Intelligent Home Energy Management Systems for Distributed Renewable Generators, Dispatchable Residential Loads and Distributed Energy Storage Devices

by

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DEDICATION

To My Parents

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ABSTRACT

The high demand for electricity and the consequent increase in electricity price as lead to recent study in reducing the total operating cost of a residential building. This research work focus on energy management in a residential green house. Two innovative approach is proposed to solve excessive operating cost of a residential green house, the system inputs which consist of temperature, activity level, and energy consumption is based on five household occupant in Atlanta, Georgia, also a Chevy volt of 16kWh is used in the case studies.

Moreover, for a single residential house, the overall goal is to reduce the total operating costs and the carbon emissions for a future residential house, while satisfying the end-users' comfort levels. This paper models a wide variety of home appliances and formulates the economic operation problem using mixed integer linear programming. Case studies are performed to validate and demonstrate the effectiveness of the proposed solution algorithm. Simulation results also show the positive impact of dispatchable loads, distributed renewable generators, and distributed energy storage devices on a future residential house.

For networked residential houses, we present an optimization of total operating cost of an interconnected nanogrid (ING) considering the effect of V2H and V2G, which helps to minimize the total operating cost. The major objective is to reduce carbon emission, total operating cost and the peak load demand while satisfying the customer preferences of each nanogrid. A mixed integer linear program (MILP) is formulated to solve the economic operation of the ING. Furthermore, case studies are performed to demonstrate the positive impact INGs have on minimizing total operating cost.

Key-words: distributed energy storage devices (DESD), renewable energy, demand response, vehicle-to- home (V2H), vehicle-to-grid (V2G).

CHAPTER 1: INTRODUCTION

Commercial and residential buildings consumed almost 40% of the primary energy and approximately 70% of the electricity in the United States in 2012, and the trend continues to escalate. Intelligent home energy management is a viable solution to reduce energy costs, maintain customer comfort levels, accommodate the integration of distributed renewable energy resources, and facilitate demand-side management (DSM) and demand response (DR) programs [1]-[3].

In [4], the authors propose a scheduling method for household appliances based on dynamic price signals. In [5] the authors present a multi objective mixed integer nonlinear programming model for optimal energy use in a smart home, by considering balance between the energy saving and comfortable lifestyle, also In [6] the authors present a novel home energy management systems for smart homes with different load profiles. The authors in [7] propose a comprehensive and general optimization based home energy management controller, incorporating several classes of domestic appliances, in [8] the authors propose several types of household appliance models, but did not explore the bi-directional power flow in which the consumer can sell electricity back to the power grids. The authors in [9] propose a bi-directional PHEV charging/discharging model, but did not analyze the effect of household appliances on the consumption of electricity.

The above-mentioned literature survey claims an urgent need for an intelligent home energy management system integrated with dispatchable loads (e.g., clothes washers and dryers), distributed renewable generators (e.g., roof-top solar panels), and DESDs (e.g., PHEVs). Fig. 1 shows the envisioned architecture and major components of a residential house.

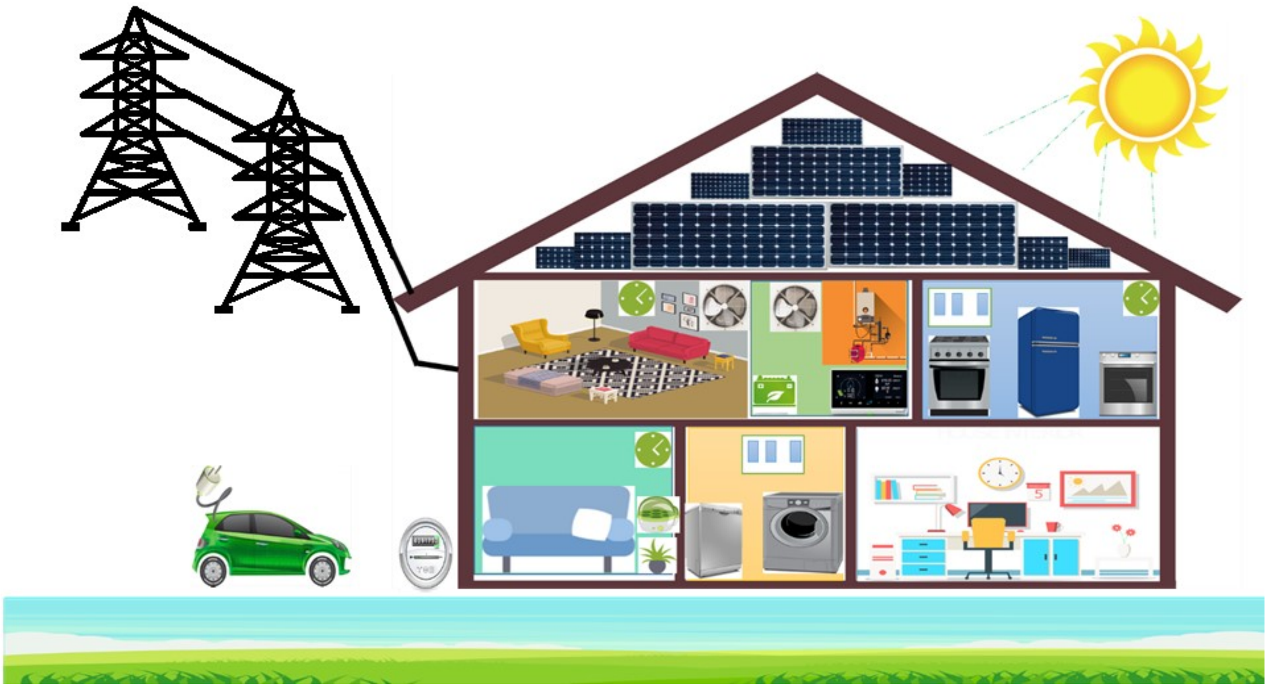

Figure 1: Envisioned architecture of a future residential house

The major contributions of this paper can be summarized as follows:

1. Modeling of a wide variety of household appliances and their operating constraints;
2. Formulation of an objective function to minimize the operation cost considering bi-directional power flow and customer preferences;
3. Analysis of the impact of dispatchable loads, distributed renewable generators, and distributed energy storage devices on a future residential house.

1.1. Why do we need distributed system?

There are several reasons why distributed system is receiving more attention. Distributed system as the potential to eliminate the cost, complexity, interdependencies, and inefficiencies associated with transmission and distribution [10].

1.2. Distributed Renewable Generator

Distributed generation is the term used when electricity is generated from sources, often renewable energy sources, near the point of use instead of centralized generation sources from power plants. Distributed renewable generator basically generate clean renewable electricity where that energy will be used. Examples of distributed renewable energy system are geothermal systems, micro-hydroelectric systems, solar panels and wind turbines.

1.3. Dispatchable Residential load

There are several residential households loads that contribute to the high rate of energy consumed in a residential house, Load can be divided into two namely;

I. Controllable e.g. washing machine, dryer

II. Uncontrollable e.g. Air conditioner, fridge, HVAC

Controllable loads are loads that their operation schedule can be shifted or manipulated without affecting the operation itself, while uncontrollable loads are loads that their mode of operation and power consumption does not depend only on the customer preferences but also on external factors, for example, an HVAC power consumption is dependent not only on the customer usage but also on external factors such as outside temperature and the activity level in the house [11].Careful analysis of the operation constraints of these loads helps to reduce the rate of energy consumed by these devices.

1.4. Distributed Energy Storage

Due to uncertainties of several renewable energy sources, the need for distributed energy storage has been the solution to this issue. Furthermore, the use of the capacity of these DER as lead to several researches to increase the capacity of energy these DER can stored.

1.5. Energy Market Pricing

In recent times, there are have been an emergence of different types of electricity pricing for the consumers which includes;

- Dynamic pricing: is a pricing that allows customers to pay fluctuating market rate for their electricity.
- Time of use (TOU): is a pricing that is determined on how much the customers uses the energy and when it been used.
- Real time pricing: a pricing in which the consumers knows actual cost of electricity at any given time.
- Critical peak pricing: a pricing that compensates customers to shift their loads during peak period in return of a financial incentives.

These several types of electricity pricing as helped to reduce the energy consumption by residential houses.

1.6. Demand Response and Demand Side Management

Demand response provides an opportunity for consumers to play a significant role in the operation of the electric grid by reducing or shifting their electricity usage during peak periods in response to time-based rates or other forms of financial incentives. Demand response programs are being used by some electric system planners and operators as resource options for balancing supply and demand. Such programs can lower the cost of electricity in wholesale markets, and in turn, lead to lower retail rates.

Demand-side management (DSM) programs consist of the planning, implementing, and monitoring activities of electric utilities which are designed to encourage consumers to modify their level and pattern of electricity usage. Chapter 1 gives introduction to energy management, while Chapter 2 describes the energy management in single residential green house and chapter 3 discuss about energy management in networked residential green house and Chapter 4 gives a summary of the paper and then generate a conclusion based on the analysis and results from the case study.

