Energy Management for Optimal Renewable Energy Usage in an Apartment Building

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DECLARATION OF THE CANDIDATE & SUPERVISOR

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ABSTRACT

Common renewable energy plants with proper energy management for a selected community can bring immense benefits to its consumers compared to isolated/individual renewable energy (RE) systems. Optimal usage of RE within boundaries provide with less burden on transmission/distribution networks, reduced energy loss, improved power quality, and financial benefits for both investors and consumers. In this study, we recognize apartment buildings, housing schemes, zoning areas, universities and other such institutes as potential target sites to implement this concept.

Energy management of the proposed common renewable energy plant is done by considering shiftable loads. Shiftable loads/noncritical loads, such as washing machines, dryers, irons, thermal storage are able to provide scheduling flexibility to achieve a lower electricity bill under the integration of renewable energy. In Sri Lanka, under time of use tariff mechanism, electricity price vary thrice a day.. Since the amount of renewable energy generation is also varying throughout the day, based on the predictability of day-ahead weather conditions and with the cooperation of the consumers, an optimum load schedule can be identified for the shiftable loads.

This research proposes to develop an algorithm for day-ahead load scheduling in an apartment building with the aim of harvesting maximum renewable energy generation. The results show that the proposed algorithm schedules shiftable loads resulting in a significant reduction in the cost of electricity to the consumers. This concept will attract investors to the renewable energy industry by making immense extra revenues and quick payback periods. Moreover, this method adds an extra marketing point to sell apartments, which makes it beneficial for the building construction industry.

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my supervisor Dr. Lidula N. Widanagama Arachchige and Dr. Asanka Rodrigo for their guidance and support from the very beginning to the end.

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Chapter 1

1. Introduction

1.1 Background

The increasing trends of energy demand and renewable energy integration appeal for new and advanced approaches for energy management. Demand for renewable energy further increases with the rising cost of conventional energy methods and social and political influence toward environmentally friendly electricity generation methods. [1] The amount and rate of renewable energy integration depend on the accessibility of renewable energy resources such as wind, solar, hydro, etc.

With the introduction of the net metering concept to Sri Lanka in 2010 together with easy loan mechanisms, the share of renewable energy has increased as shown in Figure1.1 [2]. In 2016, the net accounting method and net plus methods were introduced, and this made the solar PV energy become one of the booming businesses in the country.

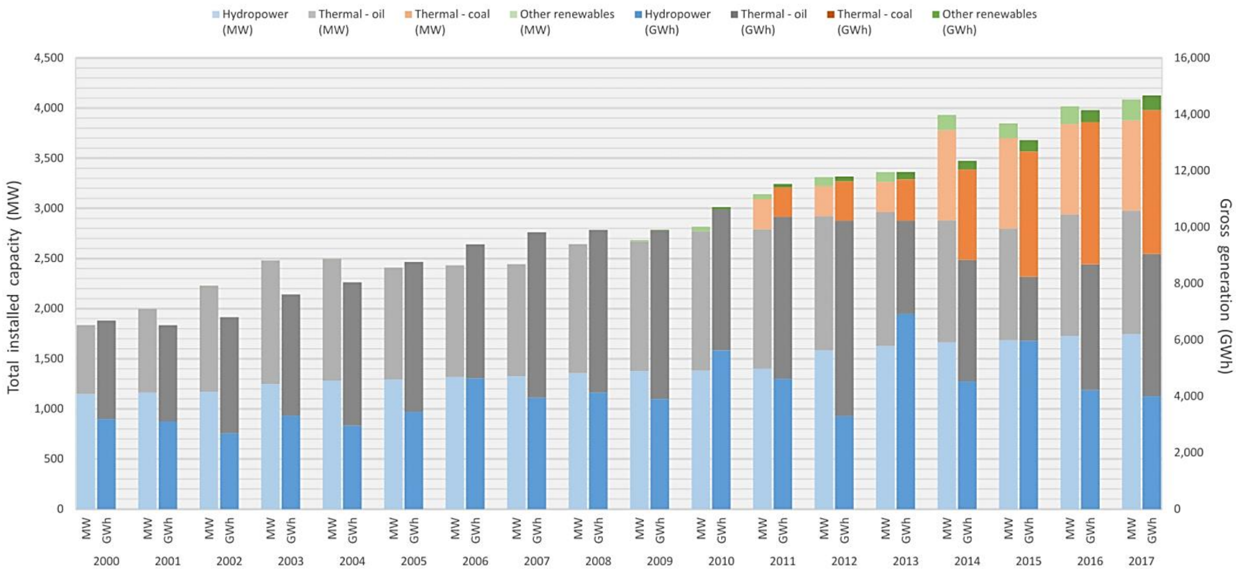


Figure 1.1: Annual electricity generation by source 2000-2017 [2]

The existing renewable energy business model is solid, less competitive and once the project size is declared, project cost, revenues, payback period are strongly predictable. This research proposes a concept to raise the existing renewable energy business to a new level to gain more financial benefits.

The other party who is going to get benefits from the proposed system is the consumers of the apartment building. Without any direct investment to the renewable energy plant, users could purchase energy for considerably lesser prices than they can purchase it from grid. To achieve this, there should be proper coordination among all the users of apartments in the building by controlling the demand and supply of renewable energy.

The proposing concept is highly suited for high rise apartment buildings, and with above-mentioned benefits, this will also make an influence on the apartment building industry.

1.2 Domestic Energy Consumption and Supplies

Key appliances in a residential building include lights, kitchen equipment (oven, rice cooker, water heater, and electric stove), air conditioner, dishwasher, washing machine, dryer, geyser and etc. Those can be divided into two groups, namely, non-shiftable and shiftable appliances. Non-shiftable/baseload appliances are generally used in during a specific time period with non-changed power levels. These appliances include essential day-to-day equipment, such as kettle, rice cooker, fridge, air conditioner, and lights, appliances, such as washing machine, thermal storage, geyser and, electrical vehicle, with flexible operation times are considered as shiftable load appliances and can be used at off-peak hours to reduce the energy cost. [3]

The ultimate objective of load scheduling is to obtain a suitable day ahead schedule (time slots) to operate shiftable loads to reduce the overall cost of the entire building.

Successfulness of the proposing concept fully depends on the customer's contribution and amount of benefits for individuals depend on the level of their contribution. Customer's involvement is expected in two ways;

1. Inform their preferred operating time periods of chosen loads to the management a day ahead.
2. Follow the final optimized schedule that is provided by the management.

The proposed apartment complex will have two energy sources namely, grid energy from Ceylon Electricity Board (CEB) and its own common renewable energy. For renewable energy 100 kW, solar PV system and 50 kW wind turbine are deployed.

1.3 Research Opportunity/Problem

Renewable energy is a booming business in Sri Lanka but energy selling price to the grid is considerably lower (upper limit of bidding price is 18.37 Rs./kWh) [4] than the domestic electricity tariff (off-peak -13Rs./kWh, day time 25Rs./kWh and peak time-54 Rs./kWh) [5] There is an opportunity to share and manage energy within the boundaries rather than selling to or purchasing directly from grid. This will be enabling the RE generation party to get more income and consumers to purchase energy for low tariff. To achieve this there should be proper coordination, legal and technical establishment among the main three parties (RE seller, consumers & grid authority) and that is developed through this study.

Being a tropical country, Sri Lanka gets a considerable amount of solar energy throughout the year. This is a good opportunity to implement the proposed system with a solar PV system. December to April is the sunniest period for Sri Lanka and the average irradiation level is estimated at around 5.0-5.5 kWh/m^2 and it will be around 4.0-4.5 kWh/m^2 during other periods of the year and 11-12% of that energy can be harvested as electricity. [6] Wind Power is also one of the fastest-growing renewable energy technologies in Sri Lanka. Figure 1.2 shows the average wind speed variation throughout the year in Colombo area and annual average wind speed is estimated to be around 10 mph. [7]

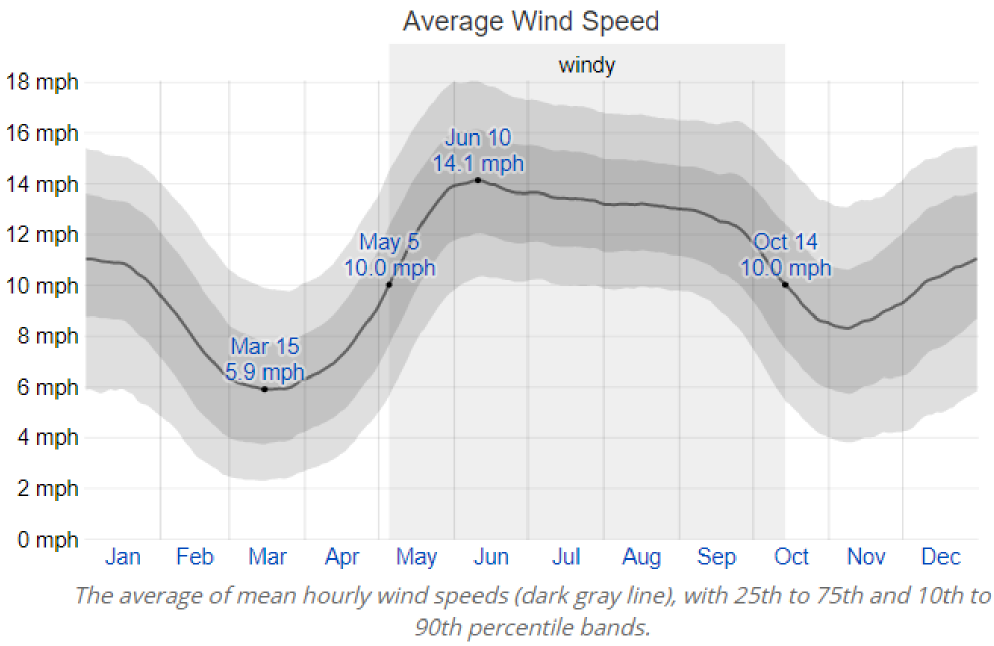


Figure 1.2: Average annual wind speed profile [7]

Energy management with load scheduling is a broad subject and there are plenty of research work carried out in the world regarding this topic [8], [9], [10], and is discussed under different energy sources and different pricing mechanisms with different optimization technologies in chapter 2, section 2.1 (literature review). In a consumer's perspective, existing methods are less flexible and fail under variations in user behaviors. The proposed method will always run based on consumer's preferences thereby adding more flexibility. Shiftable loads can be operated in isolations or combinations with other loads, and more loads can be easily adopted to the system. Chosen shiftable loads can be operated more than once per day which is an enhanced benefit that existing methods didn't offer.

The most suitable strategy with appropriate pricing mechanism and optimization technology is identified through an online survey and the literature review which is explained in chapters three and four. An optimization algorithm is developed accordingly.

1.4 Scope of the Project

The focus of this research is to identify the existing methodologies and develop an algorithm for energy management to achieve optimal renewable energy usage in an apartment building through load shifting. Mainly two parties will get the benefits from the proposed system; namely RE plant investor and apartment owners.

Solar PV (100 kW) and wind power (50 kW) have considered being connected to the grid through the net accounting method. The primary energy source is the grid energy and it will be fed through 250 kVA transformer. The time of use tariff mechanism is considered when purchasing energy from the grid and selling price of energy to grid is considered to be 18.37 Rs. / kWh which is the allowable upper limit of bidding price.

Five domestic shiftable type loads (washing machine, dryer, geyser, iron and dishwasher) and two common shiftable loads (62.5 kW chiller for thermal storage and 6 kW pump for water storage) are considered for load scheduling. Apartment building compromises with 50 apartments and hence a total of 252 number of shiftable loads are available for scheduling. The social, technical and economic feasibility of the proposed system is analyzed with the existing conventional methods and justified the necessity.

1.5 Objectives of the Study

The project will achieve the following objectives:

Main objective:

- To develop a mechanism for optimum usage of renewable energy in a housing scheme.

Specific Objectives:

- To design an optimum load scheduling mechanism for the selected noncritical loads.
- To develop a pricing mechanism for a housing scheme to recover the investment cost and motivate maximum usage of renewable energy.

When renewable energy cost is less than the grid energy it is economical for consumers to utilize renewable energy than purchasing from the grid and there should be a compromise among users to manage the renewable energy supply and demand while achieving the lowest possible daily cost.

1.6 Thesis Outline

The report started with giving an introduction about the proposed concept and background for such an establishment. It explained the domestic energy consumption patterns in urban areas and also about the existing renewable energy industry. A detailed descriptionof the window of opportunity for the proposed concept and related problems with existing methods has discussed. The scope of the research and research objectives are clearly elaborated for a chosen apartment complex model.

Research methodology has discussed under the second chapter, how the research was implemented from the start to end in steps. A detailed description of the infrastructure of the proposed system has included in the same chapter.

Next, the development of the pricing mechanism has discussed. A description about the sizing of RE plant, project cost estimation and operational strategy of the system have included in this chapter. Linear optimization-based pricing mechanism is developed and its approach has discussed in detail.

Chapter four discussed the development of the load scheduling algorithm. A literature survey was conducted to identify existing load scheduling methods, constraints in load scheduling and types of shiftable loads. The approach of algorithm development has discussed in three steps and the output of each step is illustrated.

