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Design Space Exploration and Energy Management in Residential Microgrids

Author
Vatanparvar, Korosh

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Design Space Exploration and Energy Management in Residential Microgrids

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by

Korosh Vatanparvar

Dissertation Committee:
Assistant Professor Mohammad Al Faruque, Chair
Professor Fadi Kurdahi
Assistant Professor Aparna Chandramowlishwaran

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DEDICATION

To my parents for their unbelievable sacrifices and unconditional love and support.

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NOMENCLATURE

p	Prosumer
u	Utility
a	Aggregator
DR	Demand Response
P_p^u	Electricity price for prosumer sold by utility
P_a^u	Electricity price for aggregator sold by utility $(\neg DR)$
P_p^a	Electricity price for prosumer sold by aggregator
P_u^p	Solar energy price sold by prosumer to utility
P_a^p	Solar energy price sold by prosumer to aggregator
P_u^a	Solar energy price sold by aggregator to utility $(\neg DR)$
$DR\ P_u^a$	Solar energy price sold by aggregator to utility (DR)
$DR\ P_a^u$	Electricity price for aggregator sold by utility (DR)
ROI	Number of years needed to return on investment

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ABSTRACT OF THE DISSERTATION

Design Space Exploration and Energy Management in Residential Microgrids

By

Korosh Vatanparvar

Master of Science in Electrical and Computer Engineering

University of California, Irvine, 2015

Assistant Professor Mohammad Abdullah Al Faruque, Chair

Microgrid has been shown to be profitable, reliable, and efficient for military, commercial, and university-like installations. However, until now, there has been no study to show how and when a residential microgrid may be profitable. Therefore, in this thesis, we present a design space exploration methodology of the microgrid by modeling all the energy resources at the residential level and conducting numerous simulations with various parameters. Moreover, a set of rules are defined to make the stakeholders in the microgrid profitable. Also, by analyzing the number of houses in the microgrid, we observe that the number of years it takes to return the capital costs invested in the microgrid may become adequately short for a certain range of the number of houses. For instance, if the aggregator owns the renewable energy resources, e.g., solar panels, it may profit in less than five years when 500 houses participate in the microgrid where each house owns 500 sf solar panels. On the other hand, if the prosumers own the renewable energy resources, e.g., solar panels, the aggregator may profit in about a year. Typically, for an apartment-block type housing area in U.S. there are more than 1000 houses, therefore the aggregator profitability may improve furthermore.

CHAPTER 1: INTRODUCTION AND BACKGROUND

Electrical grids are getting smarter due to tight integration of computation and communication with the physical power grid and significant research efforts are being dedicated to make them more efficient, green, and economical. Moreover, cost-effective and more efficient electrical and electronic devices are becoming available to implement complex control algorithms and manage electricity production, distribution, and consumption [1].

Currently, more than 66.5% of the electricity in U.S. is generated from coal, gas, and other fossil fuels [2]. The use of these types of fuel have adverse effects on the environment including global warming, air quality deterioration, oil spills, acid rain, etc. [3]. Therefore, there is a tremendous global push toward using renewable energy from various sources, e.g., solar, wind, and geo-thermal[1]. However, the usage of renewable energy comes with its inherent challenges including intermittency, high cost, unreliability, etc. [6]. Research has been very active in this domain to come up with ideas to address these challenges [6]. Thanks to the photovoltaic fabrication community, by leveraging wafer-bonded four-junction solar cells, they have reached the conversion efficiency of 44.7% [7]. Therefore, these cost effective solar cells may create the opportunity for the electricity consumers to produce their own renewable energy [8]. However, most of the renewable energy, e.g., solar energy is intermittent such that the electricity produced is not flat and changes during the day according to sun diffuse, cloudiness, etc. Therefore, many utilities have provided the

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[1] For example, in the state of California, all retail suppliers of electricity should meet the goal of 33% eligible renewable energy by 2020 [4]. Moreover, U.S. Environmental Protection Agency is regulating state-specific CO2 emission goal that may increase the nonhydro renewable energy capacity about 50% by 2020 [5].

consumers with a service that they may feed their extra electricity back into the utility through the same electrical grid. This bi-directional grid makes consumers to act as prosumers [9], [10]. In the scope of this thesis, we termed consumers who may have home-installed solar panels to produce renewable energy for their usage and sell excess to the utility to profit financially as prosumers.

The question is why the utilities should be interested to feed in the electricity from the prosumers. Besides the regulatory pressure on integrating more renewables, the utilities need to invest huge capital cost on building various types of power plants in case of increased demands [11]. Moreover, the electricity demand of the residential and commercial consumers are not uniform and constant, considering time, day, and seasons of a year. The electricity demand changes dramatically during a day based on various reasons including consumer commute pattern, life-style, weather, etc. Existing works show that typically, there is one, or two electricity demand peaks during a day [12]. Moreover, there may be very few unusual electricity demand peaks in a year, e.g., during the super bowl time [13]. The utility does not like the electricity demand peak, because it has to use as many as power plants as possible to supply this demanded electricity into the grid [11]. Moreover, 20% of generation capacity of the utility exists to meet electricity demand peak only, and it is in use only 5% of the time [1]. This situation is not economical and efficient.

Due to the intermittent nature of renewable energy, the electricity production may peak during the day, e.g., at noon for solar energy. Therefore, to reduce the electricity demand peak and make the most out of the renewable energy, e.g., solar energy produced during a day, energy storage, e.g., batteries are being used. The energy storage stores the extra renewable energy to be used during the peak time when the electricity might get more expensive [14], [15]. Our simulation shows that in California the peak time is between 5 and 9 P.M. [16].

To further reduce the electricity demand peak, the utilities are also exploring various mechanisms to make prior contracts with the consumers that may enable the utility to control the consumers' electricity consumption. DR and direct load control (DLC) are commonly used with incentives of changing the electricity consumption pattern [17].

