Power Generation Shortage in Developing Countries: Causes, Challenges and Solutions

by

Ameena Saad Al-Sumaiti

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Doctor of Philosophy
in
Electrical and Computer Engineering

Waterloo, Ontario, Canada, 2015

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Electricity consumers in developing countries are seeking reliable electricity services to subsidize the economy and assist the rising population. Underprivileged electricity services are major concerns for these consumers because of power generation shortage. Electricity consumers will be disconnected from the grid as a mean of reducing the total load connected to the distribution grid. In many developing countries, the problem is considered to be severe due to population growth. It is also recognized that electricity shortage negatively affects the quality of life of the residential consumers in these countries.

This thesis proposes ways to reduce the severe effect of power generation shortage on developing countries' consumers and these ways are appropriate for application in remote communities in Canada. These reductions are targeted to utility and residential electricity consumers to address the power generation shortage problem in developing countries.

The current status of electricity demand restricts grid expansion due to the limited available power generation. With population growth, there is a demand for a system reinforcement. This reinforcement is either by controlling the behavior of electricity consumers or accommodating new electricity supply resources. Since the behavior of electricity consumers is a major factor contributing to high electricity demand compared to the available power generation, this thesis will focus on optimally scheduling residential demand to minimize the negative gap between the current supply and the future expected demand by proposing two approaches based on scheduling the supply of electricity to either houses or devices within them. These approaches account for the uncertainty in many factors governing consumers' perception to utilize electricity. From the utility aspect, this thesis proposes improving the grid efficiency by considering investments in alternative sources of supply, such as renewable energy sources to support the current generation to accommodate population growth. The economical aspects to select the best distribution generation sources are shown in this thesis. The thesis will also investigate how current policies can be modified to encourage investors in the power sector to build these resources. It is well known that developing countries do not have the adequate financial resources to build these resource systems. The thesis will also target finding the proper sizes of such energy systems by considering the uncertainty in the generation from these resources to address the power generation shortage. This solution is further expanded by considering the cooperation between the utility and the residential consumers to reduce the size of renewable energy systems while considering residential consumers' demand scheduling.

The thesis sets recommendations targeting electricity services improvement to facilitate not only consumers' lives, but also countries' economies.

Acknowledgements

I praise and glorify Allah who creates a vicegerent on earth and who knows what I do not know. Thanks goes to Allah giving me strength and support during the PhD degree journey. I am heartily thankful to my home country United Arab Emirates and its rulers for their continuous encouragement and support. My deepest gratitude goes to Sheikh Mohammed Bin Zayed Al Nahayan.

I would like to thank Masdar Institute for my PhD scholarship. I would like to express my sincere gratitude to my supervisor, Professor Magdy Salama, for his endless encouragement and invaluable guidance throughout this journey. I would like to extend my appreciation to my examination committee members: Professor Mohamed El-hawary, Professor Ali Elkamel, Dr. Ramadam Elshatshat, Dr. Tarek Elfouly and Dr. Peter Douglas.

I have been lucky enough to be raised in a loving family. Life without my parents would not be the same. I would like to dedicate flowers: The first flower is a red rose and goes for my mother; the second flower is a purple flower and is dedicated to my father. Gladiolus flowers are dedicated to my beloved brothers Abdulla and Sultan, and my uncle Hussein; yellow roses to my sisters Tareefa, Mahra and Kaltham, and a lily to me. Since flowers cannot be green, I would like to dedicate white flowers to the souls of my brother Faisal and my grandmother Ameena. I would like to express my sincere thanks to my relatives in United Arab Emirates and Kuwait for their love and prayers. My deepest thanks go to my best friends in Waterloo. I would like to thank my colleagues for their advice and continuous encouragement. Lastly, my regards go to all of those who supported me in any respect during the completion of my thesis.

Dedication

To the spirit of the father of United Arab Emirates His Highness Sheikh Zayed Bin Sultan Al-Nayahan, God bless his soul and grant him paradise

To His Highness Sheikh Mohammed Bin Zayed Al-Nahayan

To my mother Aishah and father Saad, and my God mother Fatmah

With my greatest gratitude

To UAE and Kuwait

With love

Table of Contents

List of Figures

List of Tables

Nomenclature

Abbreviation	Definition
A	
a	Project indicator
A	An annual repayment (INR)
A̲	Specified number of PV systems
af	Weight assigned to a variable of the objective function that targets maximizing the demand that can be met and minimizing the number of renewable energy systems
Area	Area of a house surface experiencing heat lost (m^2)
B	
b	Project indicator
B	Surface indicator
Base	The annual base line emissions (tons)
bb	The imaginary component of the admittance matrix
B/C ratio	Benefit to cost ratio
bf	Weight assigned to a variable of the objective function that targets maximizing the demand that can be met and minimizing the number of renewable energy systems
BigM	A large number
BMN	The build margin of carbon dioxide emission (tons/MWh)
Book	Book value of the project (INR)
C	
c̲	Price of electricity to be charged (INR/kWh)
C	The capital cost of 1MW project (INR)
Carbon	The revenue from carbon credits (INR)
Cap	Size of the washing machine ($feet^3$)
Capital	The capital cost of 3MW project (INR)
Cash	The calculated after tax project cash flow when applying the current regulation (INR)
CF	Criterion function
COM	The cost of contingencies on OM (INR)
cost of capital	The cost of capital (%)
CUF	A capacity utilization factor of a generation source (%)
$CYC_{washing\text{-}machine}$	Number of cycles run by the washing machine per use (Cycles/use)
D	
d	A day number
D	A free variable to linearize (*LSupplied * Zbinary)*
D̲	The depreciation tax basis (%)
day	Number of weekdays
DB	The amount of depreciation that should be carried out until year 21 (INR)

DC_1	The first central moment of the data generated through the Monte-Carlo simulation
DC_2	The second central moment of the determined Monte-Carlo simulation data
$\overline{DC_1}$	The first central moment of the ($\tilde{x}_i - \bar{e}$) Monte-Carlo simulation generated data
$\overline{DC_2}$	The second central moment of the ($\tilde{x}_i - \bar{e}$) Monte-Carlo simulation generated data
$\overline{DC_3}$	The third central moment of the ($\tilde{x}_i - \bar{e}$) Monte-Carlo simulation generated data
debt	The loan as a percentage of the capital cost of the project (%)
dem	Hot water demand (gallons)
DF	The difference between cash flows of 1MW projects (INR)
$\underline{DF}$	Discount factor (%)
dep	The depreciation amount in a year considering the general economic analysis of 1MW project (INR)
$\underline{dep}$	The depreciation amount considering the regulations on project structure od 3MW project (INR)
Difference	The difference between cash flows of 3MW projects (INR)
DR_2	The second raw moment of the ($\tilde{x}_i - \bar{e}$) Monte-Carlo simulation generated data
DR_3	The third raw moment of the $\tilde{x}_i - \bar{e}$ Monte-Carlo generated data
DR_4	The fourth raw moment of the $\tilde{x}_i - \bar{e}$ generated data through the Monte-Carlo simulation
dT	Well's water temperature loss as a matter of radiation (ºC)
DT	The term loan duration (years)
E	
E	The total square of errors in the internal rate of returns of the project
e_{c1}	The first central moment error for wakeby distribution
e_{c2}	The second central moment error for wakeby distribution
e_{R3}	The third raw moment error for wakeby distribution
e_{R4}	The fourth raw moment error for wakeby distribution
E	Free variable replacing a nonlinearity term
EC	Electricity cost of operating a certain device (INR)
EF	The efficiency of the water heater (%)
$\underline{EF}$	Emission factor (tons/MWh)
$Efficiency_{washing\text{-}machine}$	A factor representing how efficient the washing machine is and is measured in ($feet^3$/kwh)
EK	The expected annual electricity production of the project (MWh)
equity	Equity ratio (%)

end	Number of weekends
$Energy_{washing\text{-}machine}$	Energy utilized by washing machine (kWh/use)
Eng	Electricity (kWh) generated from diesel generator
esc	An escalation rate of the electricity price (%)
F	
fan	Electric fan
fancanbesupplied	A binary variable that is one when the electric fan can be supplied with electricity and that is zero otherwise
Fcash	The after tax cash flow considering the general economic analysis of 1MW project (INR)
factor	A variable assigned a value based on regression analysis relating the variability of factor and wind speed data
FF	A fill factor
$f(sp)$	The probability density function (*pdf*) of wind speed (*sp*)
$F(sp)$	The cumulative distribution function (*cdf*) of wind speed
fuel	The cost of fuel if used (INR/Liter)
G	
G	A free variable that is a substitute to the multiplication given by ($LSupplied_{n,t,s}$* (1-$ZZbinary_{n,t,s}$)*$T_{house\ n,t,s}$)
gg	The real component of the admittance matrix
GC_1	The general extreme value distribution's first central moment
GC_2	The general extreme value distribution's second central moment
GLT	The gain/loss tax
GLTRate	The gain/loss tax rate applied on any gain or loss from the project salvage value compared to its book value (%)
H	
HC	Joule per kelvin capacity of the heat (J/ºK)
hour	One hour
HR	8760hours/year
$h(sp)$	A power function of cut in speed and rated speed of wind and the rated power output of the wind turbine (kW)
hub height	Wind turbine hub height (m)
I	
i	Bus number
$\underline{i}$	Interest rate (%)
$\bar{i}$	PV power data point order
icapital	The interest paid on the working capital (INR)
icarbon	The value added tax rate to be applied on the revenue generated from the carbon credit (%)
inf	The inflation rate (%)

interest	The amount of interest paid on the loan (INR)
IRR	Internal rate of return (%)
I_{mp}	The PV module's current as determined at the maximum power point (Ampere)
In	Income (INR)
I_{sc}	Short circuit current (Ampere)
$I_{sc@stc}$	The short circuit current of PV module determined at the standard test condition (Ampere)
IT	The tax on net income following the current regulations on 3MW project cash flow
ITRate	The tax rate applied on the net income considering the current regulations on 3MW project cash flow (%)
J	
J	The weighting coefficient representing the corresponding importance of a regulation
K	
$\hat{k}$	Parameter of the general extreme value distribution
K	The number of hours for which the well pump will be utilized (hours)
K	The electricity price from a generation source (INR/KWh)
Kk	The number of compounding periods in the year *n*
L	
LAN_{fan}	$1\text{-}U_{fan}$
light	Light demand (kW)
LL	The number of times the washing machine will be utilized
LSupplied	A binary variable that will have a value of one when the water heater can be supplied with electricity and will have a value of zero when such supply is not possible
M	
M	A number indicating the type of the device
M	Indicator of a certain month
*m**	Regulation number
MACRS	Modified attractive cost recovery system rate (%)
MachineSupply	A binary variable that will have a value of one when the washing machine can be supplied with electricity and will have a value of zero when such supply is not possible
MARR	Minimum accepted rate of return (%)
MAT	The minimum alternate tax
MATRate	The minimum alternate tax rate (%)
Max house connected load	Residential house connected load (kW)
Mi	Monthly income (INR)
MfanM	A free variable that represents the multiplication of two binary variables one indicating whether the electric fan should be ON or OFF based on the comfort level and the other is an indication of the availability of power supply for this device at that moment

MO	The expected carbon dioxide emission of the project (tons)
$Myobj_{typical\ case\ scenario}$	The objective function to be minimized in the optimization problem targeting minimizing the percentage to be spent from the gained income of a working individual in a developing country on the electricity bill (%)
N	
N	House number
$\underline{N}$	Year number
$\bar{n}$	The total number of PV power data points
N	The number of both parallel and series modules in a PV system
$NCOT$	The nominal cell operating temperature (ºC)
net income	The net income of the project (INR)
$\bar{n}(\bar{i})$	The rank of the PV power data point
npw	Calculated net present worth (INR)
NPW(TL)	The calculated net present worth when the term loan is variable (INR)
NPW(IT)	The calculated net present worth when the tax rate on taxable income is variable (INR)
NPW(P)	The calculated net present worth when the price of electricity generated from a renewable energy source is variable (INR)
number	Number of renewable energy systems
O	
O	Binary variable
Obj	An objective function in chapter 6
Objj	An objective function in Chapter 6
old height	The height at which the weather station measures wind speed (m)
OM	The operation and maintenance cost (INR)
OMI	The operating margin of carbon dioxide emission (tons/MWh)
OMS	The cost of spares for maintenance (INR)
Out	The pretax cash outflow of 1MW project (INR)
P	
P	Power rating of a device (kW)
p	The number of periods in the year $\underline{n}$
$\underline{P}$	The pretax net cash flow of a project considering the current regulations on a 3MW project (INR)
Pcash	The pretax cash flow (INR)
Pd	The active power demand in (kW) or (pu) based on the constraint
PD	The active power demand of a device that is supplied in the first optimization problem (kW)
PF	The power factor at which a device is operated
P_{fan}	The electric fan power rating (kW)
Pg	Active power supplied (pu)
P_{heat}	Space heater power rating (kW)

Phouse	The active power demand of a house (pu)
Ploss	The active losses of the system (pu)
Plow	A lower bound on what active power can be supplied (pu)
$P_{\max}$	The maximum power produced from PV system when PV losses are not considered (MW)
P_{new}	The new calculated PV system power after deducting PV system losses (MW)
PP	Probability of a wind speed state or PV power state corresponding to an hour
P_{rated}	The rated power output of the wind turbine (kW)
Psolar	The PV power output as a ratio of the used PV system rating
pump	Well pump
PumpSupply	A binary variable that is 1 when the pump can be supplied by electricity and that is 0 when power supply to such device is not possible
Pup	An upper bound on what active power can be supplied (pu)
$P_{wellpump}$	Well pump power rating (kW)
Pwind	The 10kW wind turbine power output (kW)
Q	
Q	*Heat loss or heat gain (Watt)*
Qd	The reactive power demand (pu)
QD	The reactive power demand of a device that is supplied in the first optimization problem (kVAR)
Qg	Reactive power supplied (pu)
Qhouse	The reactive power of the house devices consuming reactive power (pu)
Qup	An upper bound what reactive power that can be supplied (pu)
Qloss	The reactive power losses of the system (pu)
Qlow	A lower bound on what reactive power can be supplied (pu)
R	
R	Regulation type indicator
R	A factor to convert the demand to per unit system (pu)
RAT	1MW generation source rating
Rating	The three megawatt rating of the renewable energy source
Rating	Water heater device power rating (kW)
$Rating_{wm}$	Washing machine rated power (kW)
rebate	The rebate rate added to the project as a credit (%)
redu	The annual reduction in carbon dioxide emission
RPM	Revolutions per minute
RTS	A variability factor showing how the demand at bus *i* can vary hourly according to IEEE RTS
S	
S	Season

S	The minimum required equity rate of return (%)
Salvage	The salvage value of the hydro power project (INR)
sh	Space heater
sp	Wind speed (m/s)
$Speed_{Wind}$	Wind speed (Km/hour) generated from the fan's revolutions
sp_{cut-in}	The cut in speed of wind (m/s)
$sp_{cut-out}$	The cut out speed of wind (m/s)
sp_{rated}	The rated speed of wind (m/s)
Specified	A specified number of wind turbines
St	Number of states
state	The corresponding state to a certain probability wind speed or PV power at an hour
Sur	Thermal transmittance of a given house surface (Watt/m^2 K)
T	
t	Time of the day
Tax	Tax rate applied on net income of 1MW project (%)
$\underline{Tax}$	The amount of tax to be paid considering 3MW project (INR)
T_{cell}	The operating PV cell temperature (ºC)
$T_{external}$	The external air temperature out of the house (ºC)
T_{feel}	Felt temperature (ºC)
Therm	The thermostat set point (ºC)
T_{house}	Internal air temperature of the house (ºC)
TI	The taxes on the net income following the general economic analysis for 1MW project (INR)
$T_{operating}$	*Season's temperature operating point of the well's water* (ºC)
Transformer Rating	The rating of the transformer (kVA)
T_{stc}	The PV cell temperature measured at standard test condition (ºC)
$T_{well\text{-}water}$	The supplied well's water temperature (ºC)
U	
U_{fan}	A binary variable that is one when the fan should be ON and that is zero otherwise
$\overline{UP}$	An upper bound on the internal air temperature of the house (ºC)
us	Random variable
V	
V	Voltage (pu)
VAT	The value added tax
V_{mp}	The PV module voltage as determined at the maximum power point (V)
V_{oc}	Open circuit voltage (V)

$V_{oc@stc}$	An open circuit voltage of PV module determined at a standard test condition (V)
W	
W	A factor describing stability
washing	A positive variable that represents the multiplication of two binary variables one indicating whether the washing machine should be ON or OFF based on a consumer's demand for the device and the other is an indication of the availability of power supply for this device at that moment
WC_1	The first central moment of the distribution
WC_2	The second central moment of the distribution
well	A positive variable that represents the multiplication of two binary variables one indicating whether the well pump should be ON or OFF based on a consumer's demand for the device and the other is an indication of the availability of power supply for this device at that moment
Wh	Water heater
Wm	Washing machine
WM	A binary variable that will have a value of one when the washing machine is to be used and a value of zero when it will not be used
wnew	A positive variable that represents the multiplication of two binary variables one indicating whether the space heater should be ON or OFF based on the comfort level and the other is an indication of the availability of power supply for this device at that moment
WR_3	The third raw moment of the distribution
WR_4	The fourth raw moment of the distribution
X	
X	Wind speed data point number
$\underline{X}$	An ordered PV power data point
$\tilde{x}_i$	The Monte-Carlo simulation generated PV power data point i
Xh_{sh}	A binary value that is 1 when the space heater should be on due to customer demand and that is 0
$X_{well\text{-}pump}$	A binary variable that is 1 when the pump should be working due to demand and 0 otherwise
Y	
Y	Admittance matrix magnitude
yyy_{sh}	A binary variable that is 1 when the power supply is available from the utility to supply space heater and that is 0 otherwise
Z	
Zaco	A term used to replace the term ($1\text{-}zzbinary_{n,t,s}$)
zbinary	A binary variable that is one when the water heater should be ON to meet the demand for hot water
ZLoss	Energy consumed because of heat losses from water heater tank surfaces (kWh)
Zzbinary	A binary variable

Z_{fan}	Power consumed by electric fan considering the availability of supply and the demand for the device (kW)
Z_{sh}	Power consumed by space heater considering the availability of supply and comfort level (kW)
Z_{WM}	Power consumed by the washing machine (kW)
z_{WH}	Energy utilized by water heater as a consequence of hot water demand (kWh)
Zwh	Power consumed by the water heater due to both hot water demand and losses from water heater tank surfaces (kW)
$Z_{well\text{-}pump}$	Power consumed by well pump considering the availability of supply and demand for the device (kW)
Other Abbreviations	
α	A positive variable that represents the multiplication of two binary variables
$\widehat{\alpha}$	a variable representing the intercept of the curve relating the IRR and the regulation under study
$\overline{\alpha}$	Parameter affecting the peak location of wakeby distribution
αs	Shape parameter of Weibull distribution
$\overline{\beta}$	Parameter affecting the peak location of wakeby distribution
βs	Scale parameter of Weibull distribution
ΔB	The incremental benefit of the incremental cash flow (INR)
ΔC	The incremental cost of the incremental cash flow (INR)
ΔIRR	An incremental internal rate of return (%)
ε	Parameter of wakeby distribution
δ	Voltage angle
θ	The angle of the admittance matrix
σ	Standard deviation
ψ	A factor indicating PV system's total losses
$\psi_{module\ soiling\ loss}$	The negative value of the efficiency accounting for module soiling losses (%)
$\psi_{module\ mismatch\ loss}$	The negative value of the efficiency accounting for module mismatch losses (%)
$\psi_{DC\ cable\ loss}$	The negative value of the efficiency accounting for DC cable loss (%)
$\psi_{solar radiation loss}$	The negative value of the efficiency accounting for solar radiation loss (%)
$\psi_{module\ temperature\ loss}$	PV module's temperature loss (%)
$\tau_{voltage}$	A voltage-temperature coefficient (%/ºC)

$\iota_{current}$	The current-temperature coefficient of PV module from the manufacture (%/ºC)
λ	The operating global solar irradiance (Watt/m^2)
$\lambda_{@stc}$	The solar irradiance at the standard test condition (Watt/m^2)
ε	Parameter affecting the peak location of wakeby distribution
$\bar{\delta}$	Parameter affecting the height of wakeby distribution
$\overline{\gamma}$	Parameter affecting the height of wakeby distribution
$\Gamma(\ )$	The gamma function
$\hat{\sigma}$	Parameter of the general extreme value distribution
μ	Parameter of the general extreme value distribution

Chapter 1
Introduction

Developing countries are in demand for continuous electricity supply powering their emerging economy as well as aiding growing populations. Scheduled power interruptions due to underfunded power generation capacity directs the attention to investment in alternative sources of energy supply. With the demand growth, precipitating the existing energy use in these countries will raise global climate issues due to emissions of greenhouse gasses. Thus, the investment in clean energy sources such as renewable energy powered by solar and wind energies is a must. Some electricity customers have utilized individual PV systems to supply their houses with electricity, but not all electricity customers are able to consider such a solution due to high associated costs of such systems. This challenge shows the important role that the electric utility company can play in addressing the power generation shortage by considering these renewable energy sources to support power generation from limited fossil fuel resources. Such a utilization of renewable energy sources is more important when considering grid reinforcement by connecting new regions to the distribution grid due to population growth. Nevertheless, with the current economy of developing countries and the associated costs of renewable energy projects, the investors should take a lead in facilitating such projects. Even though there are some projects in the literature focusing on adopting renewable energy sources to supply specific loads, the power generation shortage problem still exists. For the projects to be beneficial over the long run, investors should be given incentives to expand current projects and build new systems. This solution can be facilitated by setting recommendations for governance institutions to modify the current policy in the field governing the investments in such projects.

Given the investors role in supporting energy projects and the demand for the best coordination between end user loads, available power generation, and renewable energy sources in a distribution grid motivated the author’s research to account for future population growth. The thesis targets consumers in developing countries who cannot afford their own generation. This thesis aims to set solutions that can be implemented to address power generation shortages by considering the interaction between the consumers and the electric utility companies in developing countries such that expanding the current grid to accommodate population growth is possible. The proposed solutions can also be applied in remote communities in Canada.

The domain of the current research is in the field of modeling and analysis. The research conducted in the thesis provides new insights into possible real applications of solutions to power generation shortages in developing countries. The thesis outline is shown in Figure 1.1. The thesis is organized as follows:

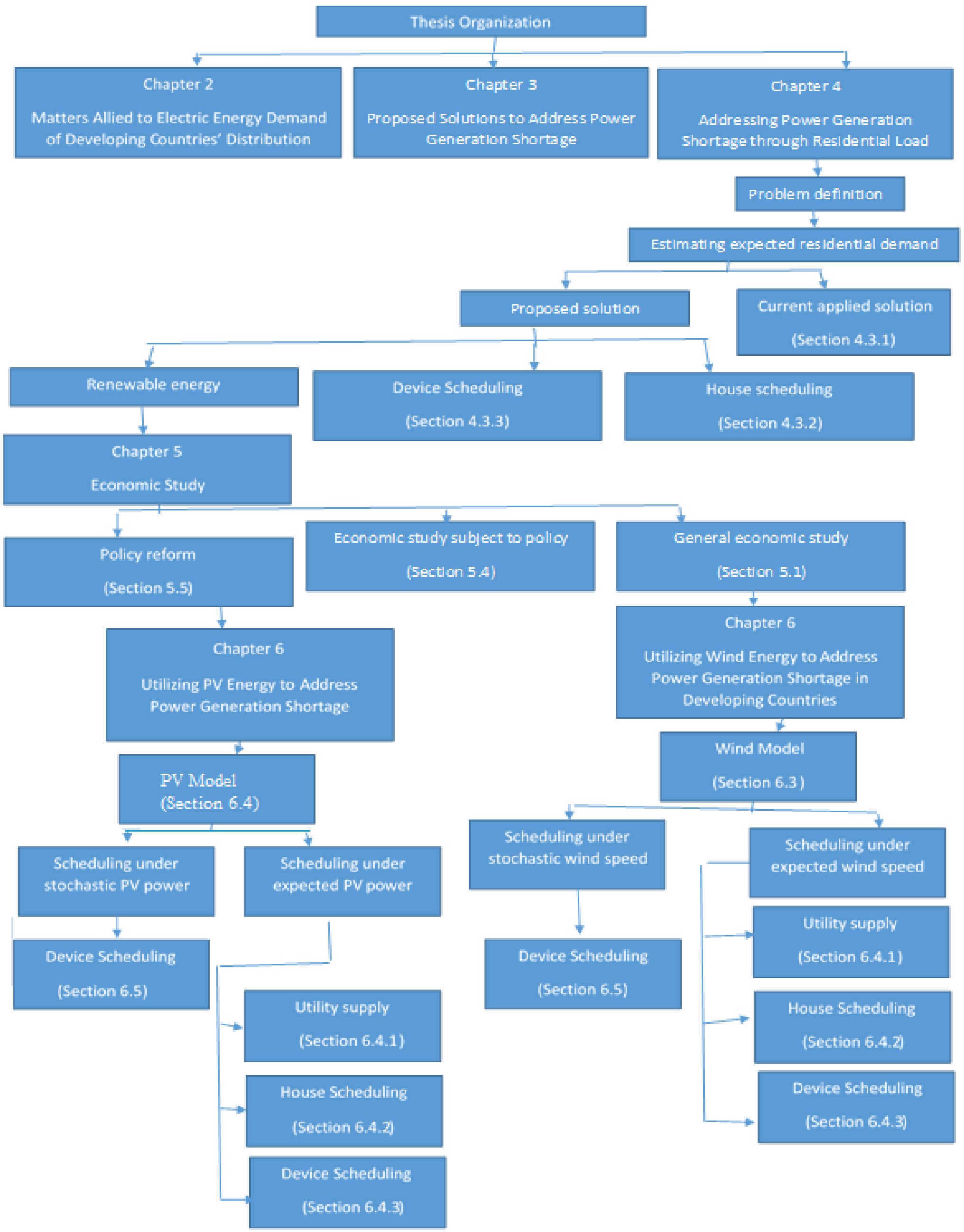


Figure 1.1: Thesis organization

Chapter 2 provides the reader with an overview on issues related to electric energy demand in the distribution system for developing countries by focusing on the current status of electricity consumption and the reasons behind the growth in electricity consumption in developing countries. Furthermore, this chapter will present the devices that are widely adopted in developing countries and their power consumption. Next, the chapter will present the power generation shortage problem (PGS) in developing countries and will describe the practical solutions that are currently applied in these countries by explaining the power generation company, the electric utility company and the residential consumers' roles in the cycle. Then, the chapter will discuss how deficient these approaches are in facing the power generation shortage and will propose alternative solutions.

Chapter 3 is focused on summarizing the proposed solutions to face PGS at both the residential electricity consumers and the electric utilities levels. At the residential consumer level, residential power interruption is studied by considering two approaches to face the problem of power generation deficiency. These are the individual houses' full power interruption, and the houses' devices power interruption. The latter is to be investigated accounting for the uncertainty in the factors governing devices' operation. On the other hand, the possible investments in alternative sources of supply are studied from an electric utility level where investors are provided with the option to participate in project funds. Different renewable energy projects are evaluated from an economical aspect under a general policy and the current policy applied in a developing country. A recommended future policy is also set to encourage investors in the field toward more renewable energy projects to accommodate population growth.

Chapter 4 will focus on presenting the proposed solutions to solve power generation shortages from a residential consumer level. The first solution is based on interrupting the full power of individual houses in typical seasons' days at different hours as a mean of reducing the demand to be connected to the grid. The second solution is based on scheduling consumers' devices to reduce the severity of the power generation shortage by maximizing the number of devices that can be supplied while maximizing consumers' comfort levels. To achieve this solution, house devices' load models are involved in accounting for consumers' preferences, individuals' working hours, stochastic weather condition, and seasonality as major factors governing consumers' demand of electricity. In this case, different aspects of treating the devices' scheduling problem are discussed.

Chapter 5 will present an economic analysis of alternative renewable energy sources available in developing countries to be utilized to address the power generation shortage. The chapter will apply a general economic study not restricted to any developing country's policy to compare alternative possible distribution generation sources as alternative to building fossil fuel power stations. The economic study is based on the incremental rate of return analysis applied to possible projects' cash flows of wind, solar PV, and diesel generator projects to select the best project for an investment from the economic perspective. Then, such analysis is to be modified according to the current policy applied to a selected developing country to understand the role a policy can play toward the investment in wind, solar PV and hydro power projects. Even though there exists renewable energy projects that are mainly utilized for certain applications such as pumping and water heating, the utilization of such resources for electricity supply was not capable of solving the power generation shortage as power interruptions are still experienced by residential electricity consumers in many developing countries. The severity of the problem is expected to spread over such countries due to population growth demand for electricity and the limited available funds restricting such projects' expansion if the current policy is to continue. Therefore, this restriction necessitates a policy reform to encourage investors to expand their projects to accommodate population growth demand for electricity such that new areas can be connected to the distribution grid. This chapter will present a criterion function approach employing optimization to reform a policy as a function of the current policy to encourage investors toward more renewable energy projects over the long run to accommodate population growth demand for electricity. The chapter will set guidelines that can be recommended to governance institutions to encourage local investors toward more renewable energy projects.

Chapter 6 will present the technical aspect in utilizing the best renewable energy project determined from the economic analysis of the possible renewable energy projects for investments to face the power generation shortage.Furthermore, Chapter 6 will discuss the current renewable energy system utilized in developing countries and will be utilized to address the power generation shortage alternative solution. The chapter proposes a novel PV system power model and how this model can be used to size the PV system to face the power generation shortage in developing countries.The selected project system based on the economic analysis applied on projects' cash flows will be modeled and the required minimum siz of the project will be determined such that the maximum demand can be met by considering either house full power interruption or house device scheduling. The effect of the selected project resource uncertainty on the expected demand that can be met is also investigated.

Chapter 7 will conclude the thesis and will summarize works to be considered in the future.

Chapter 2

Matters Allied to Electric Energy Demand of Developing Countries' Distribution Grids

This chapter will provide the reader with an overview of the present condition of energy demand and the expected electricity demand growth in developing countries. It will also present the main loads behind the current residential electricity demand. It will show the effect of rising energy demand on power generation represented by a shortage in supply and power interruptions. Then, it will discuss the current approaches applied in developing countries to abate the sternness of the problem. Afterwards, it will address the deficiency in these approaches and propose alternatives to address the problem of power generation shortage in these countries.

2.1 The Current Status of Electricity Consumption in Developing Countries

Based on [1-3], the energy utilized in developing countries is categorized into 15% residential supply, 7% commercial supply, 62% industrial supply, 15% transportation supply and 1% other demand supply. India is an example of a developing country where energy demand has increased to show an electrification rate of at least 10% of a village households such that the village is recognized to be electrified [3-5]. On the other hand, there are 404.5 million Indians living without electricity due to the power generation shortage [1, 2]. This number represents 34.5% of India's 2009 population [6].

2.2 Reasons behind Electricity Consumption Growth in Developing Countries

The deficiency in generation compared to demand is due to the growth in consumers' electricity demand. This deficiency is due to the increase in the number of houses connected to the distribution grid as well as the customers' adoption to new home appliances [3, 7]. Reference [1] emphasizes the role household income plays in determining the ownership of the appliances. A detailed multi-country study relating household income and the ownership of house appliances is presented in [7] in order to estimate the energy consumption of a residential area and the associated environmental effects in the future using an econometric parameterization model. Furthermore, references [3, 8] indicate that the falling prices of home appliances in the market is a main reason behind their ownership by consumers in developing countries. Such devices are also characterized by less efficiency compared to those adopted by consumers in industrial countries. The inefficient home devices will result in a high standby power that can contribute significantly to the increase in residential electricity demand.

2.3 Home Devices' Power Demand and Their Statics in a Developing Country

The devices that are mainly adopted by residential electricity consumers in a developing country are shown in Figure 2.1 according to [9, 10]. The power demand of home devices is also presented in the figure to understand what the power demand of such devices can be if these are efficient [3, 11-13].

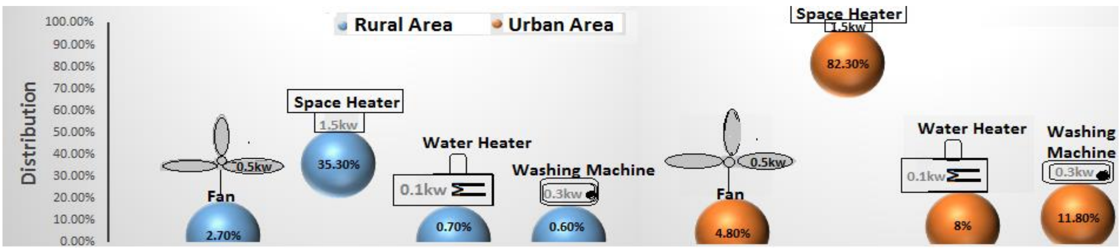


Figure 2.1: Main devices of consumers in a developing country and their wattage demand

In India, 72% of the population is considered rural [9] because more than 75% of the laborers work in agriculture [14] as agriculture lands cover most of the area in many states across India [3, 15]. Such consumers use well pumps to irrigate the lands [3, 16]. The energy demand of an efficient well pump can be 1.2kWh [11-13, 16].

2.4 Power Generation Shortage in Developing Countries

Demand power interruption is a major problem affecting consumers' daily lives and developing countries' economy development [3, 8, 17]. Electricity demand surpasses the generation capacity in India and the deficiency gap represented by load power interruption varied between 17.7% in 2005 to 23.7% in 2007 according to [3, 18]. The available power generation was 9049MW while the demand was 14749MW in 2006-2007 in Maharashtra state in India [18]. The electricity energy demand is expected to grow to reach about 167TWh in Maharashtra and about 1392TWh across India by 2016-2017 compared to 106.643TWh in Maharashtra and 697.961TWh across India in 2006-2007 [19]. The peak load is expected to be 28347.752MW in Maharashtra by 2016-2017 [19]. On the other hand, Pakistan electricity consumers encounter power cuts that can reach 20 hours daily [20]. There is a shortfall in the country's electricity by 4500MW [20].

2.5 Developing Countries' Approaches to Face Power Generation Shortage

There are many approaches that have been applied in developing countries to face the power generation shortage recognized as power interruptions. Generation companies, distribution utilities, and residential consumers have applied solutions to face the power generation shortage as will be discussed in this section.

2.5.1 Generation Company Approach to Face Power Generation Shortage

Since coal and gas resources needed by power generation companies are limited, some generation companies considered hydro power to support electricity generation[21].

2.5.2 Distribution Utility Approach to Face Power Generation Shortage

Contracts that are described to be short term are signed by a distribution utility to buy or exchange electricity with other suppliers [22]. Moreover, some distribution companies have utilized capacitors and tried to minimize electricity theft to improve the system's efficiency [23]. Some distribution utilities as in [24, 25] have initiated a power interruption schedule based on disconnecting feeders of the distribution system for certain durations during the day for non-overlapping periods as a mean of reducing the total connected load on the distribution system [3].

2.5.3 Residential Consumers' Approach to Face Power Generation Shortage

Efficient devices for lighting and pumping were used to reduce electricity demand in addition, to the residential consumers' roles in supervising electricity usage by preventing illegal electricity utilization [3, 23].

2.6 Deficiency of Current Solutions to Face PGS and Proposed Alternatives

Generating electricity from fossil fuels generation is a challenge for developing countries as these resources are limited and the distance between the location of such resources and the load centers is distant [3, 26]. Furthermore, because of the political tension placed on developing countries locally and globally due to emissions associated with utilizing fossil fuel resources, developing countries have directed their attention to mix their power to be green as in [3, 26]. Utilizing alternative sources of supply to support coal and gas limited resources and toward green energy will require availability of funds. Not all generation and distribution companies can afford such cost of projects. Thus, the investors should take a lead in facilitating the funding of these projects. Thus, there is a demand to study the available investments option in the field of distribution generation including renewable energy resources to utilize the best project based on an economic study over the life of the project. Moreover, such economic analysis will also account for developing countries' policies in the field of investment. The economic analysis will be considered in this thesis. With the current policy applied in developing countries toward renewable energy projects, some countries have considered renewable energy projects for specific applications such as pumping [27]; however, the power shortage problem still exists restricting education and economy development. The reason behind this problem is that investments in renewable energy projects are subject to policy governing their funds. Such a policy is to be upgraded to better motivate more investors in the field. The upgraded policy guarantees them reasonable profits over the long run as the current policy is not promising for project expansion, and the investments in such projects are due to political tensions toward green energy and improving supply [3, 26]. This thesis will show how the current developing country's policy can be modified to ensure the investors' benefit by setting recommendations to governance institutions to encourage investors toward more renewable energy projects to accommodate population growth.

From a utility and a residential consumer point of view, the work in [3, 23] focused on restricting feeder loads in specific areas to a percentage of the actual value by minimizing electricity theft and the removal of inefficient devices as a method of demand supervision and preventing transformer breakdown. Furthermore, consumers connected to different feeders of the distribution system currently facing the power interruptions schedule as in [3, 24, 25] will experience longer periods of power cuts if a new feeder is connected to the distribution grid. The addition of such a feeder is due to the electrification of new regions such as new villages connected to the grid or accommodating population growth in new areas. The thesis proposes scheduling either homes or their devices (which are subject to many factors such as the uncertainty in weather condition, the comfort level of the residential consumers, working hours of individuals, their preferences, and the availability of supply) such that the problem of power generation shortage is addressed and its severity is reduced. Furthermore, the coordination between home devices' scheduling and the investment in renewable energy systems (modeled to account for the uncertainty in power production) is considered to minimize the renewable energy system size as well as maximize consumers' access to electricity. Utilizing such resources and supervising consumers' demand will improve distribution system efficiency. The proposed solutions to utilize renewable energy sources as external sources of supply when considering house and device scheduling is not considered a method of energy or demand management. The main reason behind that is when the available power generation reaches its saturation level, a demand exists to inject external supply to the grid. There are two options that are either to consider renewable energy sources and the other is to consider fossil fuel generators. These resources are to be considered by utilities and investors as many consumers live in the poor sector and cannot afford purchasing generators as alternative to the high cost of renewable energy systems. Energy management is based on utilizing the available resources rather than using external resources when considering demand scheduling. Furthermore, the work in the thesis is budget based. As a result, precise utilization of the devices models is considered. In other words, the devices models should be accurate and consider every factor that can affect available supply utilization as precise prediction of demand can affect the efficient utilization of power supply and the cost paid by consumers for electricity purchase.

2.7 Chapter Summary

This chapter overviewed the present condition of electricity demand and the future growth in energy demand in developing countries. It summarized the main loads contributing to the current residential energy demand. It showed the consequences of increasing energy demand compared to power generation status represented by scheduled power interruptions. After that, it discussed the approaches applied in developing countries to subside the problem. Then, it addressed the break points in these approaches and discussed alternatives to address the power generation shortage problem in developing countries. These discussions will be the corner stone in developing the mitigation methods proposed in this thesis.

Chapter 3

Proposed Solutions to Address Power Generation Shortage

Electricity consumers in developing countries are concerned with the problem of power generation shortage. Such shortage is a matter of the high electricity demand associated with the number of consumers, electricity theft and the home devices owned by each residential electricity consumer. The available power generation is not sufficient to meet all consumers. Thus, certain regions of developing countries are not electrified and many of the consumers in electrified regions will have no electricity supply for durations that can represent more than 50% of the day as in the case of many developing countries. Power cuts are applied to feeders as a strategy to avoiding power system blackout. This thesis proposes alternative solutions to address the power generation shortage in developing countries by reinforcing the grid to accommodate population growth through supplying new regions of the developing county with electricity as will be summarized in this chapter.

3.1 Objectives

The work in this thesis is to find solutions to power generation shortage in developing countries that can facilitate reasonable standard of living. The thesis is to:

1. Estimate the expected demand of a studied system to be connected to the grid by prioritizing the loads based on importance of electricity supply into critical loads that should not undergo power interruption such as hospitals and shopping centers,…etc. and normal loads that can undergo power interruptions such as residential homes.

2. Investigate the proposed strategy that is based on scheduling homes to receive electric utility supply based on generation-expected demand status of a new feeder to be connected to the grid.

3. Propose individual homes' devices scheduling to maximize consumers' benefit of supply, subject to power supply availability for the newly added feeder, accounting for uncertainty in the factors governing the operation of such devices.

4. Search for the economical alternative sources of supply to maximize consumers' benefit of supply by addressing the electric utility and investors' role in funding such projects.

5. Analyze the role of the current policy applied in developing countries toward the selection of the best renewable energy sources to be considered for an investment.

6. Set guidelines to governance institutions to encourage the investors toward more projects of the selected best alternative source of supply to accommodate population growth by guaranteeing the investors reasonable profits over the long run.
7. Recognize the current direction of developing countries toward a selected renewable energy resource to meet the demand of certain loads and propose a novel power output model of such a resource.
8. Size the best selected project of alternative sources of supply to maximize the consumers' benefit of supply by coordinating consumers' devices scheduling with the uncertainty of such resources.

Figure 3.1 summarizes the thesis objectives. The approaches followed to achieve each of the above objectives are summarized in the next sections.

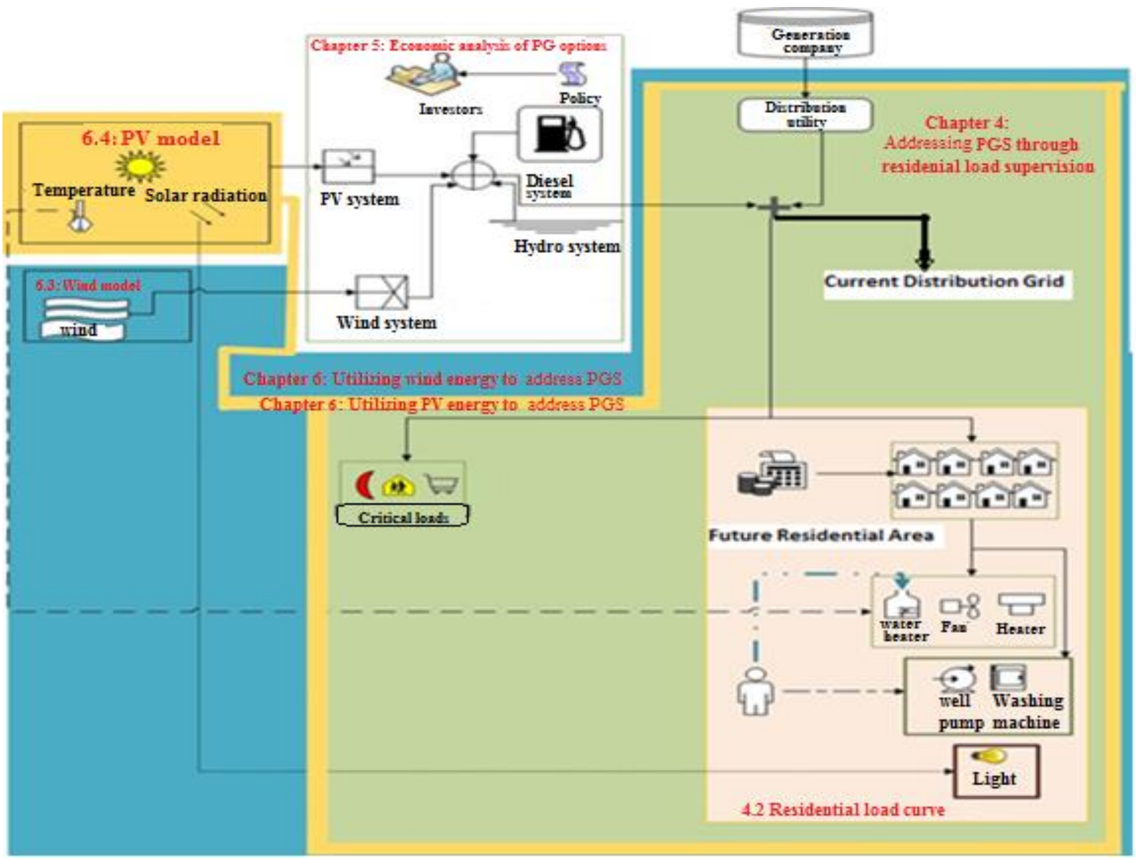


Figure 3.1: Thesis Objectives

3.2 Addressing Power Generation Shortage by Demand Supervision

Power generation is deficient compared to electricity demand in many developing countries. With population growth, the electrification rate should increase. This can indicate new regions to be added to the current distribution grid. Current consumers do not have electricity for most of the day. The addition of a new feeder to the grid will increase the negative gap between the available power generation and demand. This will be reflected into longer durations of power cuts experienced by different consumers in the distribution grid. In order to consider such an addition of new demand to the grid, this thesis will prioritize loads based on importance of supply and then reschedule loads with least priority to maximize consumers' benefit of supply with respect to available supply from the distribution grid.

The new region to be electrified is made of critical loads and normal loads. Critical loads are loads with first priority of supply. These loads can represent hospitals, nursing rooms, schools and shopping centers. On the other hand, normal loads are given least priority of supply and these represent residential houses whose devices are also prioritized. It is necessary to predict the demand of such regions to be connected to the grid by accounting for residential houses' devices operational dependency on the uncertainty in weather condition, comfort level, working hours of individuals, consumers' preferences and the dependency on a consumer decision toward a device at an hour on future decisions toward that device. Different home activities to govern the demand are discussed in literature [28]. In order to predict the expected demand, the current residential demand is scheduled to minimize percentage to be paid from the monthly income on the electric utility bill considering residential load devices' linear models. The time of use tariff is the first driver of the schedule. With the determined schedules of consumers' devices and the available power supply in the system, houses' full power interruption schedules are established to reduce the load on the feeder to meet the available demand rather than isolating the feeder from the grid. On the other hand, another solution is proposed to address the power generation shortage such that the gap between available generation and required demand is minimized by considering houses' devices power interruption. To achieve such objectives, certain components are needed to facilitate the application of this solution in developing countries. Figure 3.2 shows these components.

The application of a thermistor is needed to measure the temperature of the water in the well supplying the home water heater tank through a water pump. This measurement can be determined once as an initial condition and then the effect of the weather can be applied following the model of radiation effect on water temperature described in this thesis in Chapter 4 and Appendix B. It can be seen from this model that the outdoor temperature measurement is needed and this can be measured through an external thermometer placed outside the house or can be determined directly from the weather station. In order to determine how much hot water each consumer needs, water meters can be used to measure the demand for hot water consumption.

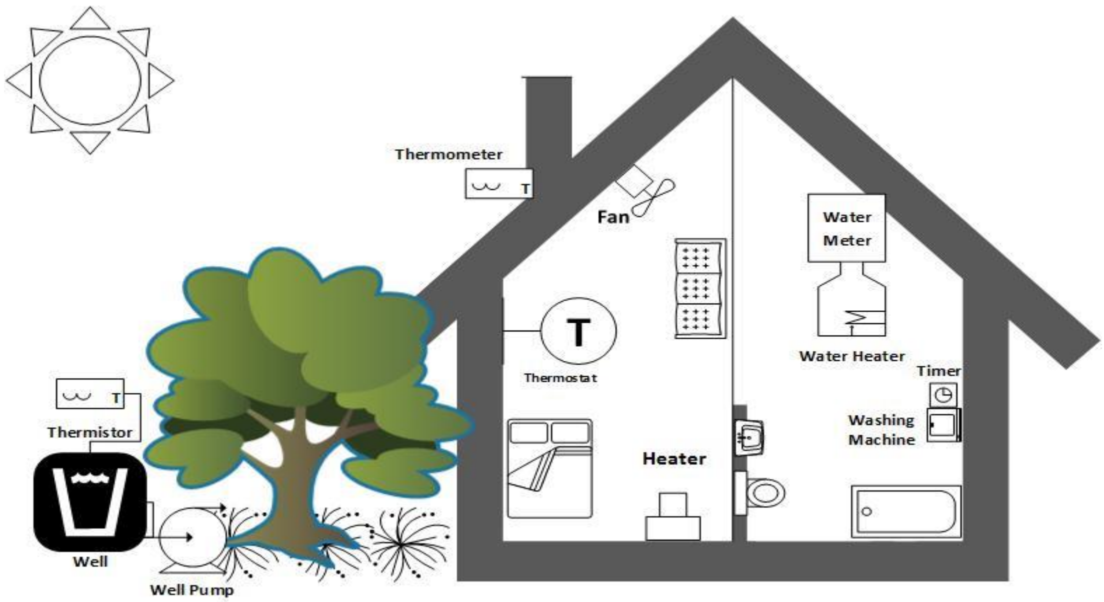


Figure 3.2: Components needed to supervise residential consumers' devices operation

Furthermore, the indoor temperature can be measured through an internal thermostat and the temperature can be used to schedule the indoor devices. With those in mind, consumers' demand scheduling can be performed according to the availability of power supply using controllers or timers governing devices' operations. The cost of such controllers has not been considered in this work. If smart metering is not possible, this work can be adopted as it models the outdoor temperature by considering its stochastic nature. It also applies linear load models that account for the outdoor and the indoor temperatures. It models the effect of the weather on water temperature, and from survey analysis, the demand for hot water can be predicted. Comfort level can be either provided by the consumer to the utility or it can follow standards. The consumer should provide the utility with information about what devices he owns and their power ratings, house dimensions and house characteristics based on which these parameters will be involved in load models.

If smart metering is enabled and the application of such controllers can be made possible, the distribution utility will control residential devices. On the other hand, if such technologies are not enabled, the utility can provide the consumers with the daily schedule of their devices or controllers can be scheduled to operate such devices based on an initiated schedule ahead of time. Residential consumers' devices are to be scheduled with respect to the available supply such that most of the devices over the day are supplied. This will facilitate the lives of consumers as they are accessible to more devices demanded rather than being disconnected from the grid. In other words, sacrificing certain devices at certain hours should be more convenient than living without electricity. This will be further clarified in Chapter 4.