Financial benefits for both investors and consumers from the proposed system has discussed under chapter 5. Through the simulation results, it has proven that the proposed system will bring immense benefits to both parties through 4 types of cost-saving sources.

Finally, it has summarized the overall process under Conclusion. Benefits for involved parties, the main key features of the algorithm, limitations of the proposed system and suggestions for further improvements are discussed under this.

Chapter 2

2. Literature Survey

2.1Load Scheduling

The literature review has don with the intention of identifying types of non critical loads, Constrains in load scheduling and load scheduling methods. Most popular load scheduling algorithms are linear, nonlinear and game theory. Each type is having its pros and cons base on application.

Y. Liang *et al.*, (2017), presents a method to minimize total energy purchase for a residential smart grid through Demand Side Management. Game theory has considered as the load scheduling method and the individual-level optimality is achieved together with the system level optimality through energy management scheme design [8]. The basic features of the concept is summarized in table 2.1.

Table 2.1: Types of noncritical loads, constrains and load scheduling method of the research

Non critical loads (shiftable loads)	Constraints used	Load scheduling method
➢ 10 household users ➢ Each household has 4 to 6 shiftable appliances including dishwashers, washing machines and phevs (plug-in hybrid electric vehicles)	➢ Shiftable appliances operation time ➢ Total energy required for a day must be supplied ➢ The minimum and maximum power consumption levels for each shiftable appliance ➢ Capacity of the transformer of the energy provider.	➢ Game theory ➢ Each user is self-optimizing the consumption and interactively converges to nash equilibrium ➢ No need of a central coordinator

The proposed scheduling method introduces a billing mechanism for the daily energy costs of each user by aligning both the individual and system level optimality while ensuring operational feasibility. Simulation studies have also shown that the proposed scheme is effective in flattening load profile and reducing total electricity purchase costs. But there is no proper justification to attract users for the proposed mechanism and only one conventional energy provider is considered in this research which they could consider alternative secondary low-cost energy sources such as renewable energy.

X. Ayón *et al.,* (2017), presents an optimal day-ahead load scheduling approach based on the flexibility of aggregate demands. The optimization algorithm has been developed for groups of residential and commercial users that include customers from various sectors. The objective function is the cost minimization of the aggregated demand. An aggregator is introduced to increase flexibility and the overall profit, and the method is tested through a case study representing a small geographical area. The demand consists of a fixed part – the minimum demand, and a variable part represented by the flexibility as a consequence of changing customer consumption patterns. The real-time prices used in this case study are the wholesale market prices. In this case, they are used as the market price predictions by the aggregator a day before the actual time of energy delivery to the consumer. The basic features of the concept are summarized below in table 2.2. [9]

<u>Table 2.2: Types of noncritical loads, constraints and load scheduling method of the research</u>

Non-critical loads	Constraints used	Load scheduling method
➢ cooling and heating loads, washing machines, dryers, dishwashers and lighting loads	➢ maximum time delay of shiftable appliances ➢ thermal comfort limits ➢ total daily demand limits (min and max) ➢ power ratings of loads	➢ linear optimization

This system is proposed for an area where thermal loads of residential and commercial buildings can be operated simultaneously. Through this, they have achieved a daily average profit of 97.9€ & 36.4€ during winter and summer respectively. Flexibility depends on the consumer's behavior and treating both residential and commercial loads as one block might be affected by the comfortability of one of the above is one issue of this concept. This concept can be further improved by considering alternative secondary low-cost energy sources such as RE, and also by implementing a rewarding and penalty system for the cooperation of the users.

T. Logenthiran *et al.*, (2012) have proposed a concept for demand-side management in a smart grid using heuristic optimization. The main intention of this research is to maximize RE usage and minimize power imported from the grid and reduce the peak load.

Demand-side management strategy (DSM) based on day-ahead load shifting technique had been proposed using a heuristic based evolutionary algorithm. Here an objective load curve is defined to be inversely proportional to the electricity market price and the proposed optimization algorithm aims to bring the final load curve as close the objective load curve. [10]

Table 2.3: Types of noncritical loads, constraints and load scheduling method of the research

Non-critical loads	Constraints used	Load scheduling method
➢ Washing machine, dryer, oven, iron, vacuum cleaner, kettle, toaster, blender water heater ➢ Welding machine arc furnace, induction motor, dc motor, fan/ac	➢ Number of devices shifted cannot be a negative value. (x_{kit} > 0) ➢ The number of devices shifted away from a time step cannot be more than the number of devices available for control at the time step ➢ Maximum allowable time delay for all devices	➢Genetic algorithm

The simulation outcomes show that the proposed algorithm is able to handle a large number of controllable devices of several types. This is achieved through substantial savings while reducing the peak load demand of the smart grid. Based on the finalized schedule, generation companies also achieve substantial savings by optimizing the generation schedule. In addition, transmission companies achieve between 15% to 20% reduction in network congestion. However, the one main limitation of this project is the lack of a profit-sharing mechanism to share the profits gained by generation and transmission companies with users.

2.2 Pricing Mechanism development

2.2.1 Levelized Cost of Energy

The levelized cost of energy is a very essential tool to evaluate viability of energy projects. According to *C. S. Lai and M. D. Mcculloch,* (2016) levelized cost of energy can be obtained by deviding total cost to build and operate a power-generating asset by the total energy output of that asset over the lifetime. Selling price of energy should be always greater than levelized cost of energy, indorder to make profits. [11]

As reported by *Allan et al.,* (2011) there are two methods commonly used to calculate the levelized costs, known as the "discounting" method, and the "annuitizing" method. [12]

1. Discounting method

The levelized costs measured under the ‘‘discounting’’ method, ELCO $_{Discount}$ is given by equation 1. It is more appropriate to use the discounting method than the annuitizing method when calculating LCOE for renewable sources because of there intermittent nature.

$$\text{ELCO}_{\,Discount} = \frac{\displaystyle\sum_{t=0}^{n} \frac{C_t}{(1+r)^t}}{\displaystyle\sum_{t=0}^{n} \frac{E_t}{(1+r)^t}} \tag{1}$$

2. Annuitizing method

The annuity method converts the costs to a constant flow over time. This is appropriate where the flow of energy output is constant. Levelized cost of energy under the annuitizing method can be evaluated using equation 2.

$$\text{LCOE}_{\,Annuitizing} = \frac{\left(\sum_{t=0}^{n} \frac{C_t}{(1+r)^t}\right)\left(\frac{r}{1-(1+r)^{-n}}\right)}{\left(\sum_{t=0}^{n} E_t\right)/n} \tag{2}$$

C_t – Future cost in year t E_t – Electrical Output in year t r – Discount rate (DR)
n – Life time of the project

4.3 Outcomes of the literature review

Linear Algorithms: Complex mathematical models are used. Real-world random processes are hard to model and will take more time to execute with a large number of variables. Linear optimization will give the best solution if the systems can be modeled accurately.

Non-Linear Algorithms: A nonlinear optimization is used to solve constrained or unconstrained nonlinear problems with one or more objective functions. Random activities are easy to represent in a non-linear way and will give a better solution related to user behavior and other random activities such as the intermittent nature of renewable energy.

Game theory: A mathematical framework used to study situations where multiple agents interact. It does not study how agents actually behave in strategic situations. (Human behavior is not always rational)

From a consumer perspective, existing such methods are less flexible and fails under variations in user behaviors. Further, the adoption of renewable energy is low and the number of chosen non-critical loads is less.

Considering the above facts, the nonlinear optimization method is used to develop the proposed algorithm for load scheduling. The linear optimization method is used for pricing mechanisms since it is a mathematical method that is used to determine the best possible outcome or solution from a given set of parameters or a list of requirements, which are represented in the form of linear relationships. The proposed method will give more priority on consumer's preferences and will give more options (shiftable loads can operate isolate/linked with other loads, maximum three occasions to operate a shiftable load in a day and easy integration of more loads to the system) in load schedule.

Considering the intermittent nature of solar and wind energy generation, discounting method is considered for estimating levelized cost of energy. Taxation, subsidies and other incentives are considered when defining the DR (discount rate). Standardized assumptions used for calculating the DR (it is 10% for non OECD countries). [13]

Chapter 3

3. Methodology

First, the commonly available noncritical loads, domestic energy consumption patterns, constraints of load scheduling, load scheduling methods, and algorithms were identified through an online survey and a literature review. Here the target consumers are considered to be more energy users with a considerably larger number of electrical appliances with a high energy consumption such as air-conditioning system, washing machine, dryer, dishwasher, geyser, *etc.*

With the help of gathered information, the average load of a house/ apartment was estimated and based on that renewable energy plant size was determined. Figure 3.1 shows a schematic representation of a proposed system for an apartment building with 50 apartments each with five domestic shiftable loads. This apartment building is proposed to be in Colombo area which is the capital of the country and all the relevant data is considered based on the same geographical area.

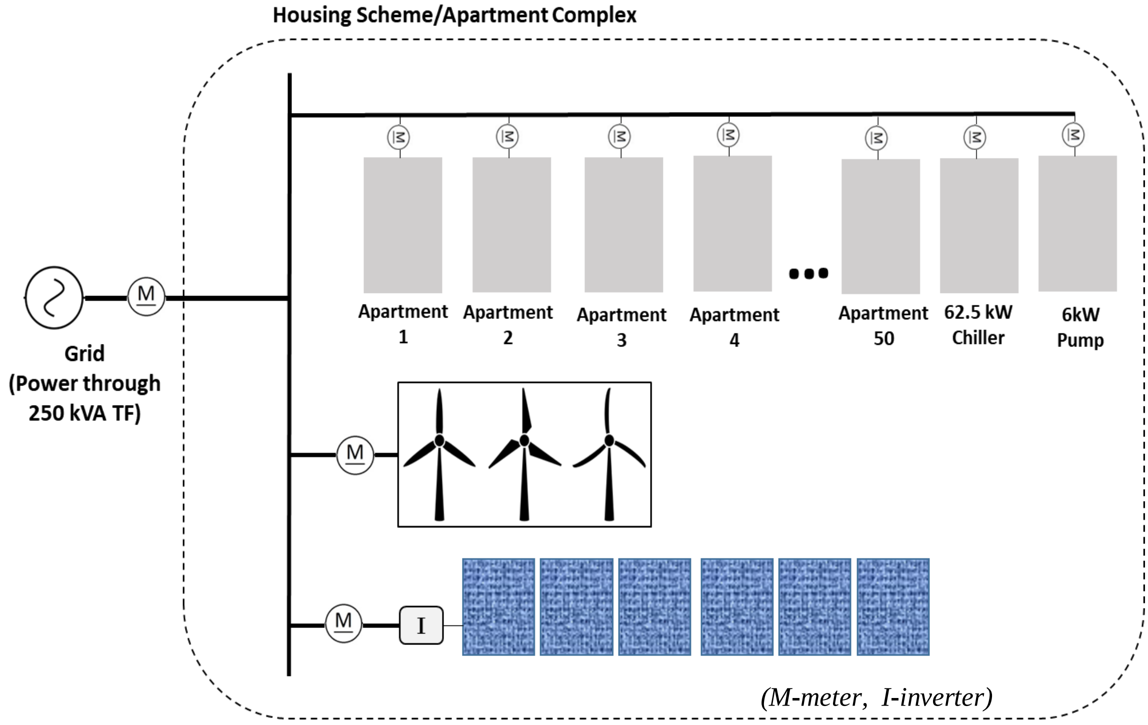


Figure 3.1: Conceptual diagram of the proposed system

The electrical system of thermal storage and water storage is also considered as shiftable loads which are controlled and operate directly by the housing scheme management.

The proposed apartment complex will have three energy sources namely; 50 kW wind turbine, 100 kW solar PV and grid energy through 250 kVA transformer. Apartment building power system is connected to the grid through the net accounting method and the amount of energy generation of RE sources and energy consumption of apartments and other common loads are measured separately. Next, the total direct investment, and the annual operation and maintenance cost are estimated based on published records by the International Renewable Energy Agency (IRENA) in 2018.[14]

Then, the operational strategy for the proposed system is introduced and a pricing mechanism is developed based on that.

Finally, the load scheduling algorithm is developed to identify the day ahead optimum load schedule for shiftable loads.

Chapter 4

4. Development of the System

4.1 Assumptions

Following assumtions were made through out the project.

- Day ahead weather forecast will have higher chances to be succesfull and data will be available in 15 minute resolution. Under such variations, two methods were introduced to mitigate the impact.
    - Real time controlling of common loads (like thermal storage and pump system)
    - Re estimate the selling prices of RE to consumers in an annual basis
- It was assumed that the consumers will inform their preferences to the management and they will follow the finalized load schedules given by the management every day. If somebody does not provide next day preferences, none of the provision for shiftable loads will be allocated. On the otherhand, violations of proposed schedule will personally affect the perticular consumer by increasing his/her electricity bill. So, a natural influence to motivate consumers to follow the schedules is there with the algorithm.
- Main shiftable appliances of each apartment will be identical. Since this is proposed for newly built apartment buldings and it is a management decision to furnish each apartment, hence all the apartments will get similar electrical appliances.
- 20,000 L insulated chilled water storage was considered and it was assumed that the temperature inside will be maintained for 8 hours without a significant drop.
- Energy purchasing from grid is based on time of use tariff method and selling price of renewable energy is considered to be as 18.37 Rs./kWh (Upper benchmark at the time of bidding in bidding type RE projects)
- Average annual weather details are considered when evaluating the overall financial viability of the proposal and simulation was done based on an observed weather profile in a random day. But some data points are manipulated to check the technical suitability under different scenarios.