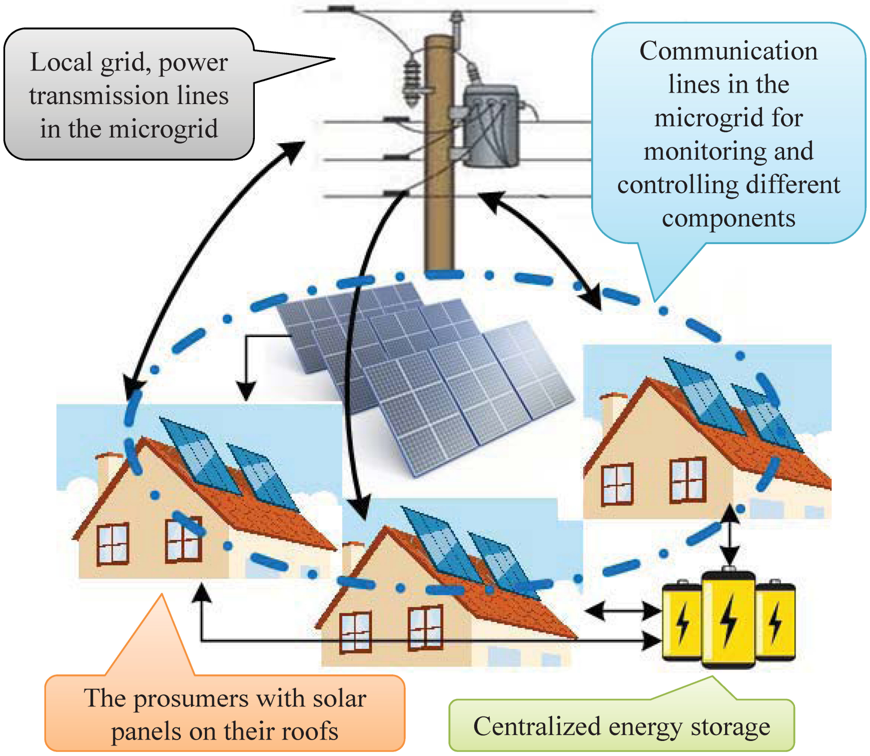

Figure 1. Residential microgrid may be formed using many single-unit houses or many apartment blocks (for details see [19]).

Moreover, to make the electrical grid more efficient, reliable, and economic, multiple consumers and producers may be grouped together in a local grid [18], [19]. The producers provide the consumers in the same microgrid[2] with renewable energy as far as they may

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[2] A microgrid is a cluster of distributed generators, electricity storage, and loads which may connect to electrical grid or operate autonomously [19].

supply (as shown in Figure 1). When there is not enough electricity available locally, the utility may power the consumers. On the other hand, when the producers have more electricity, they may sell the extra electricity to the utility. Localization of distribution and production of the electricity in a microgrid enhances the reliability and efficiency of the local grid [18].

The costs associated with installing solar panels, electricity generators, batteries, and etc., may become large enough that the ordinary prosumers may not get motivated enough to invest on the microgrid and save in the long-term. However, a residential aggregator may come between the utility and the prosumers and invest on the infrastructure for the microgrid. Therefore, the prosumers may sell their renewable energy to the aggregator and then it may be sold to the utility if not needed locally. Also, the prosumers only buy electricity from the aggregator which may be provided by the utility, solar panels, or energy storage. Therefore, with the negotiating capabilities of the aggregator, the prosumers may find incentive to participate while the aggregator profits. It has been shown that microgrid is profitable for commercial, university-like installations (in the commercial domain, profitable aggregator exists today, e.g., EnerNOC [20], [21]). However, until today, there has been no systematic study to show that how and when a residential microgrid may be profitable.

In [19], various rules are defined that may make an aggregator economically profitable and beneficial. These rules consider the number of houses that may join the microgrid, the electricity and the feed-in tariff for the prosumers, the aggregator, and the utility (the price defined by the utility to encourage the prosumers to sell renewable energy [9], [10]). However, the number of houses that participate in the microgrid, not only may affect the daily net income of the aggregator, but also may affect the capital costs needed to be invested. The daily net income is defined as the daily expenses subtracted from the daily revenues for the aggregator. Therefore, to make it profitable, the aggregator should find out that in how many years it may return the money it invested. The time it takes for the aggregator to ROI should be adequately short so that it gets motivated. On the other hand, to motivate the prosumers to participate in this microgrid arrangement, they will be offered lower electricity price, higher feed-in tariff than offered by the utility. Moreover, by using the electricity produced and stored locally, load shifting, DR, and DLC, the electricity consumption pattern of the customers may change and the electricity demand peak may reduce which benefits the utility [17], while no capital costs are needed to be invested by the utility.

To design the microgrid, various parameters need to be considered that may affect the aggregator profitability. These parameters change the capital costs and the daily net income of the aggregator. Therefore, various trade-off analysis among the influencing parameters need to be explored. Exploring the design space of a microgrid for possible system-level optimization may help a potential aggregator to decide on multiple parameters at priori and optimally [22]. A microgrid behaves differently in various scenarios in which different energy resource sizing (e.g., battery capacity, solar panel area, etc.) would be needed to be efficient and economical.

Therefore, in the scope of this thesis, we proposed a design space exploration methodology for an aggregator-based residential microgrid and presented various rules, mechanisms, and trade-off analysis to demonstrate when and how various stakeholders (utility, aggregator, prosumers, etc.) in a residential microgrid may become profitable.

CHAPTER 2: PROBLEM FORMULATION

To analyze the trade-off among various parameters involved in a microgrid for the profitability, the design-space is formulated as follows.

1) Fixed Capital Cost = capital costs (monetary cost in $) invested for centralized equipment such as batteries, microgrid management and monitoring systems, etc.
2) Variable Capital Cost = capital costs (monetary cost in $) invested for distributed power electronics such as solar panels, inverters, etc.
3) Daily Net Income = (the daily revenues for selling electricity to the utility or the prosumers) − (the daily expenses for buying electricity from the utility or the prosumers).
4) N = the number of houses participating in the residential microgrid.

Considering the various components of the capital costs associated with the microgrid design, we may formulate the aggregator return on investment as follows:

$$\Rightarrow ROI \simeq \frac{Fixed\ Capital\ Cost + Variable\ Capital\ Cost \times N}{Daily\ Net\ Income} \tag{1}$$

The denominator of (1) is not fixed and is dependent on N by the following equation:

$$Average\ Net\ Income \approx const. \times N^{\alpha} \tag{2}$$

Variable α is the growth of the daily net income with respect to the number of houses. If we have α = 1, the average net income will increase linearly with the number of houses and the ROI will not get small enough for the aggregator. However, in this thesis, we show that α is larger than one. Therefore, for a reasonable ROI target for the aggregator (γ), there is a reasonable number of houses (η) so that the aggregator profitability (ROI) will reach its target (γ) and may get better profitability with more houses participating in the microgrid (3). This formulation is derived from the observation in [19]. Moreover, this equation is not a general fact and all the variables regarding the microgrid need to be consistent, so that the equation may be valid

$$\exists \eta > 0, \exists \gamma > 0, \forall n \geq \eta : ROI \leq \gamma \tag{3}$$

Table 1. Table of specifications for modeling the residential microgrid.