3.3 Addressing Power Generation Shortage Using Alternative Sources of Supply

The deficiency in the current power generation has led developing countries to explore alternative sources of supply. Developing countries are characterized to have varied resources of renewable energy sources. These resources form a nominee solution to the limited coal and gas resources. The application of such projects is a challenge for many developing countries because of the high costs associated with such projects. Some utilities cannot afford such costs to deploy these resources to facilitate the consumers' lives through electricity supply. Thus, the investors' role in participating in such projects' funds is important. The investors are seeking reasonable profits over the long run of projects. The selection of the most economic project for an investment is an essential factor in utilizing such resources. Economic analysis of possible alternative supply projects in developing countries evaluated by following a general financial structure is considered such that the best project for an investment is selected. Furthermore, the financial structure of evaluating such projects is modified to account for a selected developing county's policy to investigate the role the policy can play toward a renewable energy project.

Then, recommendations will be set to governance institutions to update the policy governing projects' funding to encourage the investors toward more renewable energy projects such that these resources are dedicated to solve the power generation shortage associated with population growth while guaranteeing the investors with reasonable profits over the long run. The governance institutions are practicing many regulations on funding a renewable energy project such as income tax rate, a project term loan and the price of electricity generated from a renewable energy source. The current regulations applied on funding renewable energy projects can show an internal rate of return that is greater than a minimum accepted rate of return of the project. This internal rate of return is calculated based on equity assuming all debt liabilities are paid. Even though the work in literature has considered evaluating this rate at a variation of one or more parameters of the project financial structure as in [29], such work did not target setting a policy made of a set of regulations to reach a reasonable profitable return of a project. Thus, there is a demand for a guided procedure that can be followed in setting the appropriate regulations forming a motivating policy on project funding for local investors in renewable energy projects. This thesis provides the governance institutions with a guided procedure to develop a criterion function, and to use an optimization technique to select the best set of regulations to encourage local investment in a renewable energy project. This is by ensuring that the internal rate of return is higher than the minimum accepted rate of return. This can be achieved by reforming the current policy to assure the investors reasonable profits such that they can expand their current project to accommodate population growth.

Figure 3.3 summarizes the economic analysis approaches considered to evaluate projects and how to recommend a new policy on project funding encouraging the investors toward more renewable energy projects to accommodate population growth. This is further discussed in Chapter 5. It can be seen from Figure 3.3 that hydro power project is considered in the economic evaluation of the projects subject to a selected developing country's policy, but it is not involved in the incremental rate of return analysis subject to a an updated general financial structure available in literature as shown in Chapter 5. The main reason behind excluding such a project from the latter is that not all developing countries have access to hydro power generation as such resource may not be available due to the geographic location of the developing country.

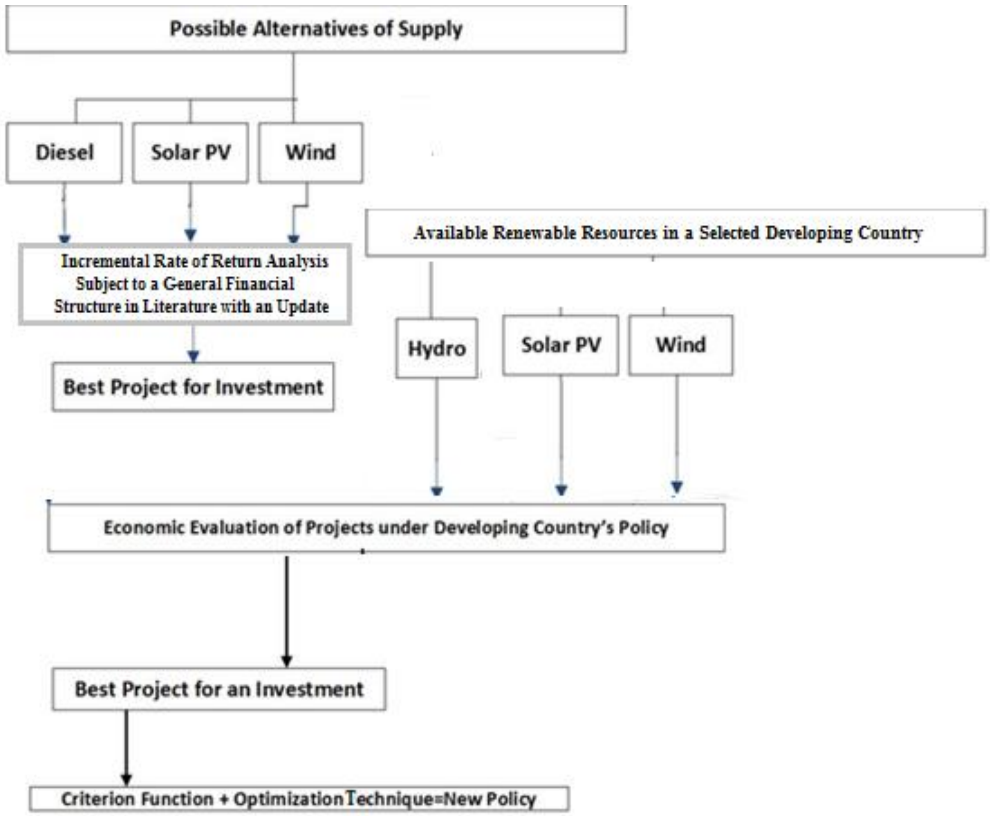


Figure 3.3: Economic analysis of possible projects for investments to address the PGS

The best economic project for an investment will be utilized to reschedule home devices such that maximum benefit of supply is provided to consumers accounting for the stochastic nature of the utilized source in the project. This will also consider minimizing the size of the system of the selected project.

From the general economic analysis on available resources, wind is shown to be a candidate project as will be shown in Chapter 5. In order to reschedule home devices to take advantage of the available renewable energy source during the day, there is a demand to model the nature of this resource in a developing country. Thus, historical data of wind speed is used to determine the Weibull probabilistic distribution parameters as this distribution is recognized to be the best distribution describing this resource characteristic. Then, the data are regenerated using the Monte-Carlo simulation and after that they are clustered to find a typical value to represent individual hours of the day. This is considered for winter and summer seasons. It is important to emphasize that the current wind speed from metrological stations is measured at the station height. The station height is less than the height of the wind turbine, thus an adjustment of the wind speed from the station height to the turbine height is to be considered using a power law that is discussed in Chapter 6 in further details. After that, the wind speed data are used to determine the power output of a selected wind turbine which is involved in the optimization problem targeting maximizing the benefits of consumers under a minimum size of the system. Moreover, residential consumers expected energy met is determined under the uncertainty of wind speed by considering the different states determined from clustering wind speed data generated from the Monte-Carlo simulation for every individual hour in a typical season day.

Since the current policy approves the current trend in developing countries toward solar energy projects which are mainly utilized for pumping applications as in [27], this thesis will consider such resources to reschedule home devices to maximize the consumers' benefit of supply while utilizing a minimum PV system size. In order to achieve that, the power output of the PV system is to be determined. This thesis proposes a novel PV power output model that provides a better estimate of the power output from the PV system such that the size of the system can be reduced. The model considers not only the solar radiation but also the temperature and other factors affecting the amount of the estimated power. This will be further discussed in Chapter 6. Then, the power of the PV system is regenerated using the Monte-Carlo simulation and clustered to determine the hourly PV power during a typical winter day and a typical summer day. This power will be involved in scheduling home devices while minimizing the PV system size and maximizing consumers' benefit of supply. This will also be considered to determine the residential expected energy that can be met accounting for the stochastic nature of the solar power by considering the different states determined from clustering the solar power generated data from the Monte-Carlo simulation for every individual hour in a typical season's day as will be shown in Chapter 6.

3.4 Modeling Techniques

Probability paper plot, the Monte-Carlo simulation, linear programming and nonlinear programming are modeling techniques used in the thesis for the purpose of data modeling and solving the problem of minimum power supply interruption. A brief description of each modeling technique considered in the thesis is provided here.

3.4.1 Probability Paper Plot & KS Test

Probability paper plots are utilized to find the best distribution representing the stochastic nature of weather variables such as temperature. More sophisticated distributions describing solar power are tested using Kolmogorov-Smirnov Test (KS Test). This test is a goodness of fit test that is used to judge if the data belongs to a certain distribution.

3.4.2 Monte-Carlo Simulation

The Monte-Carlo simulation will be considered to simulate the random behavior of weather conditions such as temperature as in Chapter 4, wind speed as in Chapter 6 and solar power as in Chapter 6.

3.4.3 Mixed Integer Linear & Non Linear Programming

In the current research, the main objective is to maximize the consumers' benefit from the available power supply by scheduling houses or houses' devices such that the number of devices not supplied is minimum in two cases: The first case is when the supply available is as is from utility; while the second case supply is associated with the availability of alternatives of supply other than the utility's current power. The problem is formulated as an optimization problem solved as two separable problems that are interconnected. The first problem is formulated as a mixed integer linear programming problem to schedule residential devices. The output of this problem is inputted into another optimization problem targeting maximizing the residential consumers' access to supply subject to power flow constraints. In this case, the problem is solved through mixed integer nonlinear programming. The main reason behind solving the problem in two stages is to reduce the computation time experienced when considering the two problems in one problem as well as avoiding the solver failure and exceeding the memory limit of the personal computer. The same approach is followed when renewable energy systems' supply in included as alternative sources of supply. More details are provided in Chapter 4 and Chapter 6.

3.4.4 Trending Analysis

Trending analysis is chosen for analyzing the goodness of fit of probability paper plot for weather temperature in Chapter 4. It is also involved in economically analyzing renewable energy project fund structure subject to policy as will be shown in Chapter 5.

3.5 Software

Excel, MATLAB and GAMS are the simulation tools used for modeling and analysis in the thesis work as described below:

3.5.1 Excel

Excel is used to model the behavior of weather conditions and to determine the best fit describing the stochastic nature of temperature. Excel is also involved in the economic analysis of projects' funding to select the best project for an investment.

3.5.2 MATLAB

MATLAB is the chosen software to perform the Monte-Carlo simulation. MATLAB is a programming environment that can be used to develop algorithms, analyze and visualize data and perform numerical computation [30].

3.5.3 GAMS

GAMS software is a universal algebraic modeling system utilized as a simulation tool for this work. This software is known for its high level system in modeling optimization problems. The software includes many solvers. CPLEX is considered to solve the MIP problem; while DICOPT is chosen to be the solver for the MINLP problem [31]. GAMS codes were run on two laptops (2.26GHz Intel Core 2 and 2.6GHz Intel Core 5). Moreover, a desktop computer is used to run some GAMS (2.8GHz Core 7).

3.6 Summary

This chapter described the objectives of the work in the thesis. It showed the type of data and modeling techniques involved in the thesis work as well as the selected software to achieve thesis objectives.

Chapter 4
Addressing Power Generation Shortage through Residential Load Supervision

Electricity consumers in developing countries are in demand for reliable electricity supply for economy progress. No electricity or Poor electricity supply due to power generation deficiency in comparison to the demand is a main concern of these consumers as they experience no electricity supply for many hours during the day. The situation is to be worsen if new regions are to be electrified. In order to account for grid expansion due to population growth and the demand to electrify new regions to be connected to the current grid, this thesis will propose approaches to face power generation shortage. In other words, this work proposes an alternative solution to no electricity supply for newly built or electrified regions. The proposed approaches will not worsen the current state of the art based on disconnecting feeders from the grid based on a predefined schedule to the face power generation shortage. This thesis proposes houses' power interruption schedules rather than scheduling feeders' isolation from the grid. It also proposes an alternative solution to reduce the effect of such power interruption by considering individual houses' devices power interruption rather than houses' full power interruption at a certain hour. The proposed solution has the advantage of providing the residential customers with electric power all the time by disconnecting certain appliances during generation deficiency rather than disconnecting the feeder from the grid for a certain hour. The proposed solution takes into consideration the comfort level of the residential customer by accounting for his daily power demand, working hours, stochastic weather condition governing the operation of his devices and the effect of consumers' actions on the devices at an hour on subsequent decisions toward these devices. Furthermore, the proposed solution considers the importance of other loads connected to the grid by giving them the priority of supply and scheduling the residential devices based on the availability of supply accordingly. The proposed work predicts what appliances to be owned by residential consumers when electrified by considering the devices adopted by other residential consumers when electrified or consumer preferences of devices to be owned when being connected to the grid.

4.1 System under Study

The system under study is a secondary feeder to be connected to the distribution grid as shown in Figure 4.1. The system is a balanced three phase system with 4 busses. The system line data can be found in

[32]. Bus 2 and bus 3 represent critical loads that should not be interrupted. These loads are assumed to vary according to IEEE Reliability Test System (RTS) [33]. Even though such variation is considered for transmission systems, it is deployed here for a secondary feeder in a distribution grid as no data are available for the hourly variation of such types of loads. Bus 4 represents a normal residential load that is proposed to be interrupted due to deficiency in the available power supplied to bus 1. Bus number 4 is composed of 8 residential houses each with a total connected load of 4kW. In order to predict the demand of residential consumers at bus 4 by understanding how their devices operate with respect to their demand, the next section is dedicated to determine the expected load curves of individual customers with respect to the devices to be owned.

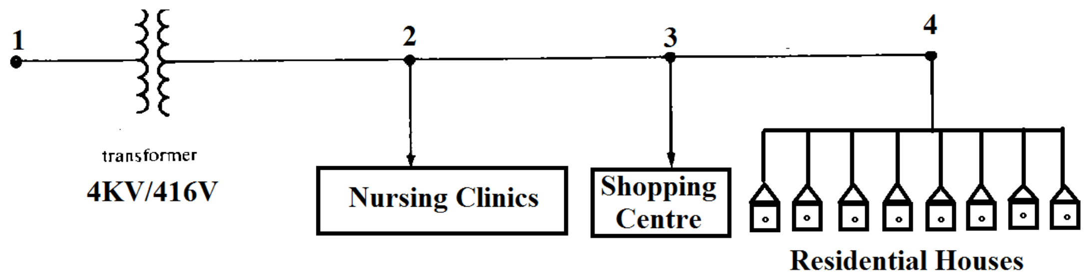


Figure 4.1: System under study

4.2 Finding Bus 4 Expected Demand

The demand of bus 4 is composed of 8 houses' demand. The houses are expected to have an electric fan, electric space heater, washing machine and water supply system composed of an electric water heater and an electric well pump when being grid connected. The ownership of such devices is based on the survey results in [9, 10] showing what devices to be owned by residential electricity consumer in urban and rural areas in developing countries and what devices can support the field of work such as a well pump for water supply and irrigation [16].

Since consumers in developing countries have limited income [34], scheduling residential loads to minimize the percentage to be spent from the monthly income on electricity bill is set as an objective to determine the expected load curves of residential consumers at bus 4 and to validate the load models operation in a mixed integer linear programming problem that can be utilized in scheduling houses' full power interruption. Even though load forecast or finding load demand using the approach discussed in [32, 35] can be utilized to predict the demand of the region to be electrified, finding the residential demand based on their devices scheduling to minimize the payments from their income on electricity bill is preferred because it considers residential devices' load models showing the dependency of operating one device at a certain hour on its demand for the next hour under the stochastic nature of weather condition. Specifically, load models involved show how one type of device operation such as a space heater can influence the energy demanded by a water heater. This will also facilitate consumers' lives as their next decisions toward their devices are based on their current decisions to operate them. In other words, customers' preferences of using their devices governed by their comfort level, weather condition [16, 36], working hours [37], the number of working members earning an income in a house to purchase the appliances and pay for electricity bills [34, 38], the working field [15], the developing country's electricity pricing scheme [39], the nature of the area that the residential electricity consumers reside in (urban or rural areas) [9, 10, 15] and the house size [40] are accounted for in such a selected approach to find residential demand. Furthermore, such an approach can show how houses' devices power interruption will affect the decision to operate such devices at future hours subject to the availability of electricity supply to such area [18]. Predicting the demand using such an approach is suitable for both online scheduling as indicated in [41] as well as offline scheduling as indicated in [16]. The advantage of the proposed work over [41, 42] is that global optimal schedule can be reached in a very short computation time that is less than a second. It considers sophisticated load models by accounting for many factors that can affect the device energy demand. It takes the effect of stochastic weather condition to predict a typical day data set representing a season which is more suitable for poor countries where smart metering and online scheduling are difficult due to unavailability of personal computers or internet infrastructure.

Figure 4.2 shows the big picture of predicting the demand at bus 4. Since market price and stochastic weather condition are major factors governing the consumers' preferences toward their devices, the next two sections are dedicated to discuss how they are modeled.

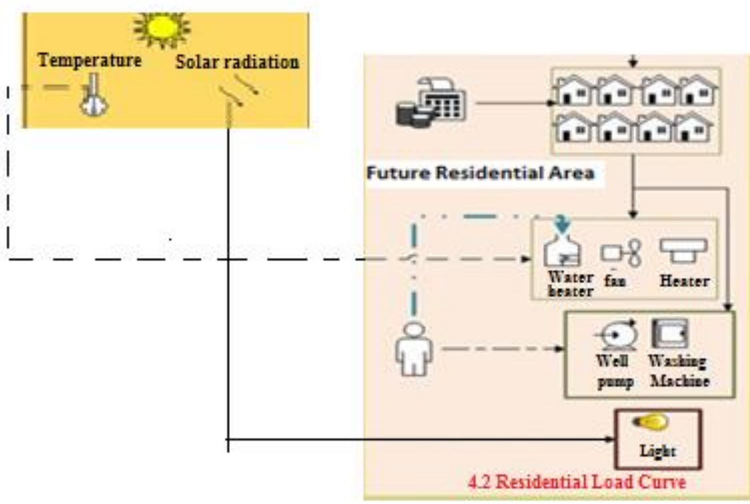


Figure 4.2: Residential demand determination

4.2.1 Market Price in a Selected Developing Country

Many developing countries apply unit pricing on electricity consumption. For example, this pricing scheme is applied in Maharashtra State in India [39]. The unit pricing scheme varies based on the residential consumer nature as explained in Figure 4.3 based on [16, 39].

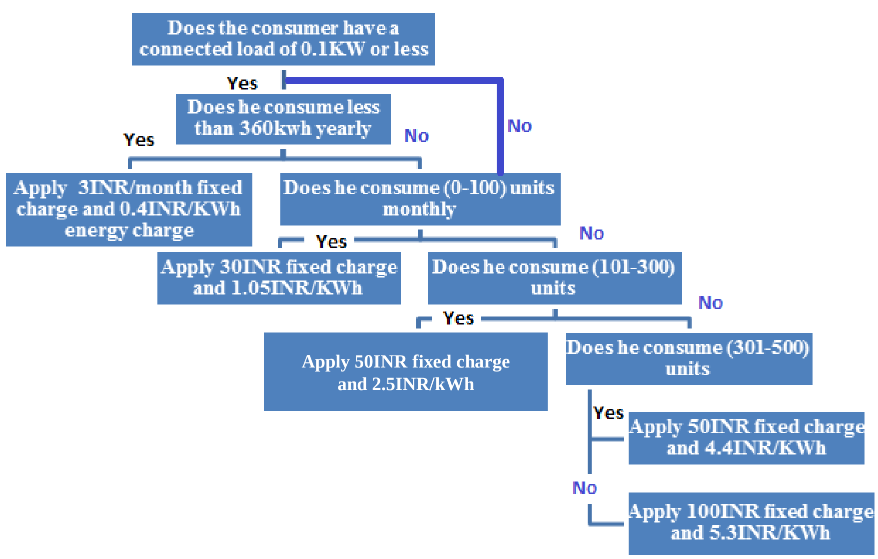


Figure 4.3: Unit pricing (INR/kWh) in an Indian state based on [16, 39]

In some states across India where smart metering is applicable, a time of use tariff is applied. For example, Maharashtra applies a time of use tariff on industrial consumers [43]. In this thesis, the time of use tariff is applied to price residential consumer energy consumption by considering the minimum

1.05INR/kWh during off peak hours and 5.3INR/kWh during on peak hours [16]. Even though these prices will be applied to an area to be electrified, it is important to emphasize that the on peak and off peak pricing are assigned to time slots of on peak and off peak grid demand, respectively.

4.2.2 Model of Stochastic Weather Nature

An accurate model of external temperature outside the house is essential for assessing the internal temperature of the house such that loads whose operations are reliant on temperature can be harnessed. The weather temperature can be valuated according to the competency of the determined probability density function to represent the frequency distribution of the external temperature outside the house. The section briefly describes the stochastic weather model used in the scheduling of houses' devices, estimating the expenses from monthly income that are dedicated to electricity bill payments, and the importance of the scheduling for poor developing countries. The accuracy of utilizing the stochastic weather model in predicting the contribution of the electricity bill to monthly income expenses [16] will be compared with that when scheduling the devices one day ahead of time. It is important to emphasize that the latter approach is the one followed in the literature.

4.2.2.1 Importance of Scheduling Home Devices Based on Stochastic Weather Model

Scheduling home devices subject to the stochastic weather model can play a vital role in developing countries where energy charges are considered to be high when they are compared to household limited income. There is a demand for a stochastic weather condition model capable of determining the nature of the daily hourly temperature such that house- device offline scheduling is possible if online scheduling is not enabled due to the lack of smart metering infrastructure or due to a failure of any communication link in the system such that device-scheduling carried out one day ahead is not possible. Such a stochastic weather model can help in predicting the contribution of the expenses from the monthly income dedicated to electricity bill payment [16]. Even though, this is considered to be an estimate, it is helpful in governing the customers' perceptions of their devices and their decisions to buy new devices, minimizing their electricity demand [16] or planning how to use the limited income for other living purposes.

4.2.2.2 Weather Temperature Model

The hourly diversity of the external temperature out of the house in different seasons shows a stochastic nature considering the historical weather data in [44, 45]. The best distribution of such data is determined using Probability Paper Plot following an extensive best fit procedure [46] as shown in Appendix A. The best distributions describing the hourly external temperature out of the house in both winter and summer seasons are shown in Figure 4.4. After that, the temperature data are regenerated using the Monte-Carlo simulation as discussed in Appendix A to account for all possible states guaranteeing such distribution. Such regenerated data are fed to the simulation platform by minimizing the data size through data supervised clustering into states such that every state is a representative of a temperature series with a probability found as in (4-1). To simplify the analysis, the state central point is a representative of that state, and consequently the value assigned to the external temperature at hour *t* is a result of adding all values obtained from multiplying a state's probability by its central point [16].

$$P(T_{external}) = \int_{T1}^{T2} f(T_{external})dT \qquad \textbf{(4-1)}$$

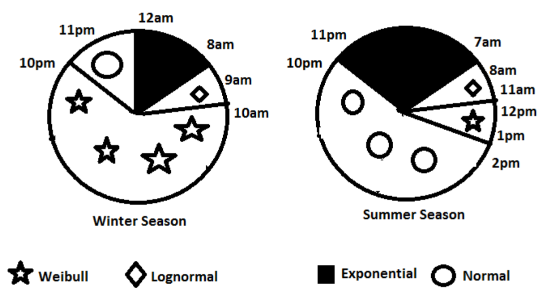


Figure 4.4: Hourly temperature distributions in winter and summer

4.2.3 Problem Formulation

The objective function of the optimization problem is given by the function below, where *myobj* is the objective function to be minimized. It indicates the percentage to be spent from the gained income of a working individual in a developing country on the electricity bill, *mi* is the monthly income, *EC* is the electricity cost of operating the following devices: *sh* indicates space heater in winter, *fan* indicates electric fan in summer, *pump* indicates well pump in any season, *wm* indicates washing machine in any season, *wh* indicates water heater in any season subject to household favorites such as showering, washing or else. It can be seen that the function is multiplied by 100 to convert it in percentage [16].

$$\min myobj_{typical\ case\ scenario} = \begin{cases} 100X\,\dfrac{1}{mi}(EC_{sh} + EC_{wm} + EC_{pump} + EC_{wh}) & \forall\ winter\ season \\ 100X\,\dfrac{1}{mi}(EC_{fan} + EC_{wm} + EC_{Pump} + EC_{wh}) & \forall\ summer\ season \end{cases} \qquad \textbf{(4-2) \& (4-3)}$$

The above *EC* costs can be calculated as follows:

$$EC_{sh} = \sum_{t=1}^{24} P_{heat}\ (day\ \ \underline{c}_{t,d}\ \ xh_{sht,d=weekday}\ hour + end\ \ \underline{c}_{t,d=weekend}\ \ xh_{sht,d=weekend}\ hour) \qquad \textbf{(4-4)}$$

$$EC_{fan} = \sum_{t=1}^{24} \left[day \;\underline{c}_{\,t,d=weekday} \,(\mathrm{P_{fan}} \quad hour \quad U_{fan}\;_{t,d=weekday}) + end \;\underline{c}_{\,t,d=weekend} \,(\mathrm{P_{fan}} \quad hour \quad U_{fan}\;_{t,d=weekend}) \right] \tag{4-5}$$

$$EC_{wm} = \sum_{t=1}^{24} end \;\underline{c}_{\,t,d} \; WM_{t,d} \; Energy_{washing-machine} \tag{4-6}$$

$$EC_{pump} = \sum_{t=1}^{24} \left[day \;\underline{c}_{\,t,d=weekday} \,(\mathrm{P_{wellpump}} \quad hour \quad x_{well-Pump}\;_{t,d=weekday}) + end \;\underline{c}_{\,t,d=weekend} \,(\mathrm{P_{wellpump}} \quad hour \quad x_{well-Pump}\;_{t,d=weekend}) \right] \tag{4-7}$$

$$EC_{wh} = \sum_{t=1}^{24} \begin{bmatrix} day \;\underline{c}_{\,t,d=1} \;(\mathrm{ZWH}\;_{t,d=weekday}) + end \;\underline{c}_{\,t,d=2} \;(\mathrm{ZWH}\;_{t,d=weekend}) \\ + day \;\underline{c}_{\,t,d=1} \;(\mathrm{ZLoss}\;_{t,d=weekday}) + end \;\underline{c}_{\,t,d=2} \;(\mathrm{ZLoss}\;_{t,d=weekend}) \end{bmatrix} \tag{4-8}$$

where $\underline{c}$ is the price of electricity to be charged, t is the time of the day, d is the day number, xh_{sh} is a binary variables that has a value of one if the device is ON and a value of zero if the device is OFF, hour is one hour, P_{heat} is the space heater power rating, P_{fan} is the electric power rating, U_{fan} is a binary variable that has a value of one if the electric fan is ON and has a value of zero if it is OFF, $Energy_{washing\text{-}machine}$ is the energy utilized by washing machine (kWh/use), WM represents a binary variable that has a value of one if the washing machine is ON and a value of zero if the washing machine is OFF, $x_{well\text{-}ump}$, represents a binary variable that has a value of one if well pump is turned ON and a value of zero if it is OFF, *hour* is one hour, $P_{wellpump}$ is an indication of the well pump power rating (kW). In one case study, $_{ZWH}$ represents the energy utilized as a consequence of hot water demand (kWh) and $ZLoss$ is the energy consumed because of heat losses from water heater tank surfaces, the values of *day* and *end* represent the number of days that are weekdays and weekends respectively such that the whole month has two fixed schedules representing each day type in one studied scenario. In another scenario, their values are set to be one such that the temperature set determined is for the number of days in a month based on the type of the day. In this scenario, all the equations shown above are summed over d [16].

The optimization problem is subject to the devices model constraints:

A. Model of Electric Space Heater [16]

In India, residential consumers use room heaters to heat their house [9]. Such devices utilize electricity rather than gas [47]. Thus, the model of the space heater available in [41, 42, 48] is used as shown below where T_{house} is the internal air temperature of the house (°C) and $T_{external}$ is the external air temperature out of the house (°C). It is important to emphasize that these constraints can be adjusted to show the relationship between any two consequent days in a season if needed as the case of one scenario under study or can be left as is, reflecting the relationship between weekday temperature and weekend temperature.

$$\begin{cases} P_{heat} \quad xh_{sh \; t=24,d=weekday} = 56X10^{-2} \; T_{house \; t=1,d=weekend} - 5 \;\; X10^{-1} \; T_{house \;\; t=1,d=weekday} - 56X10^{-3} \; T_{external \;\; t=24,d=weekday} \\ P_{heat} \quad xh_{sh \;\; t,d} = 56X10^{-2} \; T_{house \; t,d} - 5 \;\; X10^{-1} \; Thouse_{\;\; t,d} - 56X10^{-3} \; T_{external \;\; t,d} \qquad \forall_{t \neq 24:} \end{cases}$$

(4-9) & (4-10)

The initial value of the air temperature inside the house in the first weekday under study is at 1am and is indicated by the following constraint:

$$T_{house t=1,d=first\ weekday} = I^{o}C \qquad \textbf{(4-11)}$$

The comfort zone constraints governing the ON-OFF operation of the space heater are based on the “West Midlands Public Health Observatory” describing the satisfactory warmth level [49] as below:

$$\begin{cases} T_{house \;\; t,d} < 18 \;\; xh_{sh \;\; t,d} + 27 \;\; (1 - xh_{sh \; t,d}) \\ T_{house \;\; t,d} \geq 18 \;\; (1 - xh_{sh \; t,d}) - 30 \;\; xh_{sh \; t,d} \end{cases} \qquad \textbf{(4-12) \& (4-13)}$$

B. Model of Electric Fan [16]

Most of the residents in India, an example of a developing country, use fans [9] to improve their feeling of the house’s internal temperature. In fact, the purpose of the fan is not to reduce the house’s internal air temperature but rather it results in the effect of a wind chill causing the houses’ residents to experience the feeling of a less temperature in comparison to the real air temperature in the house. Such an experience can be modeled by accounting for two factors. These are the lost heat from the house surface and the effect of a wind chill as a result of turning the fan ON. These two factors are discussed below:

B.1 House Thermal Model

The house thermal model presented in [50] shows the relationship between the external outside temperature and the internal temperature of the house as given by the equation below where Sur_b is the thermal transmittance of a given house surface (Watt/m^2 K) [50, 51], $Area_b$ is the area of a house surface experiencing heat lost (m^2), *b* is a surface indication and *HC* is the joule per kelvin capacity of the heat [50]. The areas of the house surfaces are assumed considering a standard size of a house in a developing country [40]. The assumed sizes of house walls, a ceiling, a floor and windows are presented in Table 4.1 [16].

$$\frac{dT_{house}}{dt} = -\frac{\sum_{b} Sur_b \ Area_b}{HC}(T_{house}(t) - T_{external}(t)) \quad \textbf{(4-14)}$$

As the objective is to apply linear programming to schedule residential houses' devices, performing the integration on the above equation is not suitable as it will lead to a logarithmic scale form of the equation. Therefore, the discretization method described in [52] is considered. After substituting the corresponding values of the discretized house thermal model, the final form relating the internal temperature of a house at an hour to its value at the next hour accounting for the external air temperature of the house is given below [16]:

$$\begin{cases} T_{house\ t=1,d=weekend} = T_{house\,t=24,d=weekday} - \left(9.9X10^{-1} T_{house\,t=24,d=weekday} - 9.9X10^{-1} T_{external\ t=24,d=weekday}\right) & \forall t = 24 \\ T_{house\ t+1,d} = T_{i_{house}t,d} - \left(9.9X10^{-1} T_{house\,t,d} - 9.9X10^{-1} T_{external\ t,d}\right) & \forall t \neq 24 \end{cases}$$

(4-15) & (4-16)

Table 4.1: Dimensions of different surfaces in a house in a developing country

Surface of the House	Dimensions (mxm)	Surface of the House	Dimensions (mxm)
Ceiling	7.3152X10	Window 1	1x0.5
Floor	7.3152X10	Window 2	1X0.5
Wall 1	4X7.3152	Wall 3 has a window	4X10-1X5
Wall 2	4X10	Wall 4 has a window	4X7.3152-1X0.5

B.2 ***Fan Wind Chill Effect on Felt Indoor Temperature*** [16]

A fan is unlike an air conditioner because it does not reduce the internal house temperature but it produces a wind chill effect making the household residents sensing lower temperature than to the real air temperature in the house. Such effect can be modeled by finding the speed of the wind generated from the revolutions of the fan. The procedure described in [53] is used to obtain the equation below relating the felt temperature (T_{feel}) in (ºC) to the internal air temperature in the house and is updated to show the effect of the ON-OFF operation of the fan in the same equation as given below:

$$T_{feel\ t=1,d=weekend} = T_{house\,t=24,d=weekday} - factor \ * \ (33 * U_{fan\ t=24,d=weekday} - T_{house\,t=24,d=weekday}) - factor \ * \ E_{t=24,d=weekday}$$

$$T_{feel\ t+1\ ,d} = T_{housert,d} - factor \ * \ (33 * U_{fan\ t,d} - T_{house\,t,d}) - factor \ * \ E_{t,d} \qquad \forall t \neq 24$$

(4-17) & (4-18)

where *t* is an indication of the beginning of the hour and *t+1* is an indication of the end of the hour. The factor shown in the previous equations can be obtained according for the wind speed considering the data in [53] used to derive a linear regression relating the factor and the wind speed ($Speed_{Wind}$) in (Km/hour). This can be summarized by the following equations:

$$\begin{cases} factor = 7X10^{-1} & \forall\ Speed_{wind} = 70 \\ factor = 98X10^{-4}\ Speed_{wind} + 171X10^{-4} & \forall\ Speed_{wind} \le 70 \end{cases} \quad \textbf{(4-19) \& (4-20)}$$

The fan speed can be found based on the fan characteristics as given by the below equation [54]:

$$Speed_{wind_{km/hour}} = \frac{60X\pi \ \ X \ Diameter \ XRPM}{1000} \quad \textbf{(4-21)}$$

A standard ceiling fan in India as an example of a developing country can achieve specific (RPM=380) revolutions per minute [55]. As an assumption, the speed of the fan's generated wind due to its revolution is the wind speed in the house. Moreover, the utilized fan in the model is characterized with one speed and the fan radius is based on [56].

Since the objective is to utilize linear programming to schedule the fan, $E_{t,d}$ is used as a free variable that replaces the nonlinearity of the following multiplication $(1-U_{fan\ t,d})T_{house\ t,d}$. Such linearization will require other constraints to be added as described in the guide in [57]. These constraints are as follows:

$E_{t,d}$ is a representation of ($LAN_{fan\ t,d} * T_{house\ t,d}$) where $LAN_{fan\ t,d}$ is defined as ($1-U_{fan\ t,d}$) representing the opposite to the required operation of the device:

The internal air temperature of the house is not to exceed an upper bound ($\overline{UP}$) as indicated below:

$$0 \le T_{house\ t,d} \le \overline{UP} \quad \textbf{(4-22)}$$

If the opposite action to the required operation of the device is zero indicating that the device is ON at any instant of time during the day, then $E_{t,d}$,should have a zero value, subsequently. Moreover, $E_{t,d}$ is not to exceed an upper limit on the internal air temperature of the house. Therefore, the objective function is subject to the following constraint:

$$E_{t,d} \le \overline{UP}\ \ LAN_{fan\ t,d} \quad \textbf{(4-23)}$$

To guarantee $E_{t,d}$ is zero when the opposite action to the required operation on the device needed to satisfy resident's comfort is zero, the constraint of non-negativity is used:

$$E_{t,d} \ge 0 \quad \textbf{(4-24)}$$

If the opposite action to the required operation on the device is one, the below constraint is be considered to ensure that $E_{t,d}$ is equivalent to the internal air temperature of the house. Irrespective of the value of the variable representing the opposite action to the required operation on the device, $E_{t,d}$ is not to be above the value of the internal air temperature of the house:

$$E_{t,d} \leq T_{house_{t,d}} \tag{4-25}$$

To account for $E_{t,d}$ to be at least equivalent to the internal air temperature of the house under the condition that the value of the variable representing the opposite action to the required operation on the device is one, the constraint used is:

$$E_{t,d} \geq \overline{UP}(LAN_{fan\ t,d} - 1) + T_{house_{t,d}} \tag{4-26}$$

The initial air temperature that is felt in the house is described by the constraint below:

$$T_{feel\ t=1,d=weekday} = T_{house\ t=1,d=weekday} \tag{4-27}$$

The comfort conditions based on which the fan will be turned ON or OFF are:

$$T_{feel\ t,d} \geq 27X\ U_{fan\ t,d} + \ (1 - U_{fan\ t,d}) \tag{4-28}$$

$$T_{feel\ t,d} < 27X(1 - U_{fan\ t,d}) + 100\ U_{fan\ t,d} \tag{4-29}$$

C. Washing Machine Model

The washing machine model is based on [58, 59] as shown by the equation below where $Energy_{washing\text{-}machine}$ is the hourly energy demanded (kWh/use), $CYC_{washing\text{-}machine}$ is the number of cycles run by the washing machine per use, *Cap* is the size of the washing machine ($feet^3$) and $Efficiency_{washing\text{-}machine}$ is a factor representing how efficient the washing machine is and is measured in ($feet^3$/kWh).

$$Energy_{washing-machine} = \frac{CYC_{washing-machine} *\ Cap}{Efficiency_{\ washing-machine}} \tag{4-30}$$

The energy consumed by the device is not to be more than the maximum energy it can utilize per use as indicated by the following constraint where $Rating_{wm}$ is the device rated power and *hour* is an hour [16]:

$$Energy_{washing-machine} \leq Rating_{wm} \; hour \quad \textbf{(4-31)}$$

The number of times the washing machine (*LL*) to be utilized can be attuned to satisfy consumers' preferences as given by the constraint below [16]:

$$\sum_{d}\sum_{t=1}^{24} WM_{t,\,d} = LL \quad \textbf{(4-32)}$$

In the simulation results section, the washing machine schedule is for an individual who does not have any restriction on the utilization time of the device; while the results summarizing the expected consumers' demand of the area to be added to the grid will consider the suitable time for individuals to wash their clothes as indicated below where *n* is the house number:

$$\sum_{t=1}^{6} WM_{t,d,n} + \sum_{t=22}^{24} WM_{t,d,n} = 0 \quad \textbf{(4-33)}$$

D. Water Resource System and Radiation Influence on Water Temperature in the Well

The water resource system is made of both a well pump and a water heater that is an electric storage tank in type as this is the type used in Indian houses [60]. Indians use well pump as a water supply system to their houses and to irrigate their lands. Well pump is expected to operate every day for *k* hours as indicated by the constraint below where k can be attuned to satisfy the resident demand [16]:

$$\sum_{t=1}^{24} x_{well-pump_{t,d}} = k \quad \textbf{(4-34)}$$

In the simulation results section, the well pump schedule is for an individual that is not necessary involved in agriculture; while the results summarizing the consumers' demand of the area to be added to the grid will utilize the following constraints accounting for individuals working hours in agriculture as shown below where *n* is the consumer number:

$$\sum_{t=7}^{17} x_{well-pump_{t,d,n}} = k \quad \textbf{(4-35)}$$

$$\sum_{t=1}^{6} x_{well-pump_{t,d,n}} + \sum_{j=18}^{24} x_{well-pump_{t,d,n}} = 0 \quad \textbf{(4-36)}$$

The well's water undergoes temperature disparity as a result of heat gain or loss between the water surface and the air around the water in the well due to the radiation effect. Such a relationship is based on the radiation effect between two bodies as discussed in [61]. In this thesis, the derived linear radiation effect on water temperature model is presented in Appendix B. The equations below show the final equations reached from the derivation shown in Appendix B after substituting the values of the model parameters [16].

$T_{well\text{-}water}$ is the supplied well's water temperature in (ºC) as given by the following equations relating its value at one hour to another and one day type to another [16].

$$T_{well-water\,t+1,d} = T_{well-water\,t,d} + dT_{t,d} \qquad \forall\ t \neq 24 \tag{4-37}$$

$$T_{well-water\,t=1,d=weekend} = T_{well-water\,t=24,d=weekday} + dT_{t=24,d=weekday} \qquad \forall\ t \neq 24 \tag{4-38}$$

It is important to emphasize that the well's water temperature loss as a matter of radiation (*dT*) determined as in Appendix B is given below after replacing the matching parameters' values where (*Q)* represents the heat loss or heat gain in (Watt) due to radiation effect considering both bodies, water and air [16]:

$$dT_{t,d} = -(35.9999*100)*(10^{-3})*(238*10^{-3})*(1061*10^{-5})Q_{t,d} \tag{4-39}$$

The heat lost/gained by radiation is derived in Appendix B to be in the linear form as shown below after replacing the matching parameters values where $T_{operating}$ is defined as the season's temperature operating point of the well's water [62]. Also, temperature conversion from ºC to ºK in [63] is taken into consideration [16].

$$Q_{t,d} = \begin{pmatrix} 0.95*5.67*10^{-8}*3.14*(-3*(273+T_{operating})^4 \\ +4*(273+T_{operating})^3(273+T_{well\ water\,t,d}) - (273+T_{external\,t,d})^4 \end{pmatrix} \tag{4-40}$$

The initial temperature of the well's water for the first weekday in a month is given below [16]:

$$T_{well-water\,t=1,d=weekday} = \begin{cases} 10^{o}C\ in\ winter\ season \\ 26^{o}C\ in\ summer\ season \end{cases} \tag{4-41 \& 4-42}$$

The house water supply is from the well. This water is heated based on demand using an electric storage tank water heater [60]. The model of the energy consumed by a water heater requires certain elements to be defined. These are the hourly demand of hot water accounting for the availability of house members and their unavailability because of their work, the heat vanished from the tank surfaces, and the energy consumed by the water heater due to consumed hot water. Modeled Patterns of hot water consumption are available in [58, 64]. The energy consumed by a water heater to account for surface losses is based on the model in [65] involved in [16] as shown below after accounting for the tank's area and its insulation in [66], performing the appropriate unit conversions, and assuming the hot water temperature is maintained at the thermostat defined point (*Therm*) in [67] while considering the temperature conversion to Fahrenheit [68]:

$$ZLoss_{t.d} = \frac{13621.875 \ X \ 10^{-4}}{3413}\left((\frac{9}{5}Therm - \frac{9}{5}T_{houset,d}) + 32 \right) \quad \textbf{(4-43)}$$

The energy consumed by the water heater due to hot water demand (*ZWH* in kWh) based on [58] is involved in [16] as shown by the following equation where hot water demand in gallons is represented by *dem*, the water temperature coming from the well ($T_{well\text{-}water}$) in (°C) after accounting for the energy efficiency of the water heater as in [66], and the appropriate unit conversions:

$$ZWH_{t,d} = \frac{100}{93}\frac{dem_{t,d} X \left[(\frac{9}{5}Therm - \frac{9}{5}T_{well-water\,t,d} + 32) \right] X \ (82928 \ X10^{-4} Btu.gallon^{-1}.^{o}F^{-1})}{3413 Btu / kWh} \quad \textbf{(4-44)}$$

The total energy demand of a water heater is not to surpass the amount of energy it can utilize at an hour as given by the following constraint where *Rating* is the device power rating:

$$ZWH_{t,d} + ZLoss_{t.d} \leq Rating_{t,d} \ X \ hour \quad \textbf{(4-45)}$$

4.2.4 Simulation Results

Residential house's devices have been scheduled accounting for the stochastic nature of the weather condition to minimize the contribution of the expenses from the monthly income to electricity bill. This step of the research has been followed to predict what the demand of household can be when connected to the grid. The problem is addressed as a mixed integer linear programming optimization problem and solved using CPLEX solver in GAMS software [31] considering two types of days that are weekday and weekend utilizing the stochastic weather condition, the seasonality role on home's devices operation, the devices hourly operation reliance on its operation at an earlier hour, consumer's working hours in [37], household size in [69, 70], the house size in [40], the sunset hour based on [36], and the assumed bedtime times considering the nature of the season to turn two light bulbs of a house ON and OFF. GAMS codes was run on a personal laptop (2.26GHz Intel Core 2). The execution time was very short demonstrating a time drop approximately 99% compared to [41] using the particle swarm optimization and roughly 99% compared to using the tabu search [42]. For example, the execution time was 0.016 seconds when devices are scheduled in summer under the stochastic weather condition. The model statisics are as follows: there were 45 equations' blocks, 2016 single equations, 13 variables' blocks, 577 single variables, 5588 non-zero elements and 144 discrete variables. This shows that the inclusive linear load models' scheduling is very fast and appropriate resulting in a global optimal solution. The scheduling problem can be updated to fit any house in a developing country provided that the loads and their features, the size of the house and its total residents, and the job hours are specified [16].

Three scenarios are studied to investigate how the model of stochastic weather condition can affect devices' scheduling and thus consumers' electric utility payments. These scenarios are as follows [16]:

1. The Monte-Carlo simulation produces sets of temperature data for two types of the day that are weekday and weekend in a given season given that all determined temperature values are assigned the same probability. In this scenario, the sets representing each day type are the same. The optimization problem is treated for two days and to obtain the objective function, the contribution of the monthly income expenses to the electricity bill for each day type is multiplied by the corresponding number of days representing the type in a season. In such a scenario, an assumption is made that the initial conditions applied on the first weekday in the month are the same for all days of such type. As a result, two load schedules are supplied to the electricity residential consumer.
2. The Monte-Carlo simulation produces sets of temperature data for two types of the day that are weekday and weekend in a given season given that all the determined temperature values are assigned the same probability. In this scenario, the sets representing each day type are the same. The initial conditions are features of only one day in a month. For the temperature data sets for a typical day type, the author assumes their repetition in the month based on their location in that month. In this scenario, the operational dependency of a house's load on temperature at 1am on day 2 is based on its operation at 12pm on day 1 and so on for the rest of the days within the month.
3. The Monte-Carlo simulation produces sets of temperature data for two types of the day that are weekday and weekend in a given season given that the determined temperature values are clustered into states. At this instance, the value representing a state is a result of performing a summation on the results obtained from multiplying the central point of every state by its associated probability.

4. When online scheduling is possible, the problem of the load scheduling under real temperature measurements is performed for a whole month. The author compares the effectiveness of the above three scenarios with online scheduling under real measurements obtained from [44, 45].

   The first three scenarios are considered beneficial for consumers in developing countries where offline scheduling is preferred because developing countries lack technology infrastructure to consider load scheduling a head of time by a day. The results of the different scenarios are shown in Figure 4.5. Since the error is found to be small and it is almost 1.5% [16], scheduling home devices under the stochastic weather condition can resemble the devices' scheduling under real measurements.

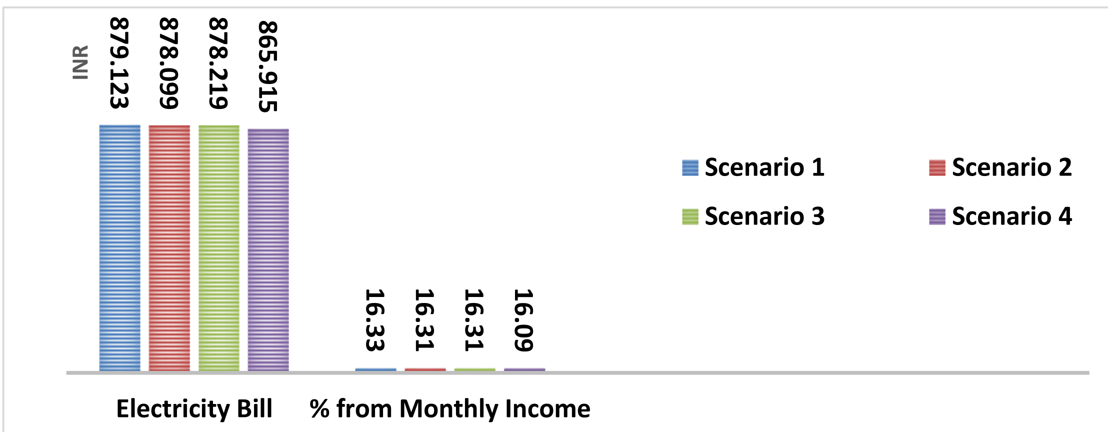


Figure 4.5: Advantage of summer load scheduling under stochastic weather temperature

Even though device scheduling under the stochastic weather condition in winter and summer seasons has been considered, it has been chosen here to present a sample results of an individual house's predicted device scheduling in summer. A summary on the final results from device scheduling based on the stochastic weather condition in a winter season is presented in Figure 4.6 for different pricing schemes compared to the old-style approach based on units of daily consumption. The Figure shows the expected electricity bill and its percentage from the monthly income in [34] for a residential household in India. In this figure, it is assumed that if electricity bill exceeds an individual's income, the bill can be divided between working individuals who earn income. Thus, each individual's income will contribute less to the electricity bill. Furthermore, higher economic groups in India can have these house's electrical devices. Figure 4.7 shows the monthly income percentage to be paid on electricity bill in summer due to scheduling two or more of the following devices (washing machine, water supply system and fan). The bill also includes the electricity costs of light bulbs in the house.

Figure 4.8 shows the ON-OFF operation of the fan in a weekday and a weekend in summer considering the house internal and external air temperatures. In this figure, the green line represents the felt temperature, and the line deviation between any two consecutive hours indicates how operating the fan can influence the felt internal air temperature within an hour [16].