4.2 Development of the Pricing Mechanism

As shown in Figure 4.1, developing the pricing mechanism is an output of a sequential process.

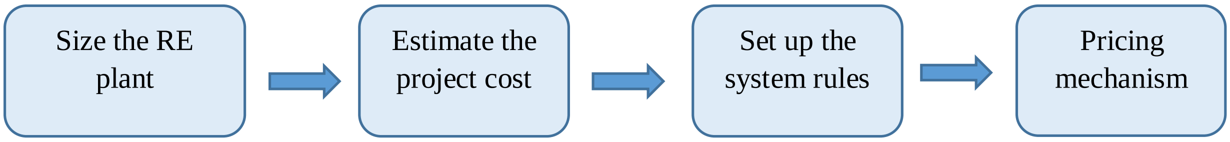


Figure 4.1: Steps to develop the pricing mechanism

4.2.1 Size of the renewable energy plant

An online survey was carried out during the pilot study to identify the domestic electricity consumption patterns. One important parameter wanted to identify was the average electricity consumption of a house in an urban area. For the question, “what is your average monthly electricity bill?” the majority were in the 4,000-5,000 Rs. a category which is around 150-200 kWh. However, the usage of high-end appliances was in poor condition. (Figure 4.2 & Figure 4.3)

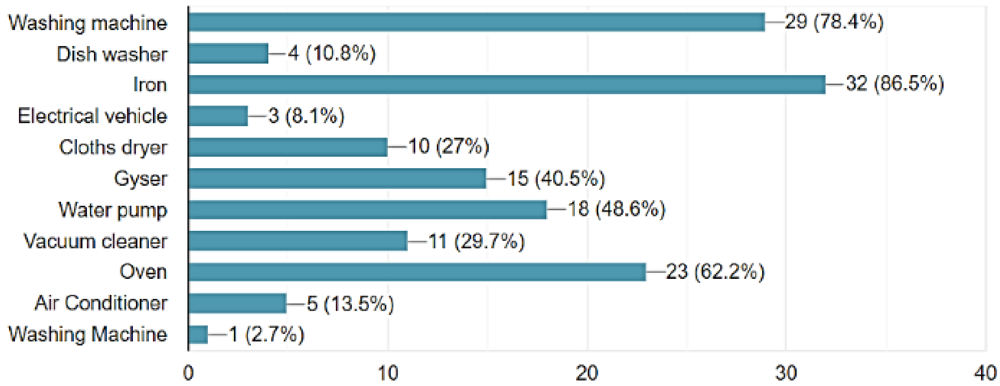


Figure 4.2: Responses for the query – “Following Electrical Equipment are available at my home”

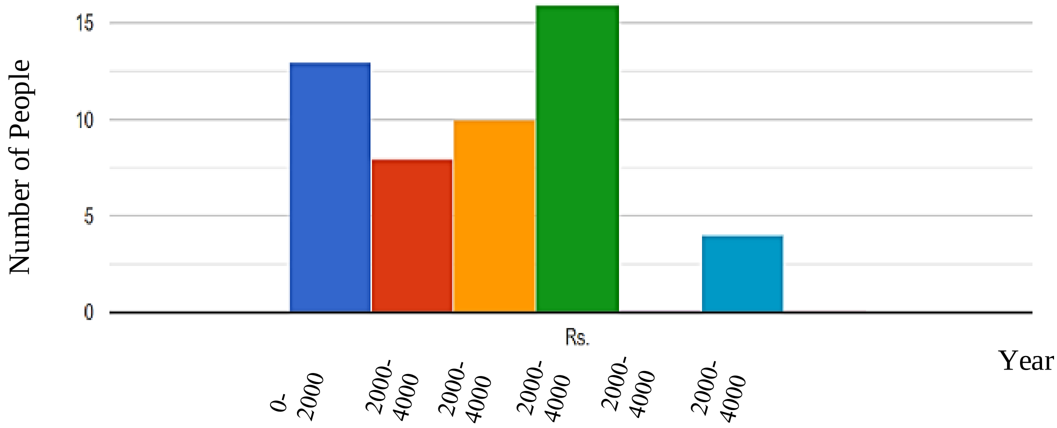


Figure 4.3: Responses for the query – "What is your average monthly electricity bill?"

Since this has proposed for high-end users in a luxurious apartment building, more electrical appliances (like dishwashers, dryers, geysers, air conditioners) would be used. Considering those facts, the average Energy consumption of an apartment is considered to be as high as 4kVA.

The size of the RE plant is always limited by a couple of constraints such as Investor's investment capacity, available area (especially for solar PV), the electricity demand of the users, and expected annual energy generation of each RE source. Considering all these facts, it is desired to have a 100kW solar PV system and a 50 kW wind turbine for the RE plant.

4.2.2 Project Cost Estimation

According to the IRENA (International Renewable Energy Agency) publication, 2018 [14] capital cost for solar PV is 1145$/kW and 1075$/kW for wind power. The estimated annual operation and maintenance cost for a solar PV system is considered as 15$/kW and for wind power, it is 20$/kW. Including all these components, the total project cost is estimated to be around 38.5 MN LKR.

4.2.3 Operational strategy of the system

4.2.3.1 Grid interconnection methods

There are several ways to integrate renewable energy to the grid in Sri Lanka. Net metering, net accounting, net plus, SPPA (small power purchasing agreement) are the most activated methods of them. [15] Comparison of the above methods can be found in Table 4.1. A net accounting scheme is selected for the proposed system considering the technical and financial suitability of all these methods.

Table 4.1: Comparison of available grid interconnection methods

Mechanism	RE Type	Limitations
Net Meter	➢ Solar PV, Micro Hydro, Biomass, Waste, Wind	➢ Credit basis ➢ Consumer has no choice between grid and RE
Net accounting	➢ Solar PV	➢ Only for Solar ➢ Consumer has no choice between grid and RE
Net Plus	➢ Solar PV	➢ Only for Solar ➢ Consumer has no choice between grid and RE
SPPA	➢ Mini-hydro, Wind, Biomass, Municipal solid waste, Waste Heat	➢ Solar PV is not included ➢ Consumer has no choice between grid and RE

4.2.4 Development of the Pricing mechanism

Users can purchase energy from the grid for time of use (TOU) tariff mechanism, which is 13 Rs/kWh during off-peak, 25 Rs/kWh during daytime and 54 Rs/kWh during peak. After the internal consumption extra, renewable energy will be sold to the grid for the price of 18.75 Rs/kWh for 20 years.

It is essential to develop a pricing mechanism for selling RE to apartment users in order to cover the investment cost and the operational cost.

Three parameters are considered in developing the pricing mechanism

1 Levelized cost of energy

Levelized cost of energy is obtained by dividing project life cycle cost by lifetime energy production in kWh as shown in Eq. (3). [11] It is estimated that levelized cost of energy for solar PV energy and wind energy is 11 Rs./kWh and 7 Rs./kWh respectively. This information is used when deciding the selling price of the energy where the selling price should be greater than the effective levelized cost of energy (LCOE).

$$\text{LCOE} = \frac{\text{Lifecycle cost (\$)}}{\text{Lifetime energy production (kWh)}} \tag{3}$$

2 Payback period

Here the simple payback period is considered. If the investor decides to go with the traditional net accounting method, it will take approximately 10 years to cover the project cost. With the proposed mechanisms, it is expected to cover the investment within 8 years and tariff are estimated accordingly.

3 Gain for customers

Another important factor that needs to be considered is the gain for consumers. Consumers will participate with the proposed mechanism only if they can purchase for a lesser price than from the grid. (Chosen prices should lie in between two graphs in figure 4.4). User's energy consumption amounts may vary from zone to zone, and it is described to consider the midpoint between two graphs as the most preferred tariff values. Selecting the midpoint in a range will be fairly beneficial for all the users irrespective of their maximum energy usage zone and it will also make sure estimated tariff will also follow the pattern of Ceylon electricity board (CEB) tariff profile.

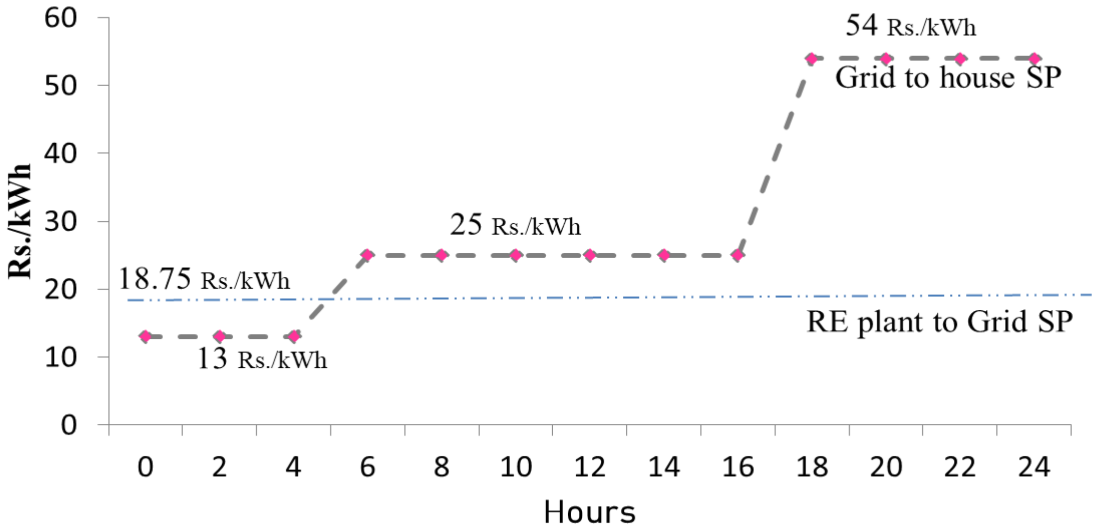
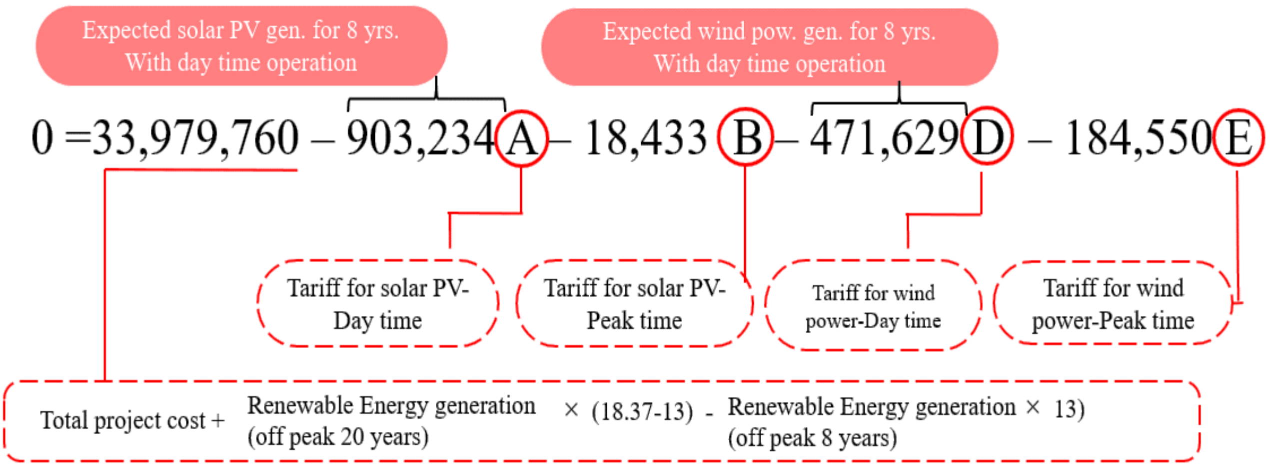


Figure 4.4: Graphs of time of use tariff and grid purchasing price of renewable energy

For this project, 8 years of payback period is considered. Total energy generation within this 8 year period is split into the three-time zones (i) day, (ii) peak and (iii) off peak and those ratios be used in the pricing formula. This method improves the control of reaching as much as closer to the target tariff rates. Best tariff values for daytime and peak time (for both wind and solar PV) are calculated by linear optimization. It is expected to obtain 1,025,280 kWh of wind energy with the first 8 years and 18%, 46% and 35% of that will be generated during peak time, day time and off-peak respectively. It is expected to obtain 921,600 kWh of solar energy with first 8 years and 2% and 98% of that will be generated during peak time and day time respectively. With the above information, tariff for the selling price of renewable energy is calculated as per the Eq. (4) for both RE types for three time zones.