Resource	Property	Value
Solar Panel	Generator Mode	*Supply Driven*
	Panel Type	*Single Crystal Silicon*
	Efficiency	*20%*
	Area Mean	*Variable*
	Area Deviation	*20%*
Inverter	Generator Mode	*Constant Power Factor*
Battery	Battery Type	*Lead Acid*
	Base Efficiency	*86%*
	Parasitic Power Draw	*190 W*
House	Floor Area Mean	*2100 sf*
	Floor Area Deviation	*20%*
	Number of Stories	*1*
	Heating System	*Gas*
	Cooling System	*Electric*
	Cooling COP	*3.3*
	Cooling Setpoint	*72˚F*
	Heating Setpoint	*69˚F*
	Window Wall Ratio	*0.13*
Water Heater	Tank Volume	*40 Gal*
	Heating Element Capacity	*3 KW*
	Power	*5 KW*
	Energy Baseline	*1 KWh*
Dish Washer	Power	*1 KW*
	Energy Baseline	*1 KWh*
Clothe Washer	Power	*1 KW*
	Motor Power	*0.8 KW*
	Energy Baseline	*750 Wh*
Dryer	Power	*5 KW*
	Energy Baseline	*2.5 KWh*
Lights	Power	*760 W*
Plugs	Power	*360 W*
Refrigerator	Power	*750 Wh*
	Energy Baseline	*1 KWh*
Freezer	Power	*500 W*
	Energy Baseline	*750 Wh*
Range	Power	*500 W*
	Energy Baseline	*1 KWh*
Microwave	Power	*200 W*
	Energy Baseline	*1 KWh*

CHAPTER 3: OUR NOVEL CONTRIBUTIONS

In summary, our design exploration in this thesis will mainly focus on the following novel contributions:

1) Defining a set of rules that may lead the stakeholders of the residential microgrid to be profitable based on the state-of-the-art market prices of components (e.g., batteries, solar panels, power electronics, etc.), electricity, and renewable energy;
2) Modeling and simulating a residential microgrid in GridLAB-D [23] considering details includes the following:
    a) more than 500 houses with various appliances listed in Table 1;
    b) transmission lines, transformers that connect the grid nodes;
    c) solar photovoltaic (PV) panels and the inverters;
    d) centralized battery and the inverters;
    e) real weather of Los Angeles and California (TMY2 climate data [24]);
    f) real utilization of appliances by households (schedule module).
3) Implementing control algorithms using GridMat [25], for managing the energy storage usage in the microgrid and the flexible loads of the houses for participating in the DR;
4) Exploring the design space of a residential microgrid and analyzing for the optimized parameters that may influence the aggregator profitability:
    a) number of houses participating in the microgrid;
    b) average area of solar panels for each house;
    c) battery capacity required to be installed by the aggregator;
    d) electricity price, feed-in tariff, and solar renewable energy credit (SREC [26]).

CHAPTER 4: RESIDENTIAL AGGREGATOR

The major incentive of the aggregator is to invest with the assumption that the ROI will be faster and aggregator profitability will start in adequately short period of time. The aggregator may invest on centralized and distributed resources that may be needed in the microgrid. The utility may implement these techniques and control algorithms and also act as the aggregator. Our exploration is orthogonal to the types of stakeholders implementing the role of the aggregator. However, the cost of implementing them locally by an aggregator may be much lower [18].

A. Our Microgrid Model

The microgrid center is the place where all the centralized equipment such as electricity management systems for electricity resources, intelligent monitoring, energy storage, power electronics, and advanced metering infrastructure are located. On the other hand, distributed resources such as: solar PV panels, intelligent metering and managing devices, power electronics, and smart appliances need to be installed for each house in the microgrid. The solar panels may be installed on top of the roofs and be used to power the whole microgrid in a distributed manner. Moreover, the metering and monitoring devices are used to measure the electricity consumption and production of each component in the microgrid, then a controller utilizes these values to dynamically configure various control parameters of the microgrid, e.g., the smart appliances in the houses (wired or wireless) for load managing purpose. These smart appliances are capable of being controlled remotely, if they want to be part of DR program [27]. All the resources used in modeling the residential microgrid are listed with details in Table 1. Also, the load demanded for heating and cooling the houses is dependent on their floor areas. To model the imbalance between the load demands from the houses, a normal distribution (Gaussian) with the mean of 2100 sf and the deviation of 20% for the floor areas has been used. Moreover, to eliminate the problem of intermittency, load shifting is used and batteries located in the microgrid center may store the extra electricity during the off-peak time of the day and then power the microgrid during the peak time and night [15]. The microgrid center is the only component that communicates with the utility. Therefore, the electricity not needed by the prosumers in the microgrid, will be transferred to the microgrid center and then possibly to the utility. The electricity generated by the solar panels and the energy storage, e.g., batteries is dc electricity and need to be converted to ac electricity. For this purpose, power electronics such as: inverters, etc., are implemented in the microgrid. Moreover, metering devices are utilized to measure the flow of the electricity in each node of the microgrid, so that the aggregator may decide when to use batteries, solar panels, or the utility to power the prosumers. Moreover, these components are considered while evaluating the expenses and revenues of the aggregator.

In the scope of this thesis, we consider two configurations shown below to build the infrastructure for the distributed equipment and the electricity resources:

B. Prosumer-Owned Renewables (POR)

In this configuration, the aggregator will setup the solar panels for the prosumers, but the owners of the solar panels are the prosumers. Therefore, all power electronics, e.g., inverters that may be needed are also owned by the prosumers. However, the aggregator needs to pay for the renewable energy produced by the prosumers.

C. Aggregator-Owned Renewables (AOR)

In this configuration, the solar panels installed are owned by the aggregator. Therefore, all power electronics, e.g., inverters that may be needed are also owned by the aggregator. However, the aggregator does not buy renewable energy from the prosumers, but they will get discounted electricity price to get motivated. The differences between these two configurations are the capital costs and the daily net income for the stakeholders, aggregator and prosumer. Therefore, it will affect the aggregator profitability and the time it takes to ROI.

D. Scenario-Specific Residential Microgrid Case Studies

Based on the amount, the aggregator wants to invest for the capital costs and the algorithms to be implemented, the following microgrid scenarios are considered.

I. *With Installed Energy Storage:* Every house has its own solar panels. The aggregator sits between the utility and the prosumers and buys renewable energy from the prosumers and sells it to the utility directly. Meanwhile, the prosumers do not need to worry about making contract with the utility. If other houses in the microgrid need the electricity, the aggregator may provide them from the extra renewable energy from other house's solar panels. If the electricity consumption in the microgrid is less than the electricity production, extra electricity will be stored in the batteries. If the batteries get full, then the aggregator sell the extra electricity to the utility. This scenario-specific configuration is as follows.

1) Solar panels are implemented in each house.
2) Renewable energy is used among the houses in the microgrid anytime.
3) Solar energy is stored in the batteries if not needed by the prosumers.
4) Additional solar energy is sold to the utility.
5) Stored electricity in batteries may be used to power houses anytime.

II. *With Installed Energy Storage and Load Shifting:* In this scenario, while keeping the configuration in the previous scenario, we add another new configuration: since, the electricity price is higher during the peak time, the aggregator tries not to buy any electricity from the utility and instead, uses the electricity stored in the batteries. It also may fully charge the battery during the off-peak time and sell it back to the utility when the feed-in tariff is higher. This may shift the load of the microgrid from the peak time to the off-peak time (load shifting). This scenario-specific configuration is as follows.