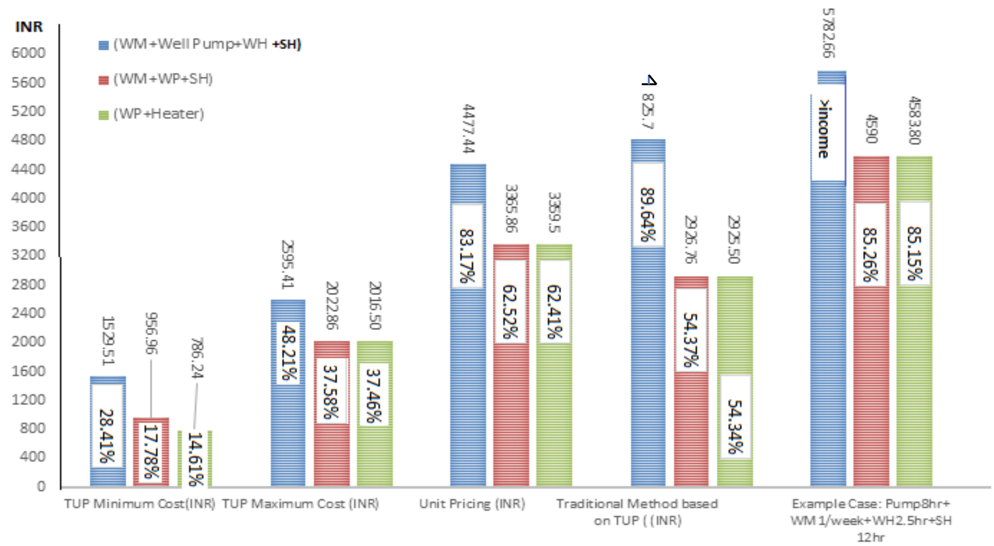


Figure 4.6: Load scheduling in winter and % to be paid from income on electricity bill

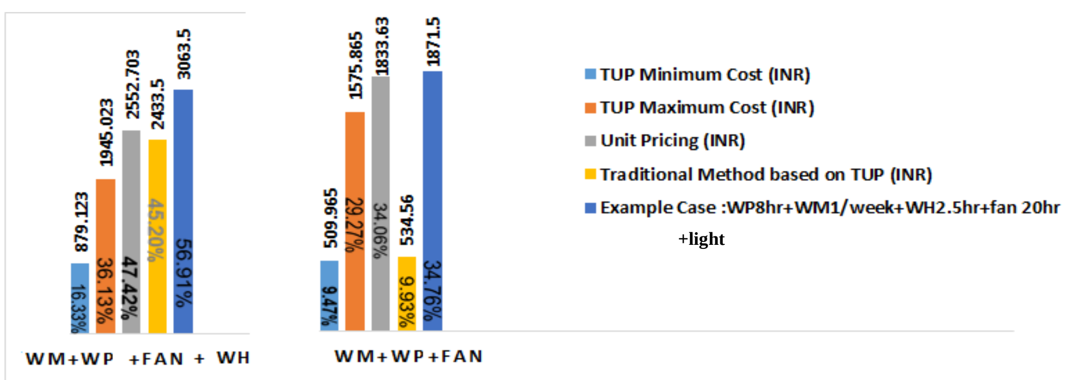


Figure 4.7: Load scheduling in summer and % to be paid from income on electricity bill

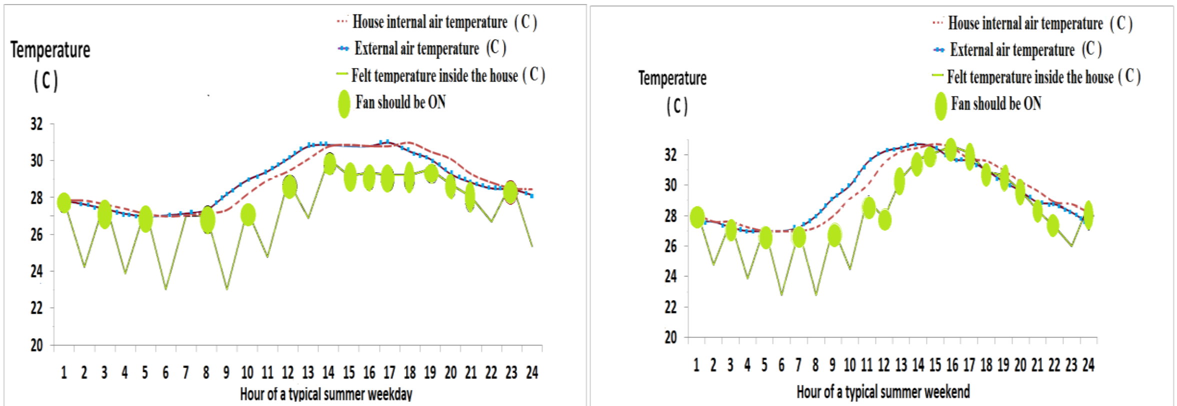


Figure 4.8: Results of scheduling a fan in typical weekday (left) and weekend (right) [16]

The temperature of the well's water can vary because of radiation, which is based on the temperature difference between the well's water and the air around it. This effect is shown in Figure 4.9 [16] where the negative sign linked to (*Q*) is a representation of a gained energy when external air temperature is greater than that of the well's water. The figure reveals a rise in water temperature during the day, which is due to high surrounding temperature compared to the temperature of the water even though radiation drops during specific hours of the day [16].

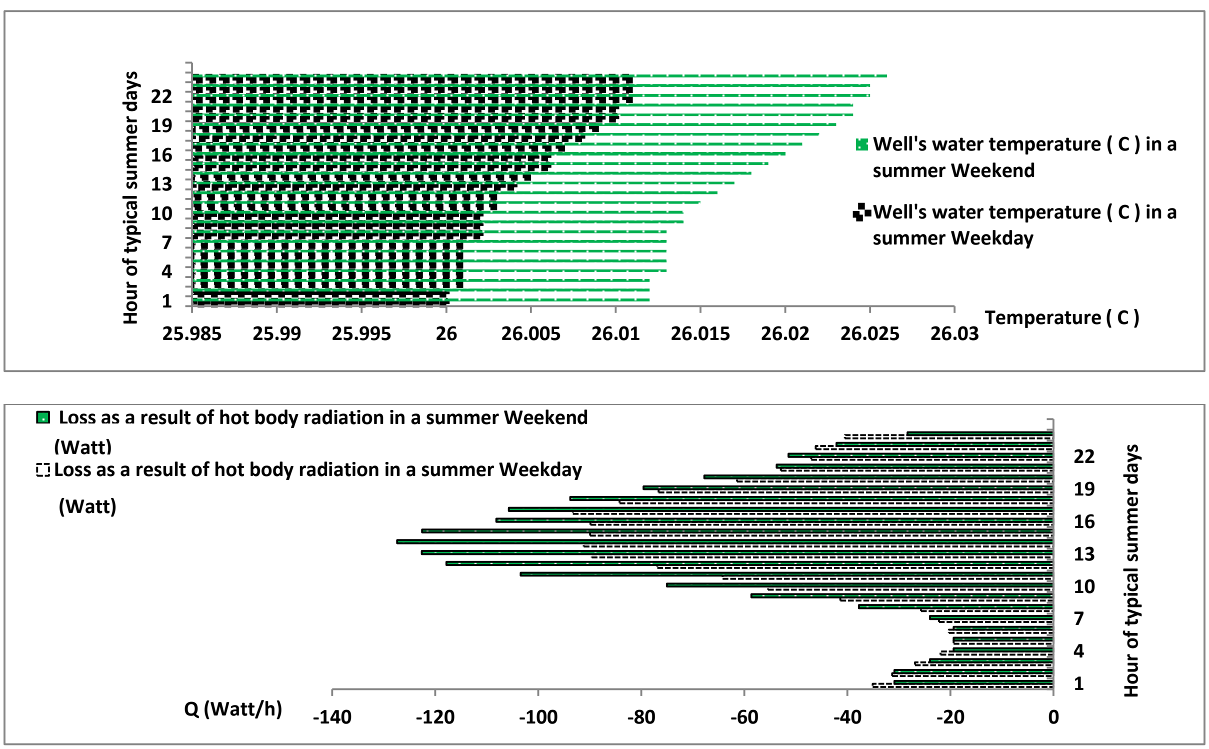
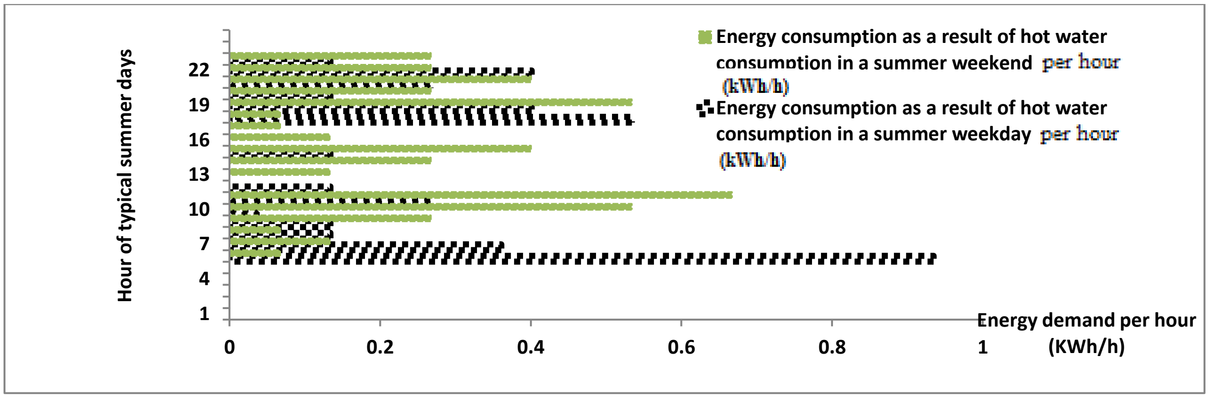


Figure 4.9: temperature of well's water (Top) and its Q gain (Bottom) in typical summer days

The daily energy consumed because of hot water use and the lost energy through the water heater tank surfaces are given in Figure 4.10 [16].



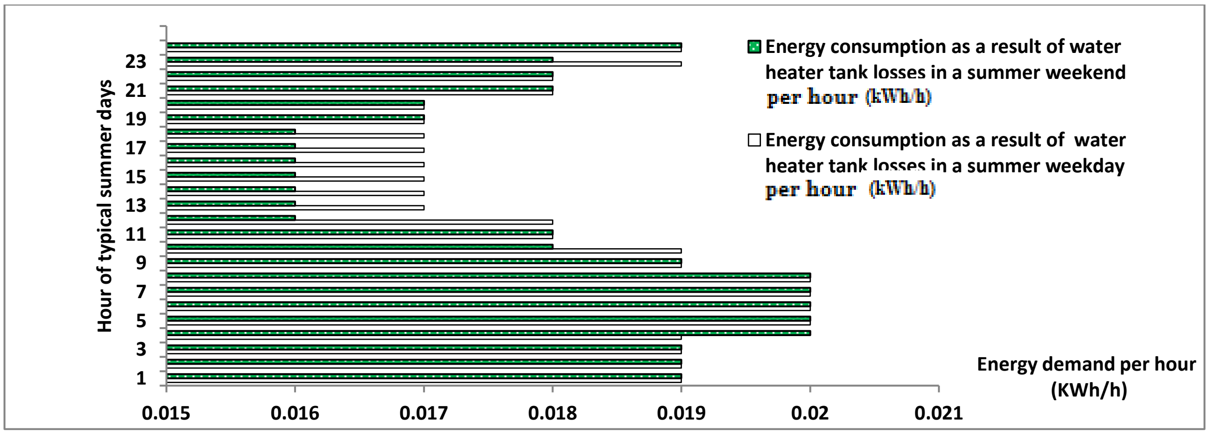


Figure 4.10: Summer energy demand per hour due to consumed hot water (Top) and losses (Bottom)

The washing machine can be turned ON at hours characterized with the minimum time of use tariff in a weekday; but can be turned ON during a weekend with no requirement on the time. Regardless the season, the well pump can be operated during off peak prices of a weekday for a total of *k* hours; however, it can be turned ON with no specification on time during the weekend for same number of hours [16].

A comparison was carried out to confirm the load scheduling results as in Figure 4.11. This comparison is based on the obtained results and the load profile of a water heater in [32, 35]. The water heater is consuming 10.21kWh daily when it is not scheduled and 4.45kWh daily when scheduling is considered as the latter value presumes the device model and its operational reliance on the effect of other devices' operation such as the space heater [16].

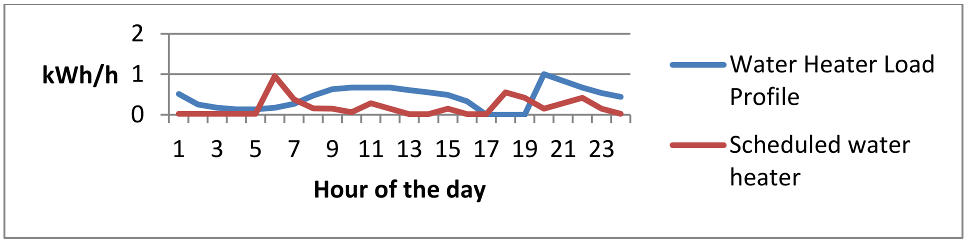


Figure 4.11: Results validation compared to current practice

4.2.5 Stochastic Weather and Inclusive Load Models Impact on Residential Electric Utility Payments

Table 4.2 presents the impact of considering the stochastic weather condition in valuing the electric utility payments of a normal Indian resident, excluding the fixed charge placed on the electricity bill and the energy price for using house lights. Such exploration is suitable for consumers with no internet to consider houses' devices scheduling a day in advance. Table 4.2 also shows the important effects of including specific factors in the inclusive linear models of home devices on supplying the consumer with a more representative schedule of the devices reflected on valuing electric utility payment. Although, the difference between the investigated scenarios might be small, it is necessary to clarify that the targeted electricity residential consumers live in a developing country where the individuals' income are limited [34] due to poor economy. Any difference in the bill is worth reviewing by the consumers to choose to purchase new homes' devices and discard old homes' devices. A 1.5% is an error representing the difference between evaluating the objective function utilizing the stochastic weather model and the utility payment estimated considering scheduling house devices a head of time by a day. A 1.74% error is added to the above error because of scheduling house devices under non-stochastic weather model compared to their schedule under stochastic weather model [16].

Table 4.2: stochastic weather and inclusive load models Effect on utility payment valuation [16]

Components considered	* INR accounting for stochastic weather conditions	^ INR neglecting stochastic weather conditions	I error I	
I) Summer home devices scheduling	730.22	742.93	1.74%	
II) Neglecting radiation effect	730.31	743.08	between II* and I*	0.01%
			between II^ and I^	0.02%
III) Neglecting tank surface losses	700.48	715.49	between III* and I*	4.073%
			between III^ and I^	3.69%
IV) Neglecting both radiation and surface losses	700.57	715.65	between IV* and I*	4.061%
			between IV^ and I^	3.67%
V) Neglecting the thermal effect of the house	724.07	748.24	between V* and I*	0.84%
			between V^ and I^	0.72%
VI) II, III, IV and V	694.41	720.96	between VI* and I*	4.90%
			between VI^ and I^	2.97%

4.2.6 Commendations

Developing countries governments can recruit traders supplying residents with a monthly house devices schedule at a low charge as 1INR. Furthermore, the present utility policy pricing consumers' demand based on their class following the energy units utilized [39] can be updated to a time of use tariff as a future aspect toward smart grid through smart metering when economy permits. This will facilitate the economic benefit for both utility and consumers besides meeting their comfort [16].

4.2.7 System Expansion: Residential Area Demand

This section presents the expected residential load curves of the new area to be electrified based on the expected owned load devices and the stochastic weather models, while accounting for customer satisfaction (comfort level, working hours, demand, …..etc.) as shown in Figure 4.12. The load curves of the eight houses are displayed below. It is important to emphasize that the optimization problem presented earlier has been presented for one house, but it is important to emphasize that it has been updated to account for the eight residential houses. Furthermore, the following constraints are added to ensure that the demand of each house does not exceed the residential house connected load that is 4kW/house, and the variability of the accumulated loads does not exceed the load variability according to IEEE RTS. These conditions are shown in the constraints below:

$$\sum_{n=1}^{8} P_{heat\,n,t,s}\, hour\ xh_{sh\ n,t,s} + z_{wh\ \ n,t,s} + P_{well-pump\ n,t,s}\ hour\ \ x_{well-pump_{n,t,s}} + Energy_{washing\text{-}machine\ \ n,t,s}\ WM_{n,t} \le Pd_{i=4}\ RTS_{t,s}\ hour \tag{4-46}$$

$$P_{heat\,n,t,s}\ hour\ \ xh_{sh\ n,t,s} + z_{wh\ \ n,t,s} + P_{well-pump_{n,t,s}} hour\ \ x_{well-pump_{n,t,s}} + Energy_{washing\text{-}machine\ \ n,j}\ WM_{n,t,s} \le Max\ house\ connected\ \ load\ \ hour \tag{4-47}$$

The term ($P_{heat}\, hour\ xh_{sh}$) is replaced with ($P_{fan}\, hour\ U_{fan}$) in summer, and s indicates the season.

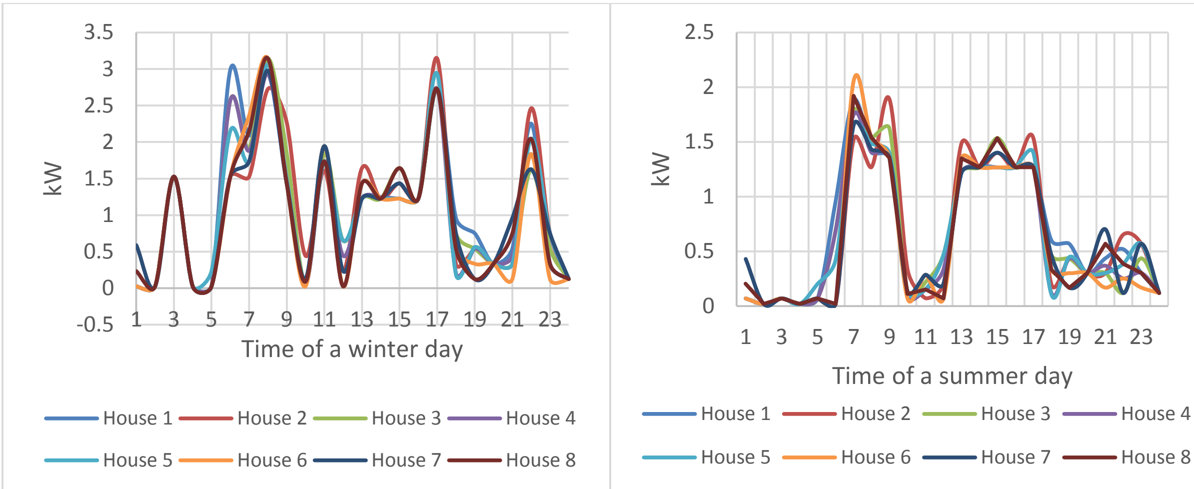


Figure 4.12: Expected residential demand of different houses of the area to be electrified (left: winter, right: summer)

The expected residential energy demand for all houses is 199.5848kWh in a typical winter day. On the other hand, the expected residential energy demand for all houses is 117.7454kWh in a typical summer day.

4.2.8 Section Summary

In this section, residential load scheduling under the stochastic weather condition had been offered to determine the residential demand of a new region to be connected to the grid to accommodate population growth. The weather condition was modelled using probability theory and the Monte-Carlo simulation and was interrelated to the load. Such a tie was undertaken in a mixed integer linear programming problem containing comprehensive load models aiming to achieve the minimum contribution of the monthly income to be spent on an electric utility payment. Scheduling the residential loads under the stochastic nature of weather condition was suitable for Indians, where most of them were not accessing the internet for a day ahead of scheduling. Results proved that following such an approach guarantees a global optimal solution in a manageable time when the problem was solved as a mixed integer linear programming. It had been presented in this section that it was significant to include comprehensive load models governed by the stochastic weather condition, since this influenced the accurate schedule of residential consumer's devices and consequently reflected on the accurate valuation of what to be spent from the monthly income on an electric utility payment. Moreover, commendations were developed for governments and utilities in developing countries for economies and consumers' benefits.

4.3 An Introduction to the Current Problem and Proposed Solutions

Electricity consumers in developing countries are in demand for reliable electric services to support the economy. Poor supply of electricity is a major concern for these consumers because of the power generation shortage compared to the demand leading to frequent power interruptions. Power interruption schedules are initiated by the electric utility to minimize the total load connected to the grid [3]. Such schedules are to isolate feeders from the grid such that the whole grid is supplied by matching the supply and the demand. With the population growth and the demand for residential expansion, new areas are to be built and electrified. The addition of such areas to the grid is a challenge to the power utilities due to the deficiency in the power supply resources. These resource deficiencies will either leave such an area not electrified (as is the case of many villages in developing countries), will supply part of a village (such that the village is recognized by the electric utility as an electrified area) , or will connect this area to the grid (worsening the power interruption schedules of other grid regions). In the current state of art that is applied in developing countries, the power interruption schedules are applied to different zones of the distribution system where every zone can represent a feeder. Under power interruption, such a feeder is not connected to the grid for certain hours daily such that all zones have the same amount of hours while being away from the grid. This section of the thesis proposes two solutions to withstand such problems in order to facilitate the addition of new areas to the grid by enhancing system expansion through new area houses' full power interruption or house devices' power interruptions as alternative solutions to feeder isolation from the grid by utilizing the available power. The application of such solutions will not worsen other feeders' durations of daily power interruptions and will allow the new consumers to be electrified, thus enhancing their lives. Even though the proposed solution is simulated over the feeder to be added to the grid, it is important to emphasize that such work can be expanded in the future to include the effect of the proposed solution on other feeders in the grid such that the distribution system can be fully studied. The presentation of the simulation results with the focus on a specific feeder of a new region to be connected to the grid representing the perspective toward distribution system expansion is for simplicity reasons.

4.3.1 System under Study: Current Generation versus Expected Demand

The system under study is shown earlier in Figure 4.1. That system had two buses with critical loads that should not be interrupted (nursing clinics and shopping center) and one bus to which residential houses are connected. The available generation to supply this region to be connected to the grid after considering feeders' power interruptions of the whole distribution system is shown in Figure 4.12 It is important to emphasize that the demand of such system is 72.05KVA and the available generation is sufficient to meet the loads at bus 2, bus 3 and about 83% of the residential load at bus 4. This available generation is about 91% of the total load to be connected to the system. This winter demand-generation gap is based on [18]. On the other hand, the available power generation is sufficient to meet the loads at bus 2, bus 3 and about 89% of the residential load in summer.

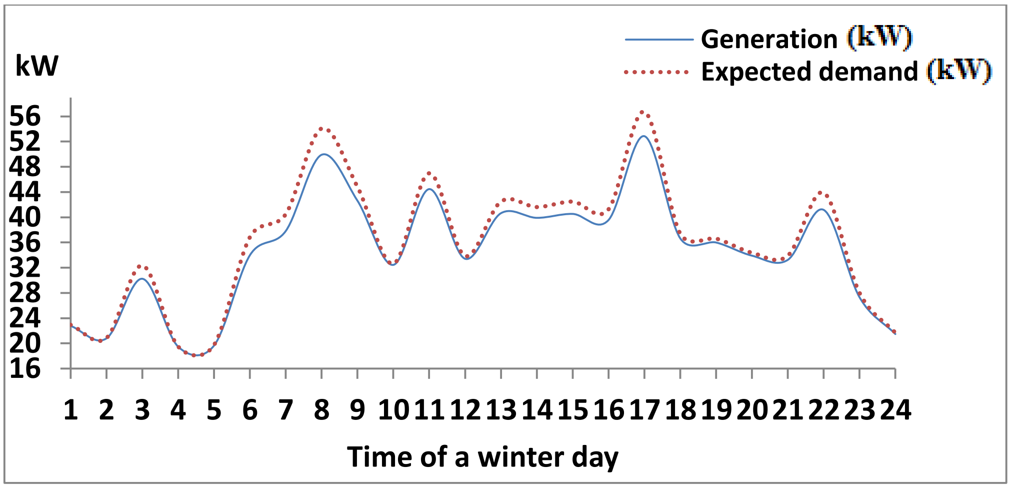


Figure 4.13: Available power generation for the new feeder and expected demand in winter

The expected demand shown in the figure represents the critical load demand (varying according to the IEEE RTS in winter), the residential load predicted demand (evaluated based on home devices' load models scheduled to minimize what will be spent from the monthly income on the electricity bill as discussed earlier in section 4.1), and the system losses (evaluated based on an optimal power flow problem targeting minimizing system losses assuming no deficiency in the system). On the other hand, the relation between generation and demand in summer is described by the figure below.

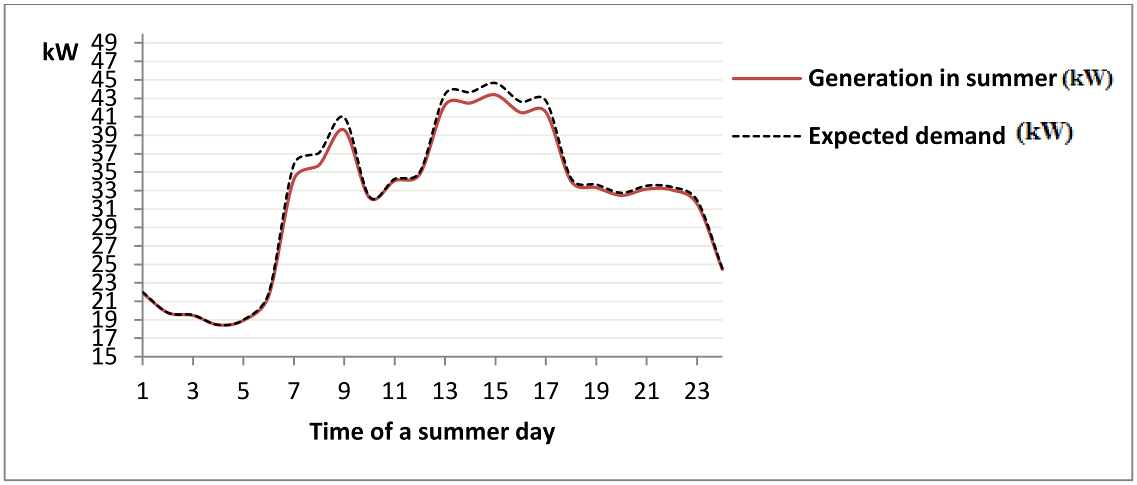


Figure 4.14: Generation versus expected demand in a typical summer day

The current approach applied in developing countries will either leave the new residential area un-electrified or will worsen the power interruption schedule on other feeders in the grid such that this area can be connected to the grid. The table below shows the expected demand to be supplied if the new area is to undergo the current applied power interruption schedule such that the new feeder encounters 10 hours of power interruption in two time slots of a summer day (3am-7am and 13pm-17pm) and 12 hours of power interruption in three time slots of a winter day (12am-3am, 8am-11 and 16pm-19am).

Table 4.3: The expected demand to be supplied under the current power interruption schedule

Winter	**Actual demand**	**Supplied demand under current power interruption schedule**
Total supplied energy (kWh)	199.5848	90.100958
Number of space heaters	48	16
Water heater (WHs)	**With tank losses:** -Energy= 42.784778kWh -Number of WHs= 192 **Without tank losses:** -Energy=37.870779kWh -Number of WHs=103	**With tank losses:** -Energy= 24.77351kWh -Number of WHs= 96 **Without tank losses:** -Energy=23.723504kWh -Number of WHs=55
Number of well pumps	64	32
Number of washing machine	8	8
Number of lights	56 x (2 lights)	32 x (2 lights)
Summer	**Actual demand**	**Supplied demand under current power interruption schedule**
Total supplied energy (kWh)	117.7454	47.1516
Number of fans	120	72
Number of water heaters (WHs)	**With tank losses:** -Energy= 27.745409kWh -Number of WHs= 192 **Without tank losses:** -Energy=26.10796 kWh -Number of WHs=103	**With tank losses:** -Energy= 19.551593kWh -Number of WHs= 112 **Without tank losses:** -Energy= 18.953261kWh -Number of WHs=80
Number of well pumps	64	16
Number of washing machines	8	0
Number of lights	48 x (2Lights)	48 x (2Lights)

The thesis proposes two solutions to take advantage of the power that can be supplied that is also not sufficient to meet the feeder demand, leaving the area under study un-electrified, by either interrupting the demand of specific homes or interrupting the devices of the homes. These two solutions are discussed below:

4.3.2 First Proposed Solution to Address PGS at Residential Level

Taking advantage of the determined expected home devices' load patterns, the demand of every house in the new feeder is determined as shown earlier in Figure 4.12. The objective is to interrupt the power of specific houses during the day such that this new feeder can be supplied. The power interruption strategy is based on selecting certain houses to be interrupted based on their expected demand at a certain hour such that all houses are supplied for the same number of hours daily. This solution will ensure that the maximum number of houses is supplied during the day, not violating the power flow constraints. The problem is solved as two separable sub-problems that are interconnected. The first sub-problem considers the available power generation, the expected residential hourly demand, and the system losses under no deficiency of supply. It also schedules the power interruption of houses with respect to the available supply such that they are all supplied for the same number of hours daily. The second problem verifies that the results obtained from the first problem do not violate power flow constraints by ensuring that the determined houses' full power interruption schedules are all met. If violations exist such that a house supplied with electricity in the first optimization problem cannot be supplied with electricity based on the second optimization problem, the new losses determined in this problem are inputted back to the first problem and rescheduling of house power interruption is considered. The problem is to be carried iteratively until the determined solution satisfies both problems. In the solution presented in this section, this issue is not faced and the schedule determined did not violate the power flow constraints.

4.3.2.1 First Optimization Problem

$$\max \quad \sum_{t=1}^{24}\sum_{n=1}^{8} o_{n,t,s}\ Phouse_{n,t,s}\ hour \qquad \textbf{(4-48)}$$

Subject to

1. Generation-demand constraints:

$$Pg_{i=1,t,s} - Pd_{i=2}\ RTS_{t,s} - Pd_{i=3}\ RTS_{t,s} - \sum_{n=1}^{8} o_{n,t,s}\ Phouse_{n,t,s} - Ploss_{t,s} = 0 \tag{4-49}$$

$$Qg_{i=1,t,s} - Qd_{i=2}\ RTS_{t,s} - Qd_{i=3}\ RTS_{t,s} - \sum_{n=1}^{8} o_{n,t,s}\ Qhouse_{n,t,s} - Qloss_{t,s} = 0 \tag{4-50}$$

2. Fairness of houses' power interruption:

$$\sum_{t=1}^{24} o_{n,t,s} = \sum_{t=1}^{24} o_{n+1,t,s} \quad \forall n \neq 8 \tag{4-51}$$

3. Available power supply constraints:

$$Plow_{t,s} \leq Pg_{i=1,t,s} \leq Pup_{t,s} \tag{4-52}$$

$$Qlow_{t,s} \leq Qg_{i=1,t,s} \leq Qup_{t,s} \tag{4-53}$$

where *Pg* is the available power supply, *Pup* is an upper bound on what active power can be supplied, *Plow* is a lower bound on what active power can be supplied, *Qup* is an upper bound on what reactive power can be supplied, *Qlow* is a lower bound on what reactive power can be supplied, *Pd* is the demand at bus *i*, *RTS* is a variability factor showing how the demand at bus *i* can vary hourly according to IEEE RTS, *o* is a binary variable that is one if the house can be supplied and zero otherwise, *Phouse* is the active power demand of house *n* at hour *t* as determined from the expected residential demand model presented in section 4.1, *Ploss* and *Qloss* are the active and reactive losses of the system respectively determined from a problem targeting minimizing the losses of the system under study assuming availability of supply, *Qg* the available reactive power supply, *Qd* is the reactive power demand of bus *i* and *Qhouse* is the reactive power of the house devices consuming reactive power such as the washing machine, well pump and electric fan. The reactive power of such devices is determined based on power factors defined in [71, 72]. It is important to emphasize that all calculations assume per unit conversion to facilitate the results input to the second optimization problem. The losses used here are set to reserve some part of the generation to system's losses within a roughly estimated bound.

4.3.2.2 Second Optimization Problem

$$\max \quad \sum_{t=1}^{24} \sum_{n=1}^{8} o_{n,t,s} \tag{4-54}$$

Subject to:

1. Power flow constraints:

$$Pg_{i,t,s} - Pd_i * RTS_{t,s} = \sum_{j=1}^{4} [V_{i,t} * V_{j,t} * Y_{i,j} * \cos(-\theta_{i,j} - \delta_{j,t} + \delta_{i,t})]) \qquad \forall i \neq 4 \tag{4-55}$$

$$Qg_{i,t,s} - Qd_i * RTS_{t,s} = \sum_{j=1}^{4} [V_{i,t} * V_{j,t} * Y_{i,j} * \sin(-\theta_{i,j} - \delta_{j,t} + \delta_{i,t})]) \qquad \forall i \neq 4 \tag{4-56}$$

$$Pg_{i,t,s} - \sum_{n=1}^{8} o_{n,t,s} \ Phouse_{n,t,s} = \sum_{j=1}^{4} [V_{i,t} * V_{j,t} * Y_{i,j} * \cos(-\theta_{i,j} - \delta_{j,t} + \delta_{i,t})]) \qquad \forall \ i = 4 \tag{4-57}$$

$$Qg_{i,t,s} - \sum_{n=1}^{8} o_{n,t,s} \ Qhouse_{n,t,s} = \sum_{j=1}^{4} [V_{i,t} * V_{j,t} * Y_{i,j} * \sin(-\theta_{i,j} - \delta_{j,t} + \delta_{i,t})]) \qquad \forall \ i = 4 \tag{4-58}$$

2. Available power supply constraints:

$$Pg_{i \neq 1,t,s} = 0 \tag{4-59}$$

$$Qg_{i \neq 1,t,s} = 0 \tag{4-60}$$

$$Plow_{t,s} \leq Pg_{i=1,t,s} \leq Pup_{t,s} \tag{4-61}$$

$$Qlow_{t,s} \leq Qg_{i=1,t,s} \leq Qup_{t,s} \tag{4-62}$$

System voltage level constraints:

$$0.95pu \leq V_{i,t,s} \leq 1.05pu \tag{4-63}$$

$$-\pi \leq \delta_{i,t,s} \leq \pi \tag{4-64}$$

3. Feeder power balance constraints:

$$\sum_{i=1}^{4} Pg_{i,t,s} - Pd_{i=2} \ RTS_{t,s} - Pd_{i=3} \ RTS_{t,s} - \sum_{n=1}^{8} o_{n,t,s} \ Phouse_{n,t,s} - Ploss_{t,s} = 0 \tag{4-65}$$

$$\sum_{i=1}^{4} Qg_{i=1,t,s} - Qd_{i=2} \ RTS_{t,s} - Qd_{i=3} \ RTS_{t,s} - \sum_{n=1}^{8} o_{n,t,s} \ Qhouse_{n,t,s} - Qloss_{t,s} = 0 \tag{4-66}$$

Ploss and *Qloss* can be calculated as given below:

$$Ploss_{t,s} = \sum_{i=1}^{4} \sum_{j=1}^{4} (0.5 * gg_{i,j} * [V^2{}_{i,t} + V^2{}_{j,t} - 2 * V_{i,t} * V_{j,t} * \cos(\delta_{j,t} - \delta_{i,t})]) \quad \textbf{(4-67)}$$

$$Qloss_{t,s} = -\sum_{i=1}^{4} \sum_{j=1}^{4} (0.5 * bb_{i,j} * [V^2{}_{i,t} + V^2{}_{j,t} - 2 * V_{i,t} * V_{j,t} * \cos(\delta_{j,t} - \delta_{i,t})]) \quad \textbf{(4-68)}$$

where V is the voltage, δ is the voltage angle, gg is the active part of the admittance matrix, bb is the reactive part of the admittance matrrix, θ is the angle of the admittance matrix and Y is the admittance matrix.

4.3.2.3 Simulation Results of the First Proposed Solution to Address PGS at Residential Level

The first optimization problem is a linear programming problem solved using CPLEX solver in GAMS; while the second optimization problem is a mixed integer non-linear programming solved using DICOPT solver in GAMS. The main reason behind solving the problem as two problems is to avoid long computation time and solver failure due to limited computer memory.

It has been found that every house will be disconnected from the grid for 6 hours daily in winter and 5 hours daily in summer as can be seen in Figure 4.15 where ON indicates a supplied house with electricity while OFF indicates otherwise. Furthermore, Figure 4.15 shows an example of a selected house power interruption schedule in summer. The relationship between the generation and demand is shown in Figure 4.16 for typical winter and summer days.

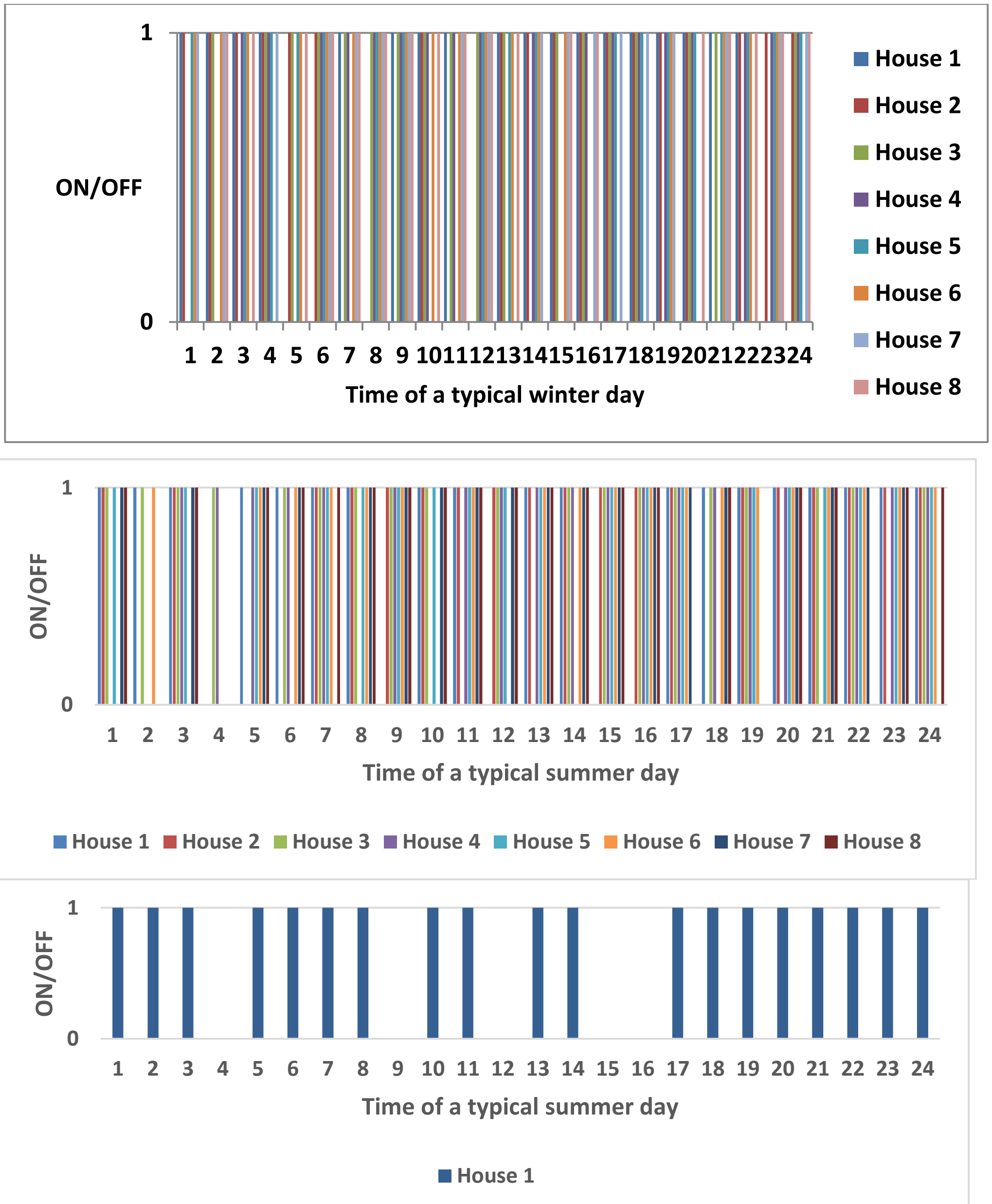


Figure 4.15: House full power interruption schedule in winter (Top) and summer (Middle), and an example on House 1 power interruption schedule (Bottom)

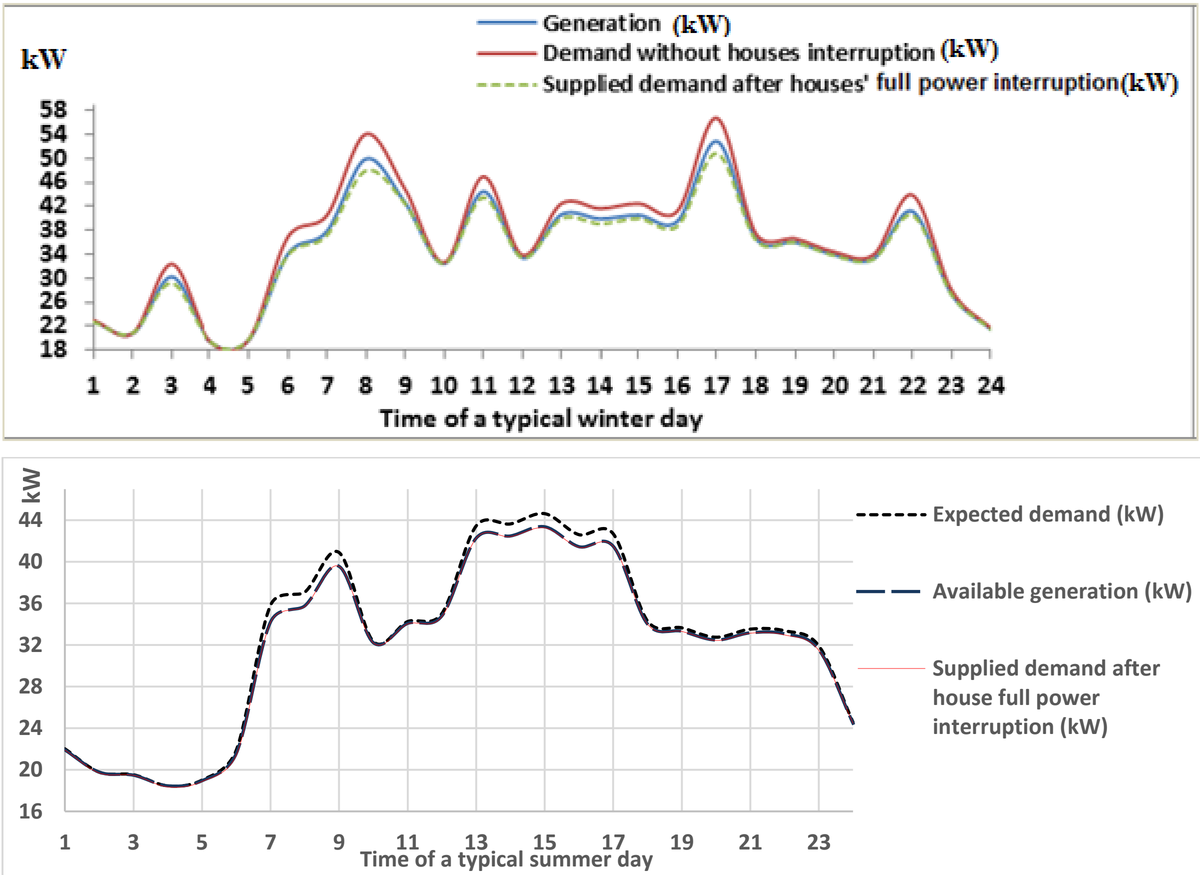


Figure 4.16: Supplied demand after houses' full power interruption in winter (Top) and summer (Bottom)

Each house will have 18 hours of electricity supply in winter and 19 hours of electricity supply in summer rather than having all the houses disconnected from the grid for more than 10 to 12 hours daily [73] due to worsening feeders' power interruption schedules after connecting the new region to the grid. The 10 to 12 hours of power interruption is the current effect of power generation shortage in a developing country due to misuse of electricity. The proposed solution forms a better alternative rather than being not electrified at all or having such huge number of power interruption hours. Such a solution will reduce the severity of power generation shortage and will permit more customers to be electrified as verified by the table below. The practical implementation of such a solution will require controllers switching such houses from the grid rather than disconnecting all houses through feeder circuit breakers. If such controllers cannot be deployed due to utility budget restrictions, consumers can take a voluntary action to disconnect their houses through insuring no usage of electricity during such hours.

Table 4.4: Expected demand to be supplied under the proposed solution

Winter	Supplied demand under current power interruption schedule	Supplied demand under the proposed solution
Total supplied energy (kWh)	90.100958	155.8802
Number of space heaters	16	37
Number of water heaters (WHs)	**With tank losses:** -Energy= 24.77351kWh -Number of WHs= 96 **Without tank losses:** -Energy=23.723504kWh -Number of WHs=55	**With tank losses:** -Energy= 34.709641kWh -Number of WHs= 144 **Without tank losses:** -Energy= 33.144907kWh -Number of WHs=82
Number of well pumps	32	49
Number of washing machines	8	6
Number of Lights	32 x (2 lights)	42 x (2 lights)
Summer	**Supplied demand under current power interruption schedule**	**Supplied demand under the proposed solution**
Total supplied energy (kWh)	47.1516	103.029173
Number of fans	72	99
Number of water heaters (WHs)	**With tank losses:** -Energy= 19.551593kWh -Number of WHs= 112 **Without tank losses:** -Energy= 18.953261kWh -Number of WHs=80	**With tank losses:** -Energy= 24.679173 kWh -Number of WHs= 103 **Without tank losses:** -Energy= 23.527944kWh -Number of WHs=89
Number of well pumps	16	56
Number of washing machines	0	7
Number of Lights	48 x (2 lights)	41 x (2 lights)

4.3.3 Second Proposed Solution to Address PGS at Residential Level

The second proposed solution to address the power generation shortage at a residential level is based on home appliances' scheduling to minimize the severe effect on consumers' lives as a matter of disconnecting a feeder from the grid or leaving the consumers' houses not electrified. The proposed solution has the advantage of providing the residential consumers with electric power all the time by disconnecting certain appliances during generation deficiency rather than disconnecting the house from the grid for a certain hour. The proposed solution takes into consideration the comfort level of the residential consumers by accounting for their daily power demand, their working hours and the stochastic weather condition governing the operation of their devices. Furthermore, the proposed solution considers the importance of other loads connected to the grid by giving them the priority of supply and scheduling the residential devices based on the availability of supply accordingly and considering the consequences of a device power interruption at a certain hour on its demand for another hour.

The devices are classified into two categories. These categories are the category of essential devices not to be power interrupted such as light and the category of devices whose operation can be dependent on one or more of the following factors: the comfort level, the house occupancy, the working hours of individuals, the uncertainty in weather condition, and the house size. The latter category involves the space heater, electric fan, water supply system (water heater and well pump) and washing machine.

This proposed solution is addressed from different aspects. The first aspect is based on considering the maximum demand to be met such that the consumers' satisfaction is mostly met, and the gap between the generation and demand is reduced bearing in mind the search for the best combination of devices to achieve this goal through device prioritization. The second aspect is based on providing the fairness to consumers such that the devices belonging to a certain type are supplied for the same number of hours daily for all consumers. The third aspect is based on scheduling all the devices without any prioritization to minimize this gap while accounting for meeting most of the consumers rather than most of the demand. The fourth aspect is based on meeting most of the demand without any prioritization of the devices except for considering lighting as an essential supply to be considered all the time.

4.3.3.1 First Aspect of Home Devices Scheduling to Address PGS

The objective is to minimize the difference between the available power generation and the expected demand subject to the power flow constraints and the loads' operational models. The device scheduling is formulated as two problems: The first problem targets maximizing the expected demand that can be met accounting for consumers' requirements to such demand, and the second problem is a verification of the results determined from the first problem after plugging the results in the power flow constraints. The problem starts with entering the first device into the optimization problem and finding its schedule. Then the schedule is to be verified by ensuring that it does not violate the power flow constraints. This schedule is to be fixed as a demand and the second device is to enter the optimization problem and so on. This strategy in finding the best schedule of end user devices is carried back and forth such that all possible combinations of the devices are considered. The difference between the generation and the demand is determined for each combination. The best combination of the devices providing the minimum difference between the available power generation and the expected demand is considered to be the schedule of the prospective consumer's devices.

1. First Optimization Problem:

$$\max \ obj_m = \sum_{t=1}^{24}\sum_{n=1}^{8} P_{\underline{m},n,t,s} \ \alpha_{\underline{m},n,t,s} \ \ hour \qquad \textbf{(4-69)}$$

where α is a free variable that represents the multiplication of two binary variables, one indicating whether the device should be ON or OFF based on the comfort level or a consumer's demand for the device and the other is an indication of the availability of power supply at that moment. α is called $wnew$ in the case of scheduling the space heater, *MfanM* in the case of scheduling the electric fan and $well$ in the case of scheduling the well pump for irrigation. The term ($P\ \alpha$) is recognized as zwh in the case of scheduling the water heater as shown in (4-101). This term is also recognized as $Z_{washing}$ as shown in (4-92), $\underline{m}$ is a number that indicates the type of the device, *n* is a house number, *t* is an hour of the day, *s* is a studied season, and *obj* is the objective to be maximized.