(4)

$$\textit{Total Error: } e_T = e_A + e_B + e_D + e_E \quad (5)$$

- The optimization algorithm is used to solve the values for A, B, D & E coefficients while reaching as much as closer to their most preferred values by observing the minimum value for the total error which is calculated by Eq. (5).
- Eq. (6) estimates the square error of A, B, D & E and also considered in achieving the final results.

$$\textit{Total Square Error: } e^2{}_T = e_A{}^2 + e_B{}^2 + e_D{}^2 + e_E{}^2 \quad (6)$$

Error of A:

$$e_A = |(most\ preferred\ value\ of\ A - \ obtained\ value\ of\ A)| = |21.68 - A| \quad (7)$$

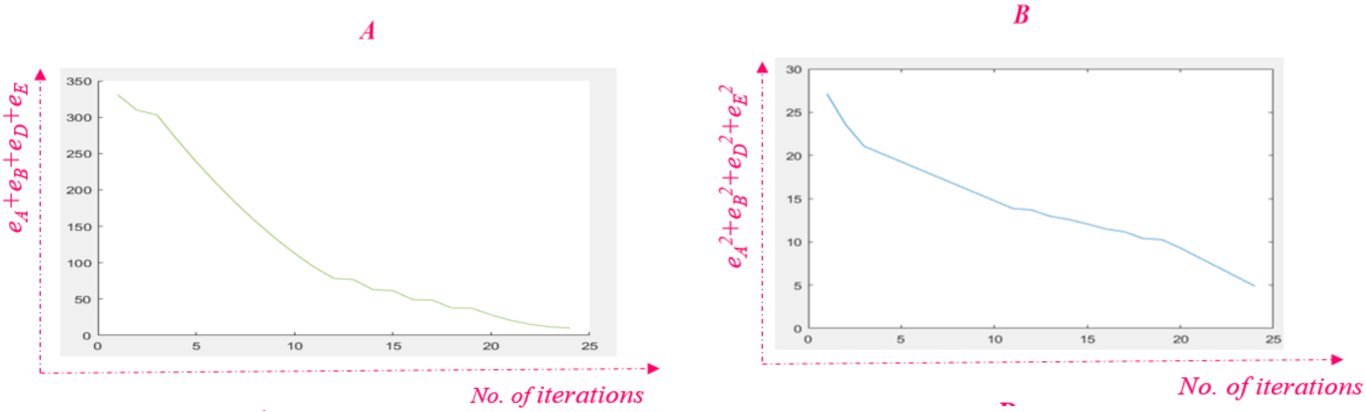


Figure 4.5: **A**-variation of total error with no if iterations; **B**-variation of total square error with no of iterations

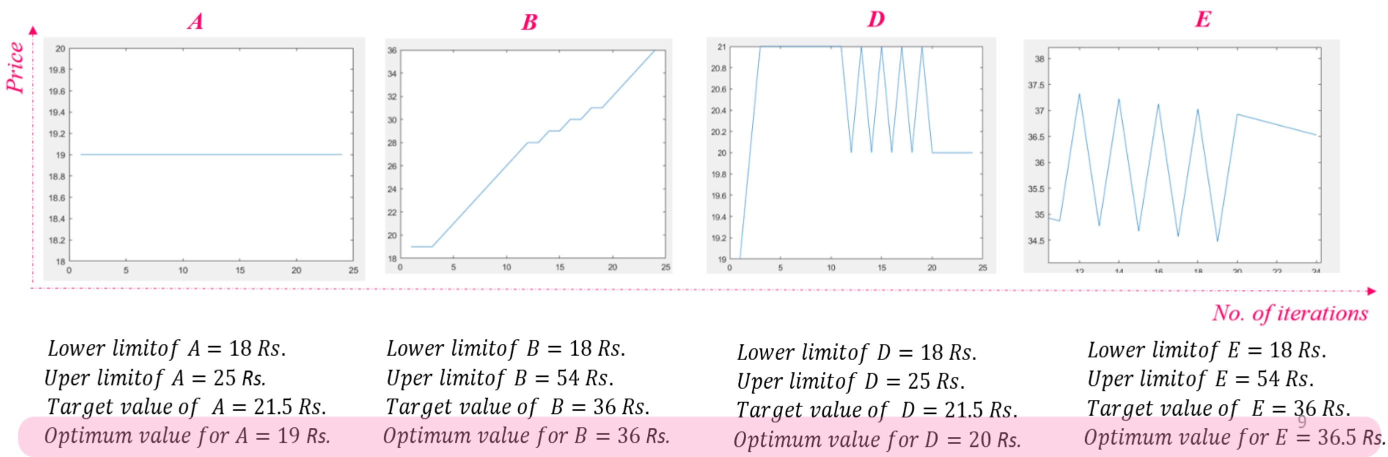


Figure 4.6: **A**-optimization curve for A (tariff for solar PV day time); **B**-optimization curve for B (tariff for solar PV peak time); **D**-optimization curve for D (tariff for wind energy day time); **E**-optimization curve for E (tariff for wind energy peak time)

Figure 4.5. A and Figure 4.5. B show the variation of total error and variation of total square error with no of iterations respectively. Figure 4.6 illustrates the optimum values of variables A, B, D and E at the lowest total error/total square error.

Based on the results of the calculation, it is desired to sell solar energy to users for 13 Rs/kWh (off-peak), 19 RS./kWh (day time) and 36 Rs./kWh (peak time) and wind energy for 13 Rs./kWh (off-peak), 20 Rs./kWh (day time) and 36 Rs./kWh (peak time). During all the three periods of the day, generated RE will be first sold to the housing scheme and the extra energy will be sold to the grid for 18.37 Rs. /kWh. If there will be any energy shortage from the RE sources, it will then be bought from the grid for the existing time of use tariff.

4.3 Development of The Load Scheduling Algorithm

Load scheduling is done in the following steps as shown in figure 4.7. The process starts by identifying the suitable noncritical loads and then identifying the constraints in load schedule. There are several load scheduling algorithms used for load scheduling. The most commonly used methods are linear, nonlinear and game theory. The most suitable method was selected after the literature survey.

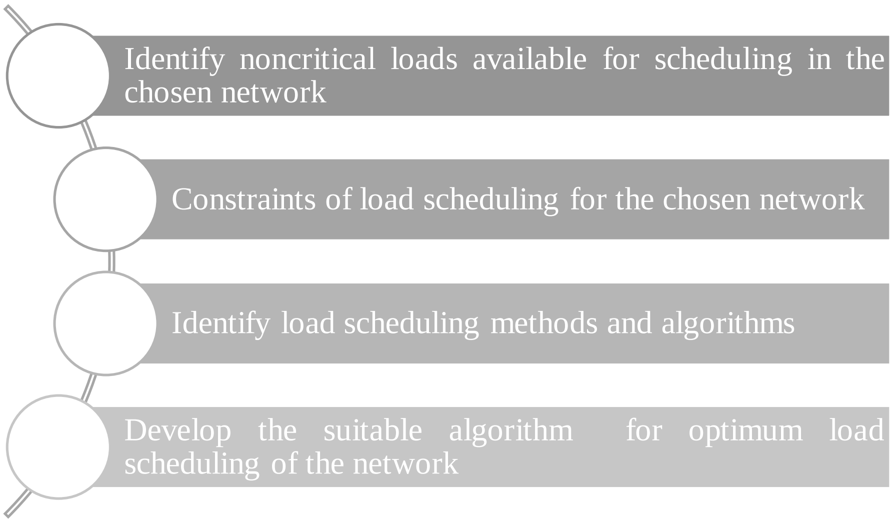


Figure 4.7: Steps of the load scheduling process

4.3.1 Non-critical loads

Shiftable loads are the loads of which the operational time is not critical and can be scheduled within a range. In practice, it is difficult to separate electrical appliances as critical or noncritical loads. Their shiftable property varies from time to time. In order to establish our system, shiftable loads are defined as follows.

To consider a particular load as a shiftable load;

1. Shiftable time (at day-time or peak time) should be greater than 1 hour
2. If the first condition is fulfilled, those devices can operate maximumly 3 times per day as a shiftable load. (for further attempts those would consider as non-shiftable loads)

The following loads will be considered as shiftable loads.

I. 2 kW washing machine for each apartment
   Operation duration-1 hour
II. 2.5 kW dryer for each apartment

Operation duration-45 minutes

III. 1.5 kW dishwasher for each apartment

Operation duration-30 minutes

IV. 1.5 kW iron for each apartment

Operation duration-30 minutes

V. 350 kW chiller with 20,000L thermal storage (insulation is enough to maintain the temperature for 8 hours)

The estimated cooling load capacity for a house is 24,000 BTU/hour. To cater to the demand for 50 apartments, a chiller with a capacity of 350 kW (Thermal) and with a 5.6 COP (coefficient of performance) is proposed. The proposed central air conditioner system with thermal storage is illustrated in figure 4.8.

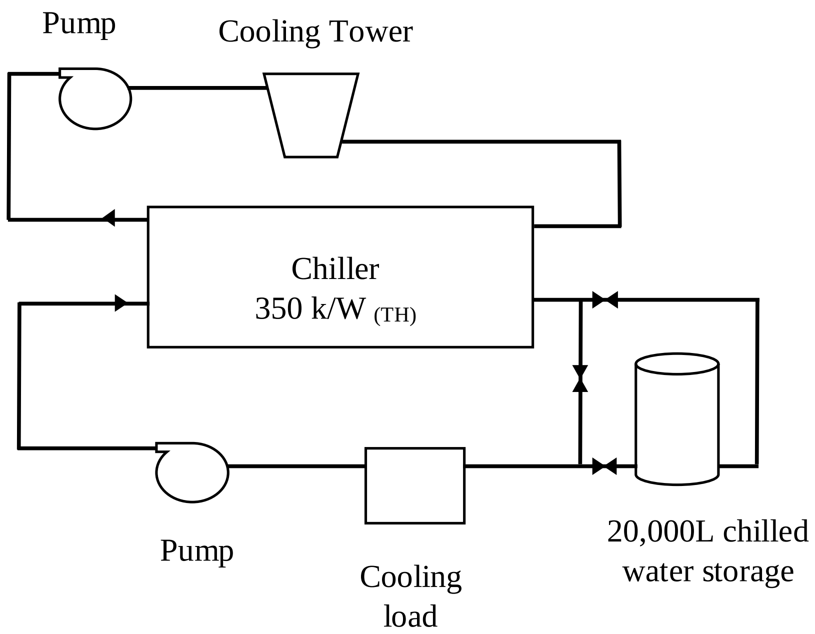


Figure 4.8: Proposed central air conditioner system

VI. 6 kW water pump

The average water requirement for an apartment is estimated as 0.6m^3 per day, with the observation of an online survey. It is proposed to keep 2 of 30,000 L tanks at the rooftop and while one tank is in use, the other tank will be filled within that day for the next day consumption. 6 kW pump with 50 m head is proposed for water filling and will fill the water at a rate of 2000L/15 min

4.3.2 Nonlinear optimization

A genetic algorithm is a method for solving both constrained and unconstrained optimization problems based on a natural selection process that mimics biological evolution. As shown in figure 4.9, the system randomly selects individuals from the current population and uses them as parents to produce the children for the next generation. Over successive generations, the population "evolves" toward an optimal solution. [16]

For the load scheduling, a modified version of the Genetic Algorithm is used.