1) Solar panels are implemented in each house.
2) Renewable energy is used among the houses in the microgrid anytime.
3) Solar energy is stored in the batteries if not needed by the prosumers.
4) Additional solar energy is sold to the utility.
5) Stored electricity in the batteries may be used to power houses anytime (lower priority).
6) The batteries will be used to power the houses during the peak time (higher priority).
7) The stored electricity will be sold with higher price to the utility during the peak time.

III. *With Installed Energy Storage, Load Shifting, and DR:* Also in this scenario, while keeping the configuration in the previous scenario, we add another new configuration: an agreement between the aggregator and the prosumers may grant a predefined access to the aggregator to control the load of the houses during the peak time (DR and DLC). During the peak time, a DR signal is triggered and some of the appliances such as: cloth dryer and washer, water heater, dishwasher, etc., will get turned off and also cooling and heating temperature set points of the heating, ventilation, and air conditioning inside the houses may be relaxed (the cooling and heating set points change in the comfort zone between 65-79 ˚F [28]). This scenario will help the aggregator to save electricity during the peak time and sell as much as stored electricity as possible to the utility. Moreover, reduction in the electricity demand peak of the prosumers may benefit the utility. This scenario-specific configuration is as follows.

1) Solar panels are implemented in each house.
2) Renewable energy is used among the houses in the microgrid anytime.
3) Solar energy is stored in the batteries if not needed by the prosumers.
4) Additional solar energy is sold to the utility.
5) Stored electricity in the batteries may be used to power houses anytime (lower priority).
6) The batteries will be used to power the houses during the peak time (higher priority).
7) The stored electricity will be sold with higher price to the utility during the peak time.
8) The aggregator reduces the load of each house during the peak time.

To make the aggregator more profitable, we want to minimize the electricity bought from the utility and instead, use the electricity produced and stored locally, to power the houses in the microgrid especially during the peak time. As mentioned earlier, utilities may also play the role of the aggregator as well and therefore the aggregator profitability will not affect the income of the utility but rather help the utility to manage the peak time more efficiently through intelligent demand side management.

E. Rules for the Profitability of the Microgrid Stakeholders

Residential customers will only be motivated to participate in a microgrid if it is offered with incentive-based economic advantages. The electricity prices defined by the utility are less flexible and dependent on the contract between the two sides. A commercial customer may get lower price than an ordinary residential customer. Moreover, contract duration may affect the electricity price and the feed-in tariff. Therefore, the aggregator—as a commercial entity—may make contract with the utility in a way that it gets the best price for buying electricity and selling renewable energy. Then the aggregator may offer a better price than the utility does to the prosumers as long as it is profitable for itself. Therefore, to compensate the inconvenience cost to the prosumers by participating in the microgrid and the DR program, better rates for the electricity sold to the prosumers and bought from the prosumers are offered (upto 16% decrease in the electricity price and/or upto 19% increase in the feed-in tariff). Moreover, monthly fixed payment or one-time payment to the prosumers may be provided instead of changing the rates, which may have the same effect on the ROI. Also, the model we have implemented, the rates are fixed, and thereby the generation level is not dependent on the rates which may be a limitation for the aggregators. Below we present a set of rules that may allow all the stakeholders of a residential microgrid, the prosumers, the aggregator, and the utility to maintain profitability.

- Proposed Rules:
    1) $P_u^p \leq P_a^p$: The aggregator pays more than the utility does to the prosumers for their renewable energy.
    2) $P_a^p \leq P_u^a$: The aggregator cannot pay the prosumers more than it gets paid for selling renewable energy to the utility.
    3) $P_p^a \leq P_p^u$: The aggregator sells electricity to the prosumers in cheaper price than the utility does.
    4) $P_a^u \leq P_p^a$: The aggregator cannot sell electricity to the prosumers in a price less than it buys from the utility.
    5) $\neg DR\ P_a^u \leq\ DR\ P_a^u$: The electricity price for the aggregator increases during DR.
    6) $\neg DR\ P_u^a\ \leq\ DR\ P_u^a$: The feed-in tariff for the aggregator increases during DR.

7) $\forall\, i, j \,:\, P_{p_i}^{a} = P_{p_j}^{a}$: The electricity price is the same for all the prosumers in the microgrid.

8) $\forall\, i, j \,:\, P_{a}^{p_i} = P_{a}^{p_j}$: The feed-in tariff is the same for all the prosumers in the microgrid.

F. Profit Evaluation

We have estimated the electricity consumption of each house, the renewable energy production by each house, the electricity bought from the utility, and the renewable energy sold to the Utility by the aggregator. Each SREC represents 1 MWh of eligible renewable energy (see Table 2). SREC may be traded on the open market. Therefore, aggregator may profit more by selling SREC. All these parameters are used to evaluate the revenues and the expenses of the aggregator during the microgrid operation. Other prices such as: monthly fees, maintenance fees, etc., may also be considered. However, these costs are out of the scope of this thesis.

In our experimental setup, whenever the value of an electricity flow in the nodes of the microgrid changes, an event will be triggered and all the updated values will be recorded with their timestamps. Below we represent the formulations we have used to evaluate the profitability.

1) Assumptions:

n	is number of houses in the microgrid
m	is number of events recorded
$\sqcap^{a}$	is total income gained upto the m th event
T	is an array of $m \times 1$
$T[i]$	is timestamp for the i th event

E	is an array of $m \times 1$
$E_b^a[i]$	is instantaneous power of electricity flow from node (a) to node (b) at the i th event
C	is an array of $m \times m$
$C_b^a[i,j]$	is a coefficient dependent on the electricity price or the feed-in tariff to find the revenue or the expense of the aggregator related to the electricity flow from node (a) to node (b) at the event

2) *Profit Equation:* We need to evaluate the time duration of each event

define $\Delta T[i]\ an\ array\ of\ m \times 1$

$$\forall\ 1 \le i \le m-1:\ \ \Delta T[i] = \Delta T[i+1] - T[i]$$

$$\Delta T[m] = 0. \tag{4}$$

We define four coefficient matrices of $m \times m$. Each coefficient element is dependent on the time of the event and the direction of the electricity flow

$$\forall 1 \le i,j \le m: C_p^a[i,j] = \begin{cases} P_a^p & i = j \\ 0 & i \neq j \end{cases} \tag{5}$$

$$\forall 1 \le i,j \le m: C_a^p[i,j] = \begin{cases} P_p^a & i = j \\ 0 & i \neq j \end{cases} \tag{6}$$

$$\forall 1 \le i,j \le m: C_a^u[i,j] = \begin{cases} DR\ P_a^u & i = j \wedge T[i] \in peak\ time \\ \neg DR\ P_a^u & i = j \wedge T[i] \notin peak\ time \\ 0 & i \neq j \end{cases} \tag{7}$$

$$\forall 1 \le i,j \le m: C_u^a[i,j] = \begin{cases} DR\ P_u^a & i = j \wedge T[i] \in peak\ time \\ \neg DR\ P_u^a & i = j \wedge T[i] \notin peak\ time \\ 0 & i \neq j \end{cases} \tag{8}$$