CHAPTER 2: ENERGY MANAGEMENT IN SINGLE RESIDENTIAL GREEN HOUSE

2.1. System Input

The simulation uses data from Atlanta, Georgia, over a period of five years, which contain five household occupants, 2015 summer data is used in order to demonstrate the amount of energy that can be captured by the solar panel during this season of high sunlight.

2.1.1. Temperature

The outside temperature data of an average summer over the period of five years from 2010-2015 in Atlanta, Georgia in the United States is obtained from the national weather website [12]. Figure 2 shows the distribution of the outside temperature, which ranges from 23-29 degrees Celsius.

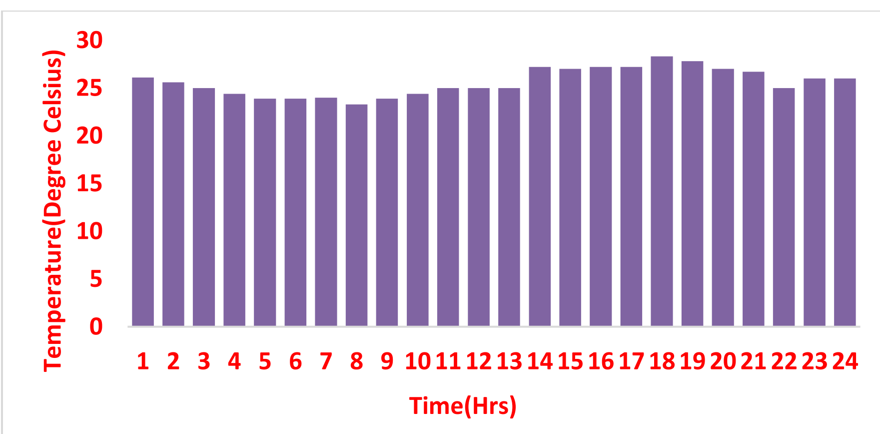

Figure 2: Outside temperature in Atlanta, Georgia

2.1.2. Activity Level

The activity level of the RGH is determined by calculating the hourly energy consumption of a typical resident in Atlanta, Georgia in terms of a percentage. Figure 3 shows the activity level of a residential house in Georgia, in which there is an increase of activity level at 2am and 11am, and a clear reduction during the night, as the occupant has less power demand [13].

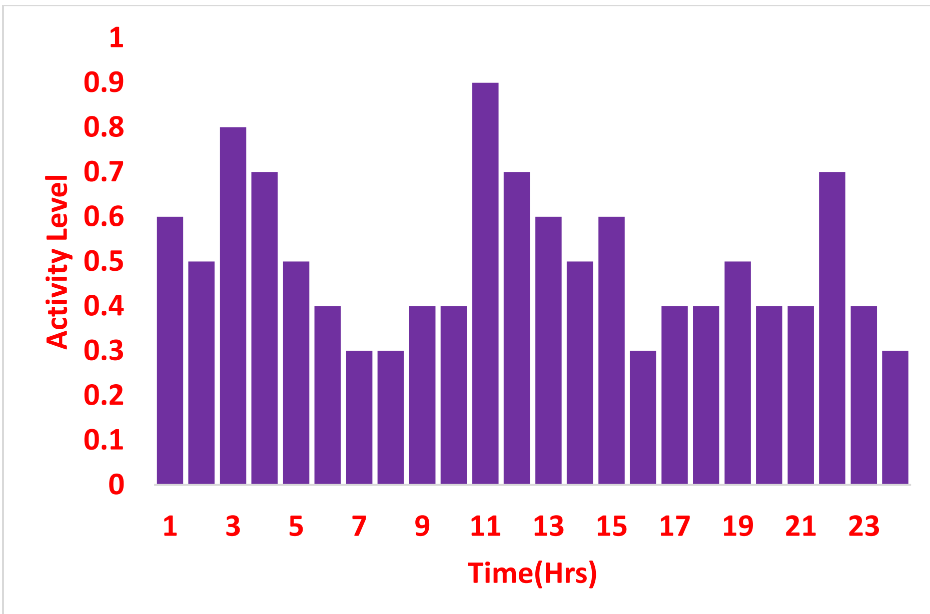

Figure 3: Activity level of a residential house in Georgia

2.1.3. Dynamic Electricity Price

In order to test the variability of the effect of PHEVs, DESDs and PVs on energy cost, a dynamic price is implemented. Figure 4 shows the dynamic electric price [14].

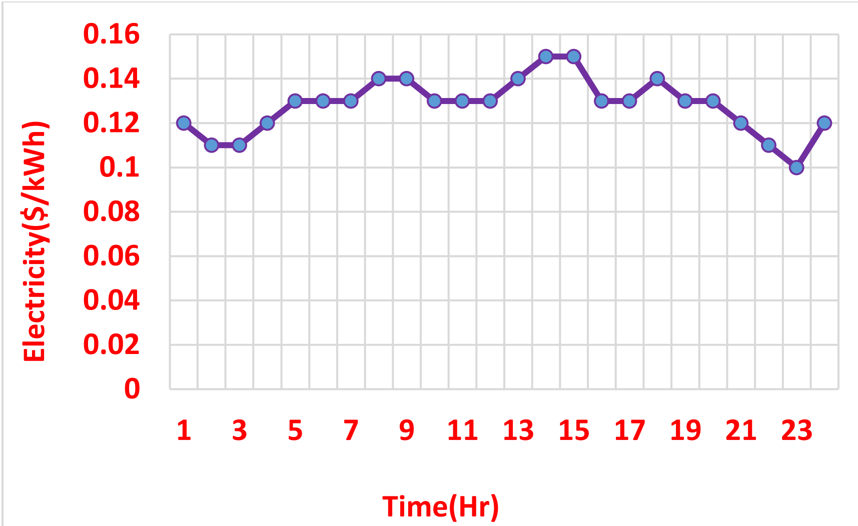

Figure 4: Dynamic electricity price

2.1.4. Solar Power Generation

A 1-kW solar panel data from Atlanta which span over an average of five years from 2010-2015 is used in this analysis.[15].The highest output was at 1pm, at 0.82 kW. Figure 5 shows the hourly solar power generation in Atlanta.

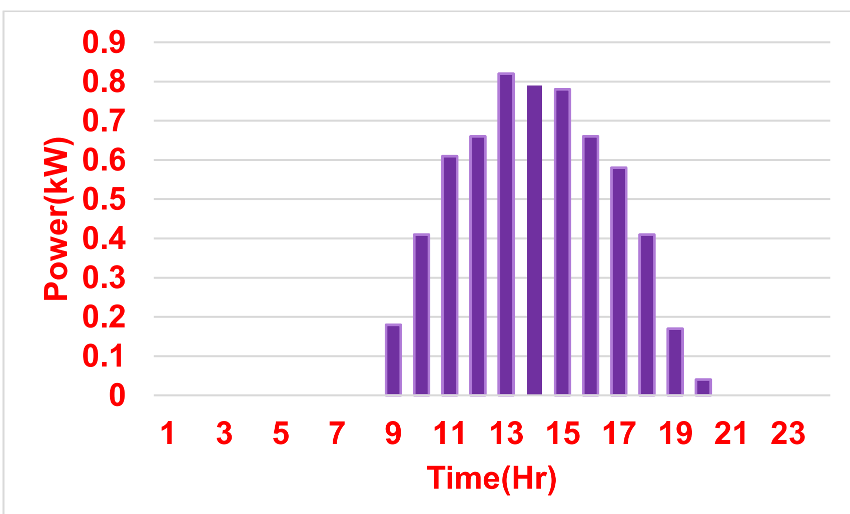

Figure 5: Solar power generation in Atlanta (1-kW generator)

2.2. Problem Formulation

To analyze the energy consumption in the residential green house, the energy consumed by the residential green house is analyzed for a full day, where t_1 starts from 1:00AM in the morning and ends at t_{24} , which correspond to 12PM in the evening.

2.3. Objective Function

The primary goal of this research is to minimize the total operating cost of a future residential house. The objective function is as follows:

$$Cost_{house} = \sum_{t=1}^{24}\left[(P_t^b Pr_t^b - P_t^s Pr_t^s)\right] + \sum_{t=1}^{24}\left[\left(P_t^{CH,DESD}\eta_1 + P_t^{DIS,DESD}\eta_1\right)\right] + \sum_{t=18}^{24}\left[(P_t^{CH,PHEV}\eta_2 + P_t^{DIS,PHEV}\eta_2)\right] \quad (1a)$$

$$Cost_{DESD\&PHEV} = \sum_{t=1}^{24}[((P_t^{CH,DESD}\eta_1 + P_t^{DIS,DESD}\eta_1) + \sum_{18}^{24}\left[(P_t^{CH,PHEV}\eta_2 + P_t^{DIS,PHEV}\eta_2)\right] \quad (1b)$$

(Equation (1a) shows the total operating cost of the residential green house, P_t^b (kW) denotes the power bought from the power grid at time interval t, while Pr_t^b denotes the dynamic electricity price ($/kWh) offered by the utility grid, P_t^s(kW) is the amount of power sold from the PV, DESD, and the PHEV at time interval t, and Pr_t^s (kWh) is a flat price agreed to by the consumer at which they will sell their power back to the grid. The bi-directional flow of PHEVs and DESDs makes it possible for a consumer to meet their household demand and still have excess energy at a time interval to sell back to the grid. Equation (1b) shows the degradation cost of the DESD and the PHEV ($Cost_{DESD\&PHEV}$), which is part of the total cost of operating the house, $P_t^{CH,DESD}$ and $P_t^{DIS,DESD}$(kW) indicate the charging power and discharging power of the DESD respectively, while $P_t^{CH,PHEV}$ *and* $P_t^{DIS,PHEV}$(kW) indicate the charging and the discharging power of the PHEV respectively, η_1 (\$/kwh) is the degradation cost associated with the charging and discharging process of the DESD, while η_2 (\$/kwh) is the degradation cost associated with the charging and discharging process of the PHEV.