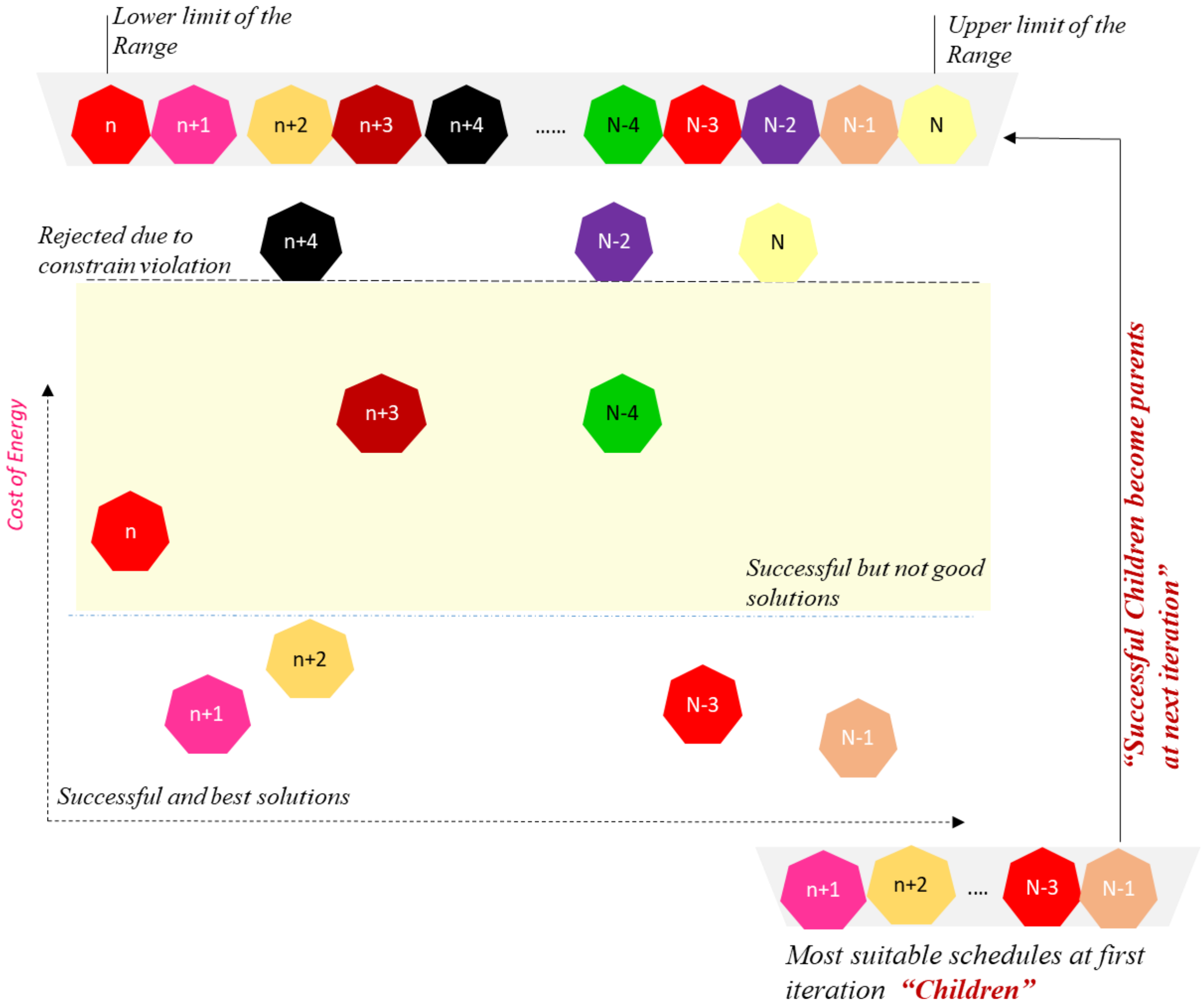


Figure 4.9: Illustration-Genetic algorithm

4.3.3 Algorithm Implementation

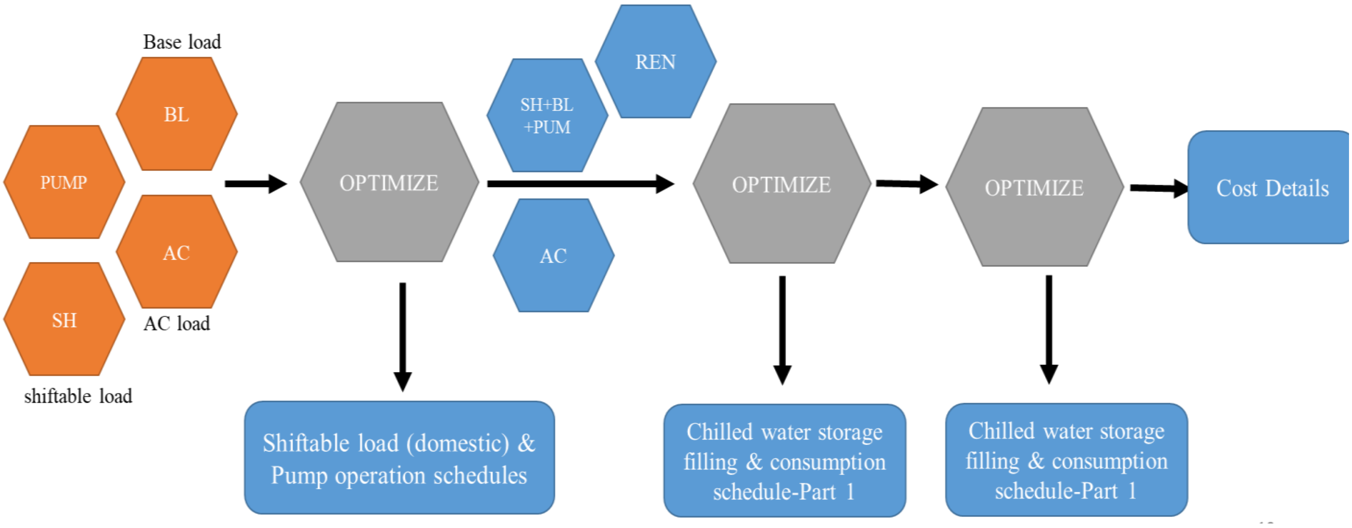


Figure 4.10: Steps of optimization

Optimization is achieved in three steps as illustrated in figure 4.10. In the first step, all the loads (other than the shiftable loads and pump) are considered as base loads and optimization is done for shiftable loads and pumps separately. The output of this stage is the shiftable load and pump operation schedule.

In the next stage, the AC load is isolated and optimized. According to the time of use tariff scheme, the highest rate is charged during peak time and next lowest one for day time. It is proposed to carry an allowable maximum capacity of chilled water from low-cost zones to use in higher cost zones and development of that schedule achieved during step 2.

Still, there can be situations where excessive renewable energy generations within a zone. During such situations, chilled water is generated and stored to use them during low RE situations within the same zone. Choosing the best time slots to generate and discharge chilled water without affecting step 2 is achieved during the last step- step 3.

Step 01

Shiftable loads and pumps are scheduled with a nonlinear optimization method using the following objective function and the output of the simulation is illustrated in figure 4.11.

Objective function 1:

$$\textit{Total Cost} = \begin{matrix}\textit{Total Cost for}\\ \textit{Shiftable Loads}\end{matrix} + \begin{matrix}\textit{Total Cost for}\\ \textit{Base Loads}\end{matrix} - \begin{matrix}\textit{Total Gain from}\\ \textit{Grid}\end{matrix} \quad (8)$$

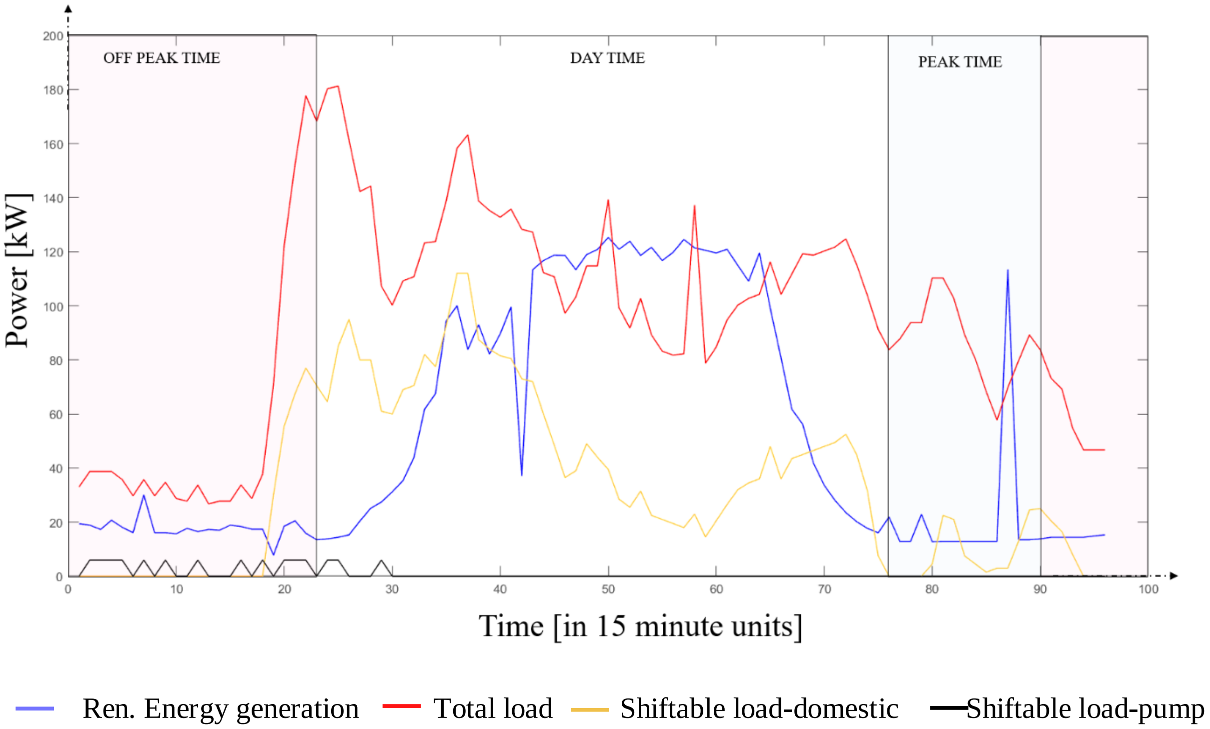


Figure 4.11: Load profiles after the optimization at level 1

Step 02

The first stage of AC load optimization is done in this step. During the off-peak (10.30 PM to 5.30 AM) 20,000 L storage is fully filled with chilled water and will start discharging at 5.30 AM. Next, the algorithm will estimate the required chilled water capacity to bring from day-time to operate in peak time. Finally, the algorithm will identify the best time slots to generate this required amount of chill water. Load profiles prior to the optimization and after the optimization is shown in figure 4.12

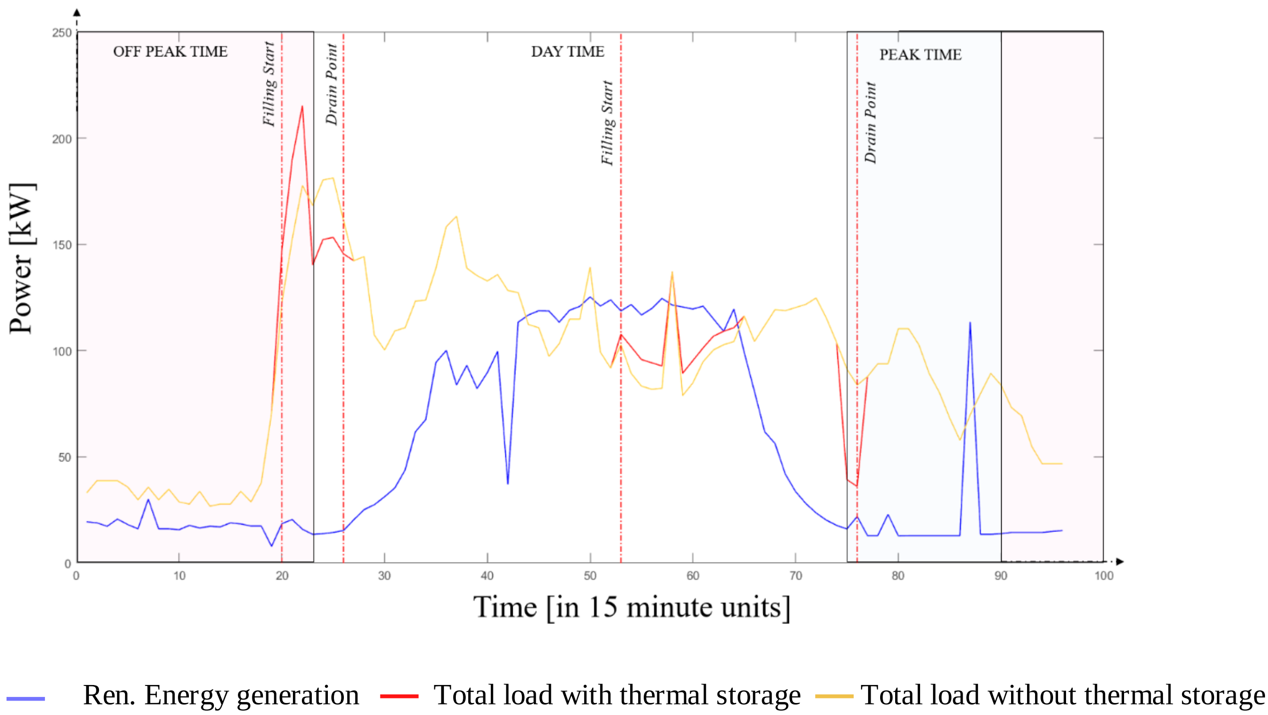


Figure 4.12: Load profiles after the optimization at level 2

Step 03

As seen in figure 4.12, there is excessive renewable energy generated during day-time and peak time. That issue is addressed in this step by generating more chilled water and using them during low RE situations. The process is to explain using an example shown in figure 4.13. Here, two main objective functions are used Eq. (9) and Eq. (10). One constraint is used to determine the storing and discharging locations and the other one is used to match the demand and supply of chilled water and the output of the simulation is illustrated in figure 4.14.