The time duration of each event is multiplied by the electricity flow and the respected coefficient to evaluate the revenues and the expenses in that event, then the revenues and the expenses for all the events are summed to find the final total income

$$Total\ Revenue = \Delta\, T^{T} \times \left(C_{p}^{a} \times \sum_{i=1}^{n} E_{p_i}^{a} + C_{u}^{a} \times E_{u}^{a} + SREC \times E_{a}^{p}\right) \tag{9}$$

$$Total\ Expense = \Delta\, T^{T} \times \left(C_{a}^{p} \times \sum_{i=1}^{n} E_{a}^{p_i} + C_{a}^{u} \times E_{a}^{u}\right) \tag{10}$$

$$\sqcap^{a} = Total\ Revenue - Total\ Expense. \tag{11}$$

Table 2. List of Prices

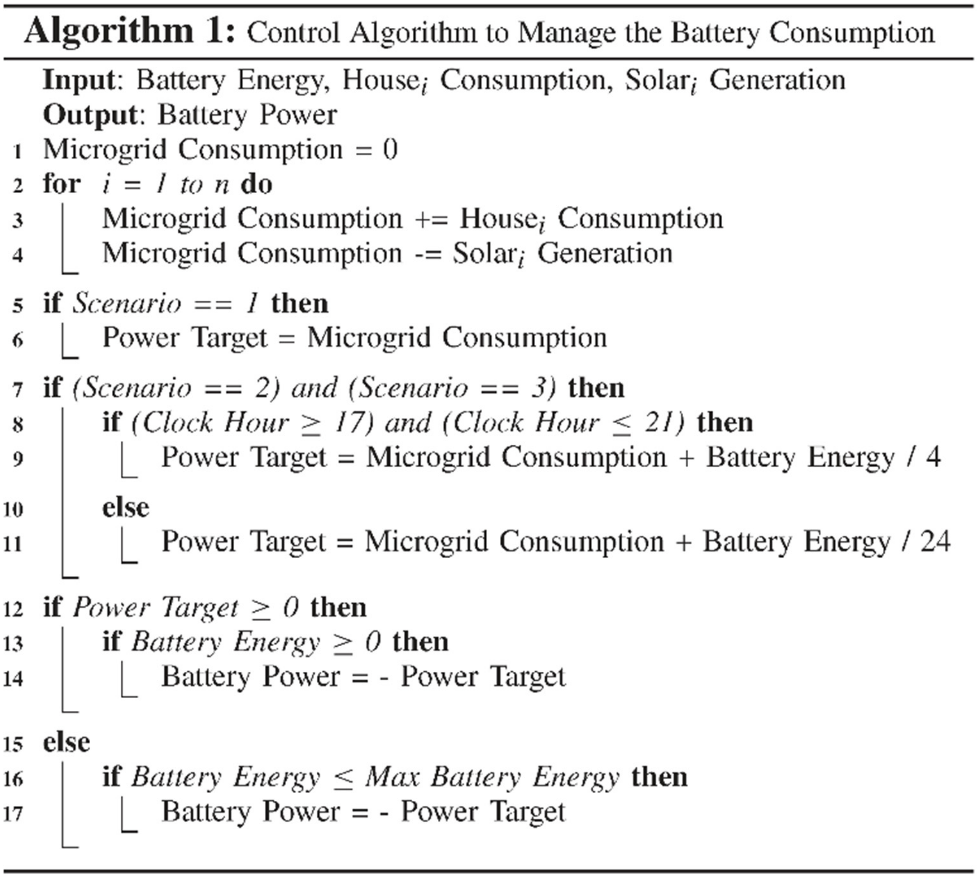
Name	Unit	Price	
		Commercial	Residential
Electricity Price	*cent/KWh*	13.57 [2]	16.18 [2]
Feed-In Tariff	*cent/KWh*	10.08 [30]	8.45 [30]
SREC	*dollar/MWh*	50 [31]	
Solar PV	*dollar/sf*	13.55 [32]	
Battery Bank	*dollar/Wh*	0.18 [32]	
Inverters	*dollar/watt*	0.61 [32]	

G. Capital Costs

Costs associated with installing and wiring equipment need to be considered (Table 2). Based on how much renewable energy the producer wants to sell, it needs to decide how many solar panels to invest on. The parameter here, is the maximum electricity that each solar panel can generate which is proportional to the solar panel area. The price rate is based on the maximum nominal power (watt) each solar panel can generate. Also to store more renewable energy, we need to add more battery banks. The type of battery banks considered for storing temporary electricity is lead-acid batteries [29]. Their price depends on the amount of electricity these batteries may store—watthour. The maximum amount of the electricity stored in the batteries limits the time and the amount of the electricity that may be used later for powering houses in the microgrid or for selling the electricity to the utility. On the other hand, excessive capacity may be useless and inefficient. Moreover, since the output power of the inverters is limited, to get larger output power from the batteries and solar panels, we need to connect multiple inverters in parallel. The price of these inverters is calculated based on the maximum power they can provide (watt). Although there are other costs related to the wiring, networking, and installing the equipment, we have excluded these costs from our current exploration.

CHAPTER 5: EXPERIMENTAL RESULT ANALYSIS

To model and simulate the residential microgrid, GridMat, a MATLAB toolbox [25] is used which connects to the state-of-the-art power distribution system simulation and analysis tool, GridLAB-D [23] and implements the control algorithms defined in MATLAB/Simulink library.



Algorithm 1: Control Algorithm to Manage the Battery Consumption

```
Input: Battery Energy, House$_i$ Consumption, Solar$_i$ Generation
Output: Battery Power
Microgrid Consumption = 0
for $i = 1$ to $n$ do
    Microgrid Consumption += House$_i$ Consumption
    Microgrid Consumption -= Solar$_i$ Generation
if $Scenario == 1$ then
    Power Target = Microgrid Consumption
if $(Scenario == 2)$ and $(Scenario == 3)$ then
    if $(Clock\ Hour \geq 17)$ and $(Clock\ Hour \leq 21)$ then
        Power Target = Microgrid Consumption + Battery Energy / 4
    else
        Power Target = Microgrid Consumption + Battery Energy / 24
if $Power\ Target \geq 0$ then
    if $Battery\ Energy \geq 0$ then
        Battery Power = - Power Target
else
    if $Battery\ Energy \leq Max\ Battery\ Energy$ then
        Battery Power = - Power Target
```

The GridMat is provided with the model of the residential microgrid and the control algorithm code. The model is simulated using GridLAB-D, while GridMat is monitoring and changing the control parameters of the model. The control parameters may vary according to the control algorithm implemented. As you may see in Algorithm 1, the power drawn from the battery is specified based on the power consumption in the microgrid. In scenario I, battery management tries to use the battery as much as possible to avoid receiving power from the utility. In scenarios II and III, the energy stored in the battery may also be sold to the utility over time. Therefore, in this way, the stored energy during the off-peak time will be sold during the peak time with higher price.