2.4. System Constraints

2.4.1. Air conditioner and heater operating constraints (HVAC)

The AC and heater work on the principle in which when the inside temperature is higher than a specific temperature [11], the AC tends to switch ON and if it is lower than a specified temperature the heater switches ON. If the inside temperature of the house, θ_{in} is at an optimal level based on the customer preference, neither of the devices will run. θ_{in} has an effect on the power consumed by the AC and heater, which can be determined by:

$$\theta_{in} = \theta_{in}\left(t-1\right) + \left[v_{ac}\ A\left(t\right) - \mathrm{u}_{ac} s_{ac(t)} + I_{ac}\left(\theta_{out}\left(t\right) - \theta_{in}\left(t-1\right)\right)\right], \forall \mathrm{t} \in \mathrm{T} \tag{2}$$

$$\theta_{in} = \theta_{in}\left(t-1\right) + \left[\mathrm{v}_{ht} A\left(t\right) - \mathrm{u}_{ht} s_{ht}(t) + I_{ht}\left(\theta_{out}\left(t\right) - \theta_{in}\left(t-1\right)\right)\right], \ \forall \mathrm{t} \in \mathrm{T} \tag{3}$$

$$S_{ac}\left(t\right) + S_{ht}\left(t\right) \leq 1, \forall t \in T \tag{4}$$

In (2) and (3) θ_{in} at any time interval depends on the previous temperature and the cooling and warming effect of the OFF state of the AC v_{ac} and the heater v_{ht}. A(t) is the activity level of the house for both equations which is essentially the energy consumption of a typical household. u_{ac} and u_{ht} is the cooling and warming effect of the ON state of the AC and heater respectively, I_{ac},andI_{ht}, is the effect of outside and inside temperature difference on the AC and heater respectively which has a huge impact on the inside temperature per time interval. (4) indicates that the AC and the heater are not to operate at the same time, where S_{ac} and S_{ht} represent the ON/OFF status of the AC and the heater respectively, which can only take binary values.

2.4.2. Fridge operating constraint

$$\theta_{fr} = \theta_{fr}(t-1) + \left[v_{fr} \ A_{fr}(t) - u_{fr} s_{fr}(t) + \alpha_{fr} \right], \forall \mathrm{t} \in \ \mathrm{T} \quad (5)$$

In equation (5), θ_{fr} indicates the inside temperature of the fridge at a time interval which is dependent on the previous temperature of the fridge $\theta_{fr}(t-1)$, the effect of the activity level on the fridge temperature $A_{fr}(t)$, in which as the activity of the house increases there will be more demand on cooling of the fridge, while v_{fr}, indicate the cooling and warming effect of the OFF state of the fridge , u_{fr} indicate the cooling and warming effect of the OFF state of the fridge and $s_{fr(t)}$ is the binary variable that controls the switching of the fridge, moreover α_{fr}, indicates the warming effect of the OFF state of the fridge. If there is more activity level on the fridge, the inside temperature of the fridge might increase beyond the set range of temperature by the residential customer which will leads to more power demand to cool it down back to the set temperature range.

2.4.3. Washer and dryer operation constraints

As discussed earlier, the washer and dryer are categorized as a controllable load, where *i* represent either the washer or the dryer. The operating constraints of the washer and dryer are shown below:

$$u_i(t) - v_i(t) = s_i(t) - s_i(t-1), \forall \mathrm{t} \in \mathrm{T}, \ \forall \mathrm{i} \in \mathrm{I} \quad (6)$$

$$u_i(t) + v_i(t) \le 1, \forall \mathrm{t} \in \mathrm{T}, \ \forall \mathrm{i} \in \mathrm{I} \tag{7}$$

$$\sum_{t \in T_i} s_i(k) = O_i^{rt}, \forall \mathrm{t} \in \mathrm{T} \tag{8}$$

$$\sum_{k=t}^{t+O_i^{mst}} s_i(k) \le O_i^{mst} + M(1 - u_i(t)), \forall \mathrm{t} \in \ \mathrm{T} \tag{9}$$

$$\sum_{k=t-U_i+1}^{t} u_i(t) \le s_i(t), \forall \mathrm{t} \in \mathrm{T} \tag{10}$$

$$\sum_{k=t-D_i+1}^{t} u_i(t) \le 1 - s_i(t), \forall \mathrm{t} \in \mathrm{T} \tag{11}$$

$$s_{dryer}(t) \le \sum_{k=1}^{\Omega} s_{washer}(t-k), \forall \mathrm{t} \in \mathrm{T} \tag{12}$$

$$s_{dryer}(t) + s_{washer}(t) \le 1, \forall \mathrm{t} \in \mathrm{T} \tag{13}$$

Equations (6) and (7) model the shut down and start up constraints for the washer and dryer in order not to damage the device, $s_i(t)$ represent the binary variable of the washer or dryer, which will be 1 if the device is switched ON or 0 if the device is switched OFF, also $u_i(t)$ and $v_i(t)$ represent the binary variable denoting the startup of the device *i* at time t and the shutdown of the device *i* at time t respectively. Equation (8) constrains the device to operate at a particular operation time, O_i^{rt}. Equation (9) constrains the device to operate at a maximum successive time, O_i^{mst}, where M represents a large positive number. Equations (10) and (11) constrain the device to operate at a minimum up time, U_i, and minimum down time, D_i, respectively. Moreover, (12) sets the dryer to operate after the washer has finished its task, and Ω represents the time gap as set by the customer preference. Equation (13) constrains the dryer and washer not to operate at the same time, in which only one operation is allowed per device.

2.4.4. Power balance equations

$$P_t^b + P_t^{used,PV} + P_t^{used,PHEV} + P_t^{used,DESD} = P_t^{RGH} + P_t^{CH,PHEV} + P_t^{CH,DESD} + P_t^s,\ \forall t \in T \tag{14}$$

Equation (14) shows the power balance equation, where P_t^b and P_t^s represent the total power bought and sold from or to the grid at a time interval. $P_t^{used,Pv}, P_t^{used,PHEV}$ *and* $P_t^{used,DESD}$ represent the power supplied to meet the residential load demand at a time interval by the PV, PHEV and DESD respectively. P_t^{RGH} represents the total power consumed by the fridge, AC, washer and dryer at a time interval. It should be noted that $P_t^{CH,PHEV}$ and $P_t^{CH,DESD}$ are the charging power demands of the PHEV and DESD, respectively, in which these devices operate as an electrical generator when discharging and energy consuming load when charging. Figure 6 shows the residential power balance topology.

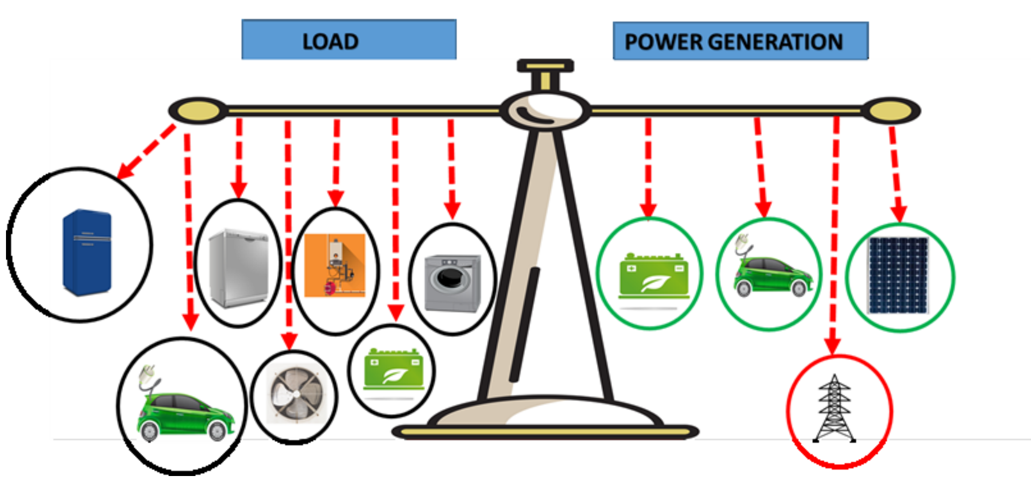

Figure 6: Power and load balance

2.4.5. DESD operation constraints

The bi-directional flow constraints of the DESD are shown below. The DESD charges when the dynamic electricity price is low and discharges to meet the household load when the electricity price is high.