The optimization problem is subject to the following constraints:

The power balance constraint relating power generation supply and the demand is given below:

$$Pg_{i=1,t,s} - Pd_{i=2} * RTS_{t,s} - Pd_{i=3} * RTS_{t,s} - R * \sum_{n=1}^{8} light_{n,t,s} - \sum_{v=1}^{\underline{m}-1} \sum_{n=1}^{8} R * P_{\underline{m},n,t,s} * \alpha_{m-v,n,t,s} - Ploss_{t,s} = \sum_{n=1}^{8} R * P_{\underline{m},n,t,s} * \alpha_{\underline{m},n,t,s}$$

(4-70)

where *i* is the bus number, *Pg* is the available generation (pu), *Pd* is the load connected to bus *i* (pu), *RTS* is the hourly variation factor of critical loads at bus i according to the IEEE Reliability test system, *light* is the light demand (kW) of an essential load that should be supplied at each house and given the priority of supply under the condition that such supply is available from sunset hours in [36] to midnight accounting for the season, α_{m-v} is a representation of the power demand of the loads that have earlier entered the optimization problem and been scheduled and whose schedules are verified and fixed as input. For instance, at the initial run of the optimization problem to schedule the device *m*, α_{m-v} is zero as no devices' schedules have yet been determined. If a heater is the first scheduled device and a washing machine is the second device to be scheduled, α_{m-v} will represent the schedule of the heater and α_m will be the free variable that indicates the schedule of the washing machine that is to be determined. *R* is a factor to convert the power demand to per unit system (pu), *P* is the power rating of device *m* that is involved in the device load model. If the device operational model does not involve this number, then it is set to one as in the case of the water heater. *Ploss* is an approximated limit on system losses that is determined from an optimization problem targeting minimizing system losses subject to power flow constraints provided that the individual house demands are given and assuming that the generation is sufficient and can meet the demand.

$$Qg_{i=1,t,s} - Qd_{i=2} * RTS_{t,s} - Qd_{i=3} * RTS_{t,s} - \sum_{v=1}^{\underline{m}-1} \sum_{n=1}^{8} R * P_{\underline{m},n,t,s} * \alpha_{\underline{m}-s,n,t,s} * PF_{\underline{m},n} - Qloss_{t,s} = \sum_{n=1}^{8} R * P_{\underline{m},n,t,s} * PF_{\underline{m},n,} * \alpha_{\underline{m},n,t,s} \quad \textbf{(4-71)}$$

where *Qg* is the available reactive power from the generation side, *Qd* is the reactive power demand of bus *i*, *PF* is the power factor at which device *m* is operated. It is important to emphasize that only the washing machine, electric fan and well pump are operated at certain power factors as determined from [71, 72].

The generation available should not exceed an upper bound as given by the following equations.

$$Plow_{t,s} \le Pg_{i=1,t,s} \le Pup_{t,s} \quad \textbf{(4-72)}$$

$$Qlow_{t,s} \le Qg_{i=1,t,s} \le Qup_{t,s} \quad \textbf{(4-73)}$$

The constraints of the devices' operational load models are as follows:

A. Space Heater Operational Load Model

The operation of the space heater is dependent on the comfort level of the customer and the availability of energy supply at the instant of demand. The power consumed by a space heater can be given by the following equation:

$$Z_{sh_{n,t}} = P_{heat n,t} * Xh_{sh_{n,t}} * yyy_{sh_{n,t}} \quad \textbf{(4-74)}$$

where P_{heat} is the power consumed by the space heater, Xh_{sh} is a binary value that is 1 when the space heater should be turned on due to customer demand and that is 0 otherwise and $\boldsymbol{yyy_{sh}}$ is a binary variable that is 1 when the power supply is available from the utility to supply it and that is 0 otherwise.

In order to solve the problem as a mixed integer linear programming problem, the term ($Xh_{sh_{n,t}} * yyy_{sh_{n,t}}$) should be linearized. In order to linearize this multiplication to simplify handling the optimization problem, the guide to mixed integer programming in [57] is followed. According to this guide, $W_{new_{n,t}}$ is a free variable that should replace the term ($Xh_{sh_{n,t}} * yyy_{sh_{n,t}}$). Thus, the following constraints are needed to adjust for such replacement. $W_{new_{n,t}}$ is never to surpass an upper bound 1 on the $Xh_{sh_{n,t}}$ and $yyy_{sh_{n,t}}$. Therefore, the inequality constraints shown next are involved:

$$W_{new\ n,t} \leq Xh_{sh\ n,t} \quad \textbf{(4-75)}$$

$$W_{new\ n,t} \leq yyy_{sh\ n,t} \quad \textbf{(4-76)}$$

For $Wnew_{n,t}$ to have a zero value given that $Xsh_{\ n,t}$ or $yyy_{sh\ n,t}$ is zero, the constraint used below is to ensure non negativity value of the variable $Wnew_{n,t}$:

$$W_{new\ n,t} \geq 0 \quad \textbf{(4-77)}$$

If $Xsh_{\ n,t} = yyy_{sh\ n,t} = 1$, another constraint is to be considered to assure that the variable $Wnew_{n,t} = 1$. Irrespective of the values determined for $Xsh_{\ n,t}$ or $yyy_{sh\ n,t}$ variables, the variable $Wnew_{n,t}$ is not to exceed a value of one as given by the following constraint:

$$W_{new\ n,t} \leq 1 \quad \textbf{(4-78)}$$

In contrast, to ensure that ($W_{new\ n,t} \geq 1$) when the multiplication of the demand for supply by the possibility of supply given as ($Xh_{sh\ n,t} \bullet yyy_{sh\ n,t}$) is 1, the following constraint is utilized:

$$W_{new\ n,t} \geq 1.(Xh_{sh\ n,t} + yyy_{sh\ n,t} - 2) + 1 \quad \textbf{(4-79)}$$

Residential consumers in India use room heaters to heat their houses in winter [9, 16]. Such devices use electricity instead of gas [16, 47]. The effect of the space heater on the internal air temperature of the house is subject to the constraint below as given by the space heater model presented in [16, 41, 42, 48] after adjusting the model to account for variables representing the availability of supply as well as consumer demand. P_{heat} is set to the device rating in kW, T_{house} is the internal air temperature of the house (°C) and $\boldsymbol{T_{external}}$ is the external air temperature of the house (°C) whose value is obtained from the stochastic weather temperature model that involves both probability paper plot and the Monte-Carlo simulation discussed earlier in section 4.2.2.2 [16] considering the best fit distribution parameters based on historical temperature data in [44]:

$$P_{heat\ n,t}\ W_{new\ n,t} = 56x10^{-2}\ T_{house\ n,t+1,s} - 5x10^{-1}\ T_{house\ n,t,s} - 56x10^{-3}\ T_{external\ n,t,s} \qquad \forall t \neq 24 \quad \textbf{(4-80)}$$

The initial air temperature inside the house is specified to be at 1am as indicated below:

$$T_{house\ n,t=1,s=\text{winter}} = I^{o}C \tag{4-81}$$

The comfort constraints governing the consumers' preferences toward utilizing the space heater is subject to the constraints below [16] as West Midlands Public Health Observatory [49] emphasizes what a suitable comfort level is:

$$\begin{cases} T_{housen,t,s=\text{winter}} < 18\ \ xh_{n,t=1}\ + 27\ \ (1 - xh_{n,t}) \\ T_{housen,t,s=\text{winter}} \geq 18\ \ (1 - xh_{n,t}) - 30\ \ xh_{n,t} \end{cases} \tag{4-82) \& (4-83}$$

B. Well Pump Operational Load Model

The well pump is a main component of the water supply system of residential consumers. The power consumed by the well pump is given by the constraint below where $P_{wellpump}$ is the well pump power consumption, *Well* is a free variable that represents ($PumpSupply_{n,t,s} * X_{well-pump_{n,t,s}}$) where *PumpSupply* is a binary variable that is 1 when the pump can be supplied by electricity and that is 0 when power supply to such device is not possible. $X_{well\text{-}pump}$ is a binary variable that is 1 when the pump should be working due to demand and 0 otherwise while accounting for the working hours of individuals in developing countries as given in [37] as such consumers need such devices to irrigate their lands [3, 16].

$$Z_{well-pump_{n,t,s}} = P_{well\ n,t,s} * Well_{pump\ n,t,s} \tag{4-84}$$

The well pump is expected to be used for *k* hours any time after 6am until 7pm as indicated below:

$$\sum_{t=7am}^{6pm} X_{weii-pump_{n,t}} = k \tag{4-85}$$

$$\sum_{t=1am}^{5am} X_{well-pump_{n,t}} + \sum_{t=7pm}^{12am} X_{well-pump_{n,t}} = 0 \tag{4-86}$$

In order to simplify the problem such that it can be treated as a mixed integer linear programming problem, the following multiplication of the variable indicating availability of supply to well pump by the variable indicating the demand for well pump ($PumpSupply_{n,t} * X_{well-pump_{n,t}}$) should be in a linear form. Therefore, the guide to mixed integer programming in [57] is tracked. Based on this guide, $Well_{n,t,s}$ that is a free variable should replace the term ($PumpSupply_{n,t} * X_{well-pump_{n,t}}$). As a result, the constraints below are necessary to adjust for such replacement:

$Well_{n,t,s}$ is not to exceed an upper limit that is 1 on the $PumpSupply_{n,t,s}$ as well as $X_{well\text{-}pump\ n,t,s}$. Therefore, the given inequality constraints below are utilized:

$$Well_{n,t,s} \leq X_{well-pump_{n,t,s}} \quad \textbf{(4-87)}$$

$$Well_{n,t,s} \leq PumpSupply_{n,t,s} \quad \textbf{(4-88)}$$

For $Well_{n,t,s}$ to have a zero value whenever $PumpSupply_{n,t,s}$ or $X_{well\text{-}pump\ n,t,s}$ has a value of zero, the constraint below guaranteeing non-negativity is to be considered:

$$Well_{n,t,s} \geq 0 \quad \textbf{(4-89)}$$

If the scenario ($X_{well\text{-}pump\ n,t,s} = PumpSupply_{n,t,s} = 1$) took place, another constraint ensuring that the variable $Well_{n,t,s}$ will have a value of one is to be included. Irrespective of the values assigned to either $X_{well\text{-}pump\ n,t,s}$ *or* $PumpSupply_{n,t,s}$ variables, $Well_{n,t,s}$ is not to exceed a value of one as indicated below:

$$Well_{n,t,s} \leq 1 \quad \textbf{(4-90)}$$

For the following condition to be satisfied ($Well_{n,t} \geq 1$) whenever the following multiplication result ($PumpSupply_{n,t} \bullet Xpump_{n,t}$) is one, the constraint below is to be involved:

$$Well_{n,t,s} \geq 1.(X_{well-pump\ n,t,s} + PumpSupply_{n,t,s} - 2) + 1 \quad \textbf{(4-91)}$$

C. Washing Machine Operational Load Model

The power consumed by the washing machine (Z_{WM} in kW) is given by the equation below where *Washing* is a free variable that represents the multiplication of the following variables ($MachineSupply_{n,t,s}$*$WM_{n,t,s}$) where $MachineSupply_{n,t,s}$ is a binary variable that will have a value of one when the washing machine can be supplied with electricity and will have a value of zero when such supply is not possible. On the other hand, $WM_{n,t,s}$ is defined to be a binary variable that will have a value of one when the device is to be used and a value of zero when it will not be used. Moreover, *CYC* is set to be the number of cycles used by the device, *Cap* is the capacity of the washing machine and *Efficiency* is the efficiency of the washing machine as modeled in [58, 59] and the corresponding values of these terms are based on [16]:

$$Z_{WM\ n,t,s} = Washing_{n,t,s} * \frac{CYC_{washing-machine_n} * Cap_n}{Efficiency_{washing-machine_n} * hour} \quad \textbf{(4-92)}$$

The term ($\frac{CYC_{washing-machine_n} * \ Cap_n}{Efficiency_{\ washing-machine_n} * hour}$) will be represented as $P_{washing\text{-}machine}$ later on in the thesis.

The washing machine should be working for *LL* hours as indicated below:

$$\sum_{t=1}^{24} WM_{\ n,t,s} = LL \tag{4-93}$$

To simplify handling the optimization problem such that it can be solved as a mixed integer linear programming problem, the term ($MachineSupply_{n,t}$*$WM_{n,t}$) is to be converted to a linear form. Therefore, the guide to mixed integer programming in [57] is tracked. Based on this guide, $Washing_{n,t,s}$, a free variable, is to replace the following multiplication ($MachineSupply_{n,t,s}$*$WM_{n,t,s}$). As a result, the following constraints are utilized to adjust for such replacement:

$Washing_{n,t,s}$ is not to exceed an upper limit that is one for the variables $MachineSupply_{n,t,s}$ and $WM_{n,t,s}$. Therefore, the constraints given below are involved in the optimization problem:

$$Washing_{\ n,t,s} \leq WM_{n,t,s} \tag{4-94}$$

$$Washing_{\ n,t} \leq MachineSupply_{n,t} \tag{4-95}$$

For a value of zero of the variable $Washing_{n,t,s}$ when either $MachineSupply_{n,t,s}$ or $WM_{n,t,s}$ is zero, a condition on the $Washing_{n,t,s}$ value such that it is not negative is stated as shown below:

$$Washing_{\ n,t} \geq 0 \tag{4-96}$$

If both of the following variables ($WM_{n,t,s}$ and $MachineSupply_{n,t,s}$) have values of ones, another constraint is to be included such that the value given to the variable $Washing_{n,t,s}$ is one.. Irrespective of the values given to any of the following variables $WM_{n,t,s}$ or $MachineSupply_{n,t,s}$, the value given to the variable $Washing_{n,t,s}$ is not to be above one as indicated by the constraint below:

$$Washing_{\ n,t,s} \leq 1 \tag{4-97}$$

The variable $Washing_{n,t,s}$ is to have a value of at least one whenever the result of the multiplication ($WM_{n,t,s}$*$MachineSupply_{n,t,s}$) is one. This condition is ensured by the following constraint:

$$Washing_{\ n,t,s} \geq 1.(WM_{\ n,t,s} + MachineSupply_{sh \ n,t,s} - 2) + 1 \tag{4-98}$$

D. Water Heater

Water heaters with a tank of 30 gallons are considered to be the typical size of a water heater to be adopted by residential electricity consumers as used by [16]. The energy demand of the water heater is dependent on the energy consumption due to hot water consumption ($ZWH_{n,t,s}$ in kWh) as given by the equation below according to the model in [58] after substituting the model parameters in [66] and is dependent on the energy consumption due to heat loss from tank surfaces ($ZLoss_{n,t,s}$ in kWh) as given below based on the model in [65] after considering the model parameters in [66, 67].

$$ZWH_{n,t,s} = \frac{1}{EF_n} \frac{dem_{n,t,s} * \left[(\frac{9}{5} Therm_{n,s} + 32) - (\frac{9}{5} T_{well-water,t,s} + 32) \right] * (82928x10^{-4} Btu..gallon^{-1}.^{o}F^{-1})}{3413 Btu / kWh} \quad \textbf{(4-99)}$$

$$ZLoss_{n,t,s} = \frac{13621.875x10^{-4}}{3413 Btu / kWh} \left((\frac{9}{5} Therm_{n,s} + 32) - (\frac{9}{5} T_{house\ n,t,s} + 32 \right) \quad \textbf{(4-100)}$$

where EF_n is the efficiency of the water heater (%) in house n, $Therm_{n,s}$ is the thermostat set point (ºC) in house n and $T_{well\text{-}water\ t,s}$ is the temperature of the water supplied from the well (ºC).

A conversion of the temperature into Fahrenheit is shown within the above two equations based on [68]. It can be seen that $ZWH_{n,t,s}$ is dependent on the volume of hot water consumed by the consumers. In literature, the patterns of hot water consumed by residential homes have been modeled in [58, 64]. In this thesis, a typical daily hot water consumption pattern is assumed and followed taking into consideration the hours during which the house is occupied as has been discussed in [16]. The expected demand for hot water of the eight houses is shown in Figure 4.17. It is important to emphasize that even though the consumers are not currently supplied, such patterns can be either measured or surveyed.

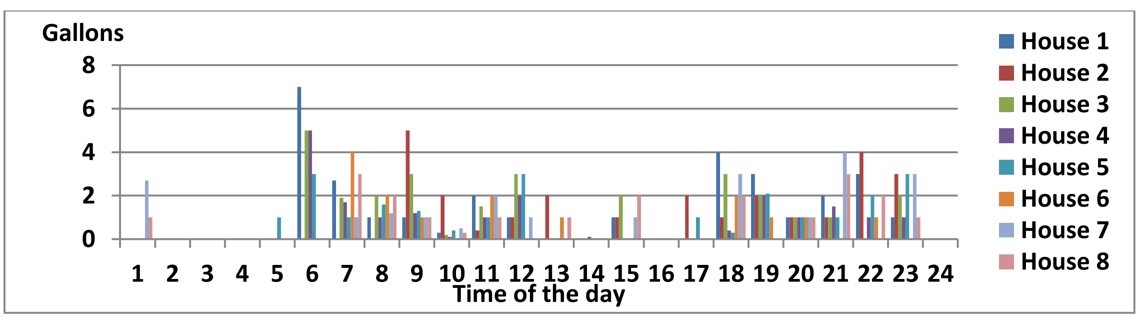


Figure 4.17: Hourly demand for hot water

In order to solve the problem as a mixed integer linear programming problem, the power consumed by the water heater (Zwh in kW) is to be modeled as shown below:

$$Zwh_{n,t,s} = D_{n,t,s} * (\frac{1}{hour * EF_n} \frac{dem_{n,t,s} * \left[(\frac{9}{5} Therm_{n,s} + 32) - (\frac{9}{5} T_{well-water\, t,s} + 32) \right] * 82928\text{x}10^{-4}}{3413})$$

$$+ \frac{13621.875\text{x}10^{-4}}{3413 * hour} \left((DD_{n,t,s} * \frac{9}{5} Therm_{n,s} + D_{n,t,s} * 32) - (G_{n,t,s} * \frac{9}{5} + D_{n,t,s} * 32 \right)$$

(4-101)

The operation of the water heater is governed by the demand for hot water. Thus, the following constraint is used where *zbinary* is a binary variable that is one when the device should be ON to meet the demand for hot water:

$$zbinary_{n,t,s} * dem_{n,t,s} = dem_{n,t,s} \qquad \textbf{(4-102)}$$

As the device is operating, there are energy losses from the device surface that should be accounted for while maintaining the linearization of the device operational model. Thus, the following constraints are added where *zbinary* and *zzbinary* are binary variables:

$$dem_{n,t,s} \geq 0.0001 * zbinary_{n,t,s} \qquad \textbf{(4-103)}$$

$$dem_{n,t,s} \geq dem_{n,t,s} * zzbinary_{n,t,s} \qquad \textbf{(4-104)}$$

During the hours in which the water heater is OFF, the energy lost through the surfaces of the water heater should not be determined to avoid the calculation of any energy demand consumed by the water heater during such hours. Thus, the following constraint is added:

$$zbinary_{n,t,s} + zzbinary_{n,t,s} = 1 \qquad \textbf{(4-105)}$$

($LSupplied_{n,t,s}$* $Zbinary_{n,t,s}$) is a multiplication of two binary variables where *LSupplied* will have a value of one if the device can be supplied and will have a value of zero if the device cannot be supplied while considering the available generation, other devices' demand and the rest of the new feeder demand. This term is linearized by considering a free variable ($D_{n,t,s}$) as shown in the constraints below:

$\boldsymbol{D_{n,t,s}}$ is not to exceed an upper limit of one for both $LSupplied_{n,t,s}$ and $Zbinary_{n,t.,s}$. Therefore, the inequality constraint below are utilized:

$$D_{n,t,s} \leq Zbinary_{n,t,s} \qquad \textbf{(4-106)}$$

$$D_{n,t,s} \le LSupplied_{n,t,s} \qquad \textbf{(4-107)}$$

To have the condition that $D_{n,t,s}$ will have a value of zero happen whenever either the variable $LSupplied_{n,t,s}$ or the variable $Zbinary_{n,t,s.}$ has a value of zero, a constraint guaranteeing that $D_{n,t,s}$ will not have a negative value is used:

$$D_{n,t,s} \ge 0 \qquad \textbf{(4-108)}$$

For the variable $LSupplied_{n,t,s}$ and the variable $Zbinary_{n,t,s.}$ to have a value of one, another constraint is be included such that the variable $D_{n,t,s}$ will have a value of one..Irrespective of the values given to either the variable $LSupplied_{n,t\,,s}$ or the variable $Zbinary_{n,t,s}$, the value of the variable $D_{n,t,s}$ is not to exceed a value of one:

$$D_{n,t} \le 1 \qquad \textbf{(4-109)}$$

On the other hand, in order to have the variable $D_{n,t,s}$ to have a value of at least one whenever the following multiplication result is one ($LSupplied_{n,t,s}$* $Zbinary_{n,t,s}$), the next inequality is set:

$$D_{n,t,s} \ge 1.(LSupplied_{n,t,s} + Zbinary_{n,t,s} - 2) + 1 \qquad \textbf{(4-110)}$$

In order to avoid having the heater ON to supply the energy loss from the tank surfaces when there is no demand for hot water, the following constraints are added following the same description of the constraints formulation discussed above for an ON/OFF operation of the water heater:

$$DD_{n,t,s} \le LSupplied_{n,t,s} \qquad \textbf{(4-111)}$$

$$DD_{n,t,s} \le 1 - ZZbinary_{n,t,s} \qquad \textbf{(4-112)}$$

$$DD_{n,t,s} \ge 1.(LSupplied_{n,t,s} + (1 - ZZbinary_{n,t,s}) - 2) + 1 \qquad \textbf{(4-113)}$$

$$DD_{n,t,s} \ge 0 \qquad \textbf{(4-114)}$$

$$DD_{n,t,s} \le 1 \qquad \textbf{(4-115)}$$

The term ($LSupplied_{n,t,s}$* $Zbinary_{n,t,s}$*$T_{house\ n,t,s}$) should be linearized for simplicity reasons in handling the optimization problem. Therefore, the guide to mixed integer programming in [57] is tracked. Following this guide, $G_{n,t,s}$, a free variable, is a substitute to the multiplication given by the following term ($LSupplied_{n,t,s}$* (1-Z$Zbinary_{n,t,s}$)*$T_{house\ n,t,s}$). Thus, the following constraints are to be included to adjust for such substitution:

$Zaco_{n,t,s}$ is used as a term to replace the term ($1\text{-}zzbinary_{n,t,s}$) as shown below:

$$Zaco_{n,t,s} = 1 - ZZbinary_{n,t,s} \quad \textbf{(4-116)}$$

In order to ensure the correct operation of the device, the following constraints are added where *BigM* is a large number set in this case to 1000:

$$G_{n,t,s} \leq BigM * LSupplied_{n,t,s} \quad \textbf{(4-117)}$$

$$G_{n,t,s} \leq BigM * Zaco_{n,t,s} \quad \textbf{(4-118)}$$

For the variable $G_{n,t,s}$ to have a value of zero whenever $LSupplied_{n,t,s}$ or (1- Z$Zbinary_{n,t,s}$) is zero, a constraint ensuring that $G_{n,t,s}$ will have a positive value or a value of zero is used:

$$G_{n,t,s} \geq 0 \quad \textbf{(4-119)}$$

When both variables $LSupplied_{n,t,s}$ and (1- Z$Zbinary_{n,t,s}$) have values of one, another constraint should be added to ensure that $G_{n,t,s}$ is equivalent to $T_{house\ n,t,s}$. Irrespective of the values given to $LSupplied_{n,t,s}$ and (1- Z$Zbinary_{n,t,s}$), the variable $G_{n,t}$ is not to exceed $T_{house\ n,t,s}$ as indicated below:

$$G_{n,t,s} \leq T_{house\,n,t,s} \quad \textbf{(4-120)}$$

For the following condition to be granted ($G_{n,t,s} \geq T_{house\,n,t,s}$) whenever ($LSupplied_{n,t,s}$ = (1-Z$Zbinary_{n,t,s}$) = 1), the constraint below is included:

$$G_{n,t,s} \geq BigM *.(LSupplied_{n,t,s} + Zaco_{n,t,s} - 2) + T_{house\,n,t,s} \quad \textbf{(4-121)}$$

The temperature of the water entering the water tank as supplied from the well is determined based on the following equation that has been earlier presented in [16]:

$$T_{well\,water\,n,t+1,s} = T_{well\ water_{n,t,s}} + dT_{n,t,s} \qquad \forall\ t \neq 24 \quad \textbf{(4-122)}$$

where *dT* is the well's water temperature loss because of the radiation effect discussed earlier and is given by the equation below based on [16]:

$$dT_{t,s} = -(35.9999*100)*(10^{-3})*(238*10^{-3})*(1061*10^{-5})Q_{t,s} \quad \textbf{(4-123)}$$

where Q is energy lost/gained because of the radiation effect and is given by the equation below based on [16] where $T_{operating}$ is the temperature operating point in the season:

$$Q_{t,s} = \begin{pmatrix} 0.95*5.67*10^{-8}*3.14*(-3*(273+T_{operatings})^4 \\ +4*(273+T_{operating})^3(273+T_{well\ water\,t,s}) - (273+T_{external\,t,s})^4 \end{pmatrix} \quad \textbf{(4-124)}$$

The initial well's water temperatures are taken at 1am and are given by the following equations [16]:

$$T_{well\ water\,t=1,s} = 10^o C \ \forall s = in\ winter \quad \textbf{(4-125)}$$

$$T_{well\ water\,t=1,s} = 26^o C \ \forall s = summer \quad \textbf{(4-126)}$$

The energy consumed by the water heater should be less than the device rating at an hour as indicated below:

$$ZWH_{n,t,s} + Zloss_{n,t,s} \leq hour * Rating_n \quad \textbf{(4-127)}$$

It is important to emphasize that when the water heater is the first device to enter the optimization problem such that it is given the priority of supply compared to other devices, the variable *Wnew* that is involved in the space heater load model is set to zero and according to this condition, the internal air temperature of the house is determined. On the other hand, when the space heater is entered into the optimization problem before the water heater, the determined internal air temperature of the house resulting from scheduling the space heater is used as an input to determine the schedule of the water heater as the latter operational load model is dependent on the internal air temperature of the house.

E. Electric Fan Operational Load Model

The power consumed by the electric fan (Z_{fan}) is given by the equation below where P_{fan} is the electric fan power consumption, *fancanbesupplied* is a binary variable that is one when the electric fan can be supplied with electricity and that is zero otherwise. U_{fan} is a binary variable that is one when the electric fan should to be turned ON at time *t*, and that is zero otherwise according to the felt internal air temperature of the house.

$$Z_{fan_{n,t}} = P_{fan_{n,t}} * U_{fan\ n,t} * fancanbe\sup plied_{n,t} \quad \textbf{(4-128)}$$

To simplify handling the optimization problem as a mixed integer linear programming problem, the following term ($U_{fan\ n,t}$* $fancanbesuplied_{\ n,t}$) is to be linearized following the procedure of mixed integer programming linearization in [57]. Thus, $MfanM_{\ n,t}$ is defined to be a free variable that will replace the term ($U_{fan\ n,t}$* $fancanbesuplied_{\ n,t}$). Therefore, the following constraints are applied in the optimization problem to adjust for such a replacement:

$MfanM_{\ n,t}$ is not to exceed an upper limit that is one for both variables $fancanbesuplied_{\ n,t}$ and $U_{fan\ n,t}$. Therefore, the given inequality constraints below are utilized:

$$MfanM_{\ n,t} \leq U_{fan_{n,t}} \quad \textbf{(4-129)}$$

$$MfanM_{\ n,t} \leq fancanbe\sup plied_{\ n,t} \quad \textbf{(4-130)}$$

For the variable $MfanM_{\ n,t}$ to have a value of zero when the variable $U_{fan\ n,t}$ or the variable $fancanbesuplied_{\ n,t}$ has a value of zero, a constraint ensuring that the variable $MfanM_{\ n,t}$ will have a value that is either positive or zero is used based on the problem requirement:

$$MfanM_{\ n,t} \geq 0 \quad \textbf{(4-131)}$$

If $U_{fan\ n,t}$= $fancanbesuplied_{\ n,t}$ =1, another constraint is to be included to assure that $MfanM_{\ n,t}$ will have a value of one. Irrespective of the values given to the variables $U_{fan\ n,t}$ or $fancanbesuplied_{\ n,t}$, $MfanM_{\ n,t}$ is not to exceed a value of one as shown below:

$$MfanM_{\ n,t} \leq 1 \quad \textbf{(4-132)}$$

For $MfanM_{\ n,t}$ to have a value of at least one when the result of the following multiplication is one ($U_{fan\ n,t}$* $fancanbesuplied_{\ n,t}$), the constraint below is utilized:

$$MfanM_{\ n,t} \geq 1.(U_{fan_{n,t}} + fancanbe\sup plied_{\ n,t} - 2) + 1 \quad \textbf{(4-133)}$$

The variability of the internal air temperature of the house from one hour to another is indicated by the constraint below as shown in [16]:

$$T_{house\ n,t+1} = T_{house n,t} - \left(9.9X10^{-1} T_{house n,t} - 9.9X10^{-1} T_{external\ n,t}\right) \qquad \forall t \neq 24 \quad \textbf{(4-134)}$$

The relationship between the felt internal air temperature of the house and the internal temperature of the house subject to the ON/OFF operation of the electric fan and the availability of supply to such a device in house *n* at time *t* is given by the constraint below:

$$T_{feel\ n,t+1} = T_{housern,t} - factor\ *\ (33*MfanM_{fan\ n,t} - T_{house\,n,t}) - factor\ *\ E_{n,t} \qquad \forall t \neq 24 \quad \textbf{(4-135)}$$

where *t* is an indication of the beginning of the hour and *t+1* is an indication of the end of the hour. The factor shown in the previous equation can be obtained according to the wind speed considering the data in [53] used to derive a linear regression relating the factor and the wind speed as described earlier by equations (4-19), (4-20) and (4-21).

$E_{t,d}$ is a free variable that originally represents $((1-U_{fan\ n,t}*\ fancanbesupplied_{\ n,t})*T_{house\ n,t})$ and is used here as a replacement of such multiplication for a linearization purpose. Such a linearization will require other constraints to be added as described in the guide in [57]. These constraints are as follows:

$E_{n,t}$ can be simplified to $(LAN_{fan\ n,t} *T_{house\ n,t})$ where $LAN_{fan\ n,t}$ is defined as given below:

$$LAN_{fan\ n,t} = (1-MfanM_{fan\ n,t}) \qquad \textbf{(4-136)}$$

The internal air temperature of the house is not to exceed an upper limit ($\overline{UP}$) as indicated below:

$$0 \leq T_{house\,n,t} \leq \overline{UP} \qquad \textbf{(4-137)}$$

If supply is available when the device is to be ON, then $E_{n,t,}$should have a zero value such that the non-negativity constraint shown below is needed.

$$E_{n,t} \geq 0 \qquad \textbf{(4-138)}$$

On the other hand, $E_{t,d}$ is not to exceed an upper limit on the internal air temperature of the house. Therefore, the objective function is subject to the following constraint:

$$E_{n,t} \leq \overline{UP}\ LAN_{fan\ n,t} \qquad \textbf{(4-139)}$$

If either the fan should be OFF or the supply is not available to meet the demand of the device, or both conditions are taking place, the constraint below is to be considered to ensure that $E_{n,t}$ is equivalent to the internal air temperature of the house. In general, $E_{n,t}$ is not to be above the value of the internal air temperature of the house:

$$E_{n,t} \leq T_{house_{n,t}} \qquad \textbf{(4-140)}$$

To account for $E_{n,t}$ to be at least equivalent to the internal air temperature of the house under the condition that either the fan is to be OFF or the supply is not available or both conditions are met, the constraint used is:

$$E_{n,t} \geq \overline{UP}(LAN_{fan\ n,t} - 1) + T_{house_{n,t}} \quad \textbf{(4-141)}$$

The initial house internal temperature that is felt is assumed as given by the constraint below [16]:

$$T_{feel\ n,t=1} = T_{house\ n,t=1} \quad \textbf{(4-142)}$$

The comfort conditions based on which the fan will be turned ON or OFF are shown in [16]:

$$T_{feel\ n,t} \geq 27X\ U_{fan\ n,t} + \ (1 - U_{fan\ n,t}) \quad \textbf{(4-143)}$$

$$T_{feel\ n,t} < 27X(1 - U_{fan\ n,t}) + 100\ U_{fan\ n,t} \quad \textbf{(4-144)}$$

2. Second Optimization Problem

The second optimization problem is used to ensure that the schedule determined from the first optimization problem is the best schedule of devices, and such a schedule does not violate power flow constraints. If violation exists, even though this violation has not been encountered here, the homes encountering power interruption in the second optimization problem are to undergo rescheduling of their devices. In this case, the determined losses from the second optimization problem is inputted into the first optimization problem. This consideration is to be applied iteratively until no violation is encountered. The objective function is as shown below:

$$\max\ \ objj_{m,s} = \sum_{t=1}^{24} \sum_{n=1}^{8} o_{n,t,s} \quad \textbf{(4-145)}$$

This problem is subject to power flow constraints as given by the following equations where *PF* is based on the power factor of the device to determine its reactive power:

$$Pg_{i,t,s} - Pd_i * RTS_{t,s} = \sum_{j=1}^{4}\ [V_{i,t,s} * V_{j,t,s} * Y_{i,j} * \cos(-\theta_{i,j} - \delta_{j,t,s} + \delta_{i,t,s})]) \qquad \forall i \neq 4 \quad \textbf{(4-146)}$$

$$Qg_{i,t,s} - Qd_i * RTS_{t,s} = \sum_{j=1}^{4}\ [V_{i,t,s} * V_{j,t,s} * Y_{i,j} * \sin(-\theta_{i,j} - \delta_{j,t,s} + \delta_{i,t,s})]) \qquad \forall i \neq 4 \quad \textbf{(4-147)}$$

$$Pg_{i,t,s} - \sum_{n=1}^{8} o_{n,t,s} * R * P_m * \alpha_{m\ n,t,s} - \sum_{v=1}^{m-1}\sum_{n=1}^{8} R * P_{m-v} * \alpha_{m-v\ n,t,s} - R * \sum_{n=1}^{8} light_{n,t,s} =$$
$$\sum_{j=1}^{4} [V_{i,t,s} * V_{j,t,s} * Y_{i,j} * \cos(-\theta_{i,j} - \delta_{j,t,s} + \delta_{i,t,s})]) \ \forall \ i = 4$$

(4-148)

$$Qg_{i,t,s} - \sum_{n=1}^{8} o_{n,t,s} * R * PF_{m,n} * P_m * \alpha_{m\ n,t,s} - \sum_{v=1}^{m-1}\sum_{n=1}^{8} R * PF_{m,n} * P_{m-v} * \alpha_{m-v\ n,t,s} =$$
$$\sum_{j=1}^{4} [V_{i,t,s} * V_{j,t,s} * Y_{i,j} * \sin(-\theta_{i,j} - \delta_{j,t,s} + \delta_{i,t,s})]) \ \forall \ i = 4$$

(4-149)

The following power balance equations are used:

$$Pg_{i=1,t,s} - Pd_{i=2} * RTS_{t,s} - Pd_{i=3} * RTS_{t,s} - R * \sum_{n=1}^{8} light_{n,t,s} - \sum_{v=1}^{m-1}\sum_{n=1}^{8} R * P_{m-v} * \alpha_{m-v,n,t,s} - Ploss_{t,s} =$$
$$\sum_{n=1}^{8} o_{n,t,s} * R * P_m * \alpha_{m\ n,t,s}$$

(4-150)

$$Qg_{i=1,t,s} - Qd_{i=2} * RTS_{t,s} - Qd_{i=3} * RTS_{t,s} - \sum_{v=1}^{m-1}\sum_{n=1}^{8} R * P_{m-v} * PF_{m-v,n} * \alpha_{m-v,n,t,s} * -Qloss_{t,s} =$$
$$\sum_{n=1}^{8} o_{n,t,s} * R * P_m * PF_{m,n} * \alpha_{m\ n,t,s}$$

(4-151)

$$Ploss_{t,s} = \sum_{i=1}^{4}\sum_{j=1}^{4}(0.5 * gg_{i,j} * [V^2{}_{i,t,s} + V^2{}_{j,t,s} - 2 * V_{i,t,s} * V_{j,t,s} * \cos(\delta_{j,t,s} - \delta_{i,t,s})]) \quad \textbf{(4-152)}$$

$$Qloss_{t,s} = -\sum_{i=1}^{4}\sum_{j=1}^{4}(0.5 * bb_{i,j} * [V^2{}_{i,t,s} + V^2{}_{j,t,s} - 2 * V_{i,t,s} * V_{j,t,s} * \cos(\delta_{j,t,s} - \delta_{i,t,s})])$$

(4-153)

The voltage level at system busses should be within a range as given by the following constraints:

$$0.95 pu \le V_{i,t,s} \le 1.05 pu \quad \textbf{(4-154)}$$

$$-\pi \le \delta_{i,t,s} \le \pi \quad \textbf{(4-155)}$$

The power is supplied from bus 1 only and it should be within a limit as indicated below:

$$Pg_{i \neq 1,t,s} = 0 \quad \textbf{(4-156)}$$

$$Qg_{i \neq 1,t,s} = 0 \quad \textbf{(4-157)}$$

$$Plow_{t,s} \leq Pg_{i=1,t,s} \leq Pup_{t,s} \quad \textbf{(4-158)}$$

$$Qlow_{t,s} \leq Qg_{i=1,t,s} \leq Qup_{t,s} \quad \textbf{(4-159)}$$

4.3.3.2 Simulation Results of the First Aspect of Home Devices Scheduling to Address PGS

Table 4.5, Table 4.6, Table 4.7 and Table 4.8 show the difference between the generation and demand excluding system losses and light demand when device *m* is scheduled first.

Table 4.5: Difference between available electricity generation and expected energy demand when starting with space heater scheduling and then the m devices by order

Space heater is the first device in scheduling	Houses demand excluding light demand (kWh)	Generation-system demand excluding light demand and system losses (kWh)
Sh	70.5	114.4678436
Sh-WM	72.9	112.0678436
Sh-Pump	140.1	44.86784362
Sh-WM-Pump	141.3	43.66784362
Sh-Pump-WM	148.5	36.46784362
SH-Pump-WM-WH	**160.650504**	**24.31733962**
Sh-WM-Pump-WH	154.282037	30.68580662
Sh-WH	98.021219	86.94662462
Sh-WM-WH	98.581047	86.38679662
Sh-WH-WM	100.421219	84.54662462
Sh-WH-WM-Pump	152.021219	32.94662462
Sh-WM-WH-Pump	151.381047	33.58679662
Sh-WH-Pump	152.021219	32.94662462
Sh-Pump-WH	112.18412	72.78372362
Sh-Pump-WH-WM	114.58412	70.38372362
Sh-WH-Pump-WM	154.121219	30.84662462

Table 4.6: Difference between available electricity generation and expected energy demand when starting with water heater scheduling and then m devices by order

Water heater is the first device in scheduling	Houses demand excluding light demand (kWh)	Generation-system demand excluding light demand and losses (kWh)
WH	36.502289	148.4655546
WH –Pump	108.502289	76.46555462
WH-WM	38.902289	146.0655546
WH-Pump-WM	110.902289	74.06555462
WH-WM-Pump	110.902289	74.06555462
WH-Sh	99.502289	85.46555462
WH-Pump-Sh	150.502289	34.46555462
WH-Sh-Pump	148.702289	36.26555462
WH-Sh-WM	101.902289	83.06555462
WH-WM-Sh	100.402289	84.56555462
WH-Sh-WM-Pump	149.902289	35.06555462
WH-Sh-Pump-WM	151.102289	33.86555462
WH-WM-Sh-PUMP	148.402289	36.56555462
WH-WM-PUMP-Sh	151.402289	33.56555462
WH-PUMP-Sh-WM	152.902289	32.06555462
WH-Pump-WM-Sh	151.402289	33.56555462

It can be seen from these tables that the case (SH-Pump-WM-WH) in Table 4.5 provides the minimum difference between the available electricity generation and expected energy demand. The active losses in this case are 18.5041kWh in a typical winter day and the light demand is 5.6kWh resulting in a daily difference of 0.21324kWh as a positive gap between the available generation and the expected total energy demand of the system under study. The energy supplied at the residential level in this case is 166.25kWh and is more than the energy supplied in the case of the house full power interruption proposed solution that is 155.0092kWh and serves as a better alternative compared to the case where consumers do not have electricity for 10-12 hours daily [73] or live not electrified. The proposed solution can improve the power supply in comparison to that solution applied in these countries. Figures 4.18, Figure 4.19, Figure 4.20, Figure 4.21, Figure 4.22 and Figure 4.23 show the schedule of the devices taking into account the comfort level, the working hours, the individual activities and the stochastic weather condition. GAMS software execustion time was 0.015 seconds when the space heater was the first device to be scheduled. In this case there were 35 blocks of equations, 6193 single equations, 7 blocks of variables, 817 single variables, 16561 non-zero elements and 384 discrete variables. The verification of the schedule in the second optimization problem required an execution time of 0.016 seconds. On the other hand, the verification time was 0.015 seconds when the well pump was scheduled after the space heater. When washing machine was scheduled after space heater and the well pump, the execustion time of the first optimization problem was 0.016 seconds, while the verification of the schedule in the second optimization problem was 0.015 seconds. When the water heater was the last device to be scheduled, the required execution time was 0.016 seconds. In this case, there were 20 blocks of equations, 3135 single equations, 12 blocks of variables, 1777 single variables, 6886 non-zero elements and 576 discrete variables. The verification of the schedule in the second optimization problem required 0.031 seconds.

Table 4.7: Difference between available electricity generation and expected residential energy demand when starting with well pump scheduling and then m devices by order

Pump is the first device in scheduling	Houses demand excluding light demand (kWh)	Generation-system demand excluding light demand and losses (kWh)
Pump	75.6	109.3678436
Pump-WH	107.030138	77.93770562
Pump-SH	138.6	46.36784362
Pump-WH-SH	150.530138	34.43770562
Pump-Sh-WH	154.261106	30.70673762
Pump-WM	78	106.9678436
Pump-WH	109.430138	75.53770562
Pump-WM-WH	108.562271	76.40557262
Pump-WM-Sh	139.5	45.46784362
Pump-Sh-WM	141	43.96784362
Pump-Sh-WM-WH	154.276899	30.69094462
Pump-Sh-WH-WM	156.661106	28.30673762
Pump-WM-Sh-WH	154.146153	30.82169062
Pump-WM-WH-Sh	150.562271	34.40557262
Pump-WH-Sh-WM	152.930138	32.03770562
Pump-WH-WM-Sh	151.430138	33.53770562

Table 4.8: Difference between available electricity generation and expected residential energy demand when starting with washing machine scheduling and then m devices by order

Washing machine is the first device in scheduling	Houses demand excluding light demand (kWh)	Generation-system demand excluding light demand and losses (kWh)
WM	2.4	182.5678436
WM-Pump	78	106.9678436
WM-WH	37.28965	147.6781936
WM-Pump-WH	108.19762	76.77022362
WM-WH-Pump	109.28965	75.67819362
WM-Sh	72.9	112.0678436
WM-WH-Sh	100.28965	84.67819362
WM-Sh-WH	97.617185	87.35065862
WM-Sh-Pump	141.3	43.66784362
WM-Pump-Sh	139.5	45.46784362
WM-Sh-Pump-WH	155.248556	29.71928762
WM-Sh-WH-Pump	152.817185	32.15065862
WM-Pump-Sh-WH	153.844392	31.12345162
WM-Pump-WH-Sh	151.69762	33.27022362
WM-WH-Pump-Sh	151.28965	33.67819362
WM-WH-Sh-Pump	149.48965	35.47819362

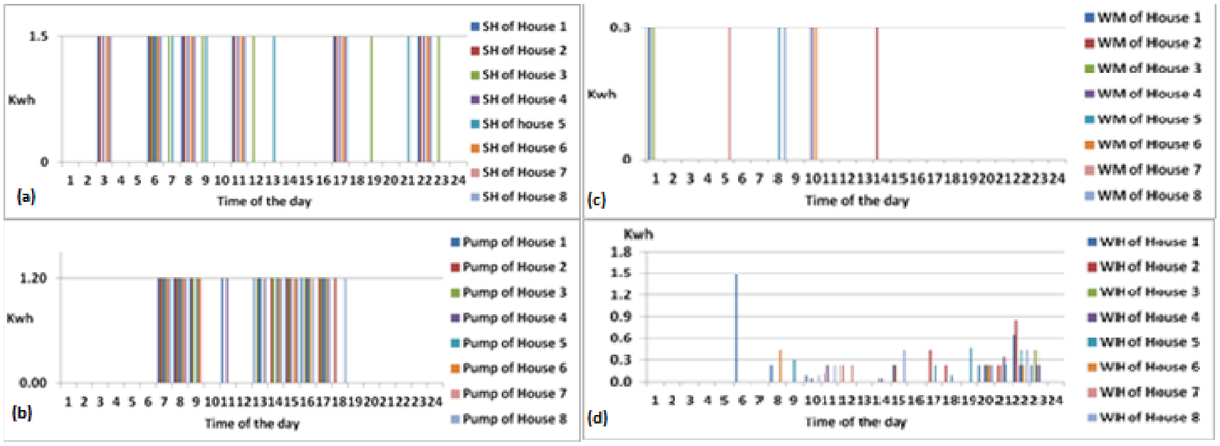


Figure 4.18: Devices' schedule of residential houses a) Space heater schedule, b) Well pump schedule, c) Washing machine schedule, d) Water heater schedule

The influence of such schedules on the possible power supply from the substation to the feeder in Figure 4.1 are shown in the figures below where scheduling each device and fixing its schedule and scheduling the rest of devices effect is considered.

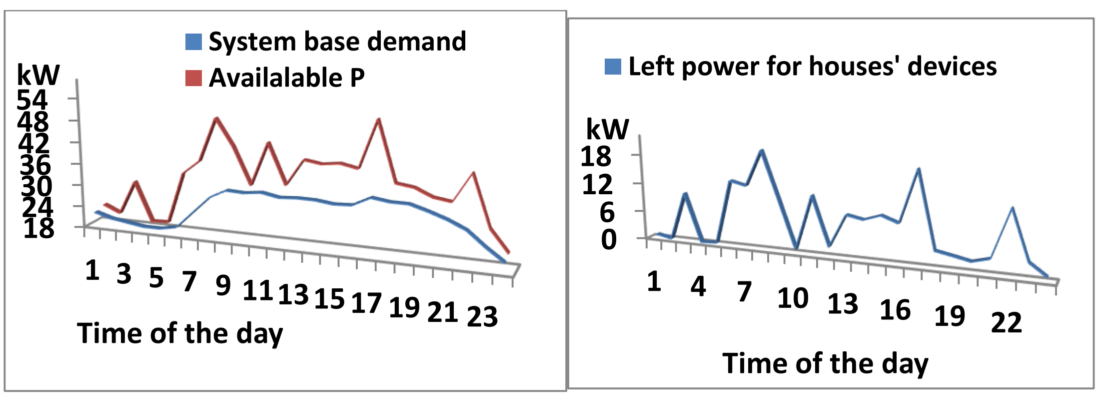


Figure 4.19: Available power supply versus the expected base power demand of the system in Figure 4.1 (System base demand =bus 2+bus 3+light at bus 4+expected losses)

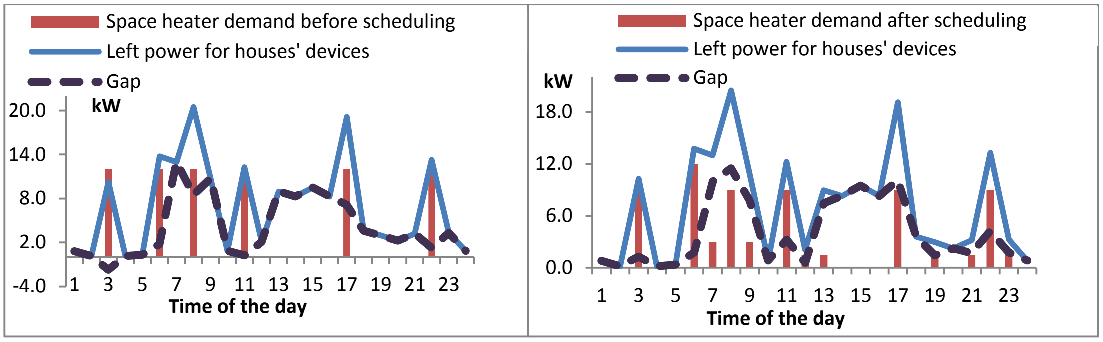
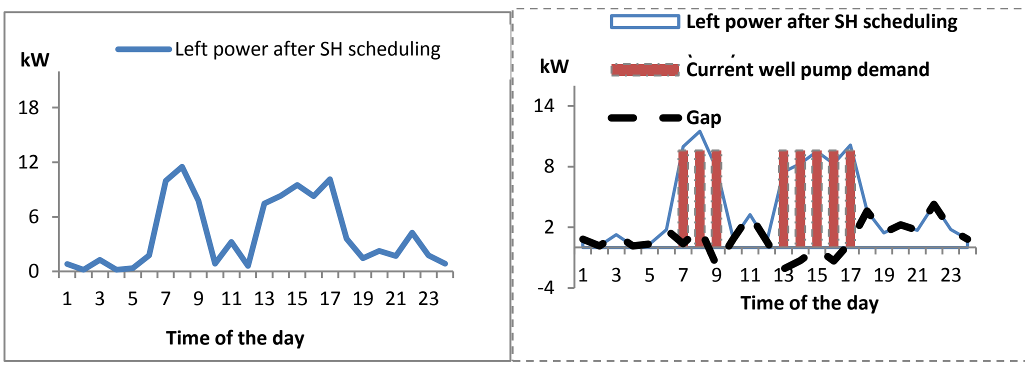
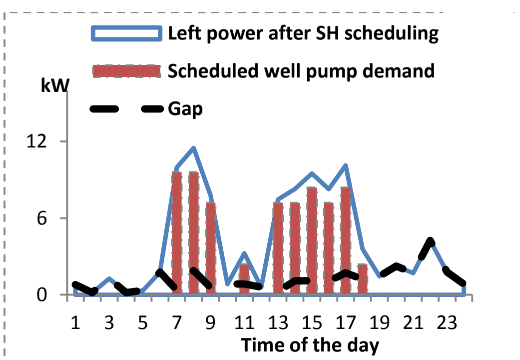


Figure 4.20: Available power supply versus required space heater demand before scheduling and scheduled space heater demands





Hours of well pump demand daily
64.00
Hours of supplied well pump daily
58.00
Percentage of met well pump demand hours
90.63%

Figure 4.21: Required and scheduled well pump demands

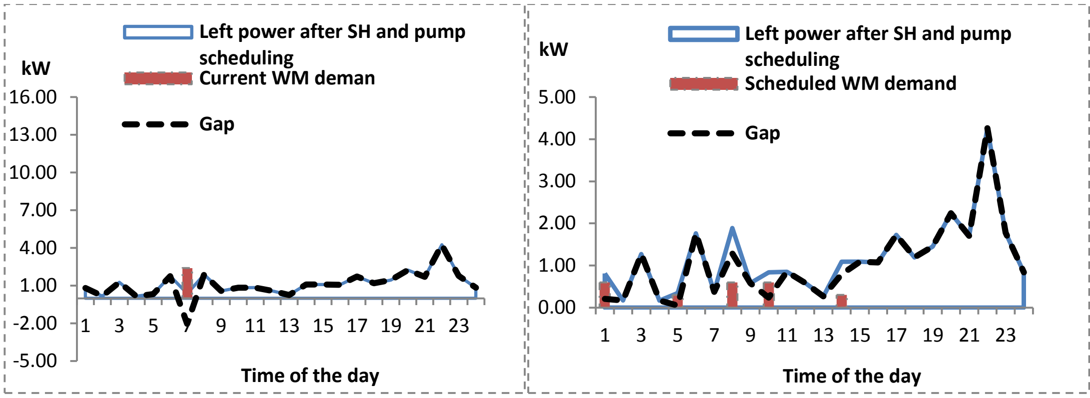
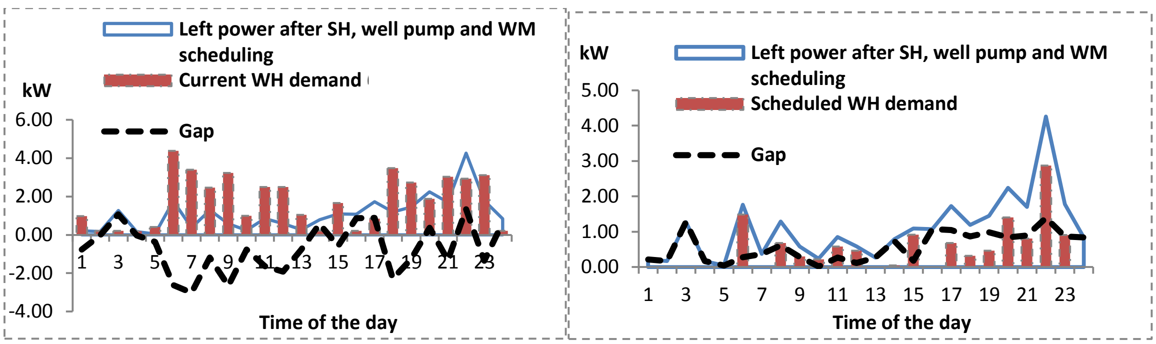


Figure 4.22: Required and scheduled washing machine demands



WH energy demanded (kWh)	40.50	Number of times WH is demanded	104
WH energy met (kWh)	12.15	Number of times WH is supplied	37
%	30%	%	36%

Figure 4.23: Required and scheduled water heater (WH) demands

4.3.3.3 Section Summary

In conclusion, the second proposed solution to solve PGS at a residential level based on rescheduling the houses' devices while taking into account the consumers' comfort level, the stochastic weather condition, the working hours, the devices' demand, and the availability of power supply during the time when the device can be used was presented. The proposed solution serves as a better alternative to the houses' full power interruption and the feeder disconnection from the grid for 10-12 hours daily or leaves new areas not electrified, since it at least allowed consumers to practice some of their daily activities. The energy met in the second proposed solution was more than the energy met in the first proposed solution and served as a better alternative to the current practice in developing countries.