The load demanded by the appliances is modeled using scheduler modules, which define the load in hourly basis. Also, managing the load demands for DR program is done by modifying the scheduler modules.

To explore and analyze the design space, numerous simulations are conducted and for each simulation, different values are applied to the scenario-specific configuration parameters such as the electricity price, the solar area, the battery capacity, and the number of houses in the microgrid to find the optimal points.

A. Number of Houses

The whole purpose of the microgrid is to use the electricity locally when possible rather than transferring the electricity all the way to the utility and then to another consumer. Also, monitoring the microgrid locally is more efficient than controlling it remotely. All these advantages may be observable in adequately large number of houses. Our experiments show that if the number of houses is too small, there is not enough electricity demand in the microgrid and the electricity produced locally will not be used efficiently and it will be stored in the batteries or be sold to the utility. Therefore, the aggregator profitability will decrease. On the other hand, if the number of houses gets too large, the consumption will be much more than the capacity of the batteries or even larger than the renewable energy produced and stored. Also the costs and complexity of the equipment might get dramatically large. Therefore, the aggregator profitability will decrease again. To analyze the relation of the number of houses with the aggregator profitability, different types of houses are connected to the microgrid and the electricity flow is simulated. The ROI for these models are measured and shown in Figure 2.

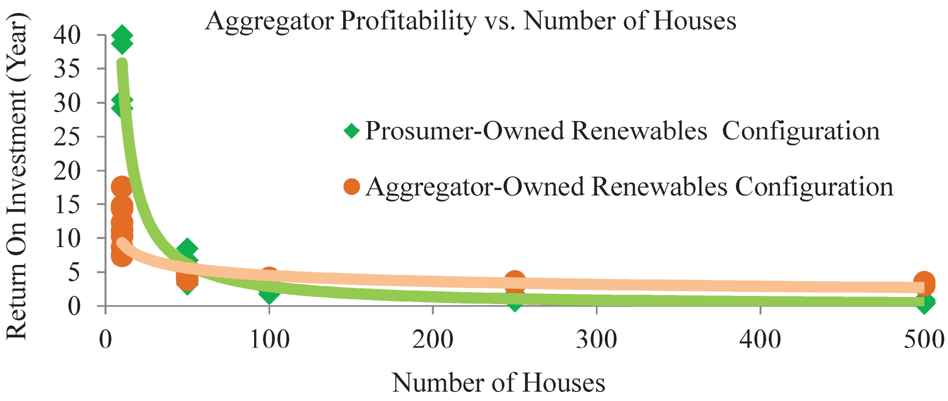


Figure 2. Analyzing the effect of the number of houses on the aggregator profitability.

It is evident that by increasing the number of houses, the ROI decreases dramatically. In the AOR configuration (see Chapter 4.C), ROI may be achieved in less than five years with more than 500 houses participating (see Figure 3).

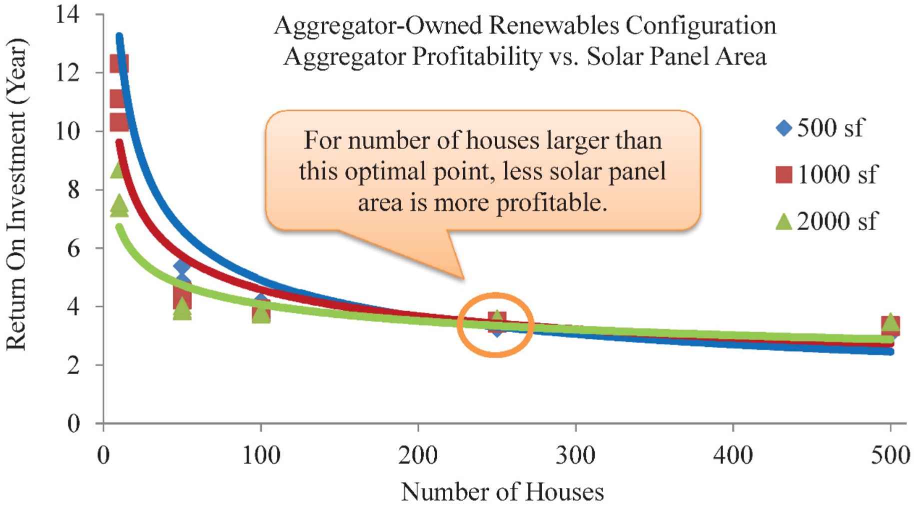


Figure 3. Analyzing the effect of the average solar panel area on the aggregator profitability for the AOR configuration.

Also, in the POR configuration (see Chapter 4.B), the ROI may be achieved in about a year with more than 500 houses participating (see Figure 4). Therefore, it shows that the capital costs of installing all solar panels by the aggregator may make it harder for the aggregator to return the money invested. Moreover, the slope of the graph shows that the profit margin of the aggregator decreases as more houses participate in the microgrid. As shown in [19], for an apartment-block type housing area it is very common to have 1000–2000 houses in the U.S. Therefore, the ROI will be significantly lower than what we have estimated for 500 houses.

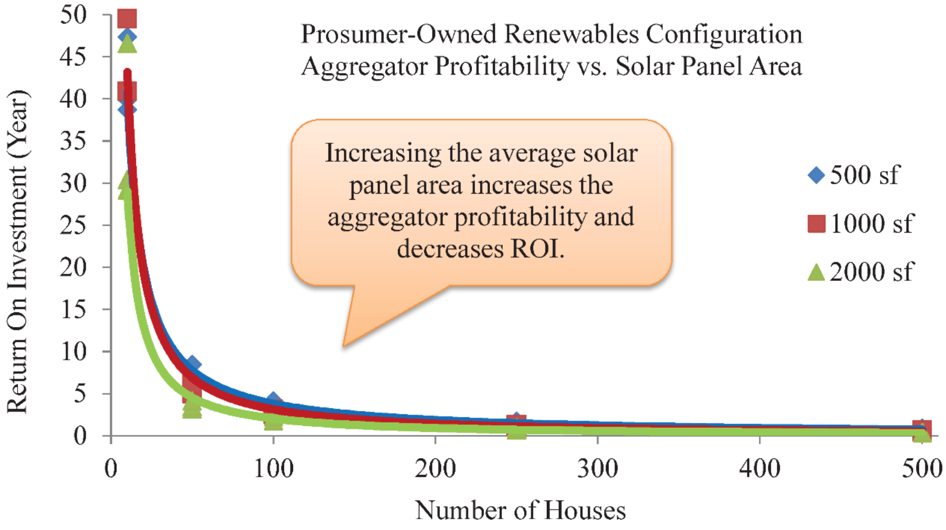


Figure 4. Analyzing the effect of the average solar panel area on the aggregator profitability for the POR configuration.