$$P_t^{used,DESD} + P_t^{s,DESD} = P_t^{DIS,DESD}\eta_{DD}, \forall t \quad (15a)$$

$$P_t^{CH,DESD} \le CR_t^{DESD} s_t^{DESD}, \forall \mathrm{t} \quad (15b)$$

$$P_t^{DIS,DESD} \le DR_t^{DESD}\left(1 - s_t^{DESD}\right), \forall \mathrm{t} \quad (15c)$$

$$SOE_t^{DESD} = SOE_{t-1}^{DESD} + P_t^{CH,DESD}\eta_{CD} - P_t^{DIS,DESD} \ \eta_{DD}, \forall \mathrm{t} \quad (15d)$$

$$SOE_1^{DESD} = SOE^{DESD,INI}, \forall t \quad (15e)$$

$$SOE_t^{DESD} \le SOE^{DESD,MAX}, \forall t \quad (15f)$$

$$SOE_t^{DESD} \ge SOE_t^{DESD,MIN}, \forall t \quad (15g)$$

Equation (15a) indicates the DESD can be used to meet the household load demand where $P_t^{s,DESD}$ represents the power sold by the DESD at a time interval t, $P_t^{DIS,DESD}$ represents the discharging power, and η_{DD} represents the discharging efficiency of the DESD. (15b) helps to limit the charging power of the DESD, where $P_t^{CH,DESD}$ is the charging power, CR_t^{desd} is the charging rate, and s_t^{DESD} is the ON/OFF status of the DESD. This constraint protects the life cycle of the DESD. (15c) controls the discharging rate of the DESD, where $P_t^{DIS,DESD}$ represents the discharging power of the DESD and DR_t^{DESD} represents the discharging rate of the DESD at time interval t. (15d) represents the state of energy of the DESD, which is dependent on the previous SOE, the charging efficiency, η_{CD}, and the charging power deducted from the discharged power at a time interval t. (15e) makes the SOE at the first interval equal to the initial state of energy, $SOE^{DESD,INI}$. Equations (15f) and (15g) constrain the SOE of the DESD to not exceed a maximum $SOE^{DESD,MAX}$ and not go below a minimum $SOE^{DESD,MIN}$ respectively.

2.4.6. PHEV operation constraints

$$P_t^{used,PHEV} + P_t^{s,PHEV} = P_t^{DIS,PHEV}\eta_{DP}, \forall t \in \left[T^a, T^d\right] \tag{16a}$$

$$P_t^{CH,PHEV} \le CR_t^{PHEV} s_t^{PHEV} \forall t \in \left[T^a, T^d\right] \tag{16b}$$

$$P_t^{DIS,PHEV} \le DR_t^{PHEV}\left(1 - s_t^{PHEV}\right), \forall t \in \left[T^a, T^d\right] \tag{16c}$$

$$SOE_t^{PHEV} = SOE_{t-1}^{PHEV} + P_t^{CH,PHEV}\eta_{CP} - P_t^{DIS,PHEV}\eta_{DP}, \forall t \in \left[T^a, T^d\right] \tag{16d}$$

$$SOE_{T^a}^{PHEV} = SOE^{PHEV,INI} \tag{16e}$$

$$SOE_t^{PHEV} \le SOE_t^{PHEV,MAX}, \forall t \in \left[T^a, T^d\right] \tag{16f}$$

$$SOE_t^{PHEV} \ge SOE_t^{PHEV,MIN}, \forall t \in \left[T^a, T^d\right] \tag{16g}$$

$$SOE_{T^{f,c}}^{PHEV} = SOE_t^{PHEV,MAX} \tag{16h}$$

The mode of operation of the PHEV is constrained to operate at particular T^a and T^d, which correspond to the arrival and departure time of the PHEV, respectively. Equation (16a) indicates the PHEV can be used to meet the residential green house (RGH) load demand, where $P_t^{s,PHEV}$ represents the power sold by the PHEV at a time interval t, $P_t^{DIS,PHEV}$ represents the discharging power, and η_{DP}represents the discharging efficiency of the PHEV. (16b) helps to limit the charging power of the PHEV, where $P_t^{CH,PHEV}$ is the charging power, CR_t^{PHEV} is the charging rate, and s_t^{PHEV} is the ON/OFF status of the PHEV. This constraint protects the life cycle of the PHEV. (16c) controls the discharging rate of the PHEV, where $P_t^{DIS,PHEV}$ represents the discharging power of the PHEV and DR_t^{PHEV} represents the discharging rate of the PHEV at time interval t. (16d) represents the state of energy of the PHEV, which is dependent on the previous SOE, the charging efficiency, η_{CP}, and the charging power deducted from the discharged power at a time interval t. (16e) makes the SOE at arrival time T^a of the driver equal to the initial $SOE^{PHEV,INI}$. (16f) and (16g) constrain the SOE of the EV not to exceed a maximum $SOE^{PHEV,MAX}$and not fall below a minimum$SOE^{PHEV,MIN}$, respectively, within T^a and T^d of the driver while connected to the bi-directional smart meter. (16h) indicates the period, $T^{f,c}$, in which PHEV must be fully charged. It should also be noted that the PHEV constraints won't be initiated until the arrival time and departure time of the driver.

2.4.7. PV operation constraints

$$P_t^{used,PV} + P_t^{s,PV} + P_t^{g,PV}, \forall t \tag{17}$$

Equation (17) shows that the PV can be used in meeting the RGH load demand, where $P_t^{g,PV}$ represents the total generation power of the solar panel.

2.4.8. Total power injected into the grid

$$P_t^s = P_t^{s,PV} + P_t^{s,DESD} + P_t^{s,PHEV}, \forall t \tag{18}$$

Equation (18) shows the total power sold, P_t^s, by the PV, DESD and PHEV respectively.

2.4.9. Power transaction regulation

In order to control the amount of power that can be sold and received from the grid, a set of constraints was modeled as shown below:

$$P_t^b \leq m1 s_t^{grid}, \forall t \tag{19}$$

$$P_t^s \leq m2(1 - s_t^{grid}), \forall t \tag{20}$$

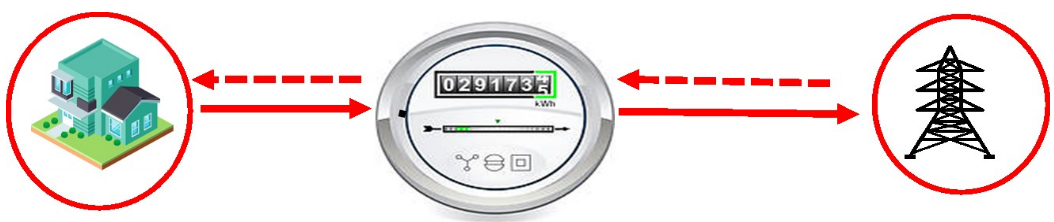

Figure 7: Power transaction regulation

Where $m1$ and $m2$ show the maximum amount of power that can be received from the grid and the maximum amount of power that can be sold to the grid, respectively. These constraints help to keep the bi-directional flow of power within the customer preference and at an agreed rate between the grid and the consumer. s_t^{grid} denotes the ON/OFF status of the grid, which will be 1 if the RGH is taking power from the grid, or 0 if the RGH is not taking power from the grid or is in an idle state. Figure 7 shows the bidirectional power flow between the house and the grid.

2.5. Case Study

Table 1 shows the power rating of the household appliances.

Table 1: Parameter values of housing appliances [16]

Device	Parameter
AC	Rated power is 1.9kw
Fridge	Rated power is 0.42kw
Washer	Rated power is 0.5kw
Dryer	Rated power is 3.5kw

2.5.1. Scenario One

In order to demonstrate the effect of PHEV and DESD bidirectional flow, which helps to reduce the total operating cost, a scenario in which no PV or DESD is initially used consisting only of a household loads, which consists of the fridge, washer and dryer, heater and AC was considered. A 1kw solar panel and a 1kw energy storage device (DESD) is used. The driver is assumed to be back at 6pm and is willing to charge as soon as the dynamic electricity price is low. A Chevy Volt of 16kwh [17] is used, which has both a charging and discharging rate of 3.3kwh.

2.5.2. Scenario Two

In this scenario, PV, DESD and PHEV bi-directional flow are considered to show the reduction in total operating cost for the day. The PV, DESD and PHEV can sell power to the grid, and the DESD and PHEV can receive power from the grid to charge their batteries. The same household load was considered in the scenario as well. In this scenario, the driver of the car is assumed to arrive at 6pm and discharge first, charging later when the electricity price is low. The next section discusses the results of the simulation of the two scenarios.