4.3.3.4 Second and Third Aspects of Addressing PGS at Residential Level

The second aspect of addressing the power generation shortage at the residential level is focused on maximizing the availability of supply to consumers rather than meeting their maximum daily energy demand. In other words, in the first aspect, the target was to minimize the gap between the available power supply and the demand without an emphasis on which consumer to be supplied. Consumers with maximum device's demand at a certain hour are most likely to be supplied. The second aspect is more concerned about maximizing the number of consumers supplied such that all will have the same number of hours for the same type of devices to be supplied. Such a fairness condition is neglected in the third aspect of addressing the power generation shortage at a residential level. This problem is further clarified in the first and second optimization problems as shown below and as summarized in the simulation results section.

1. **First optimization problem**

The objective of the problem is to maximize the demand that can be supplied and reduce the devices' power interruption. The objective function and the constraints are shown below:

$$In\ winter \rightarrow \max \quad obj_m = \sum_{t=1}^{24}\sum_{n=1}^{8} yyy_{sh\,n,t} + l\sup plied_{n,t} + MachineSupply_{n,t} + pumpSupply_{n,t}$$

$$In\ summer \rightarrow \max \quad obj_m = \sum_{t=1}^{24}\sum_{n=1}^{8} fancanbe\sup plied_{n,t} + l\sup plied_{n,t} + MachineSupply_{n,t} + pumpSupply_{n,t}$$

(4-160)

Subject to:

A. Devices operational models constraints:

These models were discussed in the first aspect of addressing the PGS at a residential level

B. *Generation-Expected Demand Constraints:*

$$Pg_{i=1,t,s} - Pd_{i=2} * RTS_{t,s} - Pd_{i=3} * RTS_{t,s} - R * \sum_{n=1}^{8} light_{n,t}, s - [R * \sum_{n=1}^{8} (P_{heat\,n,t.} \quad yyy_{sh\,n,t} + zwh_{n,t,s} + P_{washing-machine_{n,t,s}} \quad machineSupply_{n,t,s} + P_{well-pump_{n,t,s}} \quad pumpSupply_{n,t,s})] - Ploss_{t,s} = 0$$

(4-161)

where s indicates the season and the term ($P_{sh\,n,t}$ * $yyy_{n,t}$) is replaced with ($P_{fan\,n,t}$ *$fancanbesupplied_{n,t}$) in summer.

$$Qg_{i=1,t,s} - Qd_{i=2} * RTS_{t,s} - Qd_{i=3} * RTS_{t,s} - \sum_{n=1}^{8}(P_{washing-machine_{n,t,s}} \quad machineSupply_{n,t,s} * PF_{washing-machine\,n} +$$

$$P_{well-pump_{n,t,s}} \quad pumpSupply_{n,t,s} * PF_{well-pump\,n}) - Qloss_{t,s} = 0$$

(4-162)

In summer, the term ($P_{fan\ n,t}$ *$fancanbesupplied_{n,t}$*$PF_{fan\ n}$) is added to the left hand side of the above constraint and specifically to the term within the summation sign.

$$\sum_{n=1}^{8}(P_{heat_{n,t}} \ yyy_{sh\ \ n,t} + zwh_{n,t,s} + P_{washing-machine_{n,t,s}} \ machineSupply_{n,t,s} + P_{well-pump_{n,t,s}} \ pumpSupply_{n,t,s})] = \sum_{n=1}^{8}(P_{heat_{n.t}} \ wnew_{n,t} +$$

$$zwh_{n,t,s} + P_{washing-machine_{n,t,s}} \ washing_{n,t,s} + P_{well-pump_{n,t,s}} \ well_{n,t,s})]$$

(4-163)

In summer, ($P_{heat\ n,t}$ * $yyy_{sh\ n,t}$) is replaced with ($P_{fan\ n,t}$ *$fancanbesupplied_{n,t}$) and ($P_{heat\ n,t}$ * $wnew_{n,t}$) is replaced with ($P_{fan\ n,t}$ *$MfanM_{n,t}$)

The generation available should not exceed an upper bound as shown earlier in the first aspect model accounting for the season in which the model is to be utilized.

C. Fairness of consumers to access the same type of devices

Constraints are added to guarantee that all customers have the same number of hours during which the corresponding demanded device is needed during the day. These constraints represent the second aspect of addressing the PGS at a residential level, while such constraints are neglected at the third aspect of the problem. The constraints are given below:

$$For \ n \neq 8$$

$$\sum_{t=1}^{24} wnew_{n,t} = \sum_{t=1}^{24} wnew_{n+1,t} \longrightarrow in \ \ winter$$

$$\sum_{t=1}^{24} MfanM_{n,t} = \sum_{t=1}^{24} MfanM_{n+1,t} \longrightarrow in \ \ summer$$

$$\sum_{t=1}^{24} washing_{n,t,s} = \sum_{t=1}^{24} washing_{n+1,t,s}$$

$$\sum_{t=1}^{24} well_{n,t,s} = \sum_{t=1}^{24} well_{n+1,t,s}$$

$$\sum_{t=1}^{24} D_{n,t,s} = \sum_{t=1}^{24} D_{n+1,t,s}$$

(4-164), (4-165), (4-166), (4-167) & (4-168)

To ensure that each device is at least met once a day and no device is sacrificed over another during the day, the following constraints are added:

$$\sum_{t=1}^{24} wnew_{n,t} \geq 1 \longrightarrow in\ winter \quad \textbf{(4-169)}$$

$$\sum_{t=1}^{24} MfanM_{n,t} \geq 1 \longrightarrow in\ summer \quad \textbf{(4-170)}$$

$$\sum_{t=1}^{24} washing_{n,t,s} \geq 1 \quad \textbf{(4-171)}$$

$$\sum_{t=1}^{24} well_{n,t,s} \geq 1 \quad \textbf{(4-172)}$$

$$\sum_{t=1}^{24} D_{n,t,s} \geq 1 \quad \textbf{(4-173)}$$

2. **Second Optimization Problem:**

The second optimization problem is used to ensure that the schedule determined does not violate the power flow constraints as discussed earlier in the first aspect of addressing the PGS at residential level. The optimization problem formulation is shown below:

The following objective function is utilized:

$$\max \ \ objj_s = \sum_{t=1}^{24} \sum_{n=1}^{8} o_{n,t,s} \quad \textbf{(4-174)}$$

where *objj* is the objective function to be maximized, *o* is a binary variable given a value of one when the schedule found from the first optimization problem at time *t* for house *n* can be met and that is zero otherwise.

This problem is subject to power flow constraints presented by the equations below:

$$Pg_{i,t,s} - Pd_i * RTS_{t,s} = \sum_{j=1}^{4} [V_{i,t,s} * V_{j,t,s} * Y_{i,j} * \cos(-\theta_{i,j} - \delta_{j,t,s} + \delta_{i,t,s})]) \ \forall i \neq 4 \quad \textbf{(4-175)}$$

$$Qg_{i,t,s} - Qd_i * RTS_{t,s} = \sum_{j=1}^{4} [V_{i,t,s} * V_{j,t,s} * Y_{i,j} * \sin(-\theta_{i,j} - \delta_{j,t,s} + \delta_{i,t,s})]) \ \forall i \neq 4 \quad \textbf{(4-176)}$$

$$Pg_{i,t,s} - \sum_{n=1}^{8} o_{n,t,s} * R * P_{residentid-house\,n,t,s} = \sum_{j=1}^{4} [V_{i,t,s} * V_{j,t,s} * Y_{i,j} * \cos(-\theta_{i,j} - \delta_{j,t,s} + \delta_{i,t,s})]) \ \forall i = 4 \quad \textbf{(4-177)}$$

$$Qg_{i,t,s} - \sum_{n=1}^{8} o_{n,t,s} * R * Q_{residentid-house\,n,t,s} = \sum_{j=1}^{4} [V_{i,t,s} * V_{j,t,s} * Y_{i,j} * \sin(-\theta_{i,j} - \delta_{j,t,s} + \delta_{i,t,s})]) \; \forall i = 4$$

(4-178)

where $P_{residential\text{-}house\ n,t,s}$ and $Q_{residential\text{-}house\ n,t,s}$ are the residential active and reactive demand schedules as determined from the first optimization problem.

The generation-expected demand relationships are given by the equations below:

$$Pg_{i=1,t,s} - Pd_{i=2} * RTS_{t,s} - Pd_{i=3} * RTS_{t,s} - Ploss_{t,s} = \sum_{n=1}^{8} o_{n,t,s} * R * P_{residentid-house\,n,t,s}$$

(4-179)

$$Qg_{i=1,t,s} - Qd_{i=2} * RTS_{t,s} - Qd_{i=3} * RTS_{t,s} - Qloss_{t,s} = \sum_{n=1}^{8} o_{n,t,s} * R * Q_{residentid-house\,n,t,s}$$

(4-180)

$$Ploss_{t,s} = \sum_{i=1}^{4} \sum_{j=1}^{4} (0.5 * gg_{i,j} * [V^2{}_{i,t,s} + V^2{}_{j,t,s} - 2 * V_{i,t,s} * V_{j,t,s} * \cos(\delta_{j,t,s} - \delta_{i,t,s})])$$

(4-181)

$$Qloss_{t,s} = -\sum_{i=1}^{4} \sum_{j=1}^{4} (0.5 * bb_{i,j} * [V^2{}_{i,t,s} + V^2{}_{j,t,s} - 2 * V_{i,t,s} * V_{j,t,s} * \cos(\delta_{j,t,s} - \delta_{i,t,s})])$$

(4-182)

The voltage level at system busses should be within a range as g by the following constraints:

$$0.95pu \le V_{i,t,s} \le 1.05pu$$

(4-183)

$$-\pi \le \delta_{i,t,s} \le \pi$$

(4-184)

The available generation supply to the new feeder to be connected to the grid is through bus 1 and is within limits as given by the following constraints:

$$Pg_{i \ne 1,t,s} = 0$$ **(4-185)**

$$Qg_{i \ne 1,t,s} = 0$$ **(4-186)**

$$Plow_{t,s} \le Pg_{i=1,t,s} \le Pup_{t,s}$$ **(4-187)**

$$Qlow_{t,s} \le Qg_{i=1,t,s} \le Qup_{t,s}$$ **(4-188)**

3. Simulation Results

In each house, the space heater will be supplied four times daily; the water heater will be supplied nine times daily; the washing machine will be supplied once a day; and the well pump will be supplied eight times daily. The houses' total energy met is 149.8957kWh per day without light demand and is 155.4957kWh with light demand. Even though the difference in energy met is small compared to the case of house full power interruption (155.0092kWh), it is important to emphasize that in the previous case, the comfort constraints are not met. Furthermore, more energy is given to the water heaters' losses when the devices are not used as in the previous case of the houses' full power interruption. On the other hand, in a typical summer day, each house is supplied with electricity for water heating nine times, pumping seven times, washing one time and ventilation fifteen times. The residential energy met in this case is 95.61484kWh for a typical summer day. A comparison between the expected demands to be met in winter and in summer are summarized in table below.

Table 4.9: Results of the second aspect of addressing the PGS at a residential level subject to consumers' fairness of devices' supplied

Winter device	Number of devices met / energy met	
Space heater	32	Heaters
washing machine	8	washing machines
Well pump	64	well pumps
Water heater	22.69567	kWh
Summer device	Number of devices met / energy met	
Electric fan	120	Fans
washing machine	8	washing machines
Well pump	56	well pumps
Water heater	15.21484	kWh

In winter, if the fairness constraints are neglected, the houses' total energy met is 155.3637kWh per day without light demand and is 160.9637kWh with light demand. On the other hand, following the thrid aspect of addressing the PGS at a residential level will result in 97.14612kWh of energy met of all residential demand in a typical summer day. The results are summarized in table below.

Table 4.10: Results of the third aspect of addressing the PGS at a residential level neglecting the fairness constraints

Winter device	Number of devices met / energy met	
Space heater	40	Heaters
Washing machine	8	washing machines
Well pump	48	well pumps
Water heater	35.3637	kWh
Summer device	Number of devices met / energy met	
Electric fan	120	Fans
Washing machine	8	washing machines
Well pump	53	well pumps
Water heater	20.34612	kWh

GAMS execution time was 0.0172 seconds when the second aspect of the addressing PGS at residential house devices' level is studied in winter, while it was 0.016 in summer. The verification of the determined devices' schedules in a power flow problem required an execution time of 0.015 seconds. On the other hand, the third aspect of addressing the PGS at residential house devices' level in winter required an execution time of 0.0109 seconds in GAMS when considering the first optimization problem, while the required execution time was 0.031 in summer.

4.4 Fourth Aspect of Addressing PGS at Residential House Devices' Level

In summer, the objective of the problem is to reduce the houses' devices power interruptions by maximizing the demand that can be met.The objective and the constraints are shown below:

$$In\ winter: \max\ obj_m = \sum_{t=1}^{24}\sum_{n=1}^{8} P_{heat\ n.t}\ \ wnew_{shn,t}\ hour + zwh_{n,t,s}\ hour + P_{washing-machine_{n,t,s}}\ \ washing_{n,t,s}\ hour + P_{well-pump_{n,t,s}}\ \ well_{n,t,s}\ hour$$

(4-189)

$$In\ summer: \max\ obj_m = \sum_{t=1}^{24}\sum_{n=1}^{8} P_{fan_{n,t}}\ \ MfanM_{n,t}\ hour + zwh_{n,t,s}\ hour + P_{washing-machine_{n,t,s}}\ \ washing_{n,t,s}\ hour + P_{well-pump_{n,t,s}}\ \ well_{n,t,s}\ hour$$

(4-190)

Subject to:

1. Devices operational models described in Chapter 4.
2. Generation-expected demand constraints:

$$Pg_{i=1,t,s} - Pd_{i=2} * RTS_{,st} - Pd_{i=3} * RTS_{t,s} - R * \sum_{n=1}^{8} light_{n,t,s} - [R * \sum_{n=1}^{8} (P_{fan_{n.,t}} \quad MfanM_{n,t} + zwh_{n,t,s} + P_{washing-machine_{n,t,s}} \quad washing_{n,t,s} + P_{well-pump_{n,t,s}} \quad well_{n,t,s})] - Ploss_{t,s} = 0$$

(4-191)

In winter, ($P_{heat\ n,t} * wnew_{n,t}$) replaces ($P_{fan\ n,t} * MfanM_{n,t}$) in the above constraint.

$$Qg_{i=1,t,s} - Qd_{i=2} * RTS_{t,s} - Qd_{i=3} * RTS_{t,s} - \sum_{n=1}^{8} P_{washing-machine_{n,t,s}} \quad washing_{n,t,s} * PF_{washing-machine\ n}$$

$$+ P_{well-pump_{n,t,s}} \quad well_{n,t,s} * PF_{well-pump\ n,} - P_{fan_{n,t}} \quad MfanM_{n,t} * PF_{fan\ n,} - Qloss_{t,s} = 0$$

(4-192)

In winter, the term ($P_{fan\ n,t} * MfanM_{n,t} * PF_{fan\ n}$) is removed from the above constraint.

The power generation available should not exceed an upper bound based on the corresponding season as given by the following constraints.

$$Plow_{t,s} \leq Pg_{i=1,t,s} \leq Pup_{t,s}$$

(4-193)

$$Qlow_{t,s} \leq Qg_{i=1,t,s} \leq Qup_{t,s}$$

(4-194)

The second optimization problem discussed earlier in section 4.3.3.4 that is given by the objective function in (4-174) and the constraints from (4-175) to (4-188) is utilized to validate the results when accounting for power flow constraints. It is important to emphasize that devices' scheduling in summer required an execution time of 0.031 seconds in GAMS and the same time when the sechule was verified using the second optimization problem.

The table below shows the devices that are met. In a typical summer day, the feeder's total demand supplied including system losses is 763.7900kWh. Similarly, the total energy supplied to the houses undergoing devices' power interruptions is 103.8170kWh compared to 117.7454kWh actual houses' energy demand for that day; alternatively in a typical winter day, it is 163.4525kWh compared to 199.5848kWh actual houses' energy demand in that day. Table 4.9 summarizes the results.

Table 4.11: Devices supplied in typical winter and summer days following the fourth aspect of addressing the PGS at residential houses' devices level

Device in winter	Number of devices met / energy met	
Heater	39	Heaters
washing machine	8	washing machines
Well pump	59	well pumps
Water heater	26.152515	kWh
Device in summer	Number of devices met / energy met	
Electric Fan	62	Fans
washing machine	8	washing machines
Well pump	61	well pumps
Water heater	20.31698	kWh

4.5 Chapter Summary

This chapter proposed solutions to address the power generation shortage in developing countries. Such a shortage prevents the distribution system's expansion as the deficiency in supply restricts new feeders to be built for new residential areas's electricity supply. The current approaches applied in developing countries are focused on either leaving the new areas not electrified or considering their addition to the grid by worsening the feeders' power interruptions schedules such that the other areas in the grid will experience longer durations of no electricity supply (lasting more than 10-12 hours daily). The proposed solution in this thesis is to use the available generation after supplying the rest of the grid accounting for the current power interruption schedule of other feeders in the grid. This available generation will be utilized efficiently to supply the new area to be connected to the grid due to population growth and the demand for grid expansion. This utilization will not have a significant effect the current power interruption schedule of other zones in the grid and will allow new regions to be supplied guaranteeing such regions with shorter durations of power interruption. In this case, there were two main solutions that were considered in the thesis to achieve this target. The first proposed solution addressed such a deficiency in electricity supply by disconnecting the residential houses such that the available power for the new region of the grid can be utilized. The second proposed solution considered scheduling the expected devices to be owned by the residents when their houses are connected to the grid. This solution considered the devices' load models and their dependency on the stochastic weather condition. Subjecting the scheduling problem to these two conditions minimized the gap between the possible power supply and the expected demand. By this approach, it had been shown in the thesis that the residential consumers could access electricity or could avoid having long hours of power interruption.

Chapter 5

Economic Analysis of Alternative Power Generation Options

The importance of renewable energy sources in electricity generation is increasing due to the negative environmental effects resulting from the dependency on fossil fuel based electricity. The actual generation from renewable energy sources in India is 12622.18MW, but based on the Ministry of New and Renewable Energy Sources, there is a huge potential in India for electricity generation from these sources that represents 84777MW [74, 75]. The high capital cost of renewable energy projects, the variable nature of these resources and developing countries' policies on project funding are factors governing the deployment of such resources as alternative power generation options. Attention should be given to policy making and project management [74, 75] as renewable energy sources are desirable solutions to address the power generation shortage rather than depending on limited resources of commercial fuels. Renewable energy sources can be utilized in various arrangements such as wind turbine projects, hydro power projects, and PV projects [3, 76-78]. The choice of the best renewable energy source to address the power generation shortage in developing countries is important for an investor in the field as the financial structure of such projects is governed by many factors such as bank loans, promotors' contributions, government taxation system,….etc. A feasibility study of candidate projects for an investment in developing countries can facilitate the selection of the best renewable energy project to address the power generation shortage. In addition, investigating the role the policy plays in a decision toward a project is essential [78]. Furthermore, an update in the current policy applied on project funding can encourage investors toward more projects in such a field to accommodate population growth such that their benefits are maximized, and electricity consumers find a solution for power interruptions or living without electricity. The utilization of such resources can be a good solution for unemployed residential consumers as manpower will be needed when considering the investment in such resources.

Some power utilities purchase power from other suppliers according to short term contracts when possible to reduce the severity of the power generation shortage as in [3, 79]. This makes the investment in the diesel generators an option to supply consumers with electricity as the capital cost of diesel generator is lower than the capital cost of a renewable energy source. This necessitates the demand for an economic study that compares the distribution generation resources focusing on diesel generator projects and other possible renewable energy projects to select the best economic project for an investment in the energy sector. This chapter will consider two aspects of evaluating the distribution generation projects to select the best alternative for an investment in developing countries such that it can be dedicated to address the power generation shortage problem. The first aspect is based on applying the general budget structure of a project as discussed in [29, 80] with corrections to some concepts based on [81] as will be emphasized in this chapter. The work in this thesis will utilize an incremental rate of return analysis as a technique to select the best project among PV, wind and diesel generator projects for an investment. The analysis will consider the capital cost of the project under a modified accelerated cost recovery system as a recent depreciation method compared to straight line depreciation and declining balance depreciation methods presented in [80, 81], and applied in [29], for the purpose of comparing the different alternatives.

Moreover, the effect of the changes in the fuel cost on the decision making process is investigated using the incremental benefit to cost ratio method. This method is very effective especially when the internal rate of return of the project based on its capital cost is difficult to obtain.

The second aspect will be based on applying a selected developing country's policy on financing such renewable energy projects and then applying the incremental rate of return analysis on such projects' cash flow structures to determine the best project among PV, wind and hydro power projects as these resources are widely available in the developing country under study [82]. Even though some renewable energy projects have been applied in developing countries for certain tasks such as pumping [27], power generation shortage still exists. This is because of the high costs of such projects restricting electric utilities from further investments as well as the current policy role on project finance not motivating other investors toward such projects when considering projects' expansion. The practical aid, the profitable loans and the investment of developed countries in developing countries can lead to the development of homegrown economic markets assembling the capital needed to invest in renewable energy sources in developing countries. Moreover, the deficiency in the capital cost needed for the deployment of such resources can be enhanced by liberating the unexploited financial assets by political pledge and restructuring institutions [77]. Since the developing countries' policices are the main drivers behind utilizing renewable energy projects, the thesis will set guidelines to encourage investors in the field such that more renewable energy projects can be targeted to face power generation shortage and accommodate population growth demand for electricity; while assuring the investors a reasonable profit over the long run of the projects.

5.1 A General Economic Analysis of Alternatives

In any project, there are two types of costs that form the total cost of the project. These are the cost of debt signifying the bank loan (financial aid) and the cost of equity signifying the available fund (promoters' contribution). The internal rate of return of an investment in the power distribution sector is calculated based on one of these costs or both such that it is the criterion based on which a project can be considered to be acceptable for an investment or it can be rejected. When alternatives exist, the incremental rate of return analysis is an approach that can be followed to compare the projects to select the best alternative. Such a comparison is governed by two elements: the incremental internal rate of return and the minimum accepted rate of return of a project. The next section is dedicated to selecting the suitable generation source (PV, diesel generator or wind turbine) to be utilized to address the power generation shortage. The selection is based on a general financial structure discussed in [29, 80] with corrections applied to the concept of the feasibility study cost and modifications applied to the depreciation method while neglecting the emission free credits as not all developing countries apply such a concept, and some developing countries do not allow selling such credits within the country. The last concept will be accounted for when comparing the projects under the policy of a selected government where such a concept is applied. Furthermore, the next section will consider evaluating the projects based on the projects' cash flows considering the total cost of the project represented by the debt and the equity to perform the incremental rate of return analysis. On the other hand, later sections of this chapter will apply a government policy of a selected developing country on projects' cash flows to investigate the policy role on the decision toward the investment in a renewable energy project. Then, policy reforms will be recommended to governance institutions to encourage local investors toward more renewable energy projects to accommodate population growth demand for electricity by guaranteeing them the reasonable profits over the long run subject to their limited funds.

The work in this chapter has a supplementary worth to [29, 80] because it economically compares three projects (wind turbine, PV and diesel generator) to the first-rate project for an investment by applying the incremental rate of return analysis on projects' cash flows. It will also determine the incremental cash flow resulting from comparing different projects' cash flows while accounting for a recent depreciation method applied to individual projects' cash flows that is the Modified Accelerated Cost Recovery System method (MACRS). It is essential to accentuate that a project's depreciation is a part of the tax code that licenses the business to account for the capital disbursement over time by deducting it. The methods discussed in [80, 81] and applied in [29] need valuations of the useful life of the project as well as its salvage value. While investors can utilize such methods as a part of the cash flow of the project, there is a deficiency in the uniformity of reporting the depreciation expenses as stated by the authors in [81]. Then again, the modified accelerated cost recovery system method is acknowledged for the subsequent points that the authors in [81] has discussed: MACRS is reliant on the declining balance depreciation method swapping to the straight line depreciation. Moreover, MACRS embraces the expanded property class lives where a class embraces all the depreciated assets. When using MACRS, there is no requirement on judging the salvage value of the project as the recovery period of the project subsidizes the assets to be fully depreciated. In this case, the salvage value is specified to be zero. With MACRS, the annual depreciation can be established approaching shorter recovery periods such that the capital costs are amended earlier than they are in the straight line and declining balance depreciation methods. Contrasting the property class lives to the actual useful lives, it can be observed that the previous is less than the latter. In MACRS, the percentages consigned for the annual depreciation for the first and last year of the project embrace a half year settlement. Tables of annual percentages are obtainable in prose to reduce the bare bones of the calculations. Contrariwise, the straight line depreciation is for an elongated period of recovery and accordingly it is economically not an appealing preference. Depreciation deductions with such a scheme are not valued in contrast to the modified accelerated cost recovery system scheme.

Furthermore, the work in this chapter does not consider the feasibility study cost that is involved in [29] as a part of the capital cost of the project. The main reason behind neglecting such a cost in the project cash flow is that it is a sunk cost according to the authors in [81], and sunk costs are not to be involved in the capital cost of the project utilized to find the projects' internal rate of returns.

Even though a sensitivity analysis has been offered in [29], the practice was for searching the influence of the disparity in cash flow parameters on the internal rate of return of the project estimated based on equity. The work in this chapter will apply a sensitivity analysis for another purpose. The objective is to apply a sensitivity analysis to recognize the influence of the disparity in the financial structure of diverse projects on the decision to target a project with respect to the possible alternatives. The sensitivity analysis will be based on the incremental rate of return analysis. When the choice of a project among possible alternatives cannot be made following the incremental rate of return analysis, another technique known as "incremental benefit to cost ratio" is to be applied.

5.1.1 Projects Fund

The projects (1MW: wind turbine, PV and diesel generator) are economically assessed bearing in mind a debt to equity ratio of (75:25). The interest rate applied on the annual debt is 14% and the debt is to be settled in 7 years taking into consideration the life of the projects to be 25 years. Such information is based on the economically evaluated 20MW wind project in [29] under the assumption that these rules apply for all of the three evaluated projects.

5.1.2 Capital Cost of Projects

The capital cost of the 1MW projects to be evaluated can be broken down into the costs in Figure 5.1 according to [83].

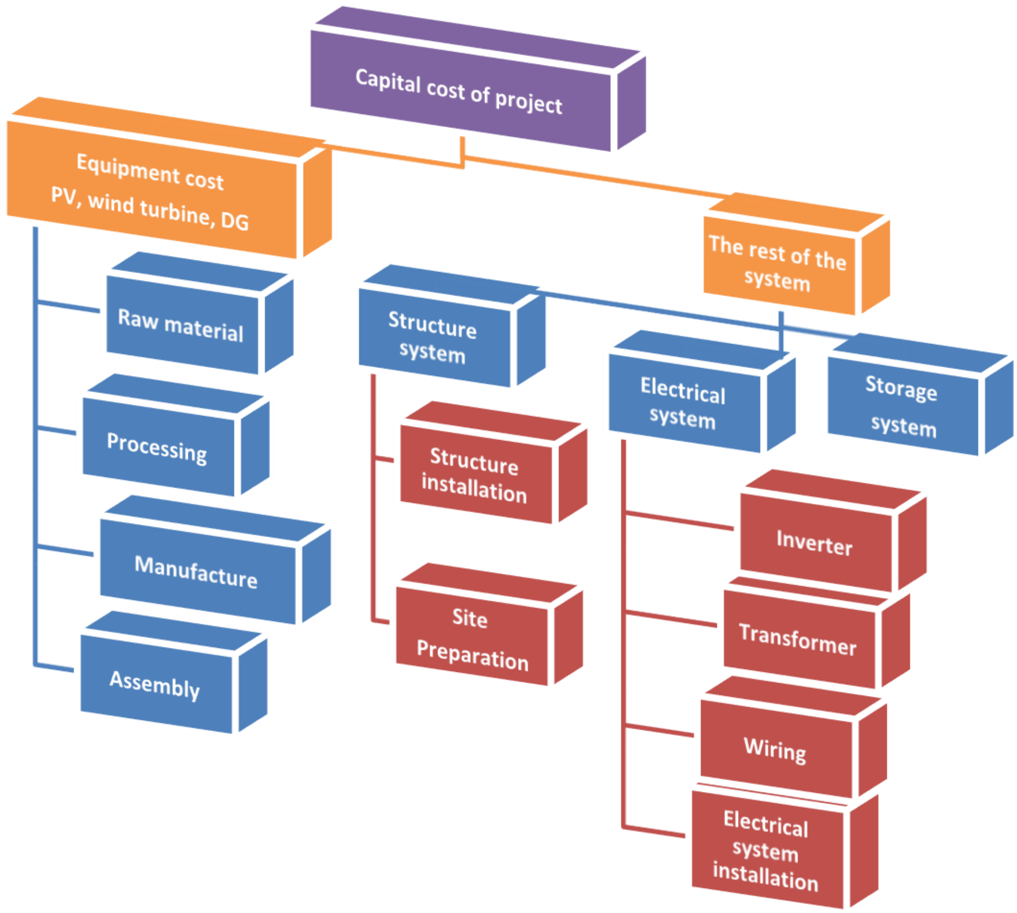


Figure 5.1: Capital cost components based on [83]

In [29, 80], the cost of feasibility study is used as an element in the capital cost of the project and is involved when calculating the internal rate of return; yet, this cost is explained by the authors in [81] to be a sunk cost and is not to take a part when setting a project's capital cost. Table 5.1 presents the capital cost of possible generation projects. The costs of the 1MW wind turbine project is found as a percentage of the 20MW wind plant analyzed in [29]; whereas the costs of the 1MW PV project is found as a percentage of the 3MW PV plant in [84], and its installation cost is obtained from [85].

Table 5.1: Capital costs of possible electricity generation projects

Currency (INR)	The cost of energy equipment	The cost of the rest of the system	Contingencies	Total cost
1MW diesel generator project	25,000,000 [86]	6,752,676.37[87]	5%	33,340,310.19
1MW wind turbine project	31,416,000 [29]	31,984,750	5%[29]	38,608,238
1MW PV project	145,000,000 [84, 85]	21,799,800	5%	175,139,790

5.1.3 Annual Costs Associated with the Projects under Economic Evaluation

The costs of the projects experienced annually can be decomposed into the fuel costs (if any) and the non-fuel operation and maintenance costs. The latter cost can be composed of many costs such as the cost of human resources, the cost of project operation and maintenance, and the related costs to the site where the project is to be implemented [88]. Table 5.2 presents such annual costs of the different projects under study that are diesel generator, wind turbine and PV projects. It is important to clarify that the annual costs to be experienced with the 1MW wind turbine project are calculated as a percentage of such costs for the 20MW wind plant in [29]; while the fuel cost of the diesel generator is determined assuming the generator is operating at full load for a year.

Table 5.2: Annual cost of projects in (INR)

Yearly costs (INR/year)	Fuel cost at 5% escalation	Operation and maintenance cost	Contingencies	Total cost excluding fuel cost
1MW diesel generator project	37,723,052 [82, 85]	2,190,000 [86]	10%	2,409,000
1MW wind turbine project	0	671,500 [29]	10%[29]	738,650
1MW PV project	0	900,000 [89]	10%	990,000

5.1.4 Debt Repayment

The amount of debt can be estimated utilizing the equation below [78, 81] where *A* is the annual repayment, *C* is the capital cost of the project (INR), $\underline{i}$ is the debt interest rate, $\underline{n}$ is the number of years over which the debt is to be repaid, and *debt* is the loan as a percentage of the capital cost.

$$A = -C \ x \ debt \ \frac{\underline{i} \ (1+\underline{i})^{\underline{n}}}{-1+(1+\underline{i})^{\underline{n}}} \tag{5-1}$$

The debt repayments are not essentially the same each year of the loan period. Likewise, this assumption applies for the interest payments. The amount of interest to be paid each year besides the yearly repayment of debt can be estimated following [90]. Furthermore, the debt yearly repayment excluding the amount of yearly interest payment can be calculated by subtracting the interest from *A* [80]. Figure 5.2 describes the loan repayment components of the different projects; while Table 5.3 shows the annual repayments for the projects.

Figure 5.2: Debt repayment for Top) Diesel generator, Middle) Wind turbine, Bottom) PV

Table 5.3: Annual repayments

INR/year	Annual repayment (A)
1MW diesel generator project	-5,831,029.645
1MW wind turbine project	-6,752,360.014
1MWPV project	-30,630,948

5.1.5 Project Depreciation Applied to Cash Flow

Project depreciation can be estimated using the straight line depreciation approach that was well known before 1981[80, 81], the declining balance depreciation approach recognized before 1981[80, 81], or the MACRS depreciation approach that was applied since 1986 until now [81, 91]. The MACRS method is applied when evaluating the different alternatives considering the incremental rate of return approach to select the candidate project for an investment. The projects evaluated are recognized to have a 25 year life span, and therefore can be categorized under the 20 year property class based on the MACRS general depreciation system [81]. The depreciation amount is to be recovered in 21 years where each year's depreciation rate can be obtained from [81, 92]. The estimated depreciation amount each year is based on the equation below [81] where *dep* is the depreciation amount in a year, *MACRS* is the MACRS rate and $\underline{D}$ is the depreciation tax basis (100%). Figure 5.3 shows the MACRS depreciation applied to the diesel generator project.

$$dep = MACRS \; x \; \underline{D} \; x \; C \qquad \textbf{(5-2)}$$

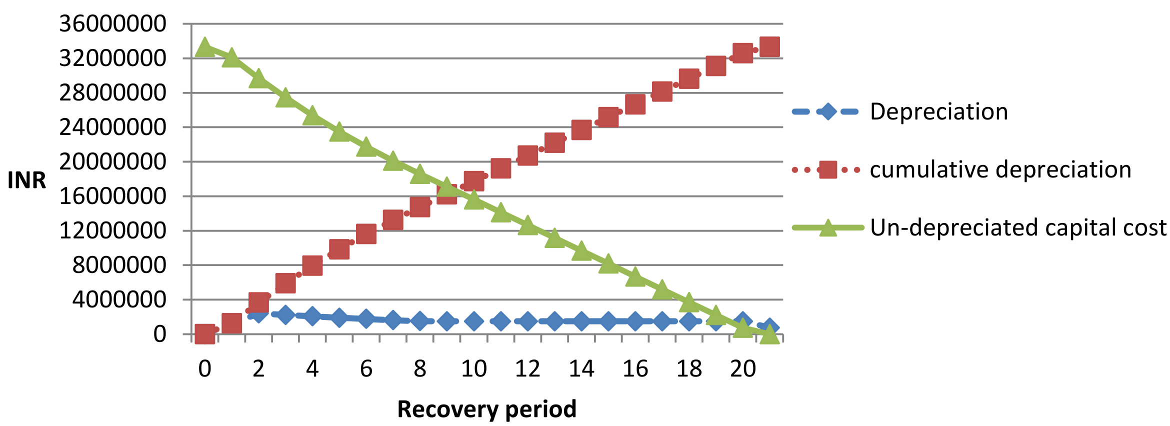


Figure 5.3: MACRS depreciation applied to the diesel generator project

5.1.6 Cash Flow for Incremental Rate of Return Analysis

Incremental rate of return analysis is a technique used to decide among possible alternative projects for an investment. The purpose of this analysis is to find an incremental internal rate of return to be compared with a minimum accepted rate of return based on which the selection of a project can be made. The analysis starts with finding the internal rate of return of individual projects and comparing it to a minimum accepted rate of return to decide if such a project is an acceptable option to be considered for comparison among other alternatives. There are two types of internal rate of return of individual projects. The first type is the equity internal rate of return. This type considers the available fund from an investor's perspective excluding any loans. The economic analysis in this case is called private analysis according to [93]. In this case, the internal rate of return on equity is to be determined. This private analysis will require the equity fund available at year zero and the after tax cash flow for further years of the project. In this case, the after tax cash flow is determined after deducting the tax from the cash flow of the project, which is mainly a function of costs and benefits over the life of the project. The tax liable to the government is to be determined after deducting the costs of depreciation and interests on the project loan from the cash flow of the project. The equity internal rate of return is determined on the final cash flow determined after tax deduction. The cash flow structure used to find the equity internal rate of return can be found in Appendix C.1, C.2 and C.3 as given by [80, 93].

The other type of internal rate of return is the debt internal rate of return that is calculated based on the amount of borrowed money at year zero and the annual repayments for subsequent years. The sum of the debt internal rate of return multiplied by its contribution to the project fund and the equity internal rate of return multiplied by its contribution to the project fund represent the project internal rate of return [93].

On the other hand, project analysis is performed on the capital cost of the project including debt and equity, operational costs, and project profits over the life of the project, while accounting for taxation deduction according to [94]. In this case, the internal rate of return will be called project internal rate of return. The equations presented in this section will concern the projects' analyses based on which the incremental rate of return analysis (comparing different alternatives) is carried out.

To perform the incremental rate of return analysis comparing different projects' cash flows, the difference in cash flows between the projects is to be determined applying the following equation [81] where $DF(\underline{n})$ is the difference between cash flows of projects at year $\underline{n}$, a and b are the projects' indicators such that project a is higher in cost than project b, and $Fcash$ is the after tax cash flow of a project at year $\underline{n}$:

$$DF(\underline{n}) = Fcash_a(\underline{n}) - Fcash_b(\underline{n}) \tag{5-3}$$

$Fcash$ can be determined applying the equation below where $Pcash$ is the pretax cash flow and TI is the taxes on the net income:

$$Fcash\ (\underline{n}) = Pcash(\underline{n}) - TI(\underline{n}) \tag{5-4}$$

The pretax cash flows that can be determined applying the following equation [80, 81, 93]:

$$Pcash\ (\underline{n}) = In\ (\underline{n}) + Out\ (\underline{n}) \quad \textbf{(5-5)}$$

The pretax cash inflow of individual projects (*In*) can be found as in the equations below where *K* is the price of electricity from a generation source (INR/kWh), *CUF* is a capacity utilization factor of a generation source, *HR* is 8760hours/year, *RAT* is a generation source rating (1MW), *Eng* is the electricity (kWh) generated from diesel generator, and *esc* is an escalation rate of the electricity price:

$$In_{renewable}(\underline{n}) = K\ x\ CUF\ x\ HR\ x\ RAT\ (1+esc)^{\underline{n}} \quad \textbf{(5-6)}$$

$$In_{DG}(\underline{n}) = K\ x\ Eng(\underline{n})\ x\ (1+esc)^{\underline{n}} \quad \textbf{(5-7)}$$

It is important to emphasize that the capacity utilization factor for a wind turbine is 20% [95], while it can vary between 19% [96, 97] and 25% for PV [98]. A Diesel generator is considered to have an efficiency of 40% [86]. The wind turbine tariff is INR4.88/kWh [99], while it is INR7.68/kWh for PV [100] and INR13/kWh for diesel generator [101]. Moreover, the emission free credit is neglected from the analysis as such credit is not provided by many developing countries.

The pretax cash outflow of individual projects (*Out*) can be found applying the following equation where *OM* is the operation and maintenance cost, *COM* is the cost of contingencies on OM, *inf* is the inflation rate (2.5%) [29], *fuel* is the cost of fuel if used as in the case of a diesel generator (INR16/L) [86] and *DT* is the term loan duration.

$$Out\ (\underline{n}) = \begin{cases} -C & \forall \underline{n} = 0 \\ -[(OM + COM)\ x\ (1+\inf)^{\underline{n}} + fuel(1+esc)^{\underline{n}}] & \forall \underline{n} > 0 \end{cases} \quad \textbf{(5-8) \& (5-9)}$$

Figure 5.4 presents the net income to be taxed for wind turbine, PV and diesel generator projects when MACRS depreciation is considered.

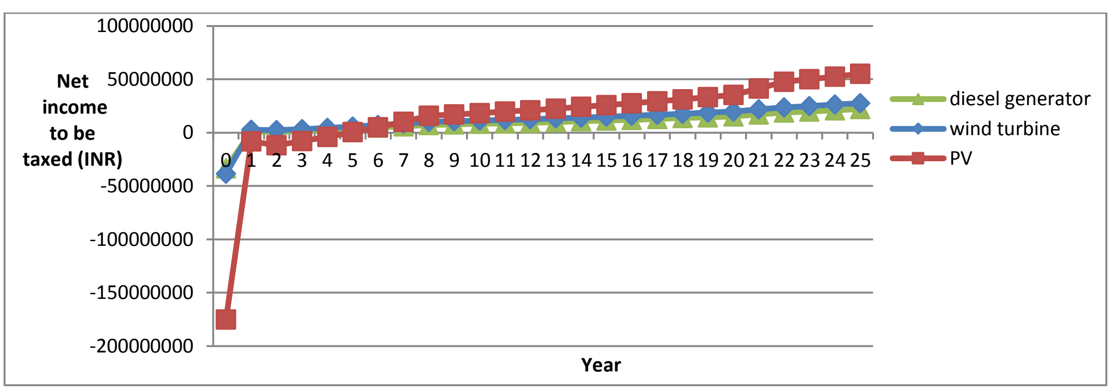


Figure 5.4: Pretax cash flow of individual projects

The taxes to be paid on the net income shown in Figure 5.4 can be determined as shown below where *Tax* is the tax rate applied on net income (*net income*) following the method in [80] as shown in Appendix C.3 and *interest* is determined as shown in Appendix C.4 based on on [78, 90].

$$TI(\underline{n}) = Tax * net\ \ income(\underline{n}) \qquad \textbf{(5-10)}$$

$$net\ \ income(\underline{n}) = Pcash(\underline{n}) - MACRS - \text{int}\,erest(\underline{n}) \qquad \textbf{(5-11)}$$

Table 5.4 shows the project internal rate of return and the equity internal rate of return of 1MW individual projects considering the effects of MACRS, straight line and declining balance depreciations on after tax cash flow. The equity IRR reflects how much investors can attain for the devoted money for project financing.

Table 5.4: IRR of projects

Depreciation	Project	Wind Turbine	PV	Diesel Generator	Incremental IRR and Decision
MACRS	IRR (%)	21.62%	11.33%	19.09%	(WT, DG) =37.88%. Choose wind
Declining balance	IRR (%)	23.29%	11.58%	20.20%	(WT, DG) =45.94%. Choose wind
Straight line	IRR (%)	21.21%	11.11%	18.70%	(WT, DG) =37.40%. Choose wind
Depreciation	Equity	Wind Turbine	PV	Diesel Generator	Rejected Project based on Equity IRR
MACRS	IRR (%)	27.39%	10.25%	22.27%	Reject PV
Declining balance	IRR (%)	32.02%	10.57%	24.64%	Reject PV
Straight line	IRR (%)	26.43%	9.98%	21.50%	Reject PV

The equations describing the straight line depreciation, the declining balance depreciation and the un depreciated capital cost are adopted from [80, 81] and presented in Appendix C.5.

The incremental internal rate of return is to be compared to a minimum acceptable rate of return to decide on what project to select among available projects. The minimum acceptable rate of return is the maximum of the subsequent indices according to the authors in [81] presenting the first three indices of the four indices: 1) Cost of borrowed money recognized as the interest rate of the debt. 2) Opportunity cost defined as the rate of return of the best rejected project as clarified by the authors in [81]. 3) Cost of capital [81] estimated using equation (5-11) where *equity* is equity ratio and *S* is minimum required equity rate of return. 4) Discount factor given by equation (5-12) as $\underline{DF}$ where *kk* is the number of compounding periods in the year and *p* is the number of periods related to $\underline{n}$ [102, 103].

$$\%\cos t\ of\ capital = 100\ \frac{[\ C\ x\ debt\ x\ \underline{i}\ (1-Tax) + C\ x\ equity\ x\ S]}{C} \qquad \textbf{(5-12)}$$

$$\underline{DF} = (1+\frac{\underline{i}}{kk})^{\frac{kk}{p}} - 1 \qquad \textbf{(5-13)}$$

The minimum rate of return on equity for the PV project is 12% [104]; whereas it is 11% for the wind turbine project [105] based on a debt to equity ratio of 70:30. In the performed analysis, it has been presumed that the minimum required return on equity for the projects is 11.5%. Based on this, the cost of capital return is 9.7%.

From the above four indices, the minimum accepted rate of return (MARR) has been specified to be 14%.

Incremental rate of return analysis is carried out to choose the top economic project comparing wind turbine, PV and diesel generator projects as alternatives of supply to address the power generation shortage in developing countries. Figure 5.5 summarizes the steps tracked to accomplish the incremental rate of return analysis; while Table 5.5 shows the results found. It can be noted from this table that the wind turbine and diesel generator projects under study are acceptable for additional comparison because the projects' calculated return on equity are higher than their equity MARR.

The incremental rate of return is 37.88% when comparing the cash flows of the wind turbine project to the diesel generator project. Because this rate is higher than the minimum accepted rate of return, the wind turbine project is chosen as the best investment option among the projects under study. In contrast, the cash flow of the wind turbine project is not considered for further comparison with the PV project cash flow. This omission is because the PV project's internal rate of return on equity is 10.25% and this percentage is less than the minimum accepted rate for the PV projects which is 12% [104].