B. Solar PV Area

Changing the area of the solar panels installed may affect the maximum electricity that each house can produce. The electricity generated by solar panels is almost linear to the area of the panels [7]. Also, to create diversity in the solar generation within the microgrid, the area of the solar panels installed for each house follows a normal distribution (Gaussian) with the specified mean and the variance of 20%. On the other hand, the aggregator does not want to invest too much on solar panels (in the AOR configuration). Therefore, the daily net income and the capital costs for different scenarios are measured and used to estimate the ROI. Figure 4 shows that in the POR configuration, increasing the solar panel area decreases the ROI in any situation. On the other hand, considering the AOR configuration (see Figure 3), for the number of houses more than about 250, the situation is reversed and increasing the solar panel area increases the ROI.

C. Battery Capacity

The capacity of the batteries may affect the daily net income of the aggregator. Having larger batteries may be useful to store more renewable energy for later use in the microgrid or selling with higher price to the utility. If the battery capacity gets larger, less solar energy will be sold instantly to the utility and instead, it will be stored for later use (sell). Moreover, the capital costs of implementing larger batteries might get very high and negatively affect profitability. Different battery capacities for models with 250 houses participating are simulated and the ROI for each one is measured. Figures 5 and 6 show the trade-off between using larger batteries and less capital cost investment. Utilizing larger batteries may increase the daily net income. On the other hand, the capital costs of installing larger batteries are also higher. It is evident from the figures that the increase in the capital costs may dominate the increase in the daily net income. Therefore, the aggregator profitability may decrease with installing larger batteries. Our exploration shows that larger batteries may be more helpful in the scenario with DR program, because more electricity can be stored for later use and the aggregator profitability may increase.

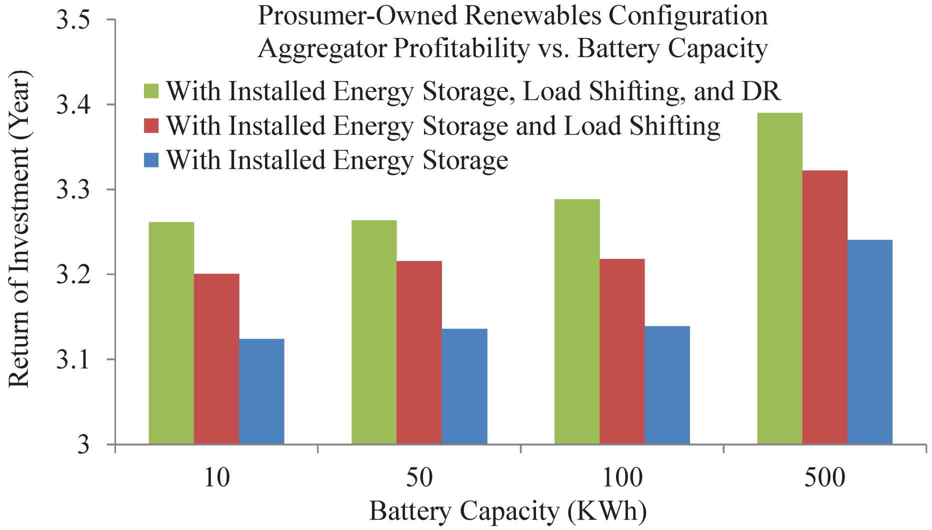


Figure 5. Analyzing the effect of battery capacity on the aggregator's profitability for the POR configuration.

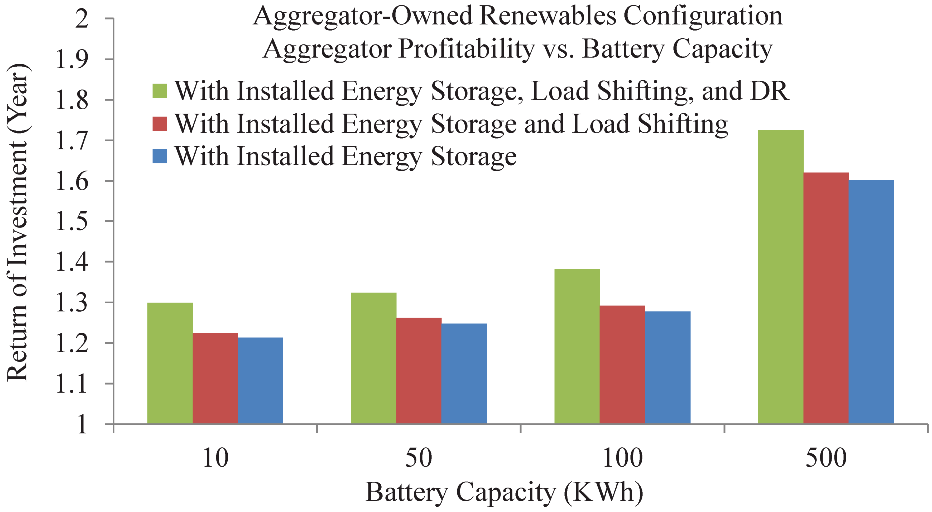


Figure 6. Analyzing the effect of battery capacity on the aggregator's profitability for the AOR configuration.

D. Pricing Effect

Once the parameters of the microgrid including the number of houses, average solar area, and the battery capacity are configured, the electricity price and the feed-in tariff for the prosumers should be precisely defined. In a microgrid with 250 houses, battery capacity of 50 KWh, and 500 sf solar panels on top of each house, multiple models with various price values are simulated and their ROI are evaluated; as shown in Figures 7 and 8, the changes in the electricity price and the feed-in tariff exponentially affect the ROI. Therefore, the aggregator may define a specific price for the prosumer according to its target ROI. Moreover, the aggregators may set the rates much better than the range specified in Chapter 4.E and maintain their profitability, while reducing the inconvenience cost to the prosumers and competing in the market.

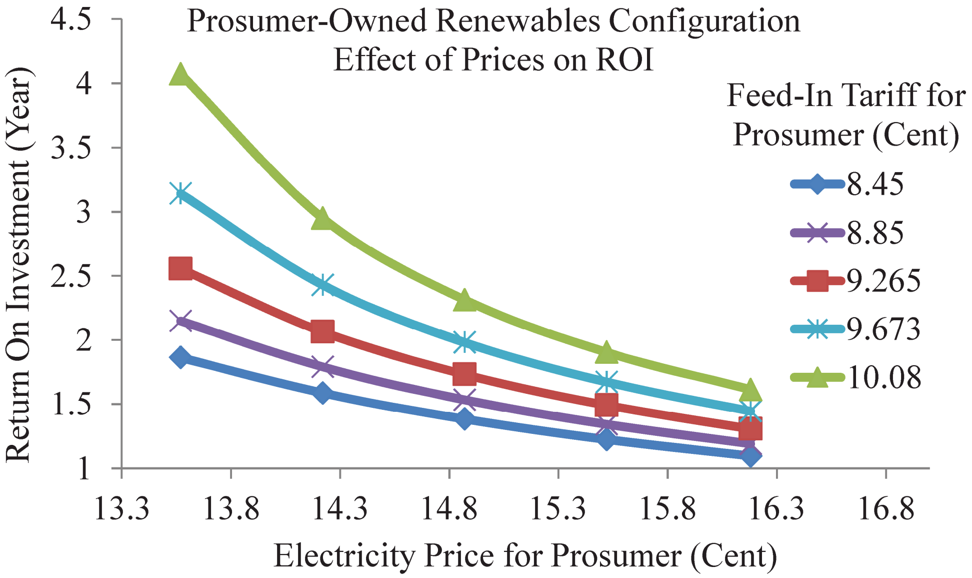


Figure 7. Relationship of electricity price with ROI.