2.6. Simulation Result

After running the simulation, the total operating cost of the RGH for the day was $4.98 for scenario I and $ 4.09 for the scenario II, which shows a difference of $0.89. Table 2 shows the unit commitment for the washer, dryer, air conditioner and fridge, also Figure 8 shows the power demand of the washer, dryer, AC and fridge, figure 9 shows the graphical chart showing Pch_esd, Pused_esd and Psold_esd, figure 10 shows charging power of the PHEV, power transferred by the PHEV to the house and power sold by the PHEV to the grid for the second scenario. Figure 11 shows the state of energy of the PHEV for the two scenarios. It can be seen in Figure 11 that in scenario I, the PHEV kept charging despite the high dynamic electricity price, while in scenario II, the PHEV discharged some of its energy to meet the household load before later charging when the dynamic price was low. This factor contributed to the total operating cost of Scenario I. Furthermore, Figure 12 shows the total power bought by the RGH for the two scenarios. It can be seen from the figure that more power was bought from the grid in scenario I during the peak period than in Scenario II, in which the combination of the bidirectional flow of the DESD and PHEV with the PV helped to reduce the amount of power bought from the grid. Table 3 shows the total cost of operating the RGH for a 24-hr interval. It can be seen that it costs less to operate the RGH when taking advantage of the effect of bidirectional ESD and PHEV.

Table 2: Unit of residential loads

Time(Hrs)	S_{wd}	S_{wd}	S_{fr}
1	0	0	0
2	0	1	1
3	0	1	0
4	0	0	0
5	0	1	0
6	0	0	1
7	0	0	0
8	0	1	0
9	0	0	1
10	0	0	0
11	0	1	0
12	0	0	1
13	0	1	0
14	0	0	1
15	0	1	0
16	0	0	1
17	0	1	0
18	0	1	0
19	0	1	1
20	0	0	0
21	0	1	1
22	1	1	0
23	1	0	0
24	0	1	1

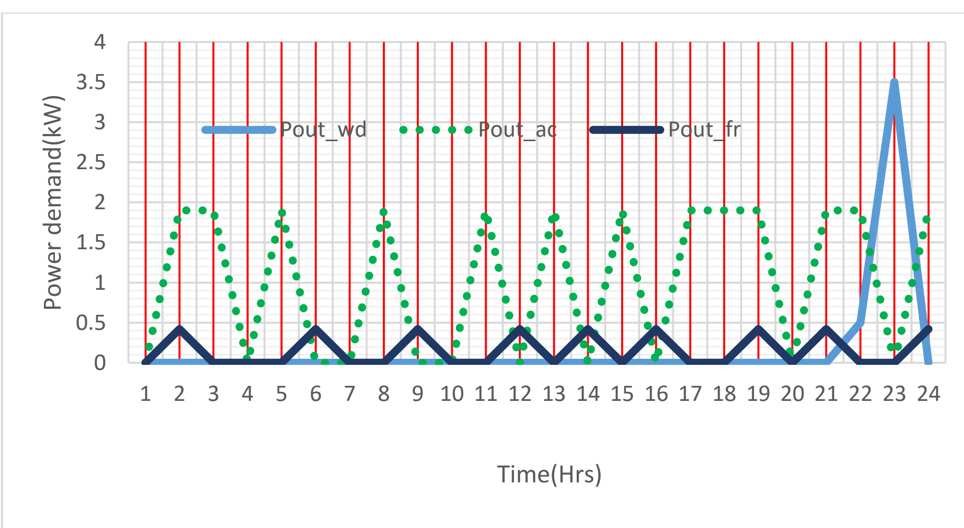

Figure 8: Power demand of selected residential loads for the two scenarios

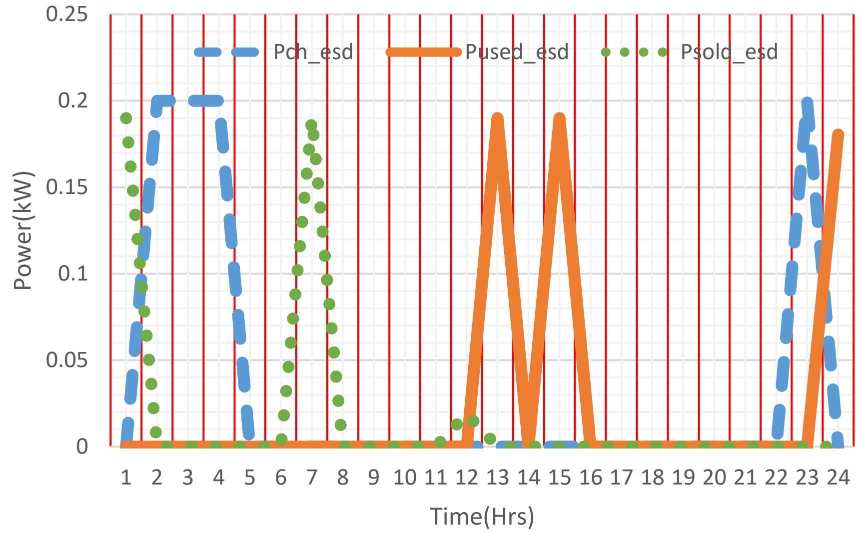

Figure 9: Graphical chart showing Pch_esd, Pused_esd and Psold_esd

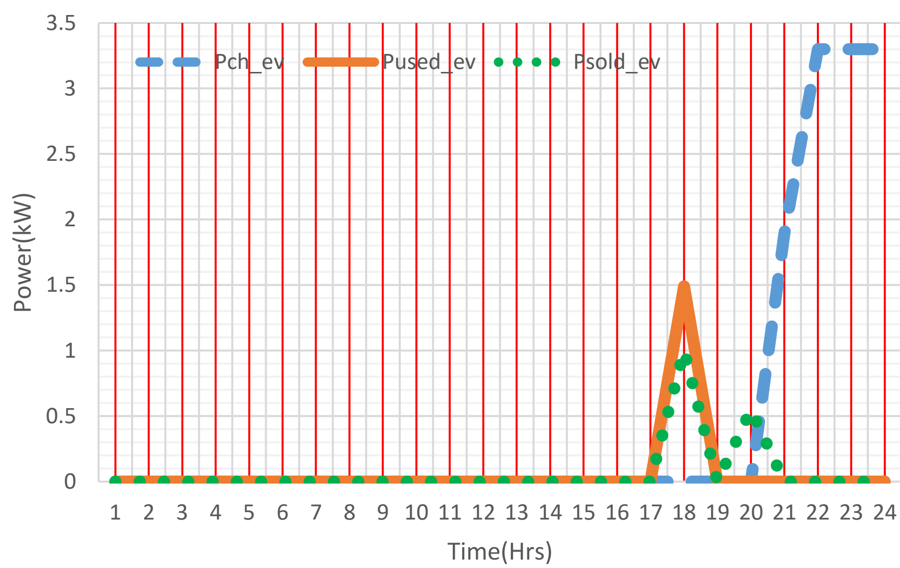

Figure 10: Graphical chart showing the Pch_ev, Pused_ev and Psold_ev

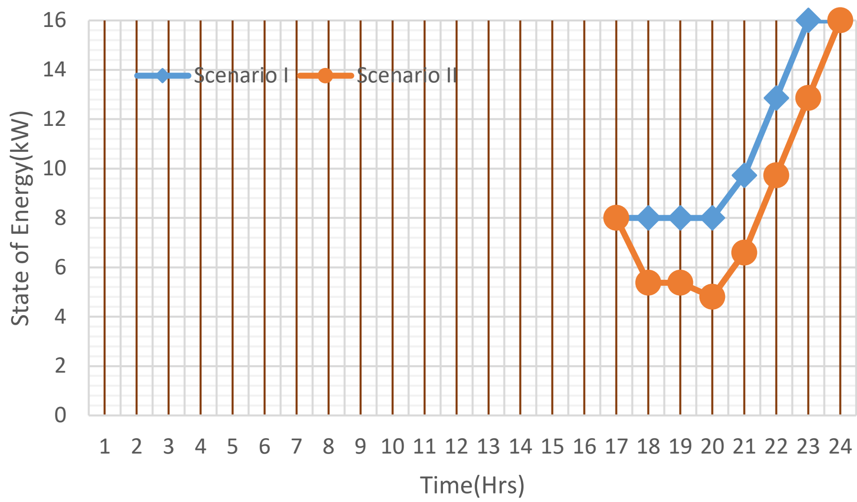

Figure 11: State of energy of the PHEV in the two scenarios.

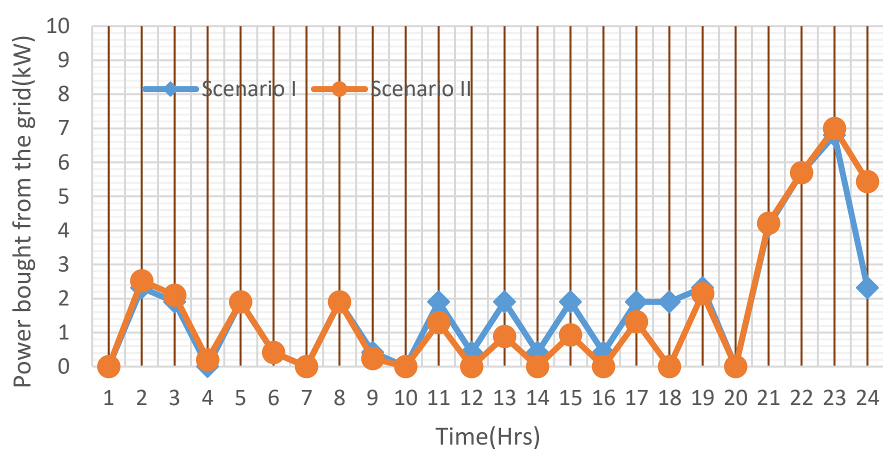

Figure 12: Power bought from the grid in the two scenarios.