Table 5.5: Incremental rate of return

<table>
<tr><th>Type of project under study</th><th>Reject or accept project based on equity IRR</th><th>Ascending order</th><th>ΔIRR on Project</th></tr>
<tr><td>Wind turbine project</td><td>Accept
Calculated equity IRR=27.39%>11%</td><td>2</td><td rowspan="3">Comparing the difference in cash flows (wind-DG) provides a project incremental internal rate of return of 37.88% that is greater than 14%. Thus, wind project is the preferable project for an investment</td></tr>
<tr><td>Diesel generator</td><td>Accept
Calculated equity IRR=22.27%</td><td>1</td></tr>
<tr><td>PV project</td><td>Reject
Calculated equity IRR=10.25%<12%</td><td>-</td></tr>
</table>

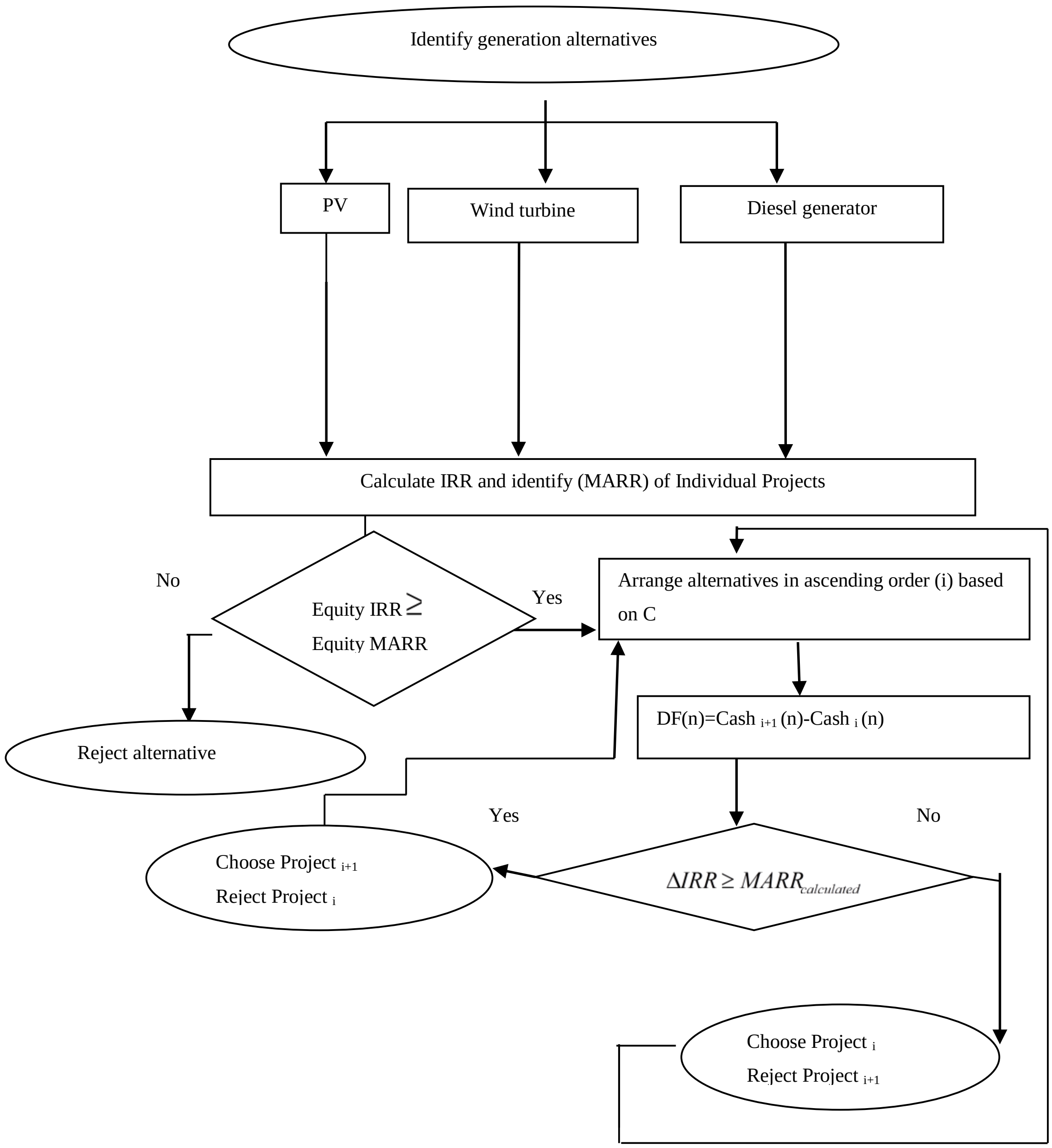


Figure 5.5: Incremental IRR analysis procedure

5.1.7 Sensitivity Analysis and Project Selection

The decision of the best economic project for an investment considering the available investment options judged based on incremental rate of return analysis is sensitive to a variation in any of the cash flow elements such as capital cost, operation and maintenance cost, fuel cost (if any) as in the case of diesel generator, debt to equity ratio, interest rate,…etc. In this section, such decision is made by following the procedure presented in Figure 5.5. The capital cost of the project and the operation and maintenance cost are chosen to be the variable elements. Such variation effect on the choice of the best project for an investment is investigated.

The capital cost variation was within [-20%, 20%] variation of the total cost of the project that has been shown in Table 5.1. Such variation effect is studied at an increment of 2.5% and Table 5.6 shows a sample of the results. Table 5.6 serves as a guide to the investor or a utility to recommend the best investment option among PV, wind turbine and diesel generator projects subject to such variation effect. For the studied variation range of the project capital cost, the project internal rate of return varies between 9.56% and 13.74% for PV, 18.87% and 25.56% for wind turbine and 16.69% and 22.46% for diesel generator. Furthermore, the wind turbine project is found to be the top economic project when compared to the PV and the diesel generator projects.

Alternatively, when the variation in the total operation and maintenance cost is allowed in the range of [-20%, 20%] of that cost, it has been found that the decision toward the wind turbine project option for an investment will remain at the top as shown in Table 5.7. Figure 5.6 shows the variation in internal rate of return with respect to the variation in the total operation and maintenance cost.

Moreover, the effect of the diesel generator's diesel price variation on the choice of the best project to be considered for an investment is studied as presented in Table 5.8.

Table 5.6: Capital cost variation effect on selecting the best project for an investment (WT: wind turbine, DG: diesel generator)

Type of project	Capital cost variation	Project IRR	Status and private IRR	Order	ΔIRR and decision
PV		13.74%	Accept 13.62% on E>12%	3	First step:(WT:DG)=45.74%>14%
WT	-20%	25.56%	Accept 36.53% on E>11%	2	Second step: (WT,PV)=9.56%<14%
DG		22.46%	Accept 28.90% on E	1	Decision: Choose WT
PV		13.05%	Accept 12.64% on E>12%	3	First step: (WT:DG)=45.01%>14%
WT		24.42%	Accept 33.70% on E >11%	2	Second step: (WT,PV)= 9.02%<14%
DG	-15%	21.03%	Accept 26.88% on E	1	Decision: Choose WT
PV		12.43%	Reject 11.75% on E<12%	-	First step: (WT,DG)=41.39%
WT		23.40%	Accept 31.29% on E>11%	2	Decision: Choose WT
DG	-10%	20.61%	Accept 25.13%	1	
PV		11.85%	Reject 10.96% on E <12%	-	(WT,DG)=39.55%>14%
WT	-5%	22.47%	Accept 29.20% on E>11%	2	Decision: Choose WT
DG		19.82%	Accept 23.61% on E	1	
PV		11.58%	Reject 10.60% on E<12%	-	(WT,DG)=38.69%>14%
WT	-2.5%	22.04%	Accept 28.87% on E>11%	2	Decision: Choose WT
DG		19.45%	Accept 22.92% on E	1	
PV		11.33%	Reject 10.25% on E<12%	-	First step:(WT,DG)=37.88%>14%
WT	0%	21.62%	Accept 27.39%on E>11%	2	Decision: Choose WT
DG		19.09%	Accept 22.27% on E	1	
PV		11.08%	Reject 9.92% on E <12%	-	(WT,DG)=37.11%>14%
WT		21.23%	Accept 26.57% on E>11%	2	Decision: Choose wind
DG	2.5%	18.75%	Accept 21.65% on E	1	
PV		10.84%	Reject 9.60% on E<12%	-	(WT,DG)=36.38%>14%
WT		20..85%	Accept 25.80% on E>11%	2	Decision: Choose WT
DG	5%	18.42%	Accept 21.07% on E	1	
PV		10.38%	Reject 9.01% on E<12%	-	(WT,DG)=35.00%>14%
WT		20.14%	Accept 24.39% on E>11%	2	Decision: Choose WT
DG	10%	17.81%	Accept 19.91% on E	1	
PV		9.96%	Reject 8.46% on E <12%	-	(WT,DG)=34.05%>14%
WT	15%	19.48%	Accept 23.13% on E>11%	2	Decision: Choose WT
DG		17.20%	Accept 18.99% on E	1	
PV		9.56%	Reject 7.96% on E<12%	-	(WT,DG)=32.78%>14%
WT	20%	18.87%	Accept 22.00% on E>11%	2	Decision: Choose WT
DG		16.69%	Accept 18.15% on E	1	

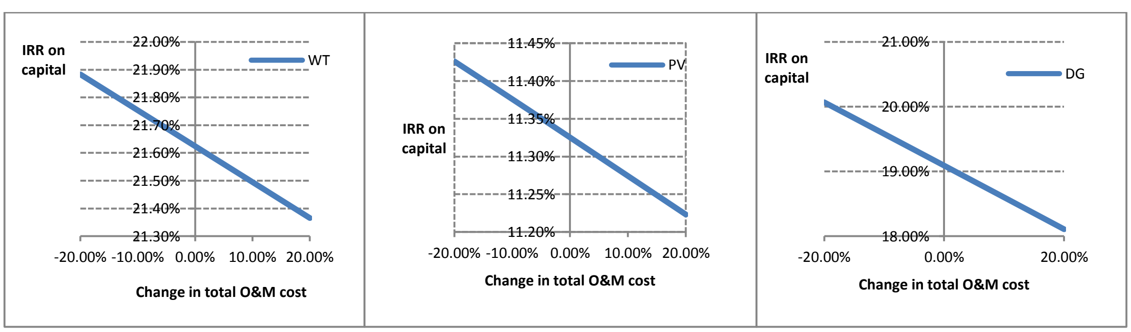


Figure 5.6: Sensitivity analysis on operation and maintenance cost variation effect on IRR $_{capital}$

Table 5.7: Operation and maintenance cost (O&M) variation effect on investment decision

Type of project	O&M cost variation	IRR on capital	Status and equity IRR	Order	ΔIRR and decision
PV	-20%	11.43%	Reject 10.38% on E<12%	-	(WT, DG)=33.59%>14% Decision: Choose WT
WT		21.88%	Accept 27.96% on E>11%	2	
DG		20.07%	Accept 31.62% on E	1	
PV	-15%	11.40%	Reject 10.35% on E<12%	-	(WT, DG) =34.67%>14% Decision: Choose WT
WT		21.82%	Accept 27.81% on E>11%	2	
DG		19.82%	Accept 28.69% on E	1	
PV	-10%	11.38%	Reject 10.32% on E<12%	-	(WT, DG)=35.74%>14% Decision: Choose WT
WT		21.75%	Accept 27.67% on E>11%	2	
DG		19.58%	Accept 26.22% on E	1	
PV	-5%	11.35%	Reject 10.28% on E<12%	-	(WT, DG)=36.81% >14% Decision: Choose WT
WT		21.69%	Accept 27.53% on E>11%	2	
DG		19.34%	Accept 24.10% on E	1	
PV	-2.5%	11.34%	Reject 10.27% on E<12%	-	(WT, DG) =37.35%>14% Decision: Choose WT
WT		21.66%	Accept 27.46% on E>11%	2	
DG		19.21%	Accept 23.15% on E	1	
PV	0%	11.33%	Reject 10.25% on E<12%	-	First step:(WT,DG)=37.88% Decision: Choose WT
WT		21.62%	Accept 27.39%on E>11%	2	
DG		19.09%	Accept 22.27% on E	1	
PV	2.5%	11.31%	Reject 10.23% on E<12%	-	(WT, DG)=38.42%>14% Decision: Choose WT
WT		21.59%	Accept 27.32% on E>11%	2	
DG		18.97%	Accept 21.43% on E	1	
PV	5%	11.30%	Reject 10.22% on E<12%	-	(WT, DG)=38.96%>14% Decision: Choose WT
WT		21.56%	Accept 27.25% on E>11%	2	
DG		18.85%	Accept 20.65 % on E	1	
PV	10%	11.27%	Reject 10.18% on E<12%	-	(WT, DG)=40.03%>14% Decision: Choose WT
WT		21.50%	Accept 27.11% on E>11%	2	
DG		18.60%	Accept 19.17% on E	1	
PV	15%	11.25%	Reject 10.15% on E<12%	-	(WT, DG)=41.10%>14% Decision: Choose WT
WT		21.43%	Accept 26.98%on E>11%	2	
DG		18.35%	Accept 17.92% on E	1	
PV	20%	11.22%	Reject 10.12% on E<12%	-	(WT, DG)=42.16%>14% Decision: Choose WT
WT		21.37%	Accept 26.84% on E>11%	2	
DG		18.11%	Accept 16.71% on E	1	

Table 5.8: Effect of diesel fuel price variation on IRR and investment decision

Price variation	Equity IRR	Capital IRR	Diesel generator project order based on capital cost	ΔIRR	Decision
-5%	22.78%	23.48%	1	Cannot be found	Follow $\frac{\Delta B}{\Delta C}$ technique
-2.5%	22.52%	21.32%	1	23.82%	WT
0	22.27%	19.09%	1	37.88%	WT
2.5%	22.01%	16.76%	1	51.22%	WT
5%	21.75%	14.18%	1	68.35%	WT

5.1.8 Incremental Benefit to Cost Ratio Technique for Diesel Price Sensitivity Analysis

When the selection of the best project for an investment from the economic perspective cannot be made by applying the incremental rate of return analysis, one of the following two techniques can be applied. The first technique is to apply a modified incremental rate of return analysis as discussed by the authors in [81]; while the second technique is to apply an incremental benefit to cost ratio technique that the authors explain in [81] and is also available in [106, 107]. It has been decided here to apply the second technique. This decison is because the first technique necessitates knowledge of the investment return that is not readily available. When diesel price is to reduce by 5%, the incremental benefit to cost ratio is applied to choose the best project for an investment comparing the possible alternatives that are the wind turbine project and diesel generator project. The technique is based on recognizing the project options and after that ranking the projects in an ascending order according to the denominator of the equation below:

$$B/C\ ratio = \frac{present\ worth\ of\ Benifits}{present\ worth\ of\ Costs} \quad \textbf{(5-14)}$$

The present worth of costs of the wind turbine project is INR 38608237.50 when considering the project cash flow. On the other hand, the present worth of costs considering the diesel generator project cash flow is INR 33340310.19. Alternatively, the present worth of benefits of the wind turbine project cash flow is INR 61612644.60; while the present worth of benefits of the diesel generator project cash flow is INR 59084442.53. B/C ratio of the diesel generator project is determined to be 1.77; while it is found to be 1.60 for the wind turbine project.

If the B/C ratio is found to have a value of less than one for any of the available project options, then the alternative is to be disregarded; otherwise the alternatives are to be ranked in an ascending order as given below:

The project option that has the lowest denominator is given a pre-decision of “Do Nothing”; while the other alternative is recognized to be “Option U” where U is the order given to the option based on the present worth of costs. In the case under study, both the wind turbine and diesel generator projects have B/C ratios that are greater than 1 and accordingly involved in the forthcoming analysis. The diesel generator project has a lower present worth of costs compared to the wind turbine project and consequently it is given the pre-decision of “Do Nothing”.

The next phase of the technique is to distinguish the increment under deliberation that is moving from the “Do Nothing” project to the “option 1” project. In the case under study, the increment is to move from the diesel generator project to the wind turbine project as shown by the notation below:

$$Do\ Nothing \longrightarrow Option\ 1 \quad \textbf{(5-15)}$$

The B/C ratio is to be calculated utilizing the incremental cash flows such that the difference between cash flows of the project is found. In other words, the two basic elements that should be estimated are ΔB and ΔC .

These values can be attained after translating the notation in (5-14) into a difference in cash flows as given below:

$$Do\ Nothing \longrightarrow Option\ 1 = Cash(n)_{Option\ 1} - Cash(n)_{Do\ Nothing} \quad \textbf{(5-16)}$$

ΔB and ΔC can be computed for the above difference in cash flows applying the equations below where *Fb* is future benefit in the above equation, *Fc* is future cost in the above equation and *MARR* is the determined MARR (14%).

$$\Delta B = \sum \frac{Fb(\underline{n})}{(MARR+1)^{\underline{n}}} \quad \textbf{(5-17)}$$

$$\Delta C = \left| \sum \frac{Fc(\underline{n})}{(MARR+1)^{\underline{n}}} \right| \quad \textbf{(5-18)}$$

ΔB is found to be INR 2648409.96; while ΔC is found to be INR 5388135.20. The incremental B/C is utilized to decide on the project to be selected for an investment. Such increment is found to be 0.49. Because this value is found to be less than one, the wind turbine project is rejected and the project recognized as “Do Nothing” is chosen. From this result, it can be concluded that the diesel generator project is the project to be considered for an investment. The method described above is summarized in Figure 5.7. It can be concluded from this analysis that the 1MW diese project will be preferred over the 1MW wind project when only the diesel fuel is to reduce by 5%. Otherwise, the 1MW wind turbine maintains to be the best project for an investment from an economic perspective.

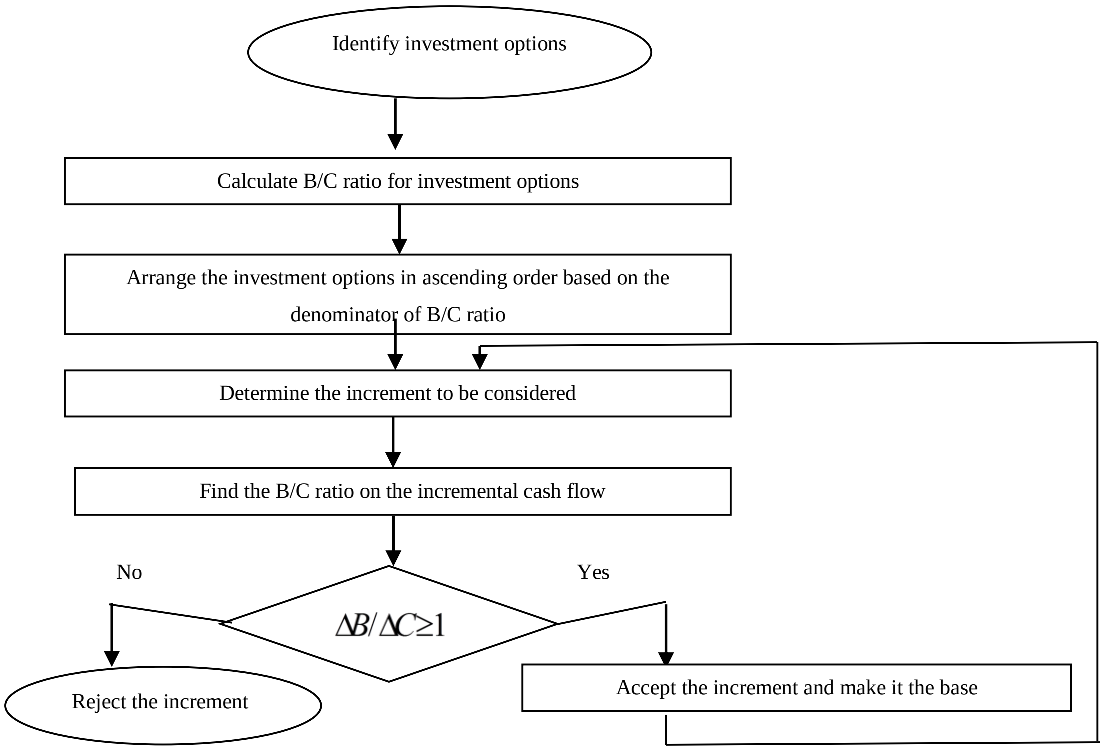


Figure 5.7: Incremental benefit to cost ratio technique

5.2 Comparison of Project Economic Analysis with the Analysis in Literature

Some projects calculate the internal rate of return based on the total cost of the project that includes the costs of debt and equity as in [108] such that the economic analysis applied on the project cash flow is called project cash flow analysis as applied in the previous sections of this chapter; while other projects calculate the internal rate of return considering the cost of equity as in [29, 109] when the investors' rate of return for the available fund is more concerned. Such a cash flow is called a private cash flow as indicated in [93] and has been applied in the previous sections to determine the internal rate of return based on equity.

A different definition of the project internal rate of return has been declared by [93] where the individual projects' cash flows represent the difference between yearly revenues and expenses accounting for the project capital cost and excluding the depreciation, the taxes, the debt repayment and the interests. Table 5.9 provides an emphasis on how such consideration of the project cash flow based on the definition in [93] will affect the selection of the most economic project for an investment considering incremental rate of return analysis. It can be seen from this table that the variation in the capital cost of project or operation and maintenance cost within $\pm$20% will still maintain the wind renewable energy project to be the best project for an investment from an economic perspective. Moreover, the effect of the variation in the diesel price for the diesel generator project on the decision to select the best project for an investment has been investigated based on the definition in [93] as shown in Table 5.10. In this case, the benefit to cost ratio is performed to determine the incremental internal rate of return when the fuel cost is reduced by 5%. The ratio was determined to be 0.4 leaving the "do nothing" project with the lowest present worth of costs that is the diesel generator project as the best project to be considered for an investment.

Table 5.9: The effect of project cash flow definition in [93] on selecting the most economic project for an investment

Type of project	Capital Cost variation	Project IRR	ΔIRR and decision	O&M cost variation	IRR on capital	ΔIRR and decision
PV		16.00%	First step:(WT:DG)=61.87%		13.23%	(WT,DG)=43.78%>14%
WT	-20%	31.73%	Second step:(WT,PV)=10.68%<14%		26.64%	Decision: Choose WT
DG		27.28%	Decision: Choose WT	-20%	24.08%	
PV		15.17%	First step: (WT:DG)=58.43%		13.20%	(WT,DG)=45.37%>14%
WT		30.13%	Second step:	-15%	26.55%	Decision: Choose WT
DG	-15%	25.96%	(WT,PV)= 10.04%<14% Decision: Choose WT		23.75%	
PV		14.42%	First step: (WT,DG)=55.37%		13.17%	(WT,DG)=46.97%>14%
WT		28.71%	Decision: Choose WT		26.46%	Decision: Choose WT
DG	-10%	24.78%		-10%	23.41%	
PV		13.74%	(WT,DG)=52.63%	-5%	13.14%	(WT,DG)=32.04%>14%
WT	-5%	27.43%	Decision: Choose WT		26.37%	Decision: Choose WT
DG		23.71%			23.07%	
PV		13.42%	(WT,DG)=62.48%		13.12%	(WT, DG)
WT	-2.5%	27.43%	Decision: Choose WT		26.32%	=49.36%>14%
DG		23.21%		-2.5%	22.91%	Decision: Choose WT
PV		13.11%	(WT,DG)=50.16%		13.11%	
WT	0%	26.28%	Decision: Choose WT	0%	26.28%	(WT,DG)=50.16%>14%
DG		22.74%			22.74%	Decision: Choose WT
PV		12.81%	(WT,DG)=49.02%		13.09%	
WT		25.74%	Decision: Choose wind		26.23%	(WT,DG)=50.96%>14%
DG	2.5%	22.29%		2.5%	22.57%	Decision: Choose WT
PV		12.53%	(WT,DG)=47.93%		13.08%	(WT,DG)=51.76%>14%
WT		25.22%	Decision: Choose WT		26.19%	Decision: Choose WT
DG	5%	21.85%		5%	22.40%	
PV		11.99%	(WT,DG)=45.90%		13.05%	(WT,DG)=53.36%>14%
WT		24.26%	Decision: Choose WT		26.10%	Decision: Choose WT
DG	10%	21.04%		10%	22.07%	
PV		11.49%	(WT,DG)=44.04%		13.02%	(WT,DG)=54.96%>14%
WT	15%	23.37%	Decision: Choose WT	15%	26.00%	Decision: Choose WT
DG		20.29%			21.74%	
PV		11.03%	(WT,DG)=42.34%	20%	12.99%	(WT,DG)=56.56%>14%
WT	20%	22.56%	Decision: Choose WT		25.91%	Decision: Choose WT
DG		19.60%			21.40%	

Table 5.10: Diesel price variation effect on IRR and investment decision based on project cash flow definition in [93]

Price variation	Capital IRR	Diesel generator project order based on capital cost	$\triangle IRR$	Decision
-5%	28.73%	1	Cannot be found	Follow $\frac{\Delta B}{\Delta C}$ technique
-2.5%	25.75%	1	30.07%	WT
0	22.74%	1	50.16%	WT
2.5%	19.66%	1	69.45%	WT
5%	16.49%	1	88.52%	WT

The components of project cash flow have been dealt with differently in the literature. The effect of such differences on the analysis of the project incremental cash flow has been investigated as will be summarized in the following points:

1. [29, 80] consider the feasibility study cost as a component of the project cost based on which project equity cost is determined as well as equity internal rate of return. On the other hand, the authors in [81] define this cost to be a sunk cost. Sunk costs are not to be included in the project cash flow as such costs are considered to be paid before financing the project. This cost has been excluded in the analysis considered in this chapter.
2. [80] defines the project depreciation tax basis as the percentage to be depreciated from the capital cost of the project over the life time of the project under both the straight line and the declining balance depreciations. For example [29] uses the concept in [80] and applies 90% as the depreciation tax basis. The remaining 10% is considered as expenses incurred at year zero. Taxes are applied on year zero as the tax rate multiplied by the difference between the incentives and grants and the 10% already depreciated cost at this year. The results determined according to this are shown in Table 9.11 for different depreciation types. The effect of such consideration on the project IRR calculated for cash flows accounting for the capital cost of project, the interest paid, the depreciation and the liable taxes is shown in the table below. It can be seen from the table below, that the wind turbine project continues to be the most economic project for an investment compared to the other projects under such consideration.

Table 5.11: Incremental IRR and Decision under the definition of project depreciation tax basis in [29] compared to MACRS depreciation

Depreciation	Project	Wind turbine	PV	Diesel generator	Incremental IRR and decision
MACRS	IRR (%)	22.00%	11.48%	19.35%	(WT, DG) =39.80%. Choose wind
Declining balance	IRR (%)	23.30%	11.58%	20.20%	(WT, DG) =45.99%. Choose wind
Straight line	IRR (%)	21.62%	11.18%	19.01%	(WT, DG) =38.99%. Choose wind
Depreciation	**Equity**	**Wind turbine**	**PV**	**Diesel generator**	**Rejected project based on equity IRR**
MACRS	IRR (%)	28.50%	10.30%	22.85%	Reject PV
Declining balance	IRR (%)	32.05%	10.58%	24.65%	Reject PV
Straight line	IRR (%)	27.55%	10.07%	22.16%	Reject PV

3. On the other hand, the depreciation tax basis is determined to be the amount that is to be deducted from the net cash flow of the project for tax basis and this amount will represent 90% of the project capital cost. After applying depreciation to the project cash flow, this amount when sum over the project duration to which the depreciation is applied should represent 90% of the project. The remaining 10% is not to be incurred at year zero as the 10% represents scrap or what is called salvage value according to [110]. The salvage value of the project is considered to be an income that [29, 80] did not account for assuming the book value to be fully depreciating at the end life of the project. This concept has been also clarified in [81, 82]. In Table 5.12, it is shown how this concept will affect the internal rate of return of the project. It is important to emphasize that MACRS is based on the zero salvage value in the last year of depreciation. Thus, 100% depreciation is only applied in the case of MACRS. Moreover, the salvage value is assumed to be equivalent to the book value. The tax applied on the difference between the two values is zero. The salvage value is to be added to the after tax cash flow at year 25. This consideration is based on the concept of gain tax in [111, 112]. When considering declining balance based on the concept of depreciation discussed in [29, 80] in which depreciation rate is applied to every year except the last year and considering the concept of 90% depreciation in [82, 110], the depreciationr rate will be carried out until year 6 and the amount of depreciation at year 7 is determined such that the sum of depreciation from year 1 to 6 represents 90% of the project cost. For subsequent years, the depreciation will be zero and the book value will maintain its value until year 25. This consideration is based on [81].

Table 5.12: Incremental IRR and decision under the above definition of project depreciation and salvage value compared to MACRS depreciation

Depreciation	Project	Wind turbine	PV	Diesel generator	Incremental IRR and decision
MACRS	IRR (%)	21.62%	11.33%	19.09%	(WT, DG) =37.88%. Choose wind
Declining balance	IRR (%)	23.19%	11.55%	20.09%	(WT, DG) =45.88%. Choose wind
Straight line	IRR (%)	21.10%	11.08%	18.60%	(WT, DG) =37.27%. Choose wind
Depreciation	**Equity**	**Wind turbine**	**PV**	**Diesel generator**	**Rejected project based on equity IRR**
MACRS	IRR (%)	27.39%	10.25%	22.27%	Reject PV
Declining balance	IRR (%)	31.80%	10.54%	24.44%	Reject PV
Straight line	IRR (%)	26.18%	9.95%	21.30%	Reject PV

4. When applying the taxation system in [29, 80], the depreciation has been accounted for, but the 50% rule for depreciation that is discussed in [113] has not been applied. This rule shows the amount to be considered for depreciation if expenses are encountered at year zero. Otherwise, if profit is gained, then the total amount of the project is to be considered for depreciation. The effect of such consideration is applied on the three types of depreciation as shown in Table 5.13.

Table 5.13: Incremental IRR and decision under the definition of project depreciation accounting for the 50% rule for depreciation

Depreciation	Project	Wind turbine	PV	Diesel generator	Incremental IRR and decision
MACRS	IRR (%)	20.79%	10.62%	18.27%	(WT, DG) =36.98%. Choose wind
Declining balance	IRR (%)	21.02%	11.58%	20.18%	(WT, DG) =28.23% Choose wind
Straight line	IRR (%)	20.59%	10.49%	18.08%	(WT, DG) =36.74%. Choose wind
Depreciation	**Equity**	**Wind turbine**	**PV**	**Diesel generator**	**Rejected project based on equity IRR**
MACRS	IRR (%)	25.57%	9.32%	20.75%	Reject PV
Declining balance	IRR (%)	31.95%	10.57%	24.61%	Reject PV
Straight line	IRR (%)	25.12%	9.16%	20.39%	Reject PV

5. It is important to emphasize that the declining balance depreciation rate defined in [29, 80] is set based on the project policy but there is a special class called the 150% declining balance depreciation that will be considered here to be compared with the MACRS depreciation. The main reason behind selecting the 150% declining balance depreciation for comparison with the MACRS is that it is known in the literature that MACRS provides larger deductions for tax purposes. Thus, if the declining balance depreciation is chosen for comparison purposes, the rate of the depreciation of declining balance should be specified carefully such that it does not interfere with the MACRS deductions. In other words, the declining balance at a specific rate can be more effective as the rate can be selected based on policy. Thus, for comparison purposes, a base line should be indicated based on which the comparison can be carried out. In this case, the base line will be what in the literature is well known to be the 150% decline

balance depreciation. [114] shows the declining balance approach to be compared with MACRS and the straight line depreciation when considering project cash flow. It indicates that the declining balance depreciation percentage should follow that of MACRS based on the property class. Since the projects under consideration belong to the 20 years property class, the rate of the declining balance depreciation should be 150% and the number of years to be considered is 25 years; however, the amount of depreciation (*DB*) should be carried out until year 21 as with MACRS. On the other hand, the straight line depreciation will continue until year 25. The effect of such depreciations on project cash flow is summarized in Table 5.14. The equation below is used to determine the amount of depreciation per year where *Book* is the book value of the project that is set to be the project cost at year zero according to the authors in [81] and *lk* is the year in which the depreciation amount is deducted. In this case, the salvage value is assumed to be the book value at year 25, and therefore no taxes will be paid in year 25 on the difference between the salvage and the book values, but the salvage value will be added as profit to the after tax cash flow at year 25 when considering the 150% declining balance depreciation.

$$DB_{\underline{n}} = \begin{cases} 1.5/25\,years \;\; (Book - \sum_{lk=1}^{n} DB_{lk}) & \forall 0 < \underline{n} \le 21 \end{cases} \qquad \textbf{(5-19)}$$

Table 5.14: Incremental IRR and decision under the above definition of project depreciation and salvage value

Depreciation	Project	Wind turbine	PV	Diesel generator	Incremental IRR and decision
MACRS	IRR (%)	21.62%	11.33%	19.09%	(WT, DG) =37.88%. Choose wind
Declining balance	IRR (%)	21.47%	11.27%	19.19%	(WT, DG) =35.76%. Choose wind
Straight line	IRR (%)	20.92%	11.02%	18.52%	(WT, DG) =36.25%. Choose wind
Depreciation	**Equity**	**Wind turbine**	**PV**	**Diesel generator**	**Rejected project based on equity IRR**
MACRS	IRR (%)	27.39%	10.25%	22.27%	Reject PV
Declining balance	IRR (%)	27.09%	10.22%	22.50%	Reject PV
Straight line	IRR (%)	25.75%	9.91%	21.15%	Reject PV

6. The authors in [81] consider the depreciation to be carried out until the undepreciated amount of the capital cost of the project is equal to the salvage value. Thus, the 150% declining balance depreciation is carried out until year 25. The undepreciated amount known as the book value is assumed to be equal to the salvage value. Such an assumption is accounted for when considering the straight line depreciation too. The effect of such a consideration on the incremental IRR is shown in Table 5.15.

Table 5.15: Incremental IRR and decision under the above definition of project depreciation and salvage value

Depreciation	Project	Wind turbine	PV	Diesel generator	Incremental IRR and decision
MACRS	IRR (%)	21.62%	11.33%	19.09%	(WT, DG) =37.88%. Choose wind
Declining balance	IRR (%)	21.47%	11.25%	19.19%	(WT, DG) =35.76%. Choose wind
Straight line	IRR (%)	20.98%	11.04%	18.57%	(WT, DG) =36.41%. Choose wind
Depreciation	**Equity**	**Wind turbine**	**PV**	**Diesel generator**	**Rejected project based on equity IRR**
MACRS	IRR (%)	27.39%	10.25%	22.27%	Reject PV
Declining balance	IRR (%)	27.09%	10.18%	22.49%	Reject PV
Straight line	IRR (%)	25.90%	9.93%	21.25%	Reject PV

It can be seen from the above comparisons that the wind turbine project will remain to be the most economic project for an investment.

5.3 Section Summary

The incremental rate of return analysis had been applied to decide which project was the most economic project to be considered by an investor comparing different electricity generation sources in developing countries. This type of analysis was based on finding the difference between cash flows of individual project options for an investment. This study has been considered in this chapter to search for the best economic alternative energy source that could be utilized to reduce the severity of the power generation shortage restricting the distribution system’s expansion to include new non electrified regions due to population growth. The incremental internal rate of return was compared to a minimum accepted rate of return to decide among possible project options for an investment in the power sector. The minimum accepted rate of return was calculated considering the cost of capital, the cost of borrowed money and the opportunity cost after eliminating rejected projects. The rejected projects were eliminated by comparing their calculated equity internal rate of returns to the minimum equity accepted rate of return available in the literature for the same category of projects. The equity internal rate of return was determined accounting for project depreciation for tax purposes utilizing the modified accelerated cost recovery system as a depreciation method. The determined internal rate of return of the projects was compared to its value under the historical depreciation methods.

Furthermore, the project internal rate of return of individual projects had been calculated based on the capital cost of the project. It had been found from the incremental rate of return analysis that the wind turbine project is the best choice for electricity generation in the distribution system given the data used in this work. Moreover, this work presented a sensitivity analysis to study the effect of the variations in either the capital cost of the project or the total operation and maintenance cost of individual projects on the decision to select the best project among available options for an investment. Moreover, an incremental rate of return sensitivity analysis to investigate the effect of the variation in the cost of diesel fuel had been considered to see the impact of such variation on the selection of the best project for an investment from an economic aspect. When it was not possible to calculate the incremental internal rate of return using the traditional method, evaluating the incremental benefit to cost ratio was an alternative.

There were different approaches in the literature to deal with individual projects' cash flows. The effect of such approaches in estimating the incremental internal rate of return had been investigated in this chapter. In conclusion, the wind turbine project remained to be the most economic project for an investment when considering different economic analyses approaches shown in this chapter for the size of the project under study.

5.4 The Role of Regulation in the Economic Evaluation of Renewable Energy Investments in Developing Countries

Developing countries' regulations play a significant role in expediting the investments in the renewable energy field [78]. This role can be critical in countries where the power generation is in shortage affecting the economic growth of the country and the quality of life of individuals in these countries. The regulations placed on the project fund structure can be a main reason behind the limited investments dedicating renewable energy sources to address the power generation shortage in these countries. This limitation is because policy reforms are not considered at an early stage to accommodate population growth. Thus, necessitating the demand to investigate the role of the policy currently applied in a selected developing country toward renewable energy projects. The most economic project is to be selected among possible renewable energy projects whose cash flows are evaluated subject to the developing country policy as will be discussed in this section. After that, a guided procedure to update the current policy to encourage investors toward more renewable energy projects to accommodate population growth will be applied on the selected most economic renewable energy project as will be further explained in section 5.5.

5.4.1 Possible Renewable Energy projects and Policy Nature Regulating Project Fund

Policy plays an important role on setting the renewable energy project fund structure. A policy is made of a set of regulations applied on such projects. These regulations provide an emphasis on the life time of the project, its capital, operation and associated maintenance costs. Furthermore, the regulations specify certain rates needed to be considered when structuring the cash flow of a project. Such rates include the escalation rate of the operation and maintenance cost and the depreciation rate over the life time of the project. Moreover, the regulations also account for the interest rates and taxes applied on the project fund. This factor is examined by classifying the interests into interest on the term loan and interest on the working capital and classifying the tax into the tax on net income, minimum alternate tax, value added tax and carbon credit tax.

India, an example of a developing country where power generation shortage is an issue, is a good example to dedicate renewable energy projects to solve such a power shortage. Solar energy, wind energy and hydro power are widely available in India. The availability of such resources can motivate the investors toward such projects, but the current policy can challenge the investor in selecting the best renewable energy project among these resources for an investment. This section will focus on selecting the most economic renewable energy project for an investment considering the incremental rate of return analysis subject to India's current policy such that this resource can be utilized to address the power generation shortage bearing in mind the demand scheduling in a developing country.

5.4.2 Types of Projects under Economic Evaluation Subject to Regulation

The renewable energy projects to be examined in the economic evaluation of the possible investment options in a developing country are the solar PV project, wind turbine project and hydro power project. This examination is considered to select the best renewable energy project for an investment accounting for the current policy placed on the project fund structure. These projects can be sponsored by both bank loans and promoters' contributions [78]. According to [82], bank loans signify 70% of the capital cost of the project and is recognized as a debt at an interest rate of 13%; whereas the financial aid by promoters is 30% of the capital cost of the project and is recognized as an equity of 30% [82].

The size of the projects examined in the study is three megawatts [78]. The solar PV and wind projects are recognized to have a life time of 25 years [82]. On the other hand, the hydro power project is recognized to have a life time of 35 years [82]. With the purpose of economically selecting the best project for an investment by applying the incremental rate of return analysis, the projects are to be assessed at the common life time that is 25 years under the assumption that the hydro power project is to be sold at this life time through an estimation of the present value of its salvage value at this year [78].

5.4.2.1 Regulation on Projects' Costs

The costs associated with the projects can be categorized into fixed costs and variable costs. The first category of costs comprises the capital cost of the project that is specified as the cost at year zero. Such a cost is to be known before the initial commercial operation of the project. The second category of costs comprises the operation and maintenance costs to undergo an escalation rate over the life time of the project of 5.72% [82]. These costs are determined according to [82] after an elevation to 3MW projects as indicated in Table 5.16. The projects are ordered ascendingly in correspondence to their capital costs. The economic analysis will be presented in Indian Rupees as India is selected to evaluate its available renewable energy sources economically. A rebate of a percentage of 2% in [95] will be accounted for by applying it on the project capital cost presented in Table 5.9 at year zero. The operation and maintenance variable costs of the studied renewable energy projects over the life time of such projects are plotted in Figure 5.8 [78]. The maintenance spares of the projects form 15% of these costs based on [82].

Table 5.16: Capital costs of studied projects for an investment to address the PGS [78]

Type of Project	3MW solar PV project	3MW wind turbine project	3MW hydro power project
Capital cost of the project (INR)	240,000,000	179,315,400	240,126,600
Project Order	2	1	3

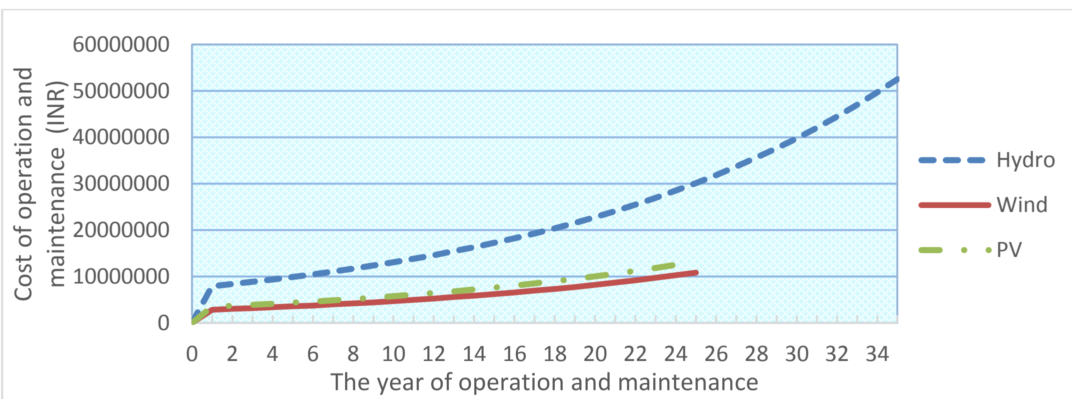


Figure 5.8: Yearly operation and maintenance costs to be encountered over the life of projects [78]

It is important to clarify that such costs are considered as regulations to find the electricity tariff for the energy produced from the renewable energy projects in [82] and targeted here [78] as rules to be tracked to find the best project for an investment in India that is an example of a developing country where a power generation shortage problem exists.

5.4.2.2 Term Duration Regulation for Loan repayment

Loan repayment is categorized into annual repayments as well as yearly interest repayments. Their sum forms a fixed repayment and is given by equation (5-1) [81]. The repayment duration is considered to be the first 12 years beginning from the year during which the projects operate commercially [78]. Such values are considered based on the regulations used to determine the electricity tariff for energy produced from the renewable energy sources in [82].

5.4.2.3 Interests regulations on Project

There are two types of interest applied on the project. The first type is the interest on debt and that represents the percentage the debtor is to pay to the bank; while the second type is the interest on the working capital [78].

The interest on debt that is 13% [82] is not essentially made in the same amount yearly and its value has been determined for different types of the projects as shown in Figure 5.9. The interest amount accounts for the annual interest rate, year number in which the repayment is to be made, the loan repayment period and the loan amount [90]. It can be noticed from the figure below that both the solar PV and hydro power projects are very close in terms of what the paid project loan's interest is to be [78].

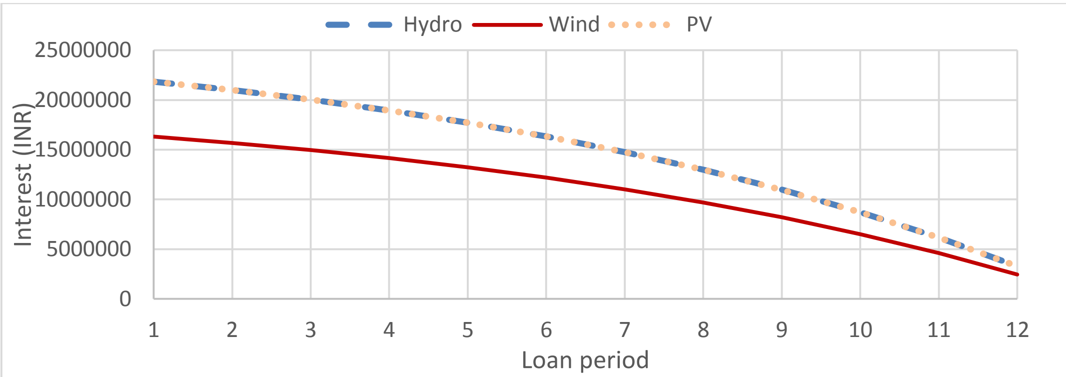


Figure 5.9: Debt interest to be made on projects' loan over the repayment period [78]

On the other hand, the interest on working capital is 13.5% [82], and in the current analysis, this value has been applied to the operation and maintenance cost [78].

5.4.2.4 Project Depreciation Regulation

Project depreciation represents the decay in the market value of the project cost [115]. Project depreciation is set for tax reasons such that less amount is paid as taxes. In [82], a maximum of 90% of the project capital cost is set to be depreciated. This percentage is utilized considering an accelerated straight line depreciation [82] to find the cash flow of the project such that incremental rate of return analysis on different projects' cash flows can be applied in this chapter. Furthermore, 5.83% is considered as the depreciation rate from the starting year of the projects' operation commercially until the twelfth year and after that 1.54% is considered to be the depreciation rate for the solar PV and wind turbine projects; however, a 0.87% depreciation rate is applied on the hydro power project starting from the thirteenth year [82]. This application is because the hydro power project will live for another 10 years. This application can be further clarified as follows: a 1.54% depreciation rate set for the PV and wind projects if multiplied by the number of corresponding remaining years that is 13 years it will give a value that is almost equal to multiplying 0.87% by the remaining 23 years of the hydro power project. It is important to clarify that, since the present value of the salvage value of the hydro power project to be determined at year 25 such that all projects under analysis can be compared for the same useful life, the 0.87% depreciation rate is followed rather than changing it to 1.54%. This application is because the hydro power project is presumed to be traded at the end of year 25 and will carry on depreciating over its remaining life time with the new owner of the investment [78].

5.4.2.5 Regulation on Carbon Credits for Renewable Energy Projects

Approximate values of how many tons of carbon dioxide a renewable energy project can reduce are available in literature for different projects such as the wind project [116], the solar PV project [117] and the hydro power project [118]. From the scientific point of view, such an emission reduction can be calculated and credited when considering such projects [78]. Carbon credits can be estimated from the yearly reduction in carbon dioxide since every carbon credit is assigned for one ton reduction of carbon dioxide [78, 119].

The annual reduction in carbon dioxide emission (*Redu*) associated with considering a renewable energy project can be estimated in tons as given by the following equation [78, 120]:

$$\mathrm{Re}du = Base - MO \tag{5-20}$$

where *Base* is the annual base line emissions (tons) and *MO* is the expected carbon dioxide emission of the project (tons). These can be determined according to [78, 120] as given below:

$$Base = EK \ . \ \frac{(BMN + OMI)}{2} \quad \textbf{(5-21)}$$

$$MO = EK \ . \ \underline{EF} \quad \textbf{(5-22)}$$

where *BMN* is defined as the build margin of carbon dioxide emission (0.80tons/MWh)[78, 121] , *OMI* is the operating margin of carbon dioxide emission (0.98tons/MWh)[121], *EF* is the emission factor set to zero (tons/MWh) for the considered renewable energy projects and *EK* is the expected annual electricity production of the project (MWh) as given below [78]:

$$EK = CUF \ . \ HR \ . \ \underline{Rating} \quad \textbf{(5-23)}$$

where *CUF* is the capacity utilization factor of renewable energy projects in [78, 82] that is 19% for the solar PV plant, 20% for the wind turbine plant and 45% for the hydro power plant, *HR* is the number of hours per year and that is 8760 hours and *Rating* is the three megawatt rating of the renewable energy source [78].

5.4.2.6 Regulation on Project Salvage Value

The salvage value of the project represents almost 10% of the capital cost of the project as indicated in [78, 82]. This value is considered to be an income gained at the termination of the project due to the spanned life time that is 25 years for the solar PV and the wind turbine projects; while it is 35 years for the hydro power project [78].

In order to compare the renewable energy projects economically to select the best project option for an investment, the projects under study are to have a common life over which the incremental rate of return analysis on cash flow is to be performed [78]. Because of this condition, the chosen era is the life time span of the first two projects. Because the hydro power project has an extended life, the salvage value of this project at the end of year 35 has been moved regressively to the end of year 25 through calculating its present worth value at this year by applying the equation below [78] where *Salvage* is the salvage value of the hydro power project and *cc* is the cost of capital defined in [122, 123] to be the value 10.95% in [78, 82].

$$Salvage(year\#25) = \frac{Salvag(year\#35)}{(1+cc)^{10years}} \quad \textbf{(5-24)}$$

5.4.2.7 Regulations on Project Taxes

There are four types of taxes applied on the projects under study. These are the minimum alternate tax (MAT), the tax on net income (IT), the value added tax (VAT) and the gain/loss tax (GLT). The minimum alternate tax is applied on the project as an alternative to the tax on the net income throughout the years where the project undergoes tax holidays and during which IT is not paid due to the loan repayment period [78]. The minimum alternate tax is given one of two values according to the book profit value. The value given is 20.00775% when the book profit value is found to be more than INR 10,000,000; while it is given a value of 19.055% when the book profit value is found to be less than INR 10,000,000 [124]. The book profit value can be calculated as shown below [78] where *book* $(\underline{n})$ is the book value of the renewable energy project determined at year $\underline{n}$, *cost basis* is the cost of the project and any costs needed to make the project ready to operate and *dep* $(\underline{n})$ is the depreciation at that corresponding year $\underline{n}$.

$$book(\underline{n}) = Cost\ basis - \sum_{\underline{n}=0}^{\underline{n}} dep(\underline{n}) \qquad \textbf{(5-25)}$$

IT will be paid after the debt repayment period is complete (after twelve years). The value added tax is applied on any benefit gained from selling carbon credits. The Gain/loss tax represents the amount of money gained or paid based on the tax rate applied on the difference between the salvage and book values of the project. This type of tax is applied on the last year of the commercial operation of the project as indicated in [111].

5.4.3 Incremental Rate of Return Analysis Subject to A Developing Country's Policy on Projects' Funding and Implementation

The incremental rate of return analysis method summarized in Figure 5.5 is applied in this chapter. This method is applied in order to find the most economic project among the PV, the wind turbine and the hydro power projects for an investment in a developing country subject to the government policy on the project funding and implementation. The best project is to be selected from an economic perspective for the purpose of addressing the power generation shortage in such a country. Given the three megawatt projects under study, the incremental rate of return analysis requires a determined minimum accepted rate of return of 13% [78] based on the approach discussed in Section 5.1.6.