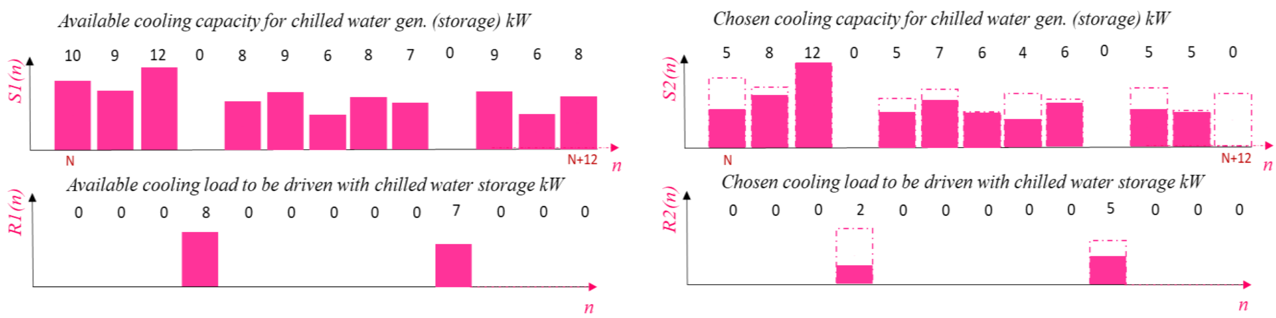


Figure 4.13: Thermal storage optimization-level 3

Objective function 2:

$$Cost = \sum_{n=N}^{N+12} S2(n) * k1 + \sum_{k=N}^{N+12} R2(n) * k2 + \sum_{k=N}^{N+12} [R1(n) - R2(n)] * k3 \qquad (9)$$

Objective function 3:

$$\sum_{k=N}^{N+12} R2(n) = \sum_{k=N}^{N+12} S2(n) \qquad k3>>k2>>>k1 \qquad (10)$$

K3-Cost of chill water generation (with Renewable energy)

K2-Cost of cooling load-driven by thermal storage

K1-Cost of cooling load-driven by grid energy

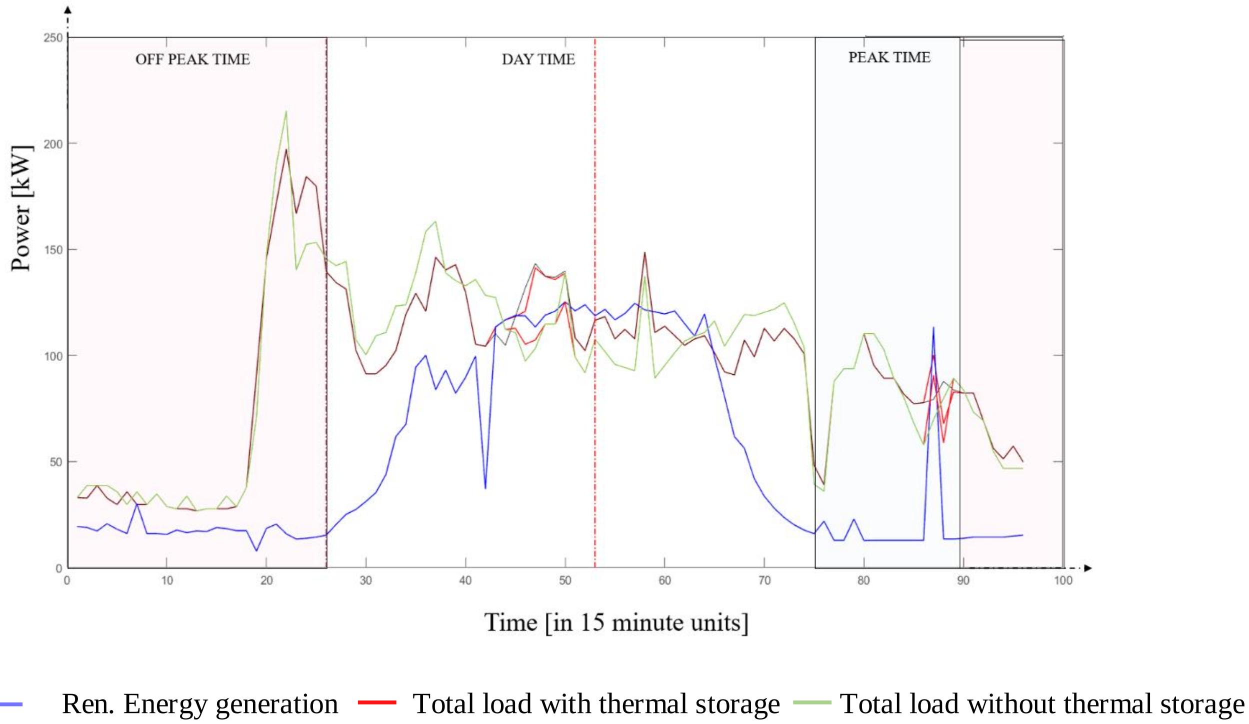


Figure 4.14: Thermal storage optimization-level 3

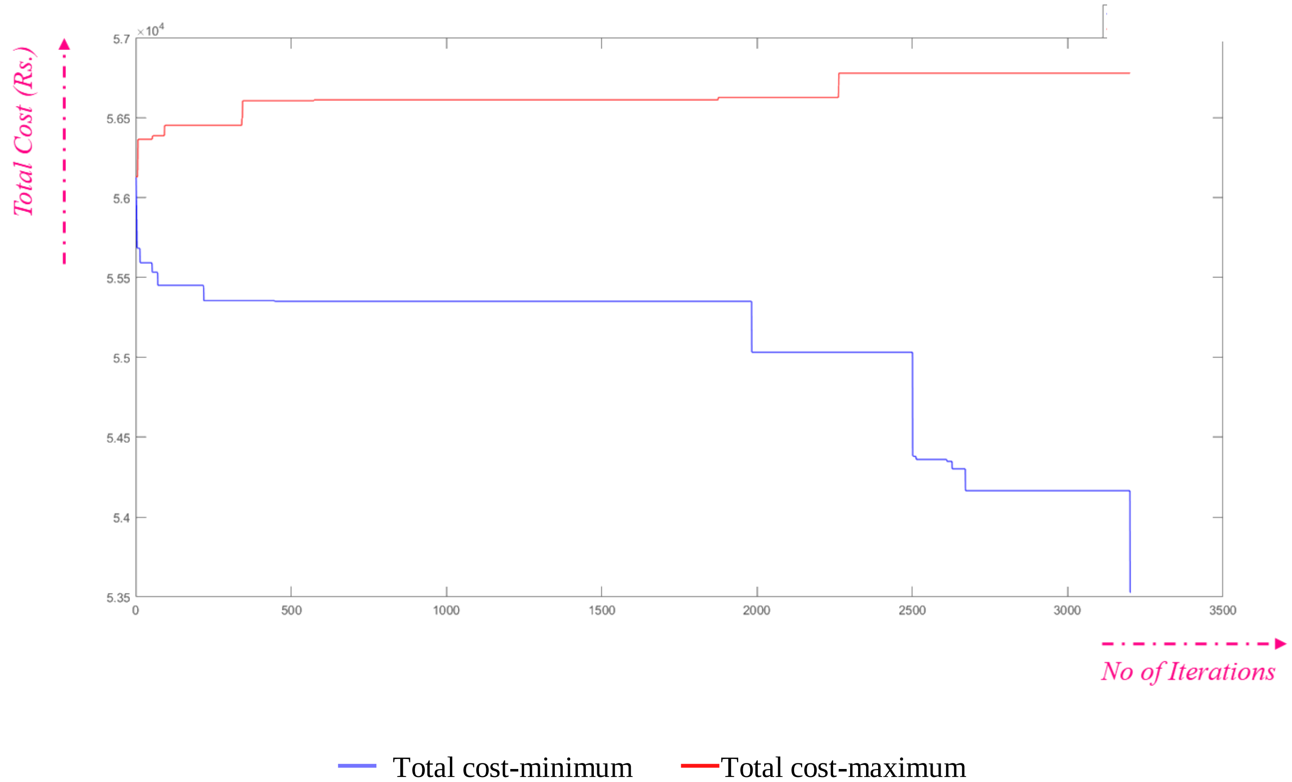


Figure 4.15: Reduction of total cost towards the number of iterations

Figure 4.15 illustrates how total cost reached its minimum over successive iterations. A possible maximum total cost is also estimated for the comparison.

4.3.4 Constraints

Constraints provide a guide to achieve the final optimum schedule for the loads. Two types of constraints are identified during the process.

- Static Constraints
  - Quantified amount of constraint is constant throughout the algorithm
    Ex- transformer capacity, the capacity of the chiller, maximum thermal storage
- Dynamic constraints
  - Quantified amount of constraint is varying throughout the algorithm
    Ex- Interrelationship between appliances, the current capacity of thermal storage

Following constraints were considered during the algorithm development

- Transformer capacity (250 kVA)
- Consumer’s preferred time for appliance operation
- Interrelationship between appliances (Eg: washing machine and dryer)
- Strength of the thermal storage insulation (chilled water storage tank & Geyser tank)
- The capacity of the thermal storage (chilled water storage tank & Geyser tank)
- The capacity of the Chiller

- The temperature of chilled water
- Total daily water demand for the housing scheme
- Pump flow rate

4.3.4.1 Interrelationship between appliances

As mentioned earlier, the user can operate an appliance not more than three times per day as a shiftable load. When identifying the optimum operation points (schedule) for the appliances, their previous operation periods act as restricted areas. But these restricted areas change with each iteration. Therefore, they are called “dynamic constraints”. Figure 4.16 shows the scheduled timing diagram for a washing machine.

24 hours of a day is divided into 15 minutes time slots and there are 96 such slots.

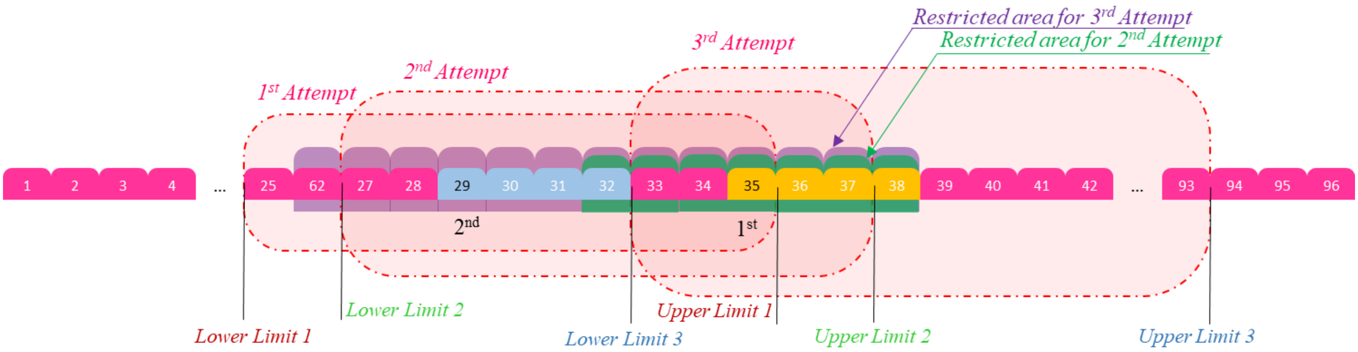


Figure 4.16: Timing diagram-scheduling for a washing machine

If the user preference for the first attempt is between 25 -37 slots and the algorithm should identify a 4-slot period as the washing machine takes 1 hour to operate within the range. If the user preference for the second attempt is between 27- 40, the only available region will be 27-34 as the device used slots 35 – 38 during their 1st attempt. If the user would like to operate the washing machine for the third time during 33- 93 time slots, only the available period is from the 39th slot to the 93rd slot.

Above restriction only consider the restrictions made by the usage of the same appliance. There are interdependent appliances like washing machines and dryers. Users are allowed to decide the operation of dryer reference to the washing machine's operation point. In such a situation other than the above restrictions there will be new restrictions. Figure 4.17 shows the timing diagram when the appliance interdependency occurs.

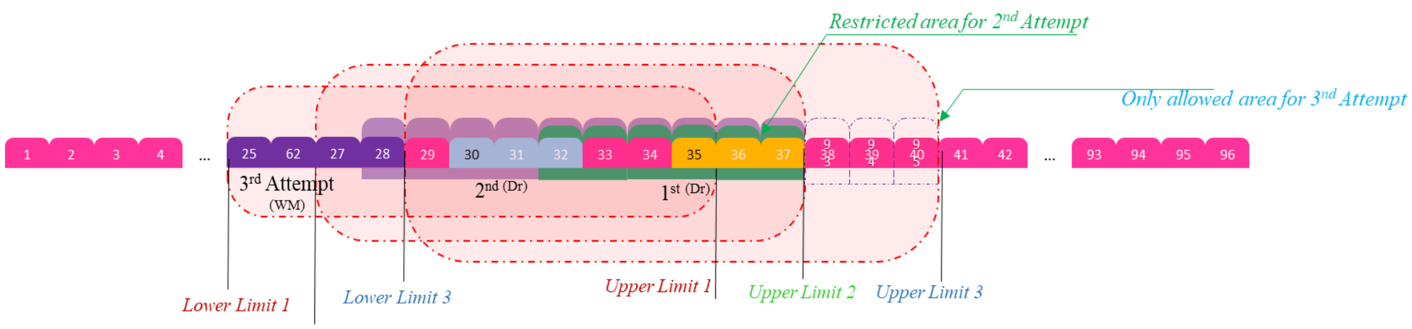


Figure 4.17: Timing diagram-interdependency between the washing machine and dryer

The operation of a geyser is the difference from the operation of other appliances. This is a storage type geyser and its tank is insulated so it can maintain the temperature for 8 hours. So, the switching ON of the geyser can be done 32 slots prior to the user's preference. If there are more than one attempt per day, the next possible range starts after the first/second usage of the geyser. There are two possible scenarios explained in figure 4.18 and figure 4.19.