Table 3: Total cost of daily operation

No PV, DESD	PV, DESD and PHEV bidirectional flow
$4.98	$ 4.09

CHAPTER 3: ENERGY MANAGEMENT IN A NETWORKED RESIDENTIAL GREEN HOUSE

3.1. Introduction

Nanogrids are miniature of microgrids, whose main purpose is to serve a single building or other single load [18]. The high operating cost of managing a nanogird has led to increasing interest in how the total operating cost can be minimized. In [19], the author presents the direct current (DC) bus signaling as a means of generator scheduling and power sharing in a nanogrid under steady state conditions. In [20], the author compares the performance and power sharing in a dual nanogrid 48V: 380V, which is interconnected by an interlink converter using average droop and a constant ratio. In [21] the authors propose a bidirectional dc-dc converter and a network controller for power exchange in an interconnected nanogrid but fail to analyze the impact of basic dispatchable residential loads. In [22], the authors present an intelligent home energy management system considering residential loads but do not take an interconnected nanogrid into account. In [23]the author developed an energy management system(EMS) that provide uninterrupted power supply to the DC load which achieve self-sufficiency by minimizing grid power consumption using a two-stage bidirectional converter interface, In [24] the design and implementation of an appliance for operation in a DC-based nanogrid is analyzed.

3.2. Interconnected Nanogrid

Interconnected nanogrids are a set of nanogrids that are connected to each other. They have the ability to transfer power amongst themselves, as well as with the grid to meet each other

household's power demand and to reduce their overall operating cost. Figure 10 shows the envisioned interconnected nanogrid framework.

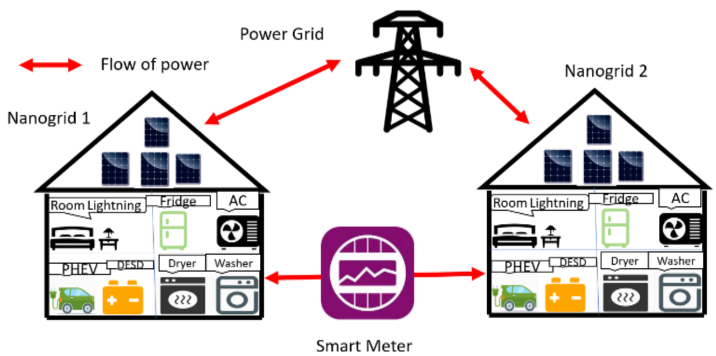

Figure 13: Envisioned architecture of a future interconnected nanogrid system

3.2.1. Why Interconnected Nanogrid?

Interconnected nanogrid is proposed because it gives more helps to further reduce carbon emission, reduce peak load demand while considering customer preferences.

3.3. Problem formulation

The objective function is to minimize the total operating cost of the interconnected nanogrid of a future residential house. The objective function is as follows:

$$\text{Cost}_{\text{ING}} = \sum_{t=1}^{24}\sum_{i}^{N}\Big[P^{b}_{grid,i}(t)Pr^{s}_{grid,i}(t)+C^{b}_{i}(t))-(P^{s}_{i}(t)Pr^{s}_{i}(t))+ (P^{ch}_{DESD,i}(t)D_{DESD,i}+P^{dis}_{DESD,i}(t)D_{DESD,i})\Big]+ \sum_{t=18}^{24}\Big[(P^{ch}_{PHEV,i}(t)D_{PHEV,i}+P^{dis}_{PHEV,i}(t)D_{PHEV,i})\Big] \quad (1)$$

i=1, 2…N

i: index of nanogrid

N: Number of interconnected nanogrids

For the scope of this work, N=2, which means two nanogrids are connected together.

Equation (1) shows the total operating cost for *i* nanogrids, in which some of the nanogrids have renewable energy sources (RES). Such nanogrids have the capability of using the energy from the RES such as a plug-in-electric vehicle (PHEV), distributed energy storage device (DESD) or photovoltaic (PV), to meet the load in its house. They can also sell this energy to either the utility or other nanogrids that need power to meet their household loads.Cost_{ING} represents the total operating cost for *i* nanogrids. $P^{b}_{grid,i}$ is the power bought from the grid by *i*th nanogrid, while $Pr^{s}_{grid,i}$($/kWh) is the dynamic electricity price, which is often a day ahead price. C^{b}_{i} ($/kW) represents the total cost of the power bought from other nanogrids during a time interval, P^{s}_{i} (kW) is the total power sold by nanogrids *i* to the grid or other nanogrids and, Pr^{s}_{i} ($/kWh) is the selling price of *i*th nanogrid to the grid or to other nanogrids. $P^{ch}_{DESD,i}$ and $P^{dis}_{DESD,i}$ represent the charging and discharging power respectively of the DESD, while $D_{DESD,i}$($/kWh) represents the degradation cost that is associated with the discharging and charging of the DESD. $P^{ch}_{PHEV,i}$ and $P^{dis}_{PHEV,i}$ represent the charging and discharging power, respectively of the PHEV and $D_{PHEV,i}$

represents the degradation cost that is associated with the discharging and charging of the PHEV. Figure 14 shows the energy transfer algorithm.

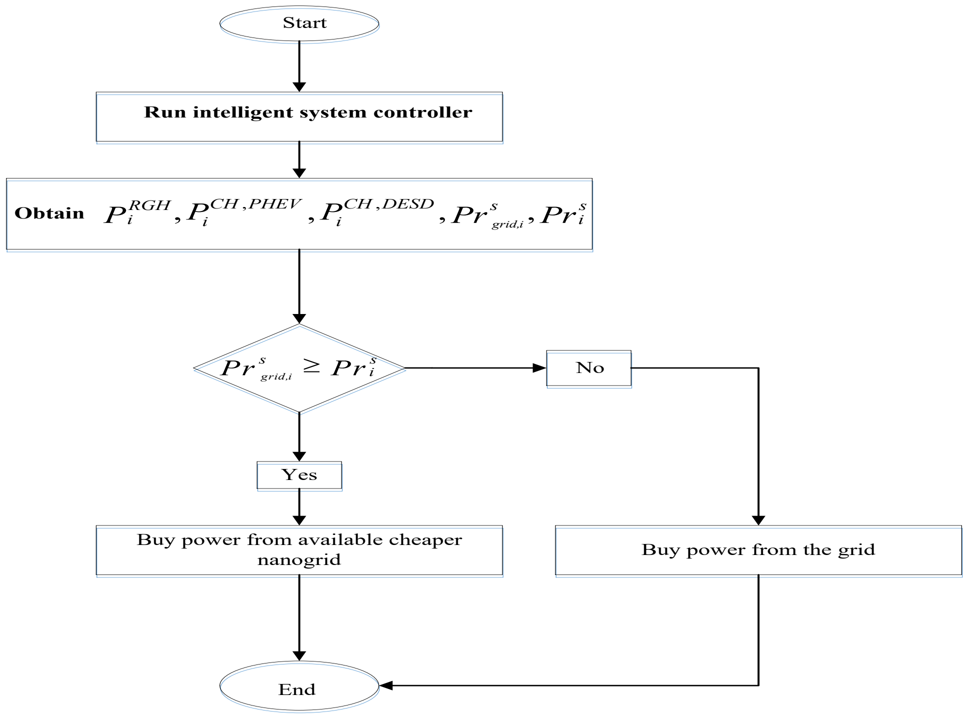

Figure 14: Energy transfer Algorithm

3.4. Case Study

Three basic scenarios were studied to illustrate the advantage of these proposed method, basic loads similar to the previous proposed method.

3.4.1. Scenario I (Interconnected Nanogrids)

In this scenario the two nanogrids are interconnected such that nanogrid #1 does not have any RES that it can use to meet its household demand or have the ability to sell its excess energy to the grid or nanogrid #2, on other hand, nanogrid #2 does have RESs, which include as PV, PHEV and DESD this gives nanogrid #2 the ability to sell its excess energy to the grid or to meet its household demand or to transfer it to nanogrid #1 if it needs it, at a flat rate of 13cents/Kwh Moreover, both households have the same type of household appliances, as discussed earlier but with different power ratings. As mentioned previously, nanogrid #2 has a 1 kW PV and a 1kW DESD as well. The driver of nanogrid #2's PHEV is assumed to be back at 6pm and is willing to charge as soon as the dynamic electricity price is low. A Chevy Volt of 16kwh is used, which has both a charging and discharging rate of 3.3kwh, Figure 15 shows the illustrative view of scenario I, while Figure 16 and Figure 17 shows the power demand of the washer, dryer, AC and the fridge for a period of 24 hrs respectively. Power bought from the grid by these two nanogrids is as shown in Figure 12. Which shows both nanogrids were able to buy less power from the grid during the peak period which is a major factor that constitute to high operating cost.