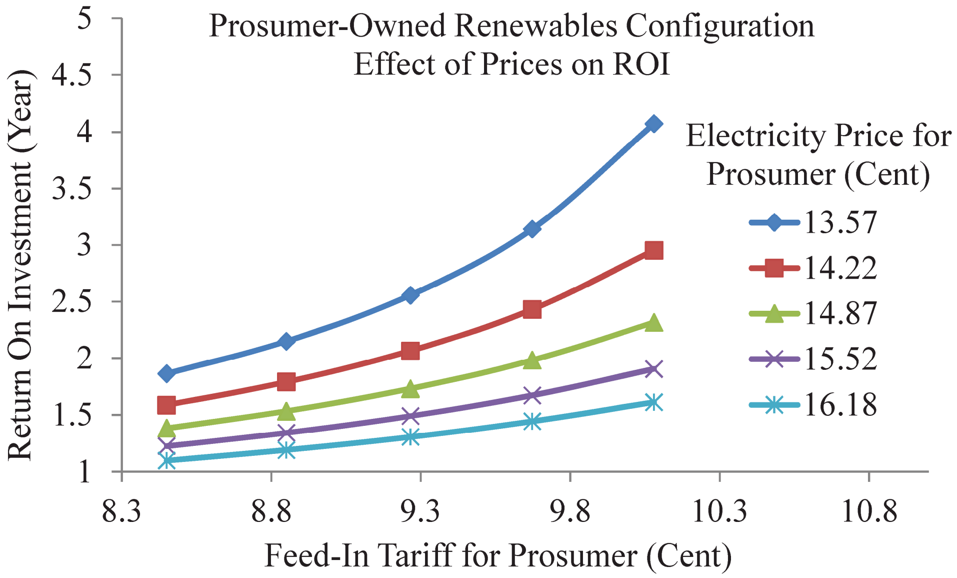


Figure 8. Relationship of feed-in tariff with ROI.

The maximum influence that each price has on the ROI of a microgrid with 250 houses, battery capacity of 50 KWh, and 500 sf solar panels on top of each house is shown in Figure 9. In the POR configuration, about 14% of the daily net income of the aggregator is due to using the renewable energy in the microgrid locally while it is about 61% for the AOR configuration. The effect of the feed-in tariff (P_a^p) depends on the solar energy production of the prosumers. For the POR configuration, about 16% of the daily net income is dependent on (P_a^p), while in the AOR configuration, there is no dependency, because the aggregator does not buy solar energy from the prosumers. Moreover, the influence of the electricity price for the prosumers (P_p^a) is about 22% in the POR configuration and 12% in the AOR configuration. Although, there is not an open market for trading SRECs in the state of California, the minimum value found in the open markets in different states are used to estimate its effect on the aggregator profitability. Furthermore, in our current implemented model, the limitation of having fixed rates may be improved in future research by soliciting the required information from the electricity market. Therefore, the aggregators may bid their generation level based on the rates and create another source of revenue.

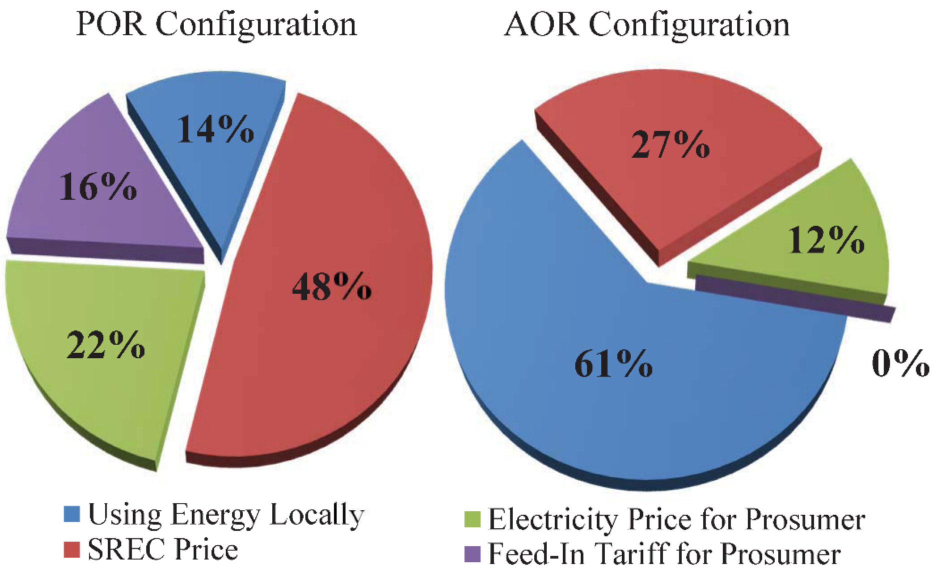


Figure 9. Maximum influence of various components on the daily net income in both configurations.

CHAPTER 6: SUMMARY AND CONCLUSION

A residential microgrid has been modeled using GridLAB-D and GridMat, and various scenarios and configurations have been explored to identify the optimal points in the design space of the residential microgrid for the profitability of the stakeholders. Our explorations show that by following the rules defined in Chapter 4.E, an aggregator may profit in about one year in the POR configuration and less than five years in the AOR configuration, if the number of houses participating in the residential microgrid is larger than 500 considering solar panel area of 500 sf per house. It concludes that the electricity consumption and the cost of renewable energy production in the residential microgrid may have reached a level that made the aggregator reasonably profitable. Moreover, it is shown in the other related works that the typical number of houses for an apartment-block type housing area in the U.S. is about 1000–2000. Therefore, the profitability of the aggregator may enhance much more than what we have estimated here for 500 houses. Moreover, we have shown that by increasing the average solar panel area for each house in the microgrid, the aggregator profitability may increase in the POR configuration, while in the AOR configuration, it may increase if the number of houses is less than about 250. Although an increase in the battery capacity may increase the daily net income of the aggregator, the aggregator profitability may decrease due to the large capital costs of the batteries. Also, our explorations show that the aggregator may adjust the ROI by changing the electricity price and feed-in tariff for the prosumers. On the other hand, the aggregator may sacrifice the ROI to compensate the inconvenience cost to the prosumers resulted from participating in the microgrid and the DR program.

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