The incremental cash flow can be determined as indicated by the equation below where *Difference (n)* is the difference between different projects' cash flows at year *n*, *a* and *b* are project indicators such that *a* is higher in cost than project *b* and *Cash* is the calculated after tax project cash flow.

$$Difference(\underline{n}) = Cash_a(\underline{n}) - Cash_b(\underline{n}) \qquad \textbf{(5-26)}$$

The after tax cash flow shown below is the result of applying the regulations governing project funding and implementation. The applications of such regulations on projects' cash flows can be summarized by equations (5-27) to (5-34).

$$Cash(\underline{n}) = \begin{cases} Capital - rebate * Capital & \forall \underline{n} = 0 \\ \underline{P}(\underline{n}) - Tax(\underline{n}) + Carbon(\underline{n}) & \forall 0 < \underline{n} < L \\ \underline{P}(\underline{n}) - Tax(\underline{n}) + Carbon(\underline{n}) + salvage & \forall \underline{n} = L \end{cases}$$

(5-27), (5-28) & (5-29)

$$\underline{P}(\underline{n}) = K \;.\; CUF \;.\; HR \;.\; \underline{Rating} \;\; -(OM(\underline{n}) + OMS(\underline{n})) \qquad \textbf{(5-30)}$$

$$\underline{Tax}(\underline{n}) = \begin{cases} MATRate(\underline{n}) \;\;.\;\; (\underline{P}(\underline{n}) - \underline{dep}(\underline{n}) - \text{int}\,erest(\underline{n}) - icapital\,(\underline{n})) & \forall \underline{n} \le Term\;\; Loan \\ ITRate(\underline{n}) \;\;.\;\; (\underline{P}(\underline{n}) - \underline{dep}(\underline{n}) - \text{int}\,erest(\underline{n}) - icapital\,(\underline{n})) & \forall \underline{n} > Term\;\; Loan \\ icarbon(\underline{n}) * carbon(\underline{n}) & \forall \underline{n} > 0 \\ GLTRate.(salvage(\underline{n}) - book(\underline{n})) & \forall \underline{n} = L \end{cases}$$

(5-31), (5-32), (5-33) & (5-34)

where *Capital* is the capital cost of the project, *rebate* is the rebate rate added to the project as a credit, *Carbon(n)* is the revenue from carbon credits (INR) determined at a current selling price of INR400/credit [125] and this price is assumed to be fixed over the life time of the project, *P(n)* is the pretax net cash flow of a project at year *n*, *Tax(n)* is the tax to be paid at year *n*, *K* is the determined tariff (INR/KWh) under regulations in [82], *OM* is the operation and maintenance cost, *OMS* is the cost of spares for maintenance, *MATRate* is the minimum alternate tax rate, *dep(n)* is the depreciation amount at year *n* of the project commercial operation (INR), *Interest* is the amount of interest paid on the loan, *icapital* is the interest paid on the working capital at a rate of 13.5% according to [82], *icarbon* is the value added tax rate to be applied on the revenue generated from the carbon credit and this rate is set as 4% based on [126], *ITRate* is the tax rate applied on the net income at year *n* and is specified by regulations to be 32.45% [82] and *GLTRate* is the gain/loss tax rate applied on any gain or loss from the project salvage value compared to its book value. In the current analysis, *GLTRate* is set to 32.45%.

When comparing the wind turbine project to the PV project, the incremental internal rate of return is found to be 14.31%. Since this value is greater than the minimum accepted rate of return, the increment is accepted, and the PV project is preferred over the wind turbine project.

After that, the PV project is to be compared with the hydro power project. In this case, the incremental internal rate of return is 5.01%. Since this value is less than the minimum accepted rate of return, the increment is rejected. Thus, the PV project remains to be the best project to be considered for an investment from the economic aspect subject to a government's policy on the project cash flow structure. Table 5.17 shows the final cash flows and the incremental cash flows of the project options.

Table 5.17: Alternative projects' cash flows and incremental cash flows

Project by order/year	0	1	2	3	4	5	6
1-Wind	-175729092.00	29853348.35	29580347.21	29282463.71	28957069.88	28601230.88	28211666.98
2-PV	-235200000.00	39571644.58	39223083.09	38842181.10	38425476.37	37969099.03	37468720.97
3-Hydro	-235324068.00	42874586.96	42254269.33	41633530.83	40963263.56	40238811.53	39455015.48
PV-wind	-59470908.00	9718296.23	9642735.87	9559717.39	9468406.49	9367868.15	9257053.99
Hydro-PV	-124068.00	3302942.37	3031186.24	2791349.73	2537787.18	2269712.50	1986294.51
Project by order/year	**7**	**8**	**9**	**10**	**11**	**12**	**13**
1-Wind	27784710.91	27316259.64	26801720.13	26235948.06	25613178.80	24926949.57	19750412.18
2-PV	36919498.88	36316009.97	35652179.50	34921199.09	34115434.50	33226321.70	26297259.56
3-Hydro	38606153.22	37685872.66	36687116.45	35602037.15	34421901.82	33136984.63	25648464.94
PV-wind	9134787.97	8999750.33	8850459.37	8685251.03	8502255.70	8299372.13	6546847.38
Hydro-PV	1686654.34	1369862.70	1034936.95	680838.06	306467.32	-89337.08	-648794.62
Project by order/year	**14**	**15**	**16**	**17**	**18**	**19**	**20**
1-Wind	19517228.58	19270706.88	19010084.14	18734553.78	18443263.09	18135310.56	17809743.15
2-PV	26012068.93	25710565.39	25391815.85	25054833.83	24698576.45	24321941.14	23923762.29
3-Hydro	25000348.99	24315160.81	23590779.87	22824964.34	22015344.15	21159413.70	20254524.02
PV-wind	6494840.35	6439858.51	6381731.70	6320280.05	6255313.36	6186630.58	6114019.14
Hydro-PV	-1011719.93	-1395404.58	-1801035.98	-2229869.50	-2683232.29	-3162527.44	-3669238.27
Project by order/year	**21**	**22**	**23**	**24**	**25**	**IRR and incremental IRR**	
1-Wind	17465553.29	17101675.76	16716984.44	16310288.78	33847733.20	14.83%	
2-PV	23502807.61	23057774.32	22587285.13	22089883.96	45612031.44	14.70%	
3-Hydro	19297874.65	18286504.94	17217284.88	16086905.43	35240302.40	15.45%	
PV-wind	6037254.32	5956098.56	5870300.69	5779595.18	11764298.24	14.31%	
Hydro-PV	-4204932.96	-4771269.39	-5370000.26	-6002978.53	-10371729.04	5.01%	

The hydro power project comes second among the compared projects since the incremental internal rate of return is 17.57% when it is compared to wind and the wind turbine project comes third among the evaluated projects.

5.4.4 Section Summary

This section was focused on economically evaluating alternative renewable energy projects whose resources are widely available in a selected developing country subject to the government regulation to be deployed to address the power generation shortage. The incremental rate of return analysis had been followed to select the most economic project for an investment subject to the policy governing project funding. Different renewable energy projects had been involved for this purpose. These are the PV, wind turbine and hydro power projects. The evaluation showed that the PV project was the best project to be considered for an investment under the government financial policy of a selected developing country. Even though section 5.3 showed that the wind turbine project was the best project to be considered for an investment when considering the general financial structure of a project, section 5.4 showed how a government's policy can affect the decision toward a renewable energy project making the PV project a better alternative.

Even though some PV projects are available in India for certain applications such as pumping [27], the policy reform is a main factor governing the utilization of such a renewable energy project to solve the power generation shortage. Policy reform is to be considered when the target is to consider more renewable energy projects to address the power generation shortage spreading across developing countries due to population growth. Policy reform is to be considered as the investors are governed by the current policy restricting expanding renewable energy projects with population growth due to limited income. This situation initiated the demand for a study that shows how to update the current policy to encourage the investors toward more PV projects. Therefore, the next section will be dedicated to show how to establish a policy that can encourage more investments toward renewable energy projects by guaranteeing the investors reasonable profits over the long run.

5.5 Guidelines for Encouraging Investment in Solar PV Energy Projects

Energy is crucial to civilization and economy progress. With developing countries' population growth, more energy resources are to be explored to meet the emergent electricity demand. Such resources' deployment is administrated by developing countries' policies. Despite the fact that the present policy applied in India, an example of a developing country where power generation shortage is a serious issue, sets PV projects at the top of renewable energy projects from an economic perspective as has been shown in the previous section; the application of such projects is limited to pumping, water heating,…etc due to the limited income of the investor subject to the policy governing the fund. Therefore, investors faced with limited income and current government policy are not capable of accommodating more renewable energy projects at a large scale to solve the power generation shortage. Policy reforms are to be given attention to facilitate the expansion of local renewable energy projects. The work in this section proposes a guided method for governance institutions to regulate funding requirements of renewable energy projects by concentrating on solar PV energy projects and to motivate local investors in the power sector. Many regulations governing funding renewable energy projects are practiced by governance institutions in developing countries. Examples on such regulations are the tax on net income regulation, the project term loan regulation and the renewable energy electricity tariff regulation.

A guided method that specifies what the appropriate combinations of such regulations is needed such that a motivating policy on project funding can be set for local investors toward more renewable energy projects and thus addressing the spread of the power generation shortage problem across the country due to population growth. The selection of such a combination depends on specifying weights for such regulations accounting for their importance on regulating project funding. Such weights can be determined by performing a sensitivity analysis on the variation of the internal rate of return of the project cash flow according to the variation in the regulation parameter under study. This section offers the governance institutions a guided method to develop a criterion function and to utilize an optimization technique to choose the weights and consequently, the best set of regulations to motivate more local investment in renewable energy projects over the long run.

5.5.1 Project Fund Regulations under Study

Developing countries' policies govern the investment in renewable energy projects. These policies can be broken down into a set of regulations. These regulations can include the project fund term loan, the tax rate placed on the project fund, the set tariff for electricity generated from solar power, the geographical location to build the project on, and how far the location is from the load centers, the percentage of the equipment manufactured locally from all the materials utilized in the project and others.

In this thesis, three regulations are studied: the term loan (TL), the income tax rate (IT) and the selling price (P) of electricity generated from the solar PV system. It is essential to emphasize that such a selection of regulations to be studied is to supply a simple example on how to use the proposed method for a policy reform. Such an example can be protracted to include all regulations that can govern the project implementation.

As has been shown in the previous section, the regulations placed on an Indian solar energy project were 12 years term loan, 32.45% tax rate on the net income and INR 8.75/kWh as the selling price of electricity generated from the solar PV system [78, 82]. The net present worth of the investment at this set of regulations is INR 23857321 and the corresponding internal rate of return is 14.70%. The net present worth value of the project was found based on the equation below where *npw* is the net present worth of the cash flow of the solar PV energy project, *Cash* is the after tax cash flow, *n* is the year number in which the cash flow is evaluated, *MARR* is the minimum accepted rate of return.

$$npw = \sum_{n=0}^{25} \frac{Cash(\underline{n})}{(MARR+1)^n} \tag{5-35}$$

The objective of this section is to reform a policy made of such defined regulations (term loan, income tax rate, selling price of electricity generated from solar PV system). The policy is to be reformed as a function of the present policy followed in a developing country. In this thesis, each of the regulations under study is categorized based on a pre-defined range of its value as shown in Table 5.18.

Table 5.18: Regulation categories

Income tax rate categories		Term loan categories		Price (INR/kWh) categories	
Low	<31%	Short	1-6 years	Low	<4.63
Medium	31%-36%	Intermediate	7-13 years	Intermediate	4.63-10.63
High	>36%	Long	>13years	High	>10.63

The policy in [78, 82] was set considering a medium income tax rate, an intermediate loan term and an intermediate tariff for electricity generated from the solar PV system. The ranges presented for such an arrangement can differ from one developing country to another.

In this thesis, these ranges have been specified assuming that there exists an n sample size data of each regulation under study and such data undergo heuristical arrangement. Such randomized data are to be input to a data management program targeting a policy reform as discussed next.

5.5.2 Data Management Program (DMP) for Policy Reform

The objective of the data management program is to choose a policy governing the project fund and implementation. The policy is to be made up of a set of regulations such that the most sensitive regulation is given more importance and therefore encouraging investors to expand their current renewable energy projects to accommodate population growth by guaranteeing them a satisfying net present worth.

The data management program will indicate to which category two regulations should belong given that one regulation category is specified by providing a data matrix. Each type of regulation designates a column in the data matrix holding a net present worth of the project as determined at every entry of the index array corresponding to a regulation number. This approach is carried out under the condition that two regulations are set at a reference point (the present policy regulations: 32.45% income tax rate, 12 years term loan and 8.75INR/kWh as PV electricity price) and one regulation is produced from the search executed by the data management program. The data management program searches for other possible regulation values to form a policy on the project fund. The search executed by the data management program depends on generating regulations' data from a normal distribution whose mean is at a reference point given that 99% of the data lay within three standard deviations (3σ) as described by Figure 5.10. The reference point is made up of the regulations at the present policy discussed in [78, 82] where the tax rate on net income, the term loan and the price of electricity generated from the solar PV system are in the medium ranges.

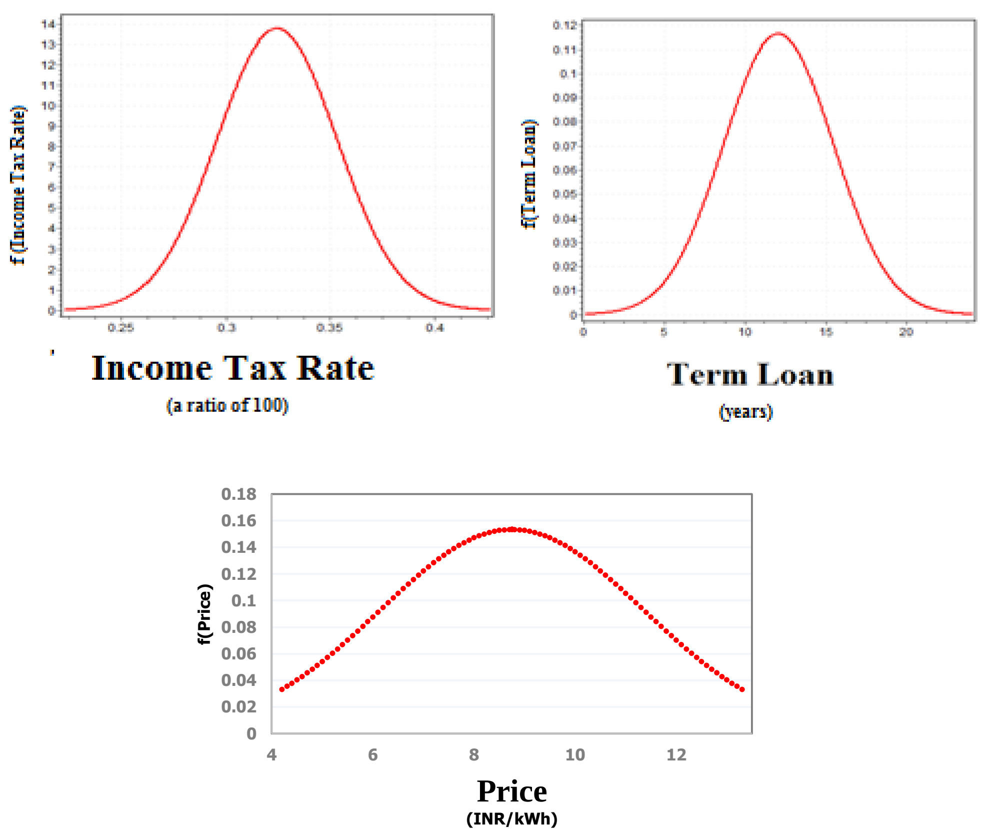


Figure 5.10: Normal probability density function describing the generated regulations data in a data management program

When all three columns are built by the data management program, the maximum net present worth of the project belonging to each column is found. All entries in the data matrix will be divided by this value with reference to its regulation type. The data matrix will be made up of ratios of the net present worth of the solar PV project. The task of the data management program is to search for the best possible set of regulations reforming a policy employing a criterion function. The criterion function reflects a policy and can be defined as the summation of pre-estimated weighting factors multiplied by the net present worth ratios obtained from the data management program. The weighting factors reflect the relative importance of the regulation value to the project fund structure. The values of these weighting factors belonging to each regulation type are derived from a sensitivity analysis carried out by the data management program on the effect of the variation of the regulation parameter value on the internal rate of return such that the sum of all weighting factors for all regulation types in a reformed policy corresponding to an index array in the data matrix is one. This condition is to be ensured by considering an optimization algorithm in the data management program such that the weighting factors determined from the sensitivity analysis can be updated. Further clarification on this point is given in sections 5.5.4 and 5.5.5 of this chapter.

The data management program will additionally search for all regulation types. The main reason behind such an expansion is the search of all possible policies designated by m criterion functions. The data management program will not only offer recommendation to be set on two regulation types given one type is specified but rather it will target for the maximum criterion function indicating the best policy to be suggested as a reform of the current policy governing the project fund and implementation such that investors are encouraged to expand their current renewable energy projects to accommodate population growth. A flow chart of the function of the data management program is shown in Figure 5.11.

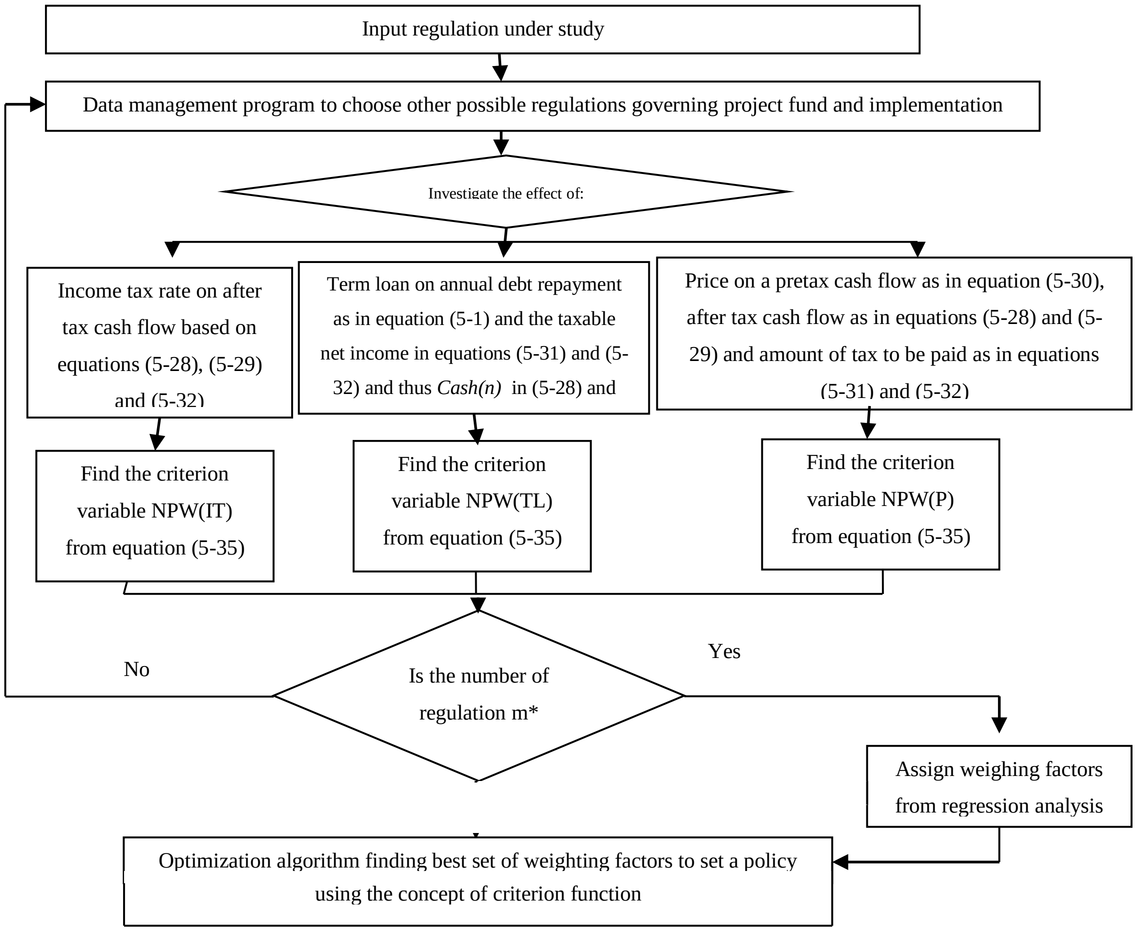


Figure 5.11: Function of the data management program

5.5.3 The Relationship between Regulations Governing Project Financial Structure and its Net Present Worth

The significant contribution of the regulations governing the project financial structure to the net present worth of the investment will be deliberated. The studied regulations governing the investment in the solar PV renewable energy project are the term loan, the income tax rate, and the price of electricity generated from the solar PV system. These regulations are studied provided that knowledge of capacity utilization factor of the solar PV system in the area where the project is to be implemented and the project capital, operation, maintenance and manpower costs are recognized.

5.5.3.1 Income Tax Rate

The idea of finding the proper income tax rate to be set on the project fund is applied by finding the adequate placement of such a rate among other regulations governing the project fund and implementation. The local investor is given a variety of rates to choose from when applying for a government fund for the solar PV renewable energy project. Any variation in the income tax rate will have an influence on the after tax cash flow described in section 5.4 by equations (5-28), (5-29) and (5-32). The type of tax rate to be studied is defined in section 5.4 as (*ITRate*).The *NPW(IT)* , shown in Figure 5.11, has been found considering the project cash flow discussed in section 5.4 at a specified minimum accepted rate of return for every index array in the data management program.

5.5.3.2 Term Loan

The data management program has been utilized to study the possible term loan regulations. Any variation in the loan durations will affect the annual debt repayment and therefore the interest to be paid every year as indicated by (5-1). It will also affect the tax holiday term specified for the solar PV project. It will affect *Cash(n)* in (5-28) and (5-29) by affecting (5-31) and (5-2). The effect of the term loan on the net present worth (*NPW(TL)*) of the solar PV project has been investigated utilizing the data management program.

5.5.3.3 Price of Electricity Generated from Solar PV System

The price of electricity generated from the solar PV system is a key factor with a significant effect on the investor decision toward the solar PV project. This price has been generated in the data management program as explained earlier. Any variation in this price will have a subsequent effect on the pretax cash flow because it affects profits developed from selling electricity generated from the solar PV system as shown by equation (5-30). Such a variation will be reflected on the value of NPW (P) of the project according to equations (5-28), (5-29), (5-31), (5-32) and (5-35).

5.5.4 Criterion Function to Select the Best Set of Regulations Governing Local Investment in Solar PV Energy Project

The objective of this section is to establish guidelines that can be followed by governance institutions to reform a motivating policy for local investors toward more solar PV energy projects to address the power generation shortage spreading across developing countries due to population growth. The guidelines are specified based on a method that formulates a value system as a mathematical statement presenting the studied regulations and their respective importance on a policy reform governing project funds and implementation in developing countries. Such a value system can be defined as a criterion function as given by the equation below:

$$Criterion\ \ Function = \sum_{r=1}^{m} J_r \frac{NPW_r}{\left|NPW_r\right|_{\max imum}} \qquad \textbf{(5-36)}$$

It can be seen that the above equation is composed of three variables. These are NPW_r that is the criterion variable of regulation *r*, J_r is the weighting coefficient representing the corresponding importance of regulation *r* and $lNPW_rl_{\text{maximum}}$ is the maximum absolute value of the criterion variable of regulation *r* where *r* refers to IT, TL or P.

The criterion function is made of the weighting factors (J_r) and the criterion variables ($NPW_{IT,}$ $NPW_{TL,}$ NPW_P). Every criterion variable ($NPW_{IT,}$ $NPW_{TL,}$ NPW_P) parades an explicit performance of the project financial structure. NPW_{IT} is the net present worth as a result of the income tax rate parameter index, NPW_{TL} is the net present worth as a result of the term loan parameter index and NPW_P is the net present worth as a result of the price parameter index. It is essential to clarify that the net present worth is not limited to a positive value. Although negative net present worth values represent rejected projects, these values will be utilized in finding the best set of regulations as a part of the criterion function. This consideration can be explained by the work presented in 1979 by both Fishburn and Kochenberger proving the commonness of risk seeking in decisions incorporating negative outputs [127]. Therefore, under such a condition, using the negative net present worth in the criterion function will not be recognized as a violation of axioms. This effect is considered in the data management system in one case study and is neglected in another case study as will be presented later on in this chapter.

5.5.4.1 Weighting Factors

The weighting factors are indicators of the relative importance of the studied type of regulation on project fund and implementation. Grouping the set of regulations to reform a policy is governed by these weighting factors. Every weighting factor (*J*) belonging to a type of regulation will indicate the regulation’s contribution to the criterion function such that the final effect of all weighting factors will lead to a reformed policy. To discover the corresponding significance of every criterion variable of regulation *r*, weighting factors are to be assigned to every studied regulation by analyzing its nature in the project. These weighting factors represent the regulation corresponding importance on the policy reform. It is necessary to clarify that the weighting factor given to every variable regulation can be characterized by either a positive or negative value according to the nature of the regulation under study in the project financial structure. Adding the absolute values of weighting factors specified for all criterion variables must give a value of one as indicated by the following equation. Supplementary clarification on how the weighting factors are found will be discussed in the next section.

$$\left|J_{IT}\right|+\left|J_{TL}\right|+\left|J_{P}\right|=1 \quad \textbf{(5-37)}$$

The best set of regulations reforming a policy to be suggested to governance institutions to boost the local investment in the solar PV energy project is determined based on the maximum value of Criterion Function (CF). This finding can be obtained when evaluating all criterion functions for all sets of regulations generated by the data management program. Figure 5.12 presents a flow chart summarizing the used method.

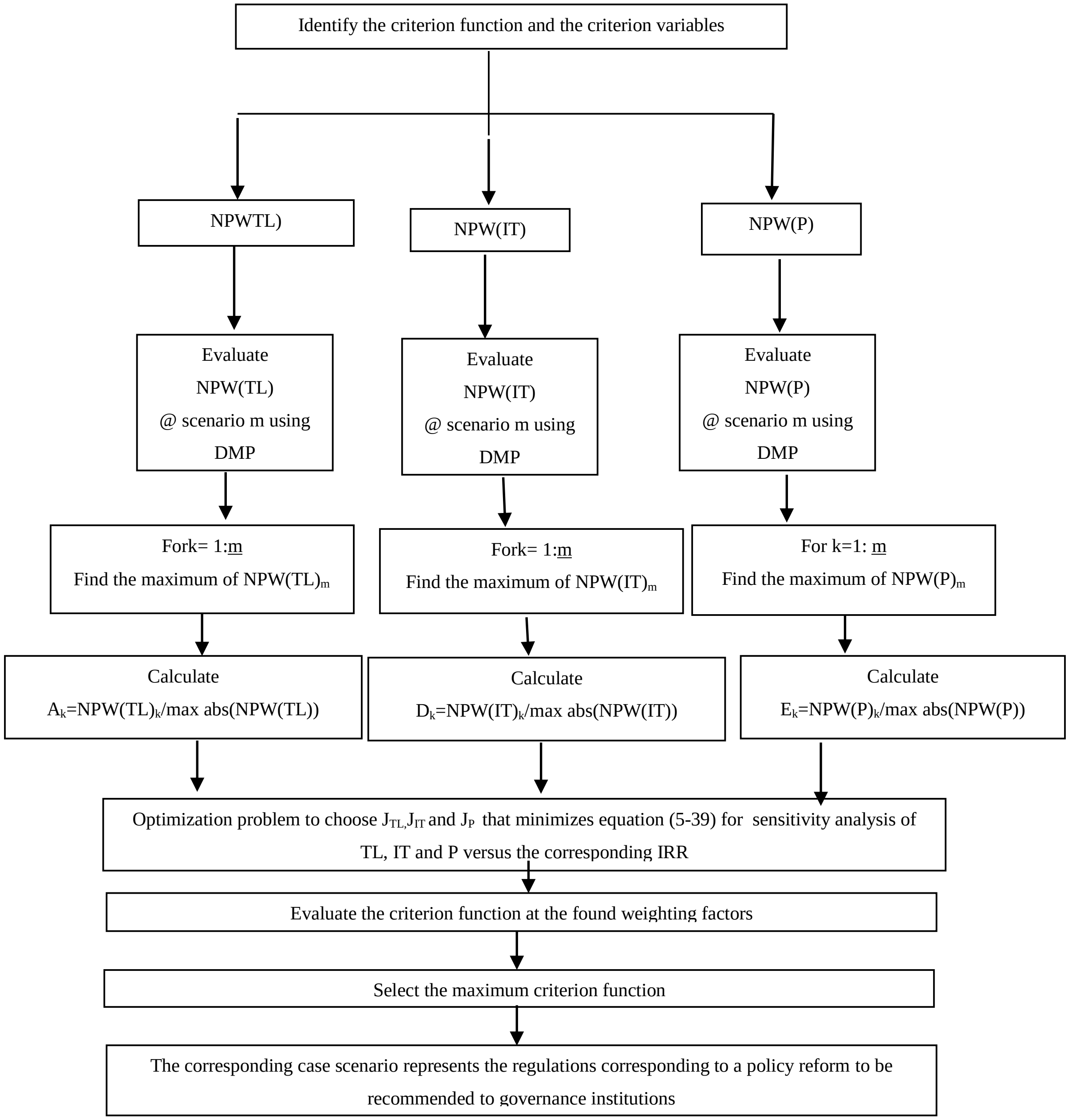


Figure 5.12: Flow chart to reform policy motivating local solar PV project investment

5.5.4.2 Sensitivity Analysis and Linear Programming to Choose the Weighting Factors

The method presented in [128, 129] has been extended to find the best set of regulations governing the Solar PV project local investment provided that the characteristics of the area under study (capacity utilization factor) and the economic characteristics of the project are recognized. The choice of the set of regulations reforming a policy is to motivate the local investors to expand solar PV renewable energy projects to address the power generation shortage spreading across the country due to population growth.

The weighting factors reflecting the relative importance of each studied regulation on project fund and implementation have been specified according to a sensitivity analysis performed on the internal rate of return of the solar PV project with respect to the variation in the regulations parameters following five approaches as will be discussed next.

The internal rate of return is found for every regulation index in the data matrix generated utilizing the data management program. The internal rate of return is graphed for each generated regulation data point. The relationship between the internal rate of returns and the generated regulation data is found to be best defined by a liner regression curve. The linear relationship determined using the least square approximation method is described by a linear equation form as shown below:

$$\mathrm{IRR}_r = J_r \; regulation_r + \widehat{\alpha}_r \quad \textbf{(5-38)}$$

where J_r and $\widehat{\alpha}_r$ are the slope and the intercept of the linear curve linking the internal rate of return (IRR_r) to a generated regulation r; correspondingly.

J_r is a weighting factor that imitates how sensitive the IRR to any disparity in the regulation under study and reflects the importance of the criterion variable since the regulation index will impact it. It is important to clarify that the other regulations are fixed at the reference point at this stage.

The main reason behind selecting the internal rate of return to be graphed versus the generated data of the studied regulation is that the curve’s slope found from the least square approximation method is to be a fractional number such that the sum of the weighting factors is one when considering all other types of regulations to be studied. The slope is expected to be less than one for every studied regulation index because the internal rate of return is less than one. The curves of IRR versus the regulations data under study are graphed as shown in Figure 5.13.

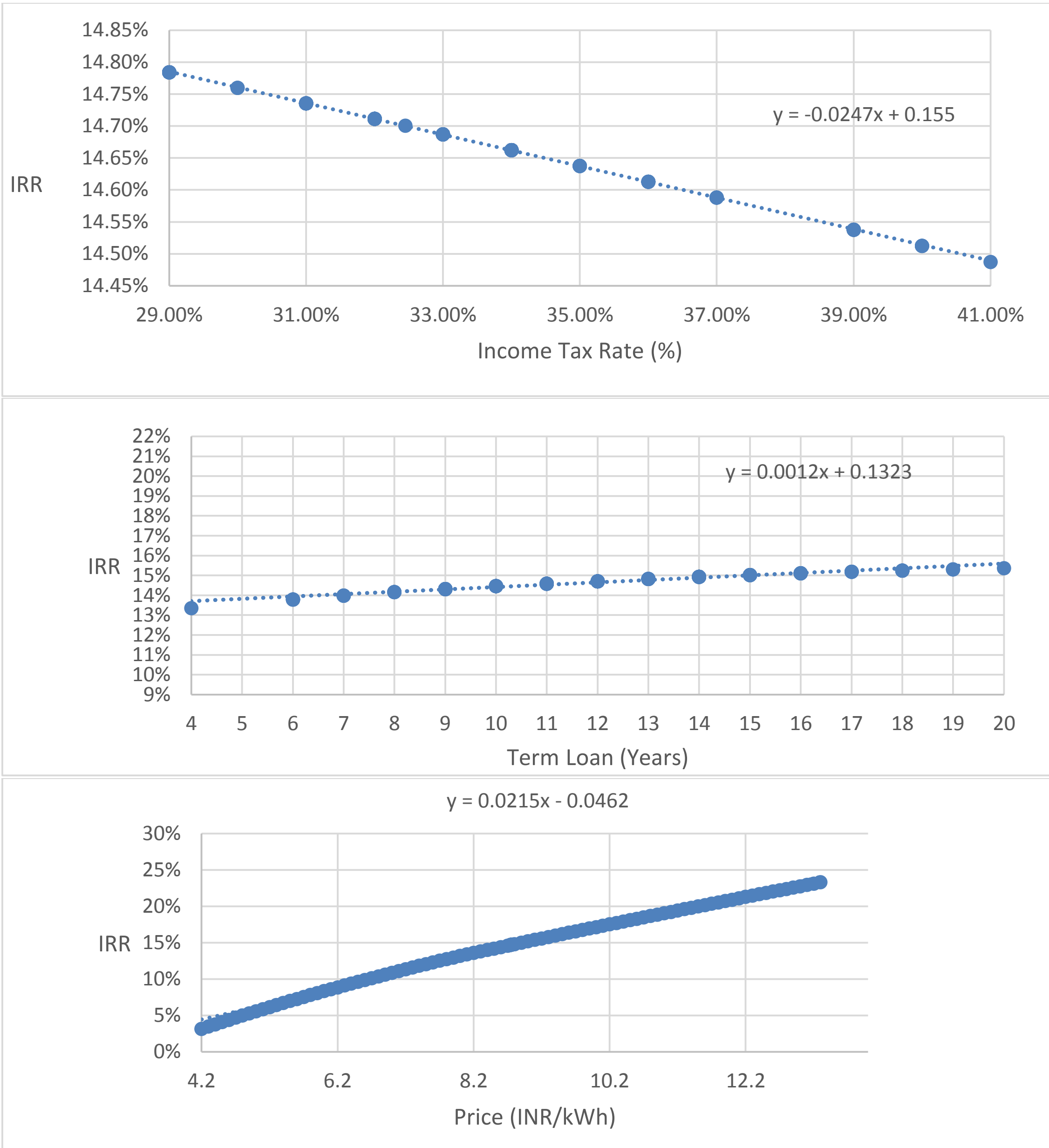


Figure 5.13: Linear Curves Relating IRR to variations in regulations' parameters

It can be seen from the above figures that J_{TL} is 0.0012 and $\hat{\alpha}_{TL}$ is 0.1323 when the regulation parameter corresponds to the term loan, J_{IT} is -0.0247 and $\hat{\alpha}_{IT}$ is 0.155 when the regulation parameter corresponds to the income tax rate and J_P is 0.0215 and $\hat{\alpha}_P$ is -0.0462 when the regulation parameter corresponds to the selling price of electricity generated from the solar PV system. It can be seen from these curves that all slopes of the curves have values that are less than one, which is a requirement of J value. On the other hand, the sum of the slopes of every linear curve shown above is found not to be one. Therefore, these slopes are not the weighting factors. As a result, an adjustment is to be made to the slopes such that their sum is one. The objective is to find the corresponding weighting factors to each regulation under study such that their sum is one. This objective can be solved using one of the three methods. These methods are either to 1. represent each slope of the determined curves in Figure 5.13 as a fraction of the absolute sum of the slopes corresponding to each linear curve such that the sum of these fractions is one, 2. consider an equal percentage variation to the reference point value of the regulation under study and investigate its effect on IRR such that the determined IRR at this variation is utilized as a ratio to the sum of the found IRR corresponding to each type of regulation variation, or 3. formulate a non linear programming optimization problem to select the optimal values of the weighting factors. The results of these methods are compared to the case when the weights are set to be equal such that the importance of one regulation over another is neglected. These methods are discussed below:

5.5.4.2.1 Weighting Factors as a Ratio of IRR Curves' Slopes

This method estimates J_r that is a weighting factor indicating how important regulation r to the policy on project fund governing investors decision to expand the renewable energy projects to account for population growth demand for electricity. The method finds J_r by representing the slope of IRR versus regulation r curve as a fraction of the absolute sum of the slopes of all curves relating IRR to alternative regulations under study such that when adding these fractions, the sum is one. The values of J_r are displayed in Table 5.19. The IRR error calculated applying such an approach by modifying the slope to the new determined value is shown in this table. It is important to clarify that such an approach is considered to assign different weighting factors to the regulations under study to explore the most sensitive regulation in decision making aspects. Though the error is found to be large, this error does not necessarily mean that the considered approach is wrong. This observation will be shown in Table 5.19 where it can be noticed that the selected set of regulations agrees with the selected set of regulations determined by applying the second approach based on utilizing non linear programming to choose such weights as discussed next.

5.5.4.2.2 Non Linear Programming to Select Weighting Factors

A non linear programming algorithm to choose the optimal values of the weighting factors is presented in this section. The objective function is based on minimizing the least square error in the internal rate of returns of the solar PV project with respect to the regulation under study in comparison to the internal rate of return determined from a linear regression relating its value to the regulation index.

The optimization problem formulation to determine the weighting factors is described below:

$$\min \ error = e_{IT} + e_{TL} + e_P \tag{5-39}$$

Subject to

$$|J_{IT}| + |J_{TL}| + |J_P| = 1 \tag{5-40}$$

$$J_{IT} \neq 0 \tag{5-41}$$

$$J_{TL} \neq 0$$

$$J_P \neq 0 \tag{5-42}$$

$$e_{IT} = \sum_{m=1}^{n} [IRR(IT)_{\underline{m}} - (J_{IT} . \ IT_{\underline{m}} + \hat{a}_{IT})]^2 \tag{5-43}$$

$$e_{TL} = \sum_{m=1}^{n} [IRR(TL)_{\underline{m}} - (J_{TL} . \ TL_{\underline{m}} + \hat{a}_{TL})]^2 \tag{5-44}$$

$$e_P = \sum_{m=1}^{n} [IRR(P)_{\underline{m}} - (J_P . \ P_{\underline{m}} + \hat{a}_P)]^2 \tag{5-45}$$

where e_{IT}, e_{TL} and e_P are the total square of errors in the internal rate of returns of the project (*IRRs*) when *IT*, *TL* or *P* are varied, respectively. $\hat{a}_{IT}$, $\hat{a}_{TL\,L}$ and $\hat{a}_P$ correspond to the intercepts of the best curve fitting the output (IRR) to the belonging input (IT, TL or P), respectively. The weighting factors represent the slopes of the best fitting curves.

The optimization problem can be considered from two perspectives. These are to either set the weighting factors to be the only decision variables, and the intercepts are given fixed values (as determined from regression analysis) or to consider the weighting factors and the intercepts of the best fitting curve (determined from the regression analysis) as decision variables in the optimization problem. These two cases will be explored. The weighting factors of the case providing minimum error in the IRR compared to actual values of IRR will be selected for future analysis. The results are displayed in Table 5.19.

5.5.4.2.3 Weighting Factors Estimation considering the Effect of Equivalent Single Variation of Regulations on Solar PV Project IRR

This case considers 25% as a variation ratio of the studied regulations and calculates the corresponding individual IRRs. In this case, the weighting factors are set as ratios of the determined IRR_r to the sum of these IRRs. The effect of such hypothesis in setting the value of *J* is presented in Table 5.19. This table also shows how the decision toward a policy can be changed when compared to the previous two cases of specifying the weights. In this case, the price is given more priority when grouping regulations under study to reform a policy.

5.5.4.2.4 Equal Weighting Factor Value to all Regulations

When project net present worth is what matters rather than a policy reform, equal weights are to be assigned to each type of regulation under study in the proposed guided method. In this case, the case with maximum net present worth is chosen. While at first glance this choice of weighting factors seems to be more beneficial for an investor toward more solar PV projects as can be seen from Table 5.19, it is important to clarify that what matters in the selection of *J* values is the importance given to the contribution of the studied type of regulation to project financing. In other words, the maximum net present worth is not concerned as much as reforming a motivating policy capable of accepting population growth. This target is achievable by considering the most sensitive parameter index corresponding to a regulation type that can be modified at any stage to accommodate population growth keeping in mind investors' benefit all the time.

5.5.4.3 Weighting Factors Values as Estimated based on the Above Proposed Alternative Methods

Weighting factors are assigned to regulations compromising a policy as an approach of specifying the relative importance of such regulations to a policy reform. The policy is reformed as a function of the current policy in a targeted developing country. The proposed approach is recognized for specifying which regulation effect is more important in a policy by assigning more weight to it such that it can be considered in the future when more renewable energy projects are to be funded to accommodate population growth demand for electricity.

Different methods are considered to estimate the weighting factors. Some of them follow an error estimation considering the consequent effect of the variation in the studied regulation index on the internal rate of return given that the other regulations' indices are set at the reference point. The reference point is represented by the current regulations placed on project fund and implementation in a developing country. Other methods discussed earlier are not compulsorily concerned with such an error. The results found when applying these methods are shown in Table 5.19. It can be seen from this table that when the error is concerned, smaller error is obtained when setting the weighting factors and the intercept of the curves (these curves fit the internal rate of returns to the generated regulation data from the data management program) as decision variables. The minimum error is found at J_{TL} of 0.001252, J_{IT} of -0.97709 and J_p of 0.021662. The effect of J values applying such an approach on IRR curves corresponding to the studied regulations is plotted in Figure 5.14. It can be seen from this figure that the income tax rate is the most sensitive regulation index and thus given more importance when planning future solar PV projects to accommodate population growth demand for electricity. Accounting for the criterion function approach whose results are discussed in the next section, it has been found that the policy is to be reformed considering 14 term loan, INR13 price and 41% tax rate on taxable income.

It can also be noticed from the table below that all proposed approaches have led to the same policy reform when the error is concerned. This observation validates the proposed algorithm in reforming a policy as a function of the current policy to accommodate more solar PV projects accounting for population growth. On the other hand, when error is not concerned, a less accurate procedure is followed considering a single equivalent variation in each type of regulation under study aside from others to estimate its effect on IRR. In such a case, 13 term loan, INR13.2 price and 39% tax rate are found to reform a new policy. It can be seen from the table below that the results found applying such an approach are very close to the results determined from the previous approach where error was concerned. Furthermore, the case in which equal weights are assigned to each regulation type is not capable of accommodating population growth electricity demand through implementing renewable energy projects even though it seems to be more beneficial from an investors' perspective. It is important to clarify that such a case might be more appealing to investors, but it is not applicable from a governments' perspective as such an accommodation of the policy will reduce income gained by government from such projects and will prioritize investors' revenue. This case also means that with population growth, the current problem of the power shortage will not be solved and will spread across developing countries as consumers have limited income to be spent on purchasing electricity. The first case where error is concerned is preferred as it considers different maxima effects of regulations on each net present worth toward reforming a policy.

Table 5.19: J_r and $\hat{\alpha}_r$ estimation for different proposed methods

Studied scenarios	Case explanation	J_r	$\hat{\alpha}_r$	Minimum error (Sum of square of errors)	Policy reform
1	• New $J_r = \dfrac{J_r \ (slope\ of\ curve\ r)}{\sum_{r=TL,IT,P} \lvert J_r \rvert = 0.0474}$ • $\hat{\alpha}_r$: From regression analysis	J_{TL} = 0.025316 J_{IT} = -0.5211 J_P = 0.453586	$\hat{\alpha}_{TL}$ = 0.1323 $\hat{\alpha}_{IT}$ = 0.155 $\hat{\alpha}_P$ = -0.0462	Error is not concerned Error= 1503.3418	41% Income tax rate 14 term loan 13 INR price
2	• J_r : Decision variable in the optimization problem • $\hat{\alpha}_r$: Decision variable in the optimization problem	J_{TL} = 0.001252 J_{IT} = -0.97708 J_P =0.021668	$\hat{\alpha}_{TL}$ =0.131474632 $\hat{\alpha}_{IT}$ =0.4730810155 $\hat{\alpha}_P$ =0.047298184	0.0795	41% Income tax rate 14 term loan 13 INR price
3	• J_r : Decision variable in the optimization problem • $\hat{\alpha}_r$: From regression analysis	J_{TL} = 0.001869 J_{IT} = -0.97529 J_P = 0.022838	$\hat{\alpha}_{TL}$ = 0.1323 $\hat{\alpha}_{IT}$ = 0.155 $\hat{\alpha}_P$ = -0.0462	9.8767	41% Income tax rate 14 term loan 13 INR price
	• Weights are given according to 25% variation in regulation indices. • Weights' effect on IRR is investigated. • $J_r = \dfrac{IRR_r}{\sum_{r=TL,IT,P} IRR_r}$	J_{TL} =0.070 J_{IT} =-0.040 J_P = 0.890	-	Error is not concerned Error=6111.4484	39% Income tax rate 13 term loan 13.2 INR price
4	• Equal weights of J_r	J_{TL} =0.333 J_{IT} =-0.333 J_P = 0.333	-	Error is not concerned Error=1721.0699	31% Income tax rate 17 term loan 12.4 INR price

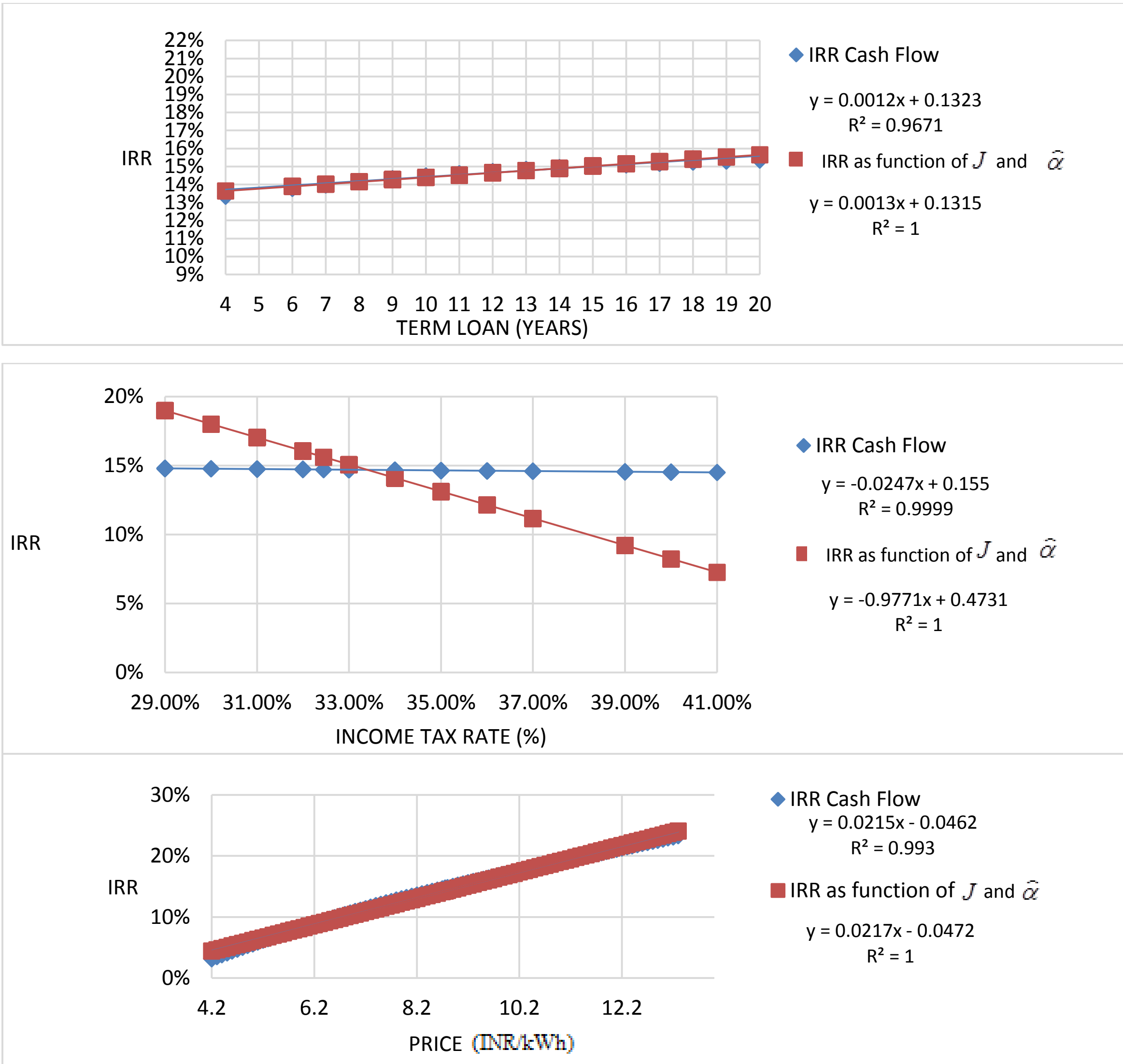


Figure 5.14: The significance of regulation *r* toward a policy reform on project fund and implementation based on scenario 2

5.5.4.4 Criterion Function Results

A decision matrix is assembled to obtain the best set of regulations reforming a policy governing the project fund and implementation applying the concept of the criterion function. This decision matrix is to provide a suitable format to organize the data in demand for the assessment of the criterion function in a tabular form. The technique is explained in Table 5.20. As can be noticed from this table, $NPW(IT)_{S}$, $NPW(TL)_{L}$ and $NPW(P)_{Q}$ denote the maximum criterion variables of $NPW(IT)$, $NPW(TL)$ and $NPW(P)$ columns, correspondingly. It is important to lay emphasis on the criterion function that is not to be calculated for any set of regulations if at any occasion the ratio of the net present worths is one. The results in the table below serve as a small version of the results acquired from the data management program and are presented here as an example of the performed procedure.