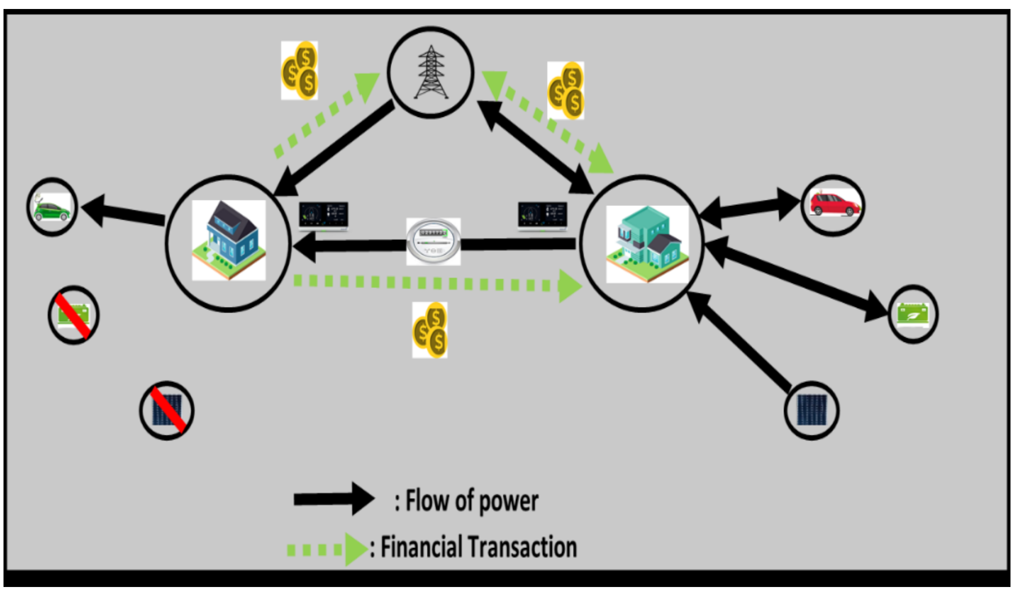

Figure 15: Illustrative view of scenario I

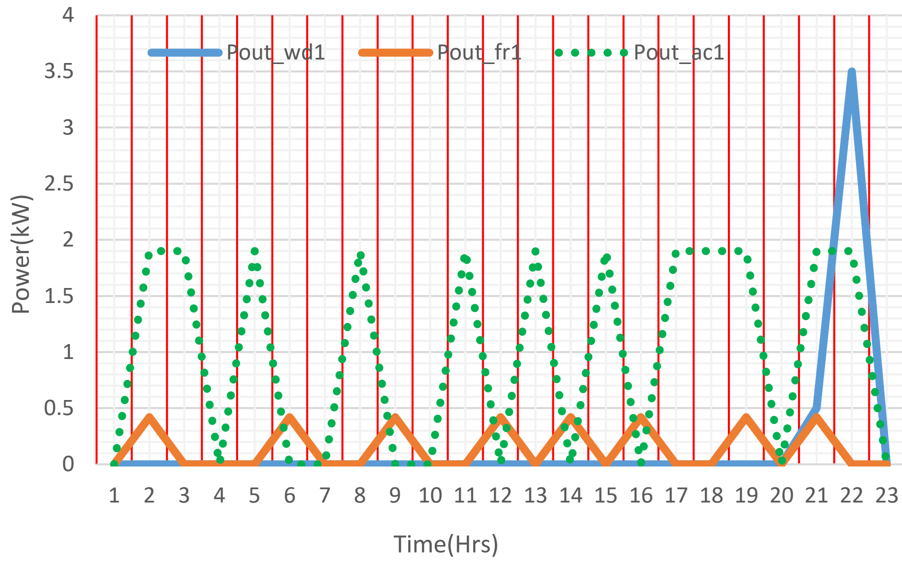

Figure 16: Power demand of selected residential loads for nanogrid I

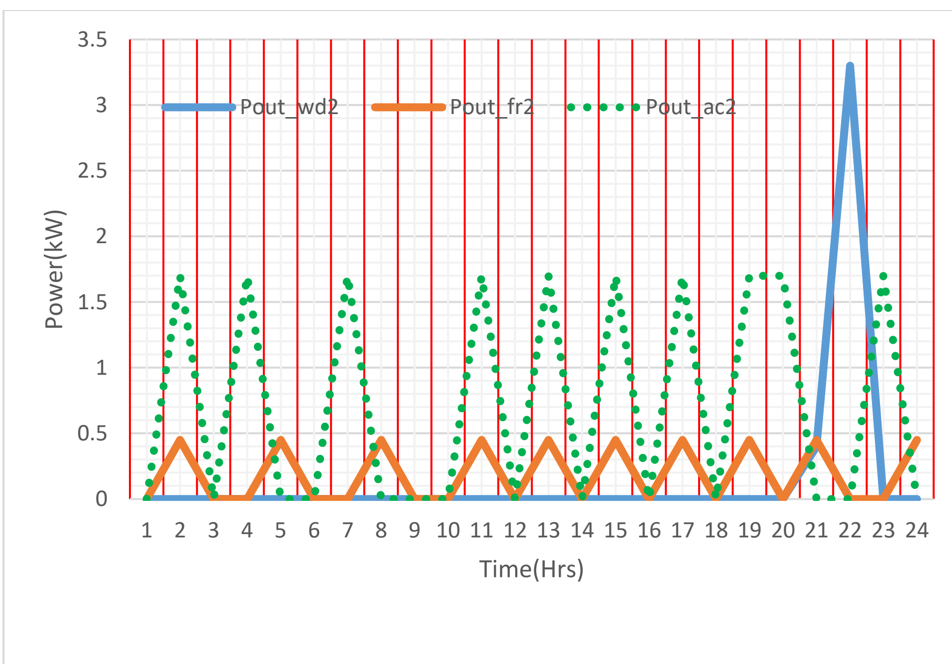

Figure 17: Power demand of selected residential loads for nanogrid II

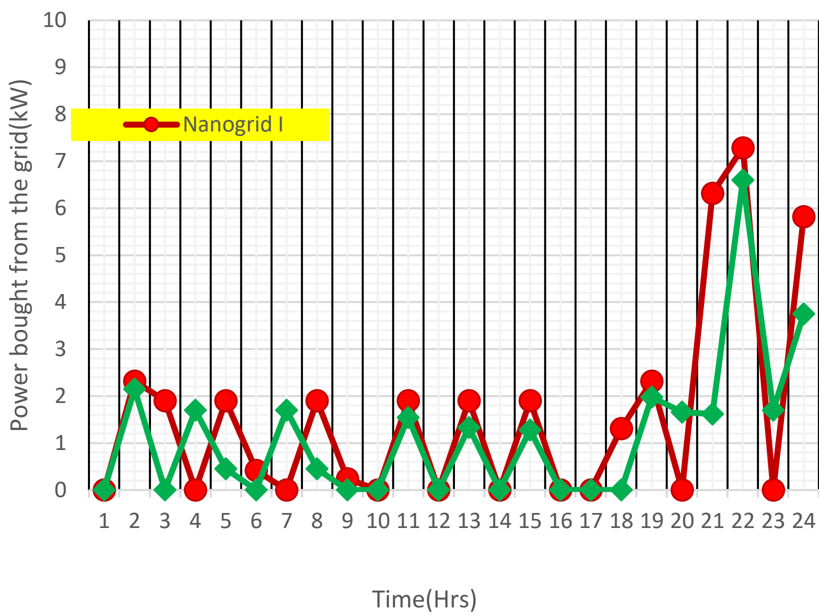

Figure 18: Power bought from the grid by Nanogrid 1& 2 (1st scenario)

3.4.2. Scenario II (Disconnected Nanogrids)

In this scenario, the nanogrids are not connected to each other, though nanogrid #2 still has a bidirectional flow ability, meaning it can utilize energy from its RES to meet its household load demand and it then sells excess energy to the grid. It should be noted however, that nanogrid #1 does not have bidirectional flow ability it relies only on the grid for its power to meet its load demand. The same basic household setup is used in this scenario as well. In addition, in this case, the driver of the PHEV of nanogrid #1 is assumed to arrive at 6pm and charges when the dynamic price is low, the driver of the PHEV of nanogrid #2 is assumed to arrive at 6pm as well, but it discharges first and charges later when the electricity price is low, Figure 17 shows the illustrative view of scenario I. Power bought from the grid by these two nanogrids is as shown in Figure 18, which shows also that both nanogrids bought less power during the peak load, however nanogrid 1 had to buy more power from the grid during this peak period.