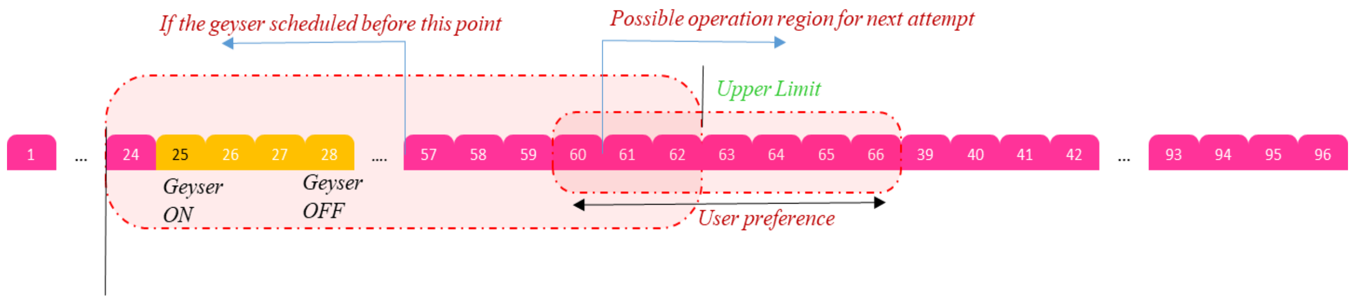


Figure 4.18: Timing diagram-operation mode 1 of geyser

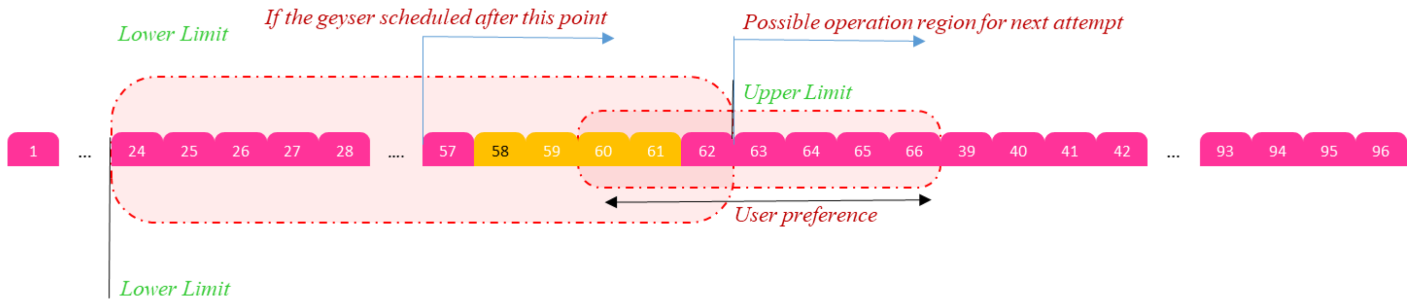


Figure 4.19: Timing diagram-operation mode 2 of geyse

Chapter 5

5 Financial Analysis

5.1 Investment and Payback

Based on published records by the International Renewable Energy Agency (IRENA) in 2018, capital cost for solar power is 1145$/kW and 1075$/kW for wind power. The estimated annual operation and maintenance cost for a solar PV system is considered as 15$/kW and for wind power, it is 20$/kW. Including all these components total project cost is estimated to be around 38.5 MN LKR.

Considering the environmental and weather conditions around the Colombo area, it is expected around 220,000 kWh electricity generation from the proposed 100 kW solar PV system in a year and 128,000 kWh of electricity from 50 kW wind turbine per year.

Figure 5.1 shows the cumulative values of expected revenues for 20 years of period. If the investor decided to go with the conventional net accounting method, it will take 10 years to recover the project cost. But with the proposed concept, total project cost can be achieved by approximately 8 years.

- *Estimated total project investment* = *30 MN Rs.*
- *Estimated total project cost (including O&M cost)* = *38.5 MN Rs.*
- *Simple payback period* = *8 years*
- *Amount of extra revenue gained with the proposed concept* = *17.6 MN Rs.*

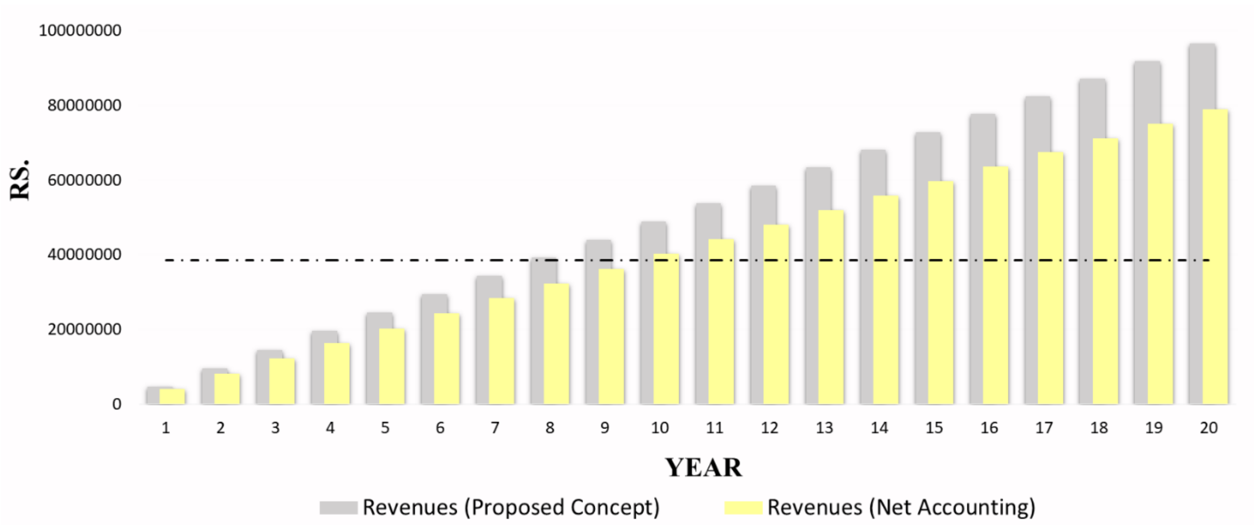


Figure 5.1: Revenues over 20 years-proposed vs. conventional methods

5.2 Benefits for the consumers

If there are no such implements, customers have to purchase electricity from the CEB for higher prices. For off-peak, it is 13 Rs. /kWh, 25 Rs./ kWh for day time and 55 Rs./kWh during peak time. With the proposed system, electricity prices are reduced for both shiftable loads and base loads, but priority is given to the shiftable loads to encourage the user's contribution to the proposed concept. There is an indirect energy saving for customers by using a central air condition system where the coefficient of performance (COP) is 5.6. Most commonly available split type air-conditioner systems in Sri Lanka have COP values lesser than 4. Figure 5.2 shows how the unit cost price changes for both critical and noncritical loads within a simulated day

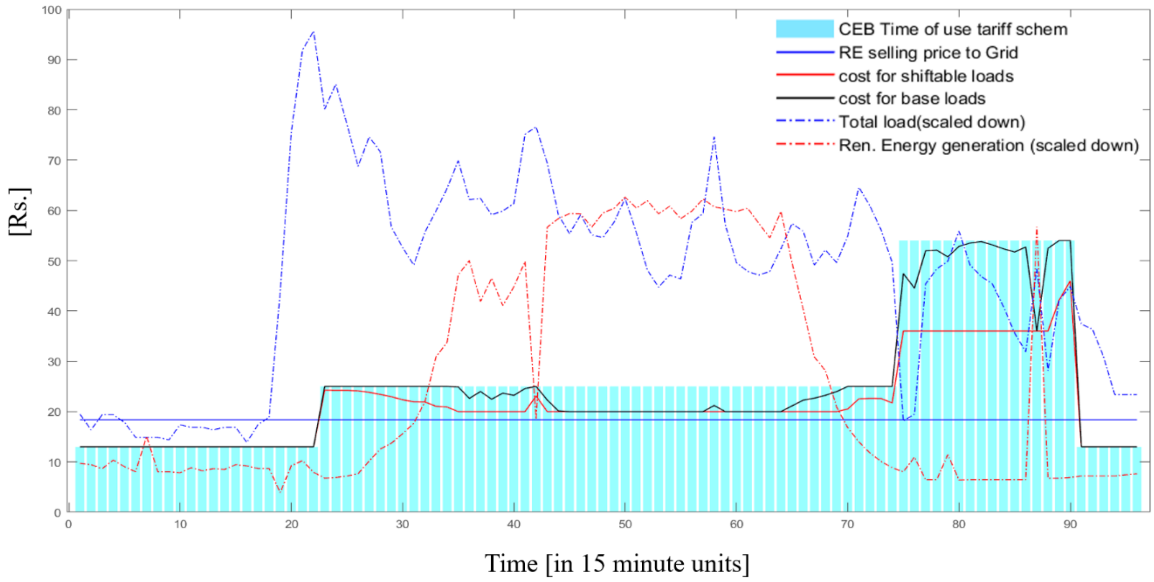


Figure 5.2: Unit cost price variation over the simulated day (for bot critical loads and base loads)

Financial benefits from the proposed method are compared with the worst scenario (with the same amount of load but with CEB time of use tariff method) in Figure 5.3. User preferences for operating shiftable loads are considered to be the same in both cases and the effect of using a central air condition system is also uncounted. Monthly average savings per house from the proposed system is around 16,000 Rs. Which is a 33% reduction for a traditional customer.

$$\text{Average monthly savings per house} = \left(\frac{30}{50}\right) \times \sum_{k=1}^{50} \left(Cost\ of\ Electricity_{\ worst} - Cost\ of\ Electricity_{\ best}\right) \quad (8)$$

$$= 16{,}100\ Rs.$$

- *Which is 33% reduction for a traditional customer*

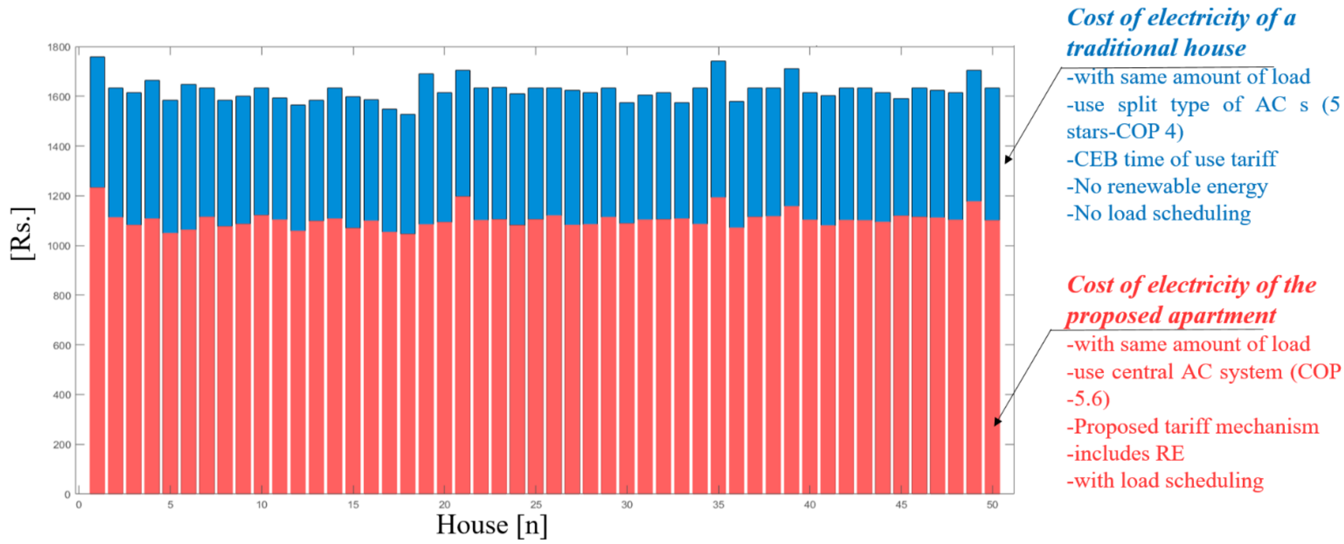


Figure 5.3: Savings for the consumers live in the proposed apartment over a conventional apartment

5.3 Share of cost-saving sources

The main four cost-saving sources are identified and 79% of cost-saving yields from the high efficient central air condition system. (Figure 6.4) By load shifting (including pumps) 13% of the cost is reduced and 8% of the cost is saved by optimizing the thermal storage for the AC system. Figure 5.4 shows the share of all cost-saving sources.

