of microgrid in the domestic domain. Second scenario (3.2) is when the aggregator will be the owner of all power generation hardware and household owners will receive cheaper electricity prices compared to what they receive from the utility in arrangement of installation power generation on top of their properties by the aggregator. Third scenario (3.3) is when prosumers are the owners of power generation hardware, and the aggregator is managing the distribution of electricity using software applications.

3.1 Shared Ownership

With four houses participating in the residential VPP, the selling price from the aggregator is assumed to be fixed for all prosumers in the residential microgrid at 8 p/kWh. The aggregator may sell the spare energy stored at the battery storage to the utility during the day at peak times, with higher price to increase profitability. Due to uncertainty of energy supply in specific areas during peak hours or higher demand, the utility may accept the aggregator’s offer with higher prices. An agreement could be arranged at later stage to bring down A2U at fixed or variable prices.

The selling price from aggregator to utility DR (A2U) is 20 p/kWh, this will increase with respect to the number of participants in the system, e.g., when aggregator has 400 participants the selling price may increase to 22 p/kWh, 4000 houses participants, the price is 24 p/kWh and so on. Also, capital investment will be increased due to higher cost of the centralised power equipment. We also, assuming a higher capital investment adding 2% interest rate as money can be borrowed from the bank for capital cost and software development. Moreover, the aggregator may buy electricity at a cheap night rate U2A (! DR) 6p/kWh to be stored in the battery storage in order to supply the houses at different events. Allowing the aggregator to have a greater capacity to negotiate capability with national grid on the prices of the surplus power, aggregator could distribute during peak demand hours. Table (1) shows the normal electricity prices that household owners receive from the utility, the provided values are the most competitive prices in the UK electricity market. Table (2) shows the selling price rates assumed in this scenario and table (3) the buying electricity prices at day and night rates.

Table (1) list of buying electricity prices from utility

Nomenclature	Customer buying prices from utility	p/kWh Unit
U2P	Utility to prosumers	15 [17]
U2C (DR)	Utility to customer day rate	16 [18]
U2C (! DR)	Utility to Customer night rate	6 [16]
Sch	Standing charge per unit	20 [19]

Table (2) list of selling electricity prices from utility

Nomenclature	Selling Prices	p/kWh Unit
U2P	Utility to prosumers	15 [17]
U2P (DR)	Utility to prosumers day rate	19
A2P	Aggregator to prosumers	8
A2P (DR)	Aggregator to utility day rate	20
A2P (! DR)	Aggregator to utility night rate	15

Table (3) list of buying electricity prices

Nomenclature	Buying Prices	p/kWh Unit
U2A (DR)	Utility To aggregator	15
U2A (! DR)	Utility to aggregator night rate	6 [16]

Table (4) shows the financial result, capital investment and profit. The aggregator return on invested capital has dropped from 13 years in case (1) to 3 years in case (4), this due to larger system capacity used and increasing number of houses.

Table (4) Financial results of scenario 1.

House Number (Cases)	Capital Investment	Aggregator profit (per year)
4	£26,717	£1,919
40	£86,900	£17,907
400	£868,100	£188,366
4000	£7,751,000	£2,016,083

3.2 Aggregator owned Renewable

In this scenario, the aggregator will be the owner of all the power generation e.g., solar panels (to be settled on the top roof of the customer houses), inverters and centralized batteries. Therefore, the aggregator does not need to buy renewable energy from house owners (prosumers), but they will receive discounted electricity price compared to what they get from the national grid (utility). The installation of the power generation on the customer's properties will be in arrangement of signing contract between aggregator and household owners, with guaranteed discounted of electricity price from the aggregator to motivate them.

The size of PV system will be constant for all houses participating in residential microgrid as 5kWp, centralized batteries and inverters capacity will based on the number of houses in the system. Similar to the previous scenario (3.1), the buying and selling prices are varying depending on the number of participants. e.g., A2U (DR) rate may increase 22, 23 and 26 p/kWh. The selling prices will be fixed from aggregator to prosumers is 13 p/kWh. As result of scenario (2), saving amount may not motivate customers to participate in the system, in agreement with the aggregator to use their properties to install power generation. Additionally, high capital cost and daily the net income of the aggregator investment. Finally, in this scenario the most appropriate breakeven point occurs on the 25th year (case 4 with 4000 houses participating), however, the lifetime of most of the power generation used in this model is 20 years. Table (5) represent the capital investment used in each case, yearly profit of aggregator and saving of each house.

Table (5) Financial results of scenario 2.

House Number (cases)	Capital Investment	Aggregator profit (per year)
4	£55,971.00	£1,467.00
40	£360,455.00	£12,832.00
400	£3,591,006.00	£133,628.00
4000	£36,759,160.00	£1,432,642.00

3.2 Prosumers Owns all Power Generation

In this scenario, the prosumers will be the owners of all power generation. The aggregator may invest in algorithm software development and distribution planning and management. The aggregator needs to buy surplus energy from prosumers during daytime production from solar systems, and sell to the utility at higher rate A2U (DR). At night, aggregator may buy electricity at cheaper rate U2A (! DR) and sell it back to prosumers to enable profitability. Among stakeholders (aggregator and prosumers) to buy and sell each other at the same price. On the other word, prosumers may invest less on their power storage means they need smaller batteries (main benefit) with less capital cost. From analysing the energy consumption data of the four houses, it estimated that on average each house uses 50% of electricity during 8AM till 8 PM, while remaining in the 8PM till 8 PM [9].

The main difference of this scenario (3) is the aggregator capital investment, which accounted as lowest capital investment of the three scenarios. Currently, the UK energy companies with more than 150,000 customers will be required to introduce export tariffs by 1 January 2020. The Smart Export Guarantee (SEG) customers installing solar panels on their homes (prosumers) or participating in any renewable community energy project will be able to sell excess energy back to the grid via their energy suppliers [20]. In this situation residential aggregator may act as energy supplier in the wholesale market, by purchasing surplus energy from prosumers and sell it back to them at the same rate with no charges. This is how residential aggregators can differentiate in the electricity market. Therefore, this can benefit prosumers to invest less money on battery storage, as any additional electricity produced by their solar panels can be exported to the grid via aggregator, and the same amount of electricity can be imported from aggregator at the same price.

Table (6) Financial results of scenario 3.

House Number (Cases)	Capital Investment	Aggregator profit (per year)
4	£5,000	£1,624
40	£10,000	£18,278
400	£100,000	£182,782
4000	£200,000	£1,867,820

4 Conclusion

This study demonstrated a cost-effective VPP operation using a residential aggregator and showed that a high penetration of distributed solar energy is a key variable. Additionally, the three cost-effective scenarios were tested with varying number of houses, penetration of participants, generation and storage capacities and aggregator capital investments. The residential microgrid is expected to achieve a quicker breakeven point than expected if the number of houses (participating) has increased in the system. The aggregator profitability may also increase when the battery storage capacity is larger, more electricity can be stored for later use or/and can be sold to utility at peak times. This study showed that the first scenario (shared ownership) was the best option due to the possibility that a household owner has, with already installed solar panels on their rooftop, there will be no barrier for them to join, as the aggregator will offer them cheaper electricity compared to utility. Additionally, future work should evaluate the effect of EV and heat pump penetration on the residential aggregator. This could be used to study the techno-economic impact of localised flexibility.

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