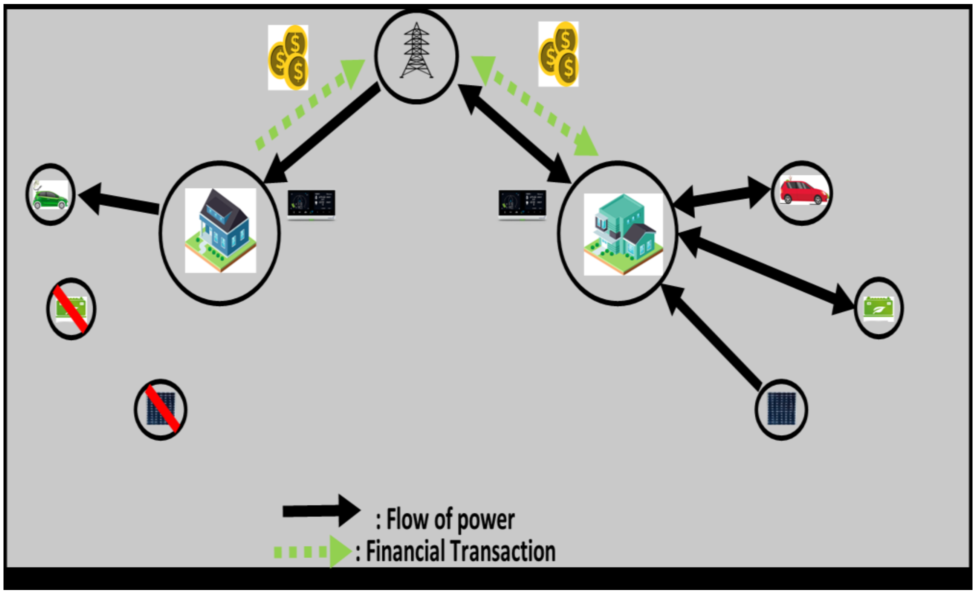

Figure 19: Illustrative view of scenario II

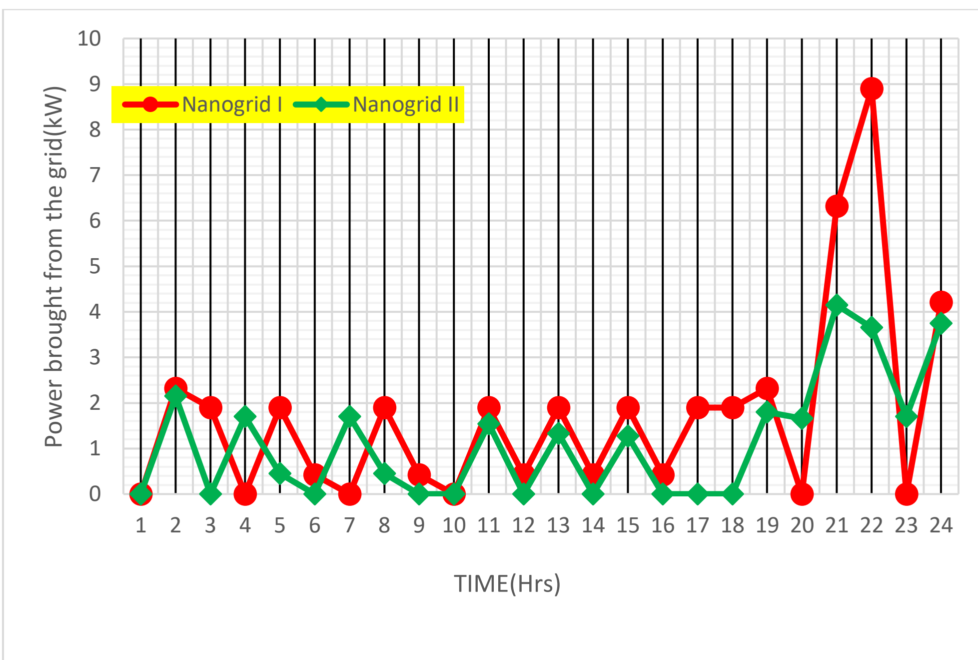

Figure 20: Power bought from the grid by Nanogrid 1&2 (2^{nd} Scenario)

3.4.3. Scenario III (Disconnected Nanogrids-NO RES)

In this scenario, the two nanogrids have no RES and they can only draw power from the grid. These nanogrids bought more power from the grid during the peak and off peak which constitute to their high operating cost, Figure 19 shows the illustrative view of scenario III. Figure 20 shows the power bought by the nanogrids.

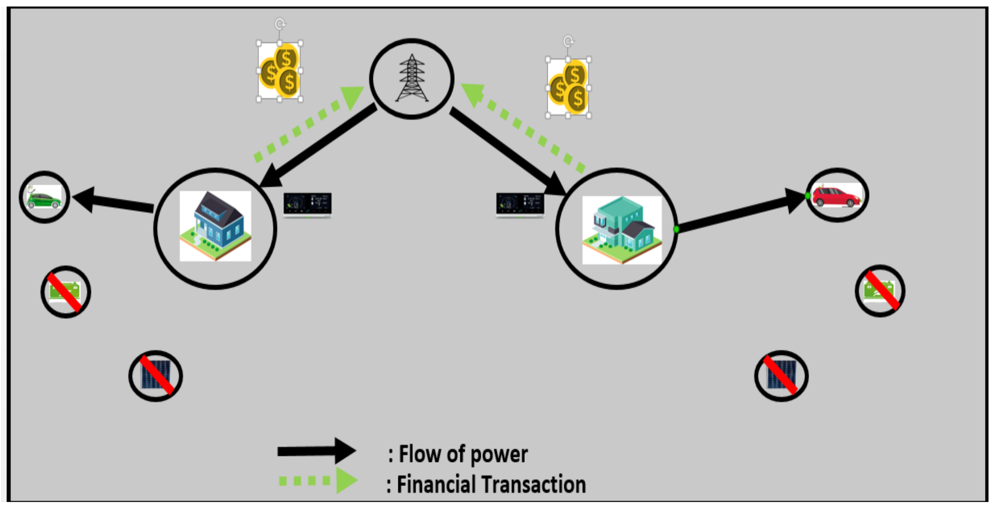

Figure 21: Illustrative view of scenario III

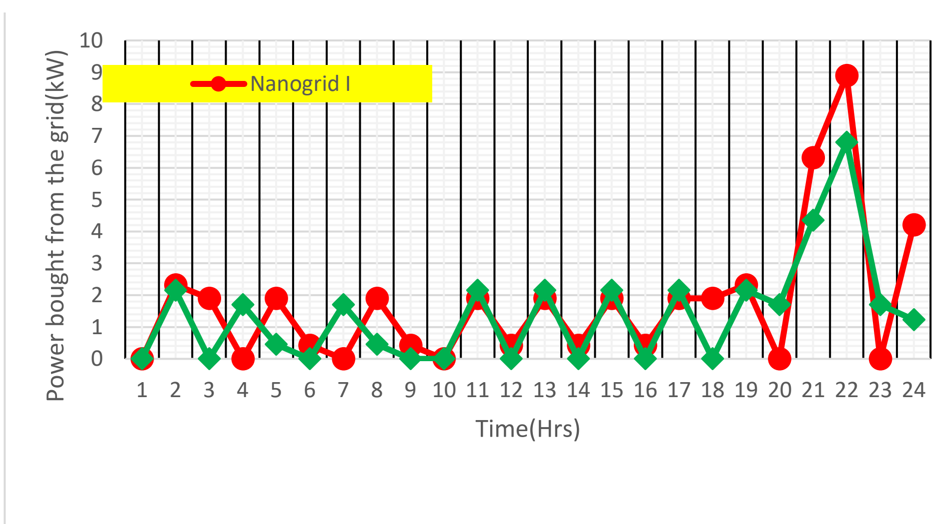

Figure 22: Power bought from the grid by Nanogrid 1&2 (3^{nd} Scenario)

3.5. Result Discussion

The formulation of the objective function and the system constraints was implemented in MATLAB and solved using Gurobi optimization solver. All the simulations were run on a computer with an Intel core i7-4790 CPU@ 3.60GHz with a 16.00 GB memory. It took 0.03secs for Gurobi to solve the simulation.

After running the simulation for the three scenarios, the total operating cost for the day of the nanogrids in scenario I is $7.4788, $7.5168 in scenario II, $8.8963 in scenario III. The simulation result of scenario I shows that interconnected nanogrids have the lowest cost, while scenario III suffers the highest operating cost as shown in Table 4.

Table 4: Total cost of daily operation

Scenario I	**Scenario II**	**Scenario III**
$7.48	$7.52	$8.89

CHAPTER 4: CONCLUSION AND FUTURE WORK

4.1. Conclusion

This research work introduces intelligent energy management system in a single residential building in which renewable energy sources, distributed renewable generation and distributed energy storage system are integrated to an intelligent controllers which help in switching the residential loads ON and OFF based on operating constraints of each devices in order to reduce the total operating cost.

Moreover, Interconnected Residential Greenhouse is proposed to further reduce the peak demand, carbon emission and the total operating cost of connected houses. The ability of the nanogrid to receive power from neighboring nanogrid gives it opportunity not to depend on the grid for energy during the peak period.

This work serves as a base which can be extended to several research areas, some of the future work is the modelling of other residential loads such as water heater, humidifier, stove, lightning and other base loads in a typical residential house while considering variable customer preferences which can result in efficient energy management in the residential house. Also the PHEV total operating cost can be further analyzed beyond the 18:00PM to 24:00PM by analyzing the total operating cost for the 24 hours by considering the total amount of gas used and total cost of charging in other charging station apart from the driver residential house.

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