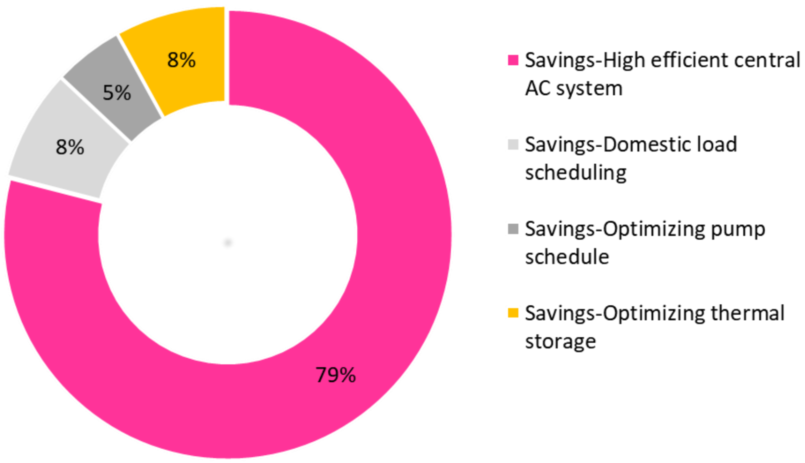


Figure 5.4: Share of cost-saving sources

Chapter 6

Conclusions

The main objective of this research was to develop a mechanism for optimum usage of renewable energy in a housing scheme/ apartment complex to ensure both the investors and consumers will be fairly benefited. To achieve this aim, this project proposed (i) an algorithm for day-ahead load scheduling that gurantees a consumption of higher proportion of energy generated by the renewable energy sources within the apartment complex, and (ii) a pricing mechanism to recover the investment cost.

6.1 Benefits for the consumers

In a consumer’s perspective, existing methods are less flexible and fail under variations in user behaviors. The proposed method will always run based on consumer’s preferences thereby adding more flexibility. Shiftable loads can be operated in isolation or in combination with other loads, and more loads can be easily adopted to the system. Chosen shiftable loads can be operated more than once per day, which is an enhanced benefit in the proposed method that is not offered in the existing methods.

Algorithm was simulated using Matlab® for the proposed system. Results indicated that with the proposed method, the customers are directly benifitted with ~33% reduction in the electricity bill through its user-friendly concept, and satisfaction of high-end lifestyle with low-cost energy where it would have cost ~16,000 Rs. or higher if the consumers were to use CEB tariff mechanism.

6.2 Benefits for the Investor

Usually, a similar type of renewable energy plant will take around 10 years to pay back its project cost under the net accounting grid integration method. However, according to the results, the proposed system will benefit its providers/investor with a quick payback period which is ~8 years. With the proposed system investors can sell renewable energy to its consumers directly for a higher price than what CEB pays. This will provide an additional income of ~16.7 million Rs. within the project period.

Placement of wind turbines on top of the building reduces the cost of tower and will also increase the annual average power generation by ~60% since wind speed increases with elevation. However, wind turbine construction at higher elevation where wind speeds are higher need be done after a proper risk assessment.

Moreover, this method adds an extra marketing point to sell apartments, which makes it beneficial for the building construction industry.

6.3 Overall Conclusions

The proposed system will help to reduce the global carbon footprint and contribute towards increasing the global renewable energy share. This will also help reducing peak time energy demand, thereby lowering the high cost associated with the energy generation.

This system can be further improved by increasing the number of shiftable loads, and developing an AI algorithm to collect information on behalf of the users by checking historical data and other logical factors.

Finally, the overall daily electricity cost can be further reduced by implementing a hardware platform allowing the consumers to operate appliances remotely.

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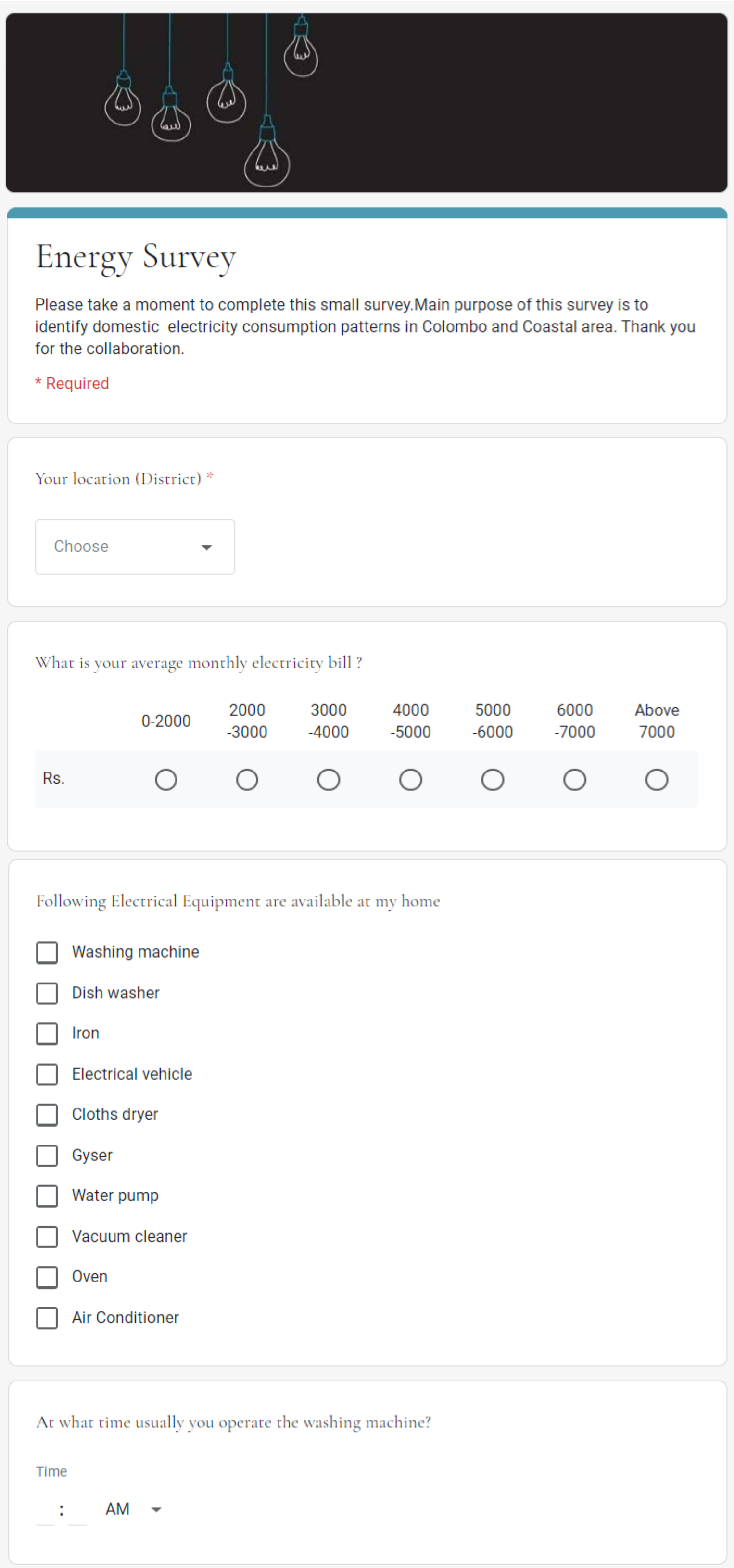
APPENDIX 01

The online questionnaire form is available from:
https://docs.google.com/forms/d/e/1FAIpQLSekxx2mjw1Y4DlEy8X4JBv44QG1ijjE0veWDRqzjEczgfgtew/viewform



Energy Survey

Please take a moment to complete this small survey.Main purpose of this survey is to identify domestic electricity consumption patterns in Colombo and Coastal area. Thank you for the collaboration.

* Required

Your location (District) *

Choose

What is your average monthly electricity bill ?

	0-2000	2000 -3000	3000 -4000	4000 -5000	5000 -6000	6000 -7000	Above 7000
Rs.	○	○	○	○	○	○	○

Following Electrical Equipment are available at my home

- ☐ Washing machine
- ☐ Dish washer
- ☐ Iron
- ☐ Electrical vehicle
- ☐ Cloths dryer
- ☐ Gyser
- ☐ Water pump
- ☐ Vacuum cleaner
- ☐ Oven
- ☐ Air Conditioner

At what time usually you operate the washing machine?

Time

: AM

At what time usually you use the dryer?

Time

: AM

At what time usually you iron cloths?

Time

: AM

At what time usually you charge your electrical vehicle?

Time

: AM

At what time usually you switch ON your geyser?

Time

: AM

At what time you usually switch ON the water pump?

Time

: AM

At what time you usually use the vacuum cleaner?

Time

: AM

Monthly electricity consumption of your home ?

Your answer

Would you like to invest for a solar PV system ? If so what will be the investment capacity ? *

- 1.5 kW (can gain around 180kWh/month) -4.5 lakhs Rs.
- 2.0 kW (can gain around 240kWh/month) -6.0 lakhs Rs.
- 2.5 kW (can gain around 300kWh/month) -7.0 lakhs Rs.
- I don't want to go for solar PV
- Other:

Submit

APPENDIX 02

Financial evaluation of renewable energy plant

Year	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***
Solar PV (100 kW)																				
Energy Generation (kWh/Yr)	119,956.65	116,957.73	116,139.03	115,326.05	114,518.77	113,717.14	112,921.12	112,130.67	111,345.76	110,566.34	109,792.37	109,023.83	108,260.66	107,502.83	106,750.31	106,003.06	105,261.04	104,524.21	103,792.54	103,066.00
Σ(kWh/Yr)	119,956.65	236,914.38	353,053.40	468,379.46	582,898.23	696,615.37	809,536.49	921,667.16	1,033,012.92	1,143,579.26	1,253,371.63	1,362,395.45	1,470,656.11	1,578,158.95	1,684,909.26	1,790,912.33	1,896,173.37	2,000,697.58	2,104,490.13	2,207,556.12
AVG Solar Gen. (kwh/yr)	110,377.81																			
O & M Cost (Rs.) 15$/kW.yr	261,000.00	130,500.00	130,500.00	130,500.00	130,500.00	130,500.00	130,500.00	130,500.00	130,500.00	130,500.00	130,500.00	130,500.00	130,500.00	130,500.00	130,500.00	130,500.00	130,500.00	130,500.00	130,500.00	130,500.00
Σ(O & M Cost)	261,000.00	391,500.00	522,000.00	652,500.00	783,000.00	913,500.00	1,044,000.00	1,174,500.00	1,305,000.00	1,435,500.00	1,566,000.00	1,696,500.00	1,827,000.00	1,957,500.00	2,088,000.00	2,218,500.00	2,349,000.00	2,479,500.00	2,610,000.00	2,740,500.00
Investment -1145$/kW	19,923,000.00																			
Invesstment + Σ(O & M Cost)	20,184,000.00	20,314,500.00	20,445,000.00	20,575,500.00	20,706,000.00	20,836,500.00	20,967,000.00	21,097,500.00	21,228,000.00	21,358,500.00	21,489,000.00	21,619,500.00	21,750,000.00	21,880,500.00	22,011,000.00	22,141,500.00	22,272,000.00	22,402,500.00	22,533,000.00	22,663,500.00
LCOE Rs./kWh	10.27																			
Solar gen Day time (%)	0.98																			
ΣC. Solar gen during day time	117558	232176	345992	459012	571240	682683	793346	903234	1012353	1120708	1228304	1335148	1441243	1546596	1651211	1755094	1858250	1960684	2062400	2163405
Tariff (Rs./kWh)	20																			
ΣC. Solar gen during peek time	2399	4738	7061	9368	11658	13932	16191	18433	20660	22872	25067	27248	29413	31563	33698	35818	37923	40014	42090	44151
Tariff (Rs./kWh)	36																			
Wind (50 kW)																				
Energy Generation (kWh/Yr)	128160	128160	128160	128160	128160	128160	128160	128160	128160	128160	128160	128160	128160	128160	128160	128160	128160	128160	128160	128160
Σ(kWh/Yr)	128160	256320	384480	512640	640800	768960	897120	1025280	1153440	1281600	1409760	1537920	1666080	1794240	1922400	2050560	2178720	2306880	2435040	2563200
O & M Cost (Rs.) -20$/kW.yr	174000	174000	174000	174000	174000	174000	174000	174000	174000	174000	174000	174000	174000	174000	174000	174000	174000	174000	174000	174000
Σ(O & M Cost)	174000	348000	522000	696000	870000	1044000	1218000	1392000	1566000	1740000	1914000	2088000	2262000	2436000	2610000	2784000	2958000	3132000	3306000	3480000
Investment 1075$/kW	14352500																			
Invesstment + Σ(O & M Cost)	14526500	14700500	14874500	15048500	15222500	15396500	15570500	15744500	15918500	16092500	16266500	16440500	16614500	16788500	16962500	17136500	17310500	17484500	17658500	17832500
Wind power gen. day time %	0.46																			
Wind power gen. peak time %	0.18																			
ΣC. wind power gen during day time	58954	117907	176861	235814	294768	353722	412675	471629	530582	589536	648490	707443	766397	825350	884304	943258	1002211	1061165	1120118	1179072
Tariff (Rs./kWh)	20																			
ΣC. wind power gen during Peek time	23069	46138	69206	92275	115344	138413	161482	184550	207619	230688	253757	276826	299894	322963	346032	369101	392170	415238	438307	461376
Tariff (Rs./kWh)	36																			
ΣC. wind power gen during Off Peek time	46138	92275	138413	184550	230688	276826	322963	369101	415238	461376	507514	553651	599789	645926	692064	738202	784339	830477	876614	922752
Tariff (Rs./kWh)	13																			
LCOE Rs./kWh	6.96																			