Table 5.20: Decision matrix layout developed for case study 2.

	For TL		*For IT*		*For P*		*CF*
Regulations set I Long term loan (17 years), intermediate tax rate (31%) and high selling price (12.4)	$\frac{NPW(TL)_1}{NPW(TL)_S}$ = 0.910622226	$J_{IT}\frac{NPW(TL)_1}{NPW(TL)_S}$ = 0.00114023	$\frac{NPW(IT)_1}{NPW(IT)_L}$ = 0.967969385	$J_{TL}\frac{NPW(IL)_1}{NPW(IL)_L}$ = -0.945789303	$\frac{NPW(P)_1}{NPW(P)_Q}$ = 0.83302609	$J_P\frac{NPW(P)_1}{NPW(P)_Q}$ = 0.018044918	*CF1* = -0.926604154
Regulations set II High tax rate (41%), long term loan (14 years) and high selling price (13INR)	$\frac{NPW(TL)_2}{NPW(TL)_S}$ = 0.791667632	$J_{IT}\frac{NPW(TL)_2}{NPW(TL)_S}$ = 0.000991282	$\frac{NPW(IT)_2}{NPW(IT)_L}$ = 0.80781631	$J_{TL}\frac{NPW(IT)_2}{NPW(IT)_L}$ = -0.789305981	$\frac{NPW(P)_2}{NPW(P)_Q}$ = 0.94434203	$J_P\frac{NPW(P)_2}{NPW(P)_Q}$ = 0.020456232	*CF2* = -0.767858467
Regulation set i . .	. . . $\frac{}{NPW(TL)_S}$	$J_{IT}\frac{\vdots}{NPW(TL)_S}$	. . . $\frac{}{NPW(IT)_L}$	$J_{TL}\frac{\vdots}{NPW(IT)_L}$	. . . $\frac{}{NPW(P)_Q}$	$J_P\frac{\vdots}{NPW(P)_Q}$	. . .
11 term loan, 29% tax rate and 9.8INR price	0.642095755	*0.000803996*	*1*	*-0.977085967*	0.350657017	*0.007595893*	*CF is not calculated*
14 term loan, 37% tax rate and 10INR price	0.791667632	*0.000991282*	0.87187754	*-0.85189931*	0.38776233	*0.008399664*	*-0.842508363*
10 term loan, 33% tax rate and 8.6INR price	0.588225521	*0.000736543*	0.93593877	*-0.914492639*	0.128025137	*0.002773266*	*-0.910982829*
11 term loan, 40% tax rate and 8INR price	0.642095755	*0.000803996*	0.823831618	*-0.804954313*	0.016281467	*0.000352687*	*-0.803797629*
11 term loan, 30% tax rate and 7.9INR price	0.642095755	*0.000803996*	0.983984693	*-0.961437635*	-0.003129351	*$-6.77877x10^{-5}$*	*-0.960701427*
Regulation set n Medium term loan (7years), intermediate tax rate (34%) and medium selling price (8.4INR)	$\frac{NPW(TL)_n}{NPW(TL)_S}$ = 0.39403899	$J_{IT}\frac{NPW(TL)_n}{NPW(TL)_S}$ = 0.000493394	$\frac{NPW(TL)_n}{NPW(IT)_L}$ = 0.919923463	$J_{TL}\frac{NPW(IT)_n}{NPW(IT)_L}$ = -0.898844306	$\frac{NPW(P)_n}{NPW(P)_Q}$ = 0.090919824	$J_P\frac{NPW(P)_n}{NPW(P)_Q}$ = 0.001969495	*CFn* = -0.896381418

Considering the decision matrix layout presented in the above table and the criterion variables obtained in the previous section, the maximum criterion function is found to be at 14 years term loan, 41% tax rate on taxable income and 48.57% increase in the current price of electricity generated from the solar PV system (8.75INR/kWh) focusing on the characteristics of the area over which the project is to be implemented and the economic aspects of the project. These regulations can be tracked by governance institutions to reform a policy encouraging local investors in the electricity supply field to consider more renewable energy projects to address the power generation shortage problem that will be spreading over developing countries due to future population growth. The local investors are to consider their long term commitment in such projects. The net present worth measured at the minimum accepted rate of return (13%) and evaluated considering the indices of the found regulations is INR144732486**.** In this case, the internal rate of return is 22.85% compared to a net present worth of INR23857321 and IRR of 14.7% at the reference point represented by 32.45% as tax rate applied on taxable income, 12 years as term loan and 8.75INR/kWh as the price of electricity generated from PV system.

5.5.5 Effect of Neglecting Risk on Policy Reform

Risk is accounted for by allowing for negative net present worth when finding the criterion function. Such a consideration is recognized as risk since negative net present worth value designates a rejected project from the economic perspective. When such a consideration is ignored, the effect will be reflected on the curve showing the relationship between IRR and the price of electricity generated from the solar PV system. This effect is because less data are chosen to avoid any rejected projects. In such a case, the slope and the intercept of this curve are 0.0191 and -0.0197, respectively. Neglecting risk symbolizes a minimum matrix size in the data management program as only positive net present worths are considered. The values corresponding to the weighting factors are shown in Table 5.21. The results from the criterion function evaluation are also presented in this table as a policy reform. As can be seen from this table, the final decision to reform a policy will not undergo a change compared to the scenario when risk is accounted for.

Table 5.21: J_r and $\hat{\alpha}_r$ estimation considering alternative methods

Studied scenarios	Case explanation	J_r	$\hat{\alpha}_r$	Minimum error (Sum of square of errors)	Policy reform
1	• New J_r = $\dfrac{J_r \ (slope\,of\,curve\,r)}{\sum_{r=TL,IT,P} \lvert J_r \rvert = 0.0474}$ • $\hat{\alpha}_r$: From regression analysis	J_{TL} = 0.026666667 J_{IT} = -0.548888889 J_P = 0.424444444	$\hat{\alpha}_{TL}$ = 0.13335481 $\hat{\alpha}_{IT}$ = 0.473 $\hat{\alpha}_P$ = -0.02348	Error is not concerned Error= 1085.4671	41% Income tax rate 14 term loan 13 INR price
2	• J_r : Decision variable in the optimization problem • $\hat{\alpha}_r$: Decision variable in the optimization problem	J_{TL} = 0.001334 J_{IT} = -0.97925 J_P =0.019416	$\hat{\alpha}_{TL}$ =0.130595221 $\hat{\alpha}_{IT}$ =0.47348772464 $\hat{\alpha}_P$ = -0.0233227096	0.0482	41% Income tax rate 14 term loan 13 INR price
3	• J_r : Decision variable in the optimization problem • $\hat{\alpha}_r$: From regression analysis	J_{TL} = 0.001963 J_{IT} = -0.97800 J_P = 0.020033	$\hat{\alpha}_{TL}$ = 0.1323 $\hat{\alpha}_{IT}$ = 0.155 $\hat{\alpha}_P$ = -0.0197	6.0280	41% Income tax rate 14 term loan 13 INR price
	• Weights are given according to 25% variation in regulation indices. • Weights' effect on IRR is investigated. • $J_r = \dfrac{IRR_r}{\sum_{r=TL,IT,P} IRR_r}$	J_{TL} =0.070 J_{IT} =-0.040 J_P = 0.890	-	Error is not concerned Error= 5016.1873	39% Income tax rate 13 term loan 13.2 INR price
4	• Equal weights of J_r	J_{TL} =0.333 J_{IT} =-0.333 J_P = 0.333	-	Error is not concerned Error= 1548.8099	31% Income tax rate 17 term loan 12.4 INR price

5.5.6 Section Summary

A guided procedure to encourage local investment in more solar PV energy projects to accommodate population growth demand for electricity was recommended to governance institutions. The discussed procedure aims reforming a policy governing investments in renewable energy projects. The policy to be reformed was developed as a function of the current policy applied on project fund in developing countries. This section concentrated on explaining the technique of how to move from the current policy to a new policy encouraging investors toward these projects such that population growth demand for electricity could be accommodated with respect to the limited expected fund. Regulations on project fund and implementation were among the topics discussed in the section. The decision making idea for selecting the best set of regulations through a simple but efficient optimization technique was discussed provided that a knowledge of the solar PV capacity utilization factor of the area where the project was to be employed and the economic aspects of the project were recognized. The technique took into consideration the performance of regulations applied on project fund and implementation as well as the sensitivity of the fund requirement to any structured variation in such regulations. To attain this objective, the data management program tabulating data and performing optimization had been implemented to determine the best weighting factors and the criterion function. From a practical point of view, this section had shown that the value assigned to income tax rate may outweigh the gain from the term loan of the solar PV project and the set electricity tariff for the solar PV system.

5.6 Chapter Summary

This chapter presented an economic analysis of alternative renewable energy sources available in developing countries to be utilized to address the power generation shortage problem. The chapter started with applying an economic study comparing alternative possible distribution generation sources as alternatives to building fossil fuel power stations. The economic study was based on the incremental rate of return analysis applied on possible projects’ cash flows. In general, when economically comparing wind, solar PV and diesel generator as alternative sources of supply by applying a general financial structure of project cash flow, it had been found that the wind project was the best candidate project for an investment for the project size under study. On the other hand, when performing the economic analysis subject to a current developing country’s policy regulating project fund and implementation, it had been found that the solar PV project was the best project for an investment when comparing wind, solar PV and hydro power projects for the project size under study. The role of the government policy is the main driver behind utilizing such resources. Even though there exist solar energy projects dedicated to supply pumps and water heaters in developing countries, the utilization of such resources for electricity supply has not solved the power generation shortage problem as power interruptions are still experienced by residential electricity consumers in many developing countries. The severity of the problem is spreading over such countries due to population growth demand for electricity and the limited available fund restricting such projects' expansion if the current policy is to continue. Thus, there was a need for a policy reform to encourage investors to expand their projects to accommodate population growth demand for electricity such that new areas can be connected to the distribution grid. This chapter had presented a criterion function approach utilizing optimization to reform a policy as a function of the current policy to encourage investors toward more PV energy projects over the long run to accommodate population growth demand for electricity. This approach was to search for regulations set forming a new motivating policy in the field. This set was determined by assigning higher weighting factors to the most sensitive regulation governing project fund and implementation. By recognizing such weighting factors, it was possible to update the current policy. The study is advantageous and can be extended to involve more regulations to be under study rather than the selected regulations in this chapter that were term loan, tax rate assigned to taxable income and electricity tariff of the solar PV system.

Chapter 6
Utilizing Renewable Energy to Address Power Generation Shortage in Developing Countries

Wind and solar energies are a candidate alternatives to fossil fuel power generation. Such renewable energies can be utilized to address the power generation shortage problem in developing countries. Besides the wind energy's advantage of being a clean source of energy, the capacity utilization factor of wind energy in developing countries is high as has been shown in [82]. Considering the general financial structure of the wind energy project not subject to a specific policy governing the project fund and implementation, the investment in the wind energy project has been proven to be the best alternative to other distribution generation systems from an economical perspective as has been shown in the previous chapter. On the other hand, solar PV energy is an excellent candidate to address the power generation shortage problem from an investor's perspective as this type of energy is proven to be the best alternative than other energy production sources subject to the current policy applied in developing countries. Furthermore, this type of energy has been deployed to serve different applications as water pumping and water heating at a small scale due to limited income. Since developing countries are undergoing political tension toward a green mix of supply [3, 26] and because of the deficiency in the available power generation to address the growing energy demand, the objective of this chapter is to find the minimum sizes of wind and PV systems to address the power generation shortage problem in developing countries and accommodate a new feeder to be connected to the grid accounting for the growth in population and the demand for system expansion.

Wind and PV systems are to be grid connected and the power generation shortage is to be addressed in this chapter by considering scheduling residential houses' demand in developing countries based on the available wind and PV power and the utility supply to maximize consumers' access to electricity and minimize the size of the wind amd PV systems needed. Furthermore, the chapter will propose a novel PV power model that can be utilized effectively to address the power generation shortage in developing by countries considering the investment in the minimum number of PV systems possible while considering both house full power interruption scheduling and residential house's devices scheduling.

6.1 Wind and Solar PV Systems' Allocation

The wind and solar PV systems are to be utilized to address the power generation shortage problem. This problem is practically symbolized by worsening frequent power interruption schedules in the other feeders of the grid if new areas are to be connected to the grid to accommodate population growth or restricting grid expansion by leaving the new area unsupplied with electricity while preserving the current power interruption schedule on the rest of the grid.

Proper sizes of the wind turbines and solar PV systems are to be selected to support electricity supply to the new feeder to be connected to the grid that is shown in Figure 4.1. The wind turbines are to be allocated in areas characterized with high wind speed, while the solar PV system is to be allocated in areas characterized with high solar radiation. The sizes of the wind turbines and solar PV systems is to be estimated based on the amount of power demanded by the new feeder assuming that the rest of the grid does not undergo worsening power interruption schedules. The deployment of such consideration is from a grid perspective such that investors can sell electricity to utility consumers. It is important to emphasize that the system is not treated as a micro-grid and such allocation of the wind turbines and solar PV systems does not necessarily mean that these systems are connected to bus 1 where reverse power flow to the other feeders in the grid is prevented. The objective in this chapter is to find the best size of the wind turbines and solar PV systems that can meet the maximum demand of this new feeder assuming that the determined size represents the amount of power needed for that part of the grid only based on the available wind speeds, solar radiation and weather temperature. Since the best size of the wind turbines and solar PV systems meeting the maximum demand is to be determined by accounting for residential consumer devices' scheduling, it is necessary to provide a brief description of the wind turbine and solar PV systems in the next section. The models of these systems are presented later on in this chapter.

6.2 Description of Wind Turbine and Solar PV Systems

The wind turbines and solar PV system is to supply power to a small size feeder to be connected to the grid due to population growth. Small scale wind turbines and solar PV systems are to be sized to respond to the power generation shortages in developing countries. By utilizing the available wind and solar energies to schedule houses or their device demands such that most of the demand is met under a minimum possible size of of their systems, this solution will reduce the severity of the power interruptions. The uncertain effect of wind and solar energies on the expected energy to be supplied to residential consumers is also investigated. This section will provide a brief description of the wind turbine and solar PV systems.

The wind turbine purchase guide in [130] shows that wind turbines can be classified into four categories that are remote communities, farms and rural areas, off-grid and on-grid residential wind turbines. Each category has its corresponding wind turbine power rating ranges. Based on this categorization, the minimum wind turbine ratings that can be applied for such areas are recognized. From this prospective, it is required to either consider the off grid residential wind turbines, the on grid residential wind turbines or the farms' wind turbines. The off grid residential wind turbines can be connected to the rooftop of houses and mainly involved to supply electricity demand of such houses. In this case the power produced is considered small as the corresponding height of the turbine is considered small as indicated in [131]. The power rating of such a wind turbine is 1kW and the turbine is characterized with a low cut in speed that is suitable for the height of the wind turbine [131]. Since the application of such wind turbines is considered to be for off grid applications as indicated in [130], in this case wind energy cannot be sold back to the grid and the only beneficiary of the wind generated electricity is the consumer. On the other hand, the on grid residential wind turbines can vary from 1kW to 10kW and such systems can supply power to the grid, and the beneficiary is as well the consumer [130]. Since this work does not target residential wind turbines but rather investors in wind energy projects who seek reasonable profits over the long run, the minimum wind turbine size that can be allocated in wind farms and can be utilized is 10kW. Therefore, the minimum size of the wind turbine chosen in this chapter is 10kW as this size forms the edge point between the residential grid connected wind turbine size requirement and the minimum size of the wind turbines that can be purchased by an investor and allocated in the wind farms as individual residents cannot accommodate the high price of wind turbines with their low income discussed in [34].

Since the average wind speed is considered to be low in [132] at the standard weather station height, and the typical 10kW wind turbine has a height of 24m that agrees with the guide in [130], a convergence of the wind speed from the current height of the weather station to the new height of the wind turbine is required for a better accurate utilization of wind energy as will be shown in section 6.3. Even though the new average wind speed is still considered to be low, the 10kW wind turbine chosen based on its characteristics guarantees the power generation at low wind speeds. The chosen 10kW wind turbine has a cut in speed of 2.5m/s, a rated wind speed of 7.5m/s and a cut out speed of 16m/s according to [133]. It is important to emphasize that with such a selection of the wind turbine, wind utilization is not considered to be effective in terms of cost as the wind speed falls below the minimum requirement of the wind speed for the grid connected applications. Since the system under study is a small scale system that has been chosen to address the current power generation shortage problem in developing countries, this small scale 10kW wind turbine is considered. If a large distribution system is studied, investors can target wind turbines at a large scale with high hub heights to guarantee the best utilization of wind energy.

On the other hand, the minimum grid connected solar PV system is 2kW according to [134]. Thus, it has been assumed that the PV system size is 5kW and it can be more or less based on connecting or disconnecting PV modules as indicated in [135]. The PV system whose model will be presented in details in section 7.4 is the 1MW PV system. Since the 5kW PV system is assumed to be the typical size of the PV system, the PV power output of the 5kW is derived as a ratio of the 1MW PV system.

Two typical seasons are under study: winter and summer. In order to represent the month in a season by a typical day to facilitate the analysis and application of wind speed and PV power in residential demand scheduling, the data of wind speed and PV power output are utilized to derive probabilistic distributions describing the behavior of the data such that they can be used for operational planning applications. The hourly wind speed and PV power output are to be generated from the Monte-Carlo simulation according to the corresponding probabilistic distribution describing the data. After that, the data are to be clustered. The main reason behind such consideration is to reduce the size of the data obtained from the MCS. It is important to emphasize that the clusters represent states describing the wind speed or PV power output in an hour. The clustering algorithm considered in this work is based on Sturges' rule [136] which finds the number of clusters based on the total number of observations. The probability of each cluster is to be determined from the distribution describing the behavior of the data as will be discussed in details in section 6.4 that serves as an example on such application when dealing with PV power output. The values representing the hourly wind speed and the hourly power output of the PV system are to be found as expected values of the corresponding wind speeds and the corresponding power produced by the PV system, respectively. Such expected values are to be calculated as the summation of all possible states of the wind speeds or PV power output multiplied by the corresponding probability of their states. These values are to be determined for each time segment within a typical day representing a month in a studied season. The determined states corresponding to each hour of the day will be utilized to investigate the uncertain effect of the variable wind and solar resource on the expected residential energy that can be met.

6.3 Wind Speed and Power Model

Wind speeds determined from metrological locations are at the standard height that is 10m. Such measurements of wind speed are not used for applications of wind energy projects as indicated in [137]. Wind energy applications at large scale can require wind turbines' heights that are at least 60m [137]. Thus, an adjustment of the wind speed from the weather station height to the wind turbine hub height is considered as described by the equation below [137, 138] where *sp* is the wind speed and *w* is a factor describing stability and is set to 1/7 for neutral stability according to [138, 139].

$$sp_{new} = sp_{old} \ (\frac{hub \ height}{old \ height})^{\omega} \quad \textbf{(6-1)}$$

Wind power can be determined based on wind speed. Since uncertainties is a characteristic of wind speed, modeling wind speed using the best probabilistic distribution function that describes its behavior provides the main parameters that can illuminate the features of a wide range of wind speed data such that they can be utilized for operational planning purposes as in the case of houses' devices scheduling to minimize the generation-demand gap. Since it is known in literature that wind speed follows Weibull distribution, this chapter will consider the hourly wind speed data in winter and summer of a selected developing country to find the parameters of Weibull distribution. Three years wind speed data are utilized from [132] and will be considered to determine the parameters of Weibull probability density function described by the equation below [140], where $f(sp)$ is the probability density function (*pdf*) of wind speed (*sp*), αs is the shape parameter and βs is the scale parameter, such that every hour will have its own wind speed Weibull distribution described by its corresponding parameters that better fits that wind speed in the studied season.

$$f(sp) = \frac{\alpha s}{\beta s^{\alpha s}} \frac{sp}{\beta s}^{\alpha s - 1} e^{-(\frac{sp}{\beta s})^{\alpha s}} \quad \textbf{(6-2)}$$

The Monte-Carlo simulation is used to model wind speed profile as wind speed is a random variable. It targets the prediction of the behavior of wind speed from a set of parameters describing Weibull distribution. The Monte-Carlo simulation for random sampling of wind speed from Weibull distribution using inverse transform technique is used as Weibull distribution has analytical expression available for the inverse cdf as shown below where $F(sp)$ is the cumulative distribution function (*cdf*) of wind speed [141], *us* is a random variable and *x* corresponds to a wind speed data point number.

$$F(sp) = 1 - e^{-(\frac{sp_x}{\beta s})^{\alpha s}} = us_x \quad \textbf{(6-3)}$$

$$sp_x = \beta s(-\ln(1 - us_x))^{\frac{1}{\alpha s}} \quad \textbf{(6-4)}$$

Two typical seasons are considered under study. These are winter and summer. In order to represent the month in a season by a typical day to facilitate the analysis and application, the wind speed data are utilized to derive the Weibull probabilistic distributions describing the behavior of the data for every hour of the day. Then, the data are regenerated using the Monte-Carlo simulation in order to derive a typical day's hourly data. The stopping criteria in the simulation is based on specified errors for both standard deviation and the mean of generated data from the simulation with respect to the distribution variance and mean which are functions of Weibull distribution's paramters to be below a specified tolerance. The distribution mean and variance of Weibull distribution based on its parameters are given by the following equations [142, 143]:

$$mean = \beta s * \Gamma(1 + 1/\alpha s) \quad \textbf{(6-5)}$$

$$\mathrm{var}\,iance = \beta s^2[\Gamma(1 + 2/\alpha s) - \Gamma^2(1 + 1/\alpha s)] \quad \textbf{(6-6)}$$

To get the typical day's data and to reduce the size of the data, such generated data are clustered into states following the algorithm in [136] where the number of clusters is determined based on the total number of observations. The value of the wind speed corresponding to a certain hour is determined as an expected value of the wind speed that is calculated as the summation of all possible states of wind speed multiplied by the corresponding probability of that state considering the approach in [144].

The next step is to determine the power output of the wind turbine. The power output curve of wind turbine versus wind speed [141] should be similar to the curve in Figure 6.1.

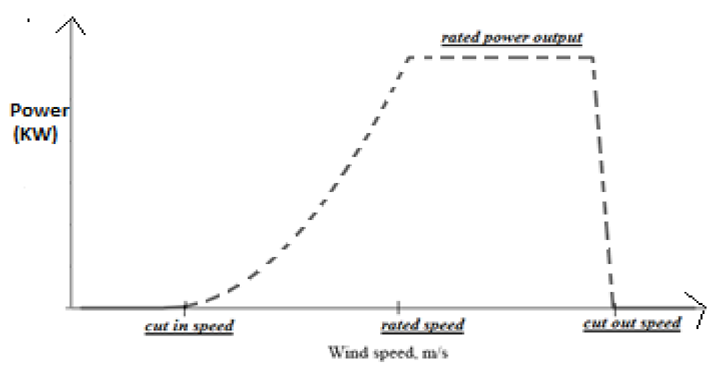


Figure 6.1: Power output characteristics of wind turbine according to [141]

The power output generated from the wind turbine is a function of wind speed as described below [140, 141, 145] where $sp_{cut\text{-}in}$ is the cut in speed of wind, sp_{rated} is the rated speed of wind, $sp_{cut\text{-}out}$ is the cut out speed of wind, P_{rated} is the rated power output of the wind turbine and *h(sp)* is a power function of cut in speed, rated speed of wind and the rated power output of the wind turbine.

$$P_{sp} = \begin{cases} 0 & 0 \le sp \prec sp_{cut-in} \\ h(sp) & sp_{cut-in} \le sp \prec sp_{rated} \\ P_{rated} & sp_{rated} \le sp \prec sp_{cut-out} \\ 0 & sp \ge sp_{cut-out} \end{cases}$$ **(6-7), (6-8) , (6-9) & (6-10)**

$h(sp)$ can be determined by applying equation (6-11) where *a*, *b* and *c* are constants whose values will be determined by applying equations (6-12), (6-13) and (6-14); respectively [140, 141, 146].

$$h(sp) = (a + b\ sp + c\ sp^2)P_{rated}$$ **(6-11)**

$$a = \frac{1}{(sp_{cut-in} - sp_{rated})^2}\left[sp_{cut-in}(sp_{cut-in} + sp_{rated}) - 4\ sp_{cut-in}\ sp_{rated}\left(\frac{sp_{cut-in} + sp_{rated}}{2\ sp_{rated}}\right)^3\right]$$ **(6-12)**

$$b = \frac{1}{(sp_{cut-in} - sp_{rated})^2}\left[4(sp_{cut-in} + sp_{rated})\left(\frac{sp_{cut-in} + sp_{rated}}{2\ sp_{rated}}\right)^3 - (3\ sp_{cut-in} + sp_{rated})\right]$$ **(6-13)**

$$c = \frac{1}{(sp_{cut-in} - sp_{rated})^2}\left[2 - 4\left(\frac{sp_{cut-in} + sp_{rated}}{2\ sp_{rated}}\right)^3\right]$$ **(6-14)**

The resultant wind power values are shown in the figure below for typical winter and summer days.

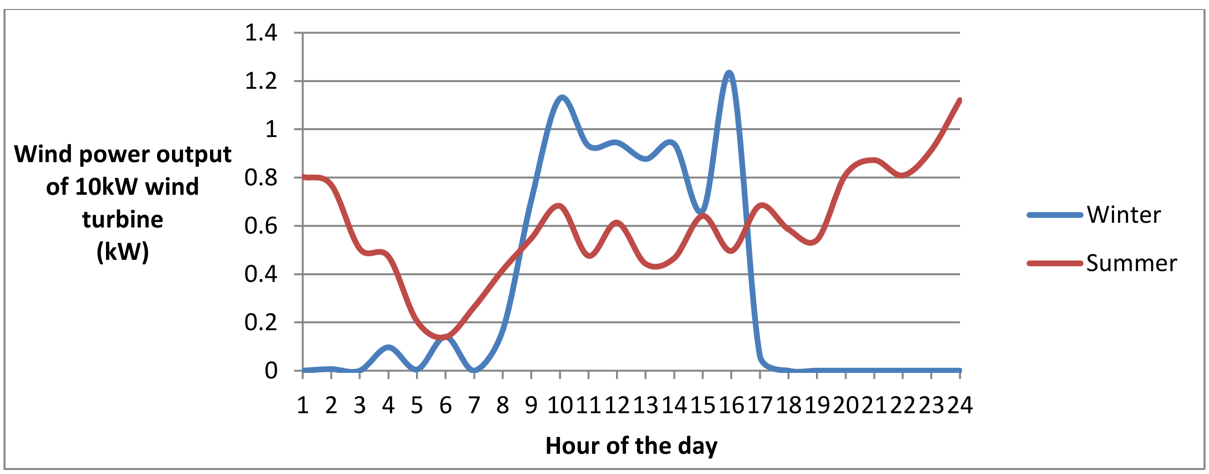


Figure 6.2: wind power for typical winter and summer days

6.4 Solar PV System Model

A novel probabilistic PV power output model is proposed in this section. This model of PV power output is appropriate to schedule the PV system for addressing the power generation shortage represented by the frequent residential power cuts' events lasting for many hours daily in developing countries. The main reason behind proposing such a model is that it is not feasible to adopt a storage system to regulate the energy production of the PV system because of its high cost. The PV power output model presented in this section considers the main factors affecting power production. These factors are the solar irradiance, the ambient air temperature and the effect of the cell's temperature on system losses. Most of the work in the literature has focused on modeling one factor only, solar irradiance [147-149]. These models are suitable for finding the PV power output excluding the effect of temperature as solar power is dealt with as a function of surface area (m^2) as well as solar irradiance (Watt/m^2). Other works in the literature have accounted for the solar irradiance and temperature but the treatment of the probabilistic model is different. For example, [150] considers Bayesian auto regressive time series model for estimating the clearness index utilized in a short term forecasting. It also considers the Monte-Carlo simulation to evaluate the PV power distribution function to random sampling of the clearness index. The deficiency of such a model is that a large error exists when there is a demand to indicate the PV power by a single value because the clearness index and the PV power are non-linearly related making it hard to arrange the importance of the distribution parameters to define this single value. On the other hand, [144, 151] model the horizontal solar radiation for every clearness index. It is important to emphasize that solar irradiance can be categorized into global, direct and diffuse solar irradiance. It is thought that [144, 151] addressed global horizontal irradiance. If this is the case, then considering such a model of clearness index is not desired because the global horizontal radiation is a function of clearness index according to [16]. This condition is accounted for in the proposed PV power output model in this thesis. Furthermore, the temperature probabilistic nature is neglected in [144, 151] and [152] that uses the average value of temperature data. In this thesis, the PV power output data utilized in finding the best probabilistic distribution describing the data account for the hourly effect of cell temperature on PV system power production by taking into consideration PV losses due to cell temperature compared to the temperature at standard test condition. Such an effect is neglected in [150] that rather uses PV system efficiency as in [150, 153, 154]. Even though system efficiency in [150, 153, 155] accounts for temperature loss fundamentally, this value is fixed all the time making modeling such an effect not accurate for finding the hourly power output from PV as losses will vary hourly with respect to cell's temperature variation. Such an effect is treated in [156] through system's efficiency considering it, but the treatement of the problem is for daily solar irradiance rather than estimating the hourly power output of the PV system.

Innovative probabilistic distributions, wakeby and general extreme value distributions, are utilized to characterize the PV power output because such distributions are recognized to be flexible and reliable tracing the extremes and the tails of the distributions. This is essential when reinforcing the data through the Monte-Carlo simulation to account for the randomness of the data of a month or a season such that a typical day's data set, or representative states can be obtained to aid scheduling residential power interruption events and analysis. The PV power output model in this chapter uses historical data for seven years of both solar irradiance and ambient air temperature in each month in a season for the city of Amritsar in India [157]. India is selected as an example of a developing country where power generation shortage is experienced daily and it is affecting the country's economy and development.

6.4.1 Estimating PV Power in a Developing Country

The purpose of this section is to calculate the PV power output data considering both solar irradiance and air temperature to be involved in finding a probabilistic distribution characterizing the data behavior in a month in a season. From the probabilistic distribution, power data can be regenerated using the Monte-Carlo simulation such that a typical day's hourly PV power data set can be obtained when considering data clustering such that it is possible to schedule power interruption events of houses or some devices. This application is also effective for investigating the effect of the probabilistic nature of PV power on the expected energy that can be supplied to the grid by addressing the uncertainty in PV power output by clustering the data from the Monte-Carlo simulation into representative states to reduce the size of the utilized data.

The PV system under study has a size of 1MW and is made of two module types as given in Table 6.1. The power of PV system can be calculated by following the equation below where P_{new} is the new calculated PV system power after deducting system losses discussed in [153, 158], t is the time of the day, m represents a month and s represents a season, P_{max} is the maximum power produced from PV system when PV losses are not considered as in (6-16), and ψ is a factor indicating system total losses as in (6-17) and (6-18) where module temperature losses shown by (6-19) can be obtained from [159]:

$$P_{new}(t,m,s) = P_{\max}(t,m,s) + \psi * P_{\max}(t,m,s) \qquad \textbf{(6-15)}$$

The maximum power from the PV system given by the equation below [144] depends on four factors which are the open circuit voltage of the module (V_{oc}) in (6-20)[160-162], the short circuit current (I_{sc})

in (6-21) [144, 151, 152, 154], the number of both parallel and series modules in a PV system (*N*) and the fill factor (*FF*) in (6-22) [135, 144, 151, 163]. The first two factors are dependent on the temperature of the cell as given by (6-23) according to [144, 151, 152, 164, 165].

$$P_{\max}(t,m,s) = V_{oc}(t,m,s) * I_{sc}(t,m,s) * N * FF \tag{6-16}$$

$$\psi = -\begin{cases} ((\psi_{solar\ radiation\ loss}+1)+(\psi_{module\ mismatch\ loss}+1)+(\psi_{DC\ cable\ loss}+1)+(\psi_{module\ soiling\ loss}+1)) & \forall T_{cell}(t,m,s) \le T_{stc} \\ (\psi_{solar\ radiation\ loss}+1)+(\psi_{module\ mismatch\ loss}+1)+(\psi_{DC\ cable\ loss}+1)+(\psi_{module\ soiling\ loss}+1)+(\psi_{module\ temperature\ loss}) & \forall T_{cell}(t,m,s) > T_{stc} \end{cases}$$

(6-17) & **(6-18)**

$$\psi_{module\ temperature\ loss} = \varsigma_{power}[T_{cell}(t,m,s) - T_{stc}] \tag{6-19}$$

$$V_{oc}(t,m,s) = V_{oc@stc}\left(1+\tau_{voltage}[T_{cell}(t,m,s)-T_{stc}]\right) \tag{6-20}$$

$$I_{sc}(t,m,s) = I_{sc@stc}\left(1+\iota_{current}[T_{cell}(t,m,s)-T_{stc}]\right) * \frac{\lambda(t,m,s)}{\lambda_{@stc}} \tag{6-21}$$

$$FF = \frac{V_{mp} * I_{mp}}{V_{oc} * I_{sc}} \tag{6-22}$$

$$T_{cell}(t,m,s) = T_{external}(t,m,s) + \frac{\lambda(t,m,s)}{\lambda_{@NCOT}}[NCOT - T_{NCOT}] \tag{6-23}$$

where $\psi_{module\ soiling\ loss}$ is the negative value of the efficiency accounting for module soiling losses, $\psi_{module\ mismatch\ loss}$ is the negative value of the efficiency accounting for module mismatch losses, $\psi_{DC\ cable\ loss}$ is the negative value of the efficiency accounting for DC cable loss, $\psi_{solar radiation loss}$ is the negative value of the efficiency accounting for solar radiation loss, $\psi_{module\ temperature\ loss}$ is module's temperature loss. These losses are discussed in [153, 158]. $V_{oc@stc}$ is an open circuit voltage of PV module determined at a standard test condition measured in Volt, $\tau_{voltage}$ is a voltage-temperature coefficient measured in %/^{o}C, T_{cell} is the operating PV cell temperature given in ^{o}C as shown in (6-19), T_{stc} is the PV cell temperature measured at standard test condition in ^{o}C, $I_{sc@stc}$ is the short circuit current of PV module determined at the standard test condition in Ampere, $\iota_{current}$ is the current-temperature coefficient of PV module from the manufacture measured in %/^{o}C, λ is the operating global solar irradiance in Watt/m^2, $\lambda_{@stc}$ is the solar irradiance at the standard test condition in Watt/m^2,

V_{mp} is PV module voltage as determined at the maximum power point, I_{mp} is the PV module's current as determined at the maximum power point, *NCOT* is the nominal cell operating temperature reached by PV module open circuited cells at an ambient air temperature of (T_{NCOT}), a wind velocity of 1m/s and a solar irradiance at the surface of the cell of ($\lambda_{@NCOT}$). In this case, the solar cells are attached as an open back side as in [166]. The values of these parameters are provided in Table 6.1.

Table 6.1: Parameters used in PV power output model

Parameter	Value	Parameter	Value
$\tau_{voltage}$ [167]	-0.365%/ºC	T_{NCOT} [144, 151, 152, 164]	$20^o C$
$\iota_{current}$ [167]	0.035%/ ºC	$\lambda_{@NCOT}$ [144, 151, 152, 164]	$800\ Watt/m^2$
V_{mp} [167]	$28.63V$ for $225PV$ module $29.60V$ for $240PV$ module	ς_{power} [167]	-0.45%/ºC
I_{mp} [167]	$7.93A$ for $225PV$ module $8.12A$ for $240PV$ module	$\psi_{module\ mismatch\ loss}(PV_{module-tolerance})$ due to connection of series/ parallel modules [167]	-97.6%
I_{sc} [167]	$8.52A$ for $225PV$ module $8.58A$ for $240PV$ module	$\psi_{DC\ cable\ loss}$	-98.7%
V_{oc} [167]	$37.50V$ for $225PV$ module $37.50V$ for $240PV$ module	$\psi_{solar radiation loss}$ due to reflection from glass on PV surface	-97%
$NOCT$ [167]	$45^o C$	$\psi_{module\ soiling\ loss}$ due to dust	-95.5%
$\lambda_{@stc}$ [168]	$1000\ Watt/m^2$	T_{stc} [168]	$25^o C$

The probabilistic nature of the PV power output will be modeled for every hour in the day such that each month in a season can be represented by a typical day suitable for utilizing the PV power for scheduling supply for houses or their devices to minimize the severity of the power generation shortage. Furthermore, the model will be used to derive representative states of the solar PV power output at an hour such that uncertainty in power production from this variable resource can be addressed to estimate the expected energy that can be supplied to residential demand as will be shown later in this chapter.

6.4.2 Chosen Probabilistic Distributions

59 distributions to fit the PV power data are tested considering Kolmogorov-Smirnov Test (KV Test). It is found that 85% of the time, wakeby distribution is the best distribution characterizing the hourly calculated PV power as found from the previous section. Therefore, wakeby distribution is chosen to define the probabilistic performance of the hourly PV system's power. To prove the distribution when using the Monte-Carlo simulation for PV power data regeneration such that the uncertainty is

addressed, the error between the distribution featuring the data and the data obtained through the Monte-Carlo simulation is determined.

There are specific hours at which wakeby distribution is hard to be regenerated using the Monte-Carlo simulation due to the difficulty in meeting the stopping criteria for that distribution in the simulation platform. In this case, wakeby distribution is the second best fit. As an alternative to avoid such a difficulty, the first best fit distribution is chosen to characterize the probabilistic behavior of the hourly PV power data. This distribution is the general extreme value distribution.

6.4.2.1 KV Test

The Kolmogorov-Smirnov Test is used to determine how good the distribution is in fitting the PV power data. By using such a test, it is possible to determine if the data relates to a specific distribution. The test is based on increasingly ordering the data as ($\underline{x}_1$, $\underline{x}_2$,……, $\underline{x}_{\bar{n}}$) and then calculating the empirical cumulative distribution as given by the following equation [169, 170] where $\bar{n}(\bar{i})$ represents the rank of the PV power data point given that the first data point in the ordered set is given the order zero and $\bar{n}$ is the total number of PV power data points.

$$\bar{E}_{\bar{n}}(\underline{x}) = \bar{n}(\bar{i}) / \bar{n} \qquad \textbf{(6-24)}$$

The maximum vertical difference between the theoretical cumulative distribution function (*F*) and the empirical cumulative distribution function defines a *KS* statistic that can be determined following the equation below according to [169, 170]. It is essential to clarify that the best fit of the data representing the power generated from the PV system will be characterized by the smallest value of the *KS Statistic*.

$$KS\ \ Statistic = \max_{1 \le \bar{i} \le \bar{n}} \left(F_{\bar{n}}(\underline{x}_{\bar{i}}) - \frac{(\bar{i}-1)}{\bar{n}}, \frac{\bar{i}}{\bar{n}} - F_{\bar{n}}(\underline{x}_{\bar{i}})\right) \qquad \textbf{(6-25)}$$

6.4.2.2 Wakeby Distribution

Wakeby distribution accurately models the probabilistic behavior of PV power by accounting for events in the tail of the wakeby distribution to aid the application of solar power production to consequently schedule houses or their devices' supply. Wakeby distribution for PV power modelling is preferred over bimodal beta distribution for solar irradiance modelling, where data in the latter are to be categorized into two groups each with unimodal distribution as indicated in [144]. Such categorization is not needed with wakeby distribution. Wakeby distribution is operative for high production return phases as well as matching events in frequency analysis in comparison to what can be predicted with the present data [171]. Wakeby distribution is an innovative distribution that is well known for overcoming the shortages in traditional distributions [172]. This distribution is well known for its five parameters. This is considered to be a prominent increase in the number of parameters describing a distribution in comparison to the traditional distributions that are described by either two or three parameters [172]. Wakeby distribution is known for following the shapes of skew distributions, such as extreme value distribution, log-normal distribution and Pearson type III distribution. Since it is represented by five parameters, its flexibility is visible in attaining extensive range of distributional shapes in comparison to traditional distributions. According to the value of these parameters, wakeby distribution can feature a heavy upper tail leading to data sets with occasional high outliers. Wakeby distribution is appropriate to feature realistic observations as a result of its finite lower bound. Moreover, its random samples may be produced easily given its quantile function [173].

The transformation below [174] characterizes wakeby distribution where $\underline{x} \geq \varepsilon$.

$$\underline{x} = \varepsilon + \frac{\bar{\alpha}}{\bar{\beta}}\left(1-(1-F)^{\bar{\beta}}\right) - \frac{\bar{\gamma}}{\bar{\delta}}\left(1-(1-F)^{-\bar{\delta}}\right) \tag{6-26}$$

This equation can be simplified, as shown below [172], because what to be considered when plotting the distribution is how the parameters are related. The values of $\bar{\alpha}$, $\bar{\beta}$ and ε affect the peak location when plotting the distribution. On the other hand, $\bar{\delta}$ and $\bar{\gamma}$ affect the height when plotting the distribution.

$$\underline{x} = -\bar{a}(1-F)^{\bar{b}} + \bar{c}(1-F)^{-\bar{d}} + \bar{e} \tag{6-27}$$

where $\bar{a} = \frac{\bar{\alpha}}{\bar{\beta}}$, $\bar{b} = \bar{\beta}$, $\bar{c} = \frac{\bar{\gamma}}{\bar{\delta}}$, $\bar{d} = \bar{\delta}$, and $\bar{e} = \varepsilon + \frac{\bar{\alpha}}{\bar{\beta}} - \frac{\bar{\gamma}}{\bar{\delta}}$.

The probability density function of wakeby distribution is described by the equation below where *j* can be calculated following (6-29) [174, 175].

$$f(\underline{x}) = \frac{(1 - F(\underline{x}))^{\bar{\delta}+1}}{\bar{\alpha} j + \bar{\gamma}} \quad \textbf{(6-28)}$$

$$j = (1 - F(\underline{x}))^{\bar{\beta}+\bar{\delta}} \quad \textbf{(6-29)}$$

Wakeby distribution is fitted to the hourly PV power data during day light hours for twelve months in a year, involving seven years solar irradiance data as well as air temperature data.

6.4.2.3 General Extreme Value Distribution

When it is hard to regenerate the wakeby distribution data using the Monte-Carlo simulation because of the stopping criteria of this simulation, the general extreme value distribution as the first best distribution fitting the data during such hours is utilized as a substitute to wakeby distribution, where the value of the $\bar{d}$ parameter is above 0.5 resulting in an infinite variance and therefore leading to a significant error in the Monte-Carlo generated third and fourth raw moments. The general extreme value distribution has cumulative and probabilistic density functions described by the equations below [176, 177]. This type of distribution is recognized for describing extreme events.

$$F(\underline{x}) = \begin{cases} \exp(-(1+\hat{k}z)^{-\frac{1}{\hat{k}}}) & \hat{k} \neq 0 \\ \exp(-\exp(-z)) & \hat{k} = 0 \end{cases} \quad \textbf{(6-30) \& (6-31)}$$

$$f(\underline{x}) = \begin{cases} \frac{1}{\hat{\sigma}} \exp(-(1+\hat{k}z)^{-\frac{1}{\hat{k}}})(1+\hat{k}z)^{-1-\frac{1}{\hat{k}}} & \hat{k} \neq 0 \\ \frac{1}{\hat{\sigma}} \exp(-z - \exp(-z)) & \hat{k} = 0 \end{cases} \quad \textbf{(6-32) \& (6-33)}$$

where $z = \frac{\underline{x} - \mu}{\hat{\sigma}}$ and $\hat{k}, \mu$ and $\hat{\sigma}$ are the parameters describing the general extreme value distribution.

6.4.2.4 Monte-Carlo Simulation for Advanced Distributions

The Monte-Carlo simulation is used to regenerate the PV power data following wakeby and general extreme value distributions to imitate the uncertainty in the solar power by presenting how frequent the determined outputs are. This is critical when the target is to evaluate the generation adequacy in the distribution grid by using the PV generated power model for demand scheduling in developing countries. The stopping criteria used in the Monte-Carlo simulation is described below:

The stopping criteria of wakeby Monte-Carlo simulation depends on the error in the values of the four moments. These are the first central moment, the second central moment, the third raw moment and the fourth raw moment. This error is set to be below a tolerance specified by 0.1%. These moments are described by the equations below:

The first central moment (WC_1) is described by the wakeby distribution mean as given below [172]:

$$WC_1 = \frac{\bar{a}}{\bar{b}+1} - \frac{\bar{c}}{1-\bar{d}} \tag{6-34}$$

The second central moment (WC_2) represents the variance of the distribution as indicated below [172]:

$$WC_2 = \frac{\bar{c}^2}{1-2\bar{d}} - \frac{2\bar{a}\bar{c}}{1+\bar{b}-\bar{d}} + \frac{\bar{a}^2}{1+2\bar{b}} - \left(\frac{\bar{c}}{1-\bar{d}} - \frac{\bar{a}}{1+\bar{b}}\right)^2 \tag{6-35}$$

The third raw moment of the wakeby distribution (WR_3) can be calculated as given below [172]:

$$WR_3 = \frac{\bar{c}^3}{1-3\bar{d}} - \frac{3\bar{c}^2\bar{a}}{1+\bar{b}-2\bar{d}} + \frac{3\bar{c}\bar{a}^2}{1+2\bar{b}-\bar{d}} - \frac{\bar{a}^3}{1+3\bar{b}} \tag{6-36}$$

The fourth raw moment of the wakeby distribution (WR_4) is determined as shown below [172]:

$$WR_4 = \frac{\bar{c}^4}{1-4\bar{d}} - \frac{4\bar{c}^3\bar{a}}{1+\bar{b}-3\bar{d}} + \frac{6\bar{c}^2\bar{a}^2}{1+2\bar{b}-2\bar{d}} - \frac{4\bar{c}\bar{a}^3}{1+3\bar{b}-\bar{d}} + \frac{\bar{a}^4}{1+4\bar{b}} \tag{6-37}$$

The first central moment of the data obtained through the Monte-Carlo simulation (DC_1), considering (6-26) is shown below [46] where $\bar{n}$ is the number of the Monte-Carlo generated data points ($\tilde{x}_i$).

$$DC_1 = \frac{1}{\bar{n}} \sum_{i=1}^{\bar{n}} \tilde{x}_i \tag{6-38}$$

The second central moment of the determined Monte-Carlo simulation data (DC_2), considering (6-26) is shown below [46]:

$$DC_2 = \frac{1}{\bar{n}} \sum_{i=1}^{\bar{n}} (\tilde{x}_i - DC_1) \tag{6-39}$$

The second raw moment (DR_2) of the ($\tilde{x}_i - \bar{e}$) Monte-Carlo simulation generated data accounts for the first central moment ($\overline{DC_1}$) as well as the second central moment ($\overline{DC_2}$), as indicated below where (6-42) follows [178, 179].

$$\overline{DC_1} = \frac{1}{n}\sum_{i=1}^{\bar{n}}(\tilde{x}_i - \bar{e}) \qquad \textbf{(6-40)}$$

$$\overline{DC_2} = \frac{1}{n}\sum_{i=1}^{\bar{n}}((\tilde{x}_i - \bar{e}) - \overline{DC_1}) \qquad \textbf{(6-41)}$$

$$DR_2 = \overline{DC_1}^2 + \overline{DC_2} \qquad \textbf{(6-42)}$$

The third raw moment (DR_3) of the $\tilde{x}_i - \bar{e}$ Monte-Carlo generated data is related to the first central moment ($\overline{DC_1}$) and the third central moment ($\overline{DC_3}$) as well as the second raw moment (DR_2), which is in turn related to ($\overline{DC_1}$), as well as the second central moment ($\overline{DC_2}$), as indicated below where (6-43) follows [180], (6-44) follows [181, 182] and (6-45) follows [178, 179]:

$$\overline{DC_3} = \overline{DC_2}^{1.5} .\ Skewness \qquad \textbf{(6-43)}$$

$$Skewness = \frac{\sum_{i=1}^{\bar{n}}(\tilde{x}_i - \bar{e}) - \overline{DC_1}}{(\bar{n}-1)\overline{DC_2}^{1.5}} \qquad \textbf{(6-44)}$$

$$DR_3 = \overline{DC_3} + 3\overline{DC_1}\ .\ DR_2 - 2\overline{DC_1}^3 \qquad \textbf{(6-45)}$$

The fourth raw moment (DR_4) of the $\tilde{x}_i - \bar{e}$ generated data through the Monte-Carlo simulation is related to the first central moment ($\overline{DC_1}$), the fourth central moment ($\overline{DC_4}$), the second raw moment (DR_2) and the third raw moment (DR_3), as indicated below, where (6-46) follows [180], (6-47) follows [181, 183] and (6-48) follows [178, 179].

$$\overline{DC_4} = \overline{DC_2}^2 .\ Kurtosis \qquad \textbf{(6-46)}$$

$$Kurtosis = \frac{\sum_{i=1}^{\bar{n}} (\tilde{x}_i - \bar{e})\overline{DC_1}}{(\bar{n}-1)\overline{DC_2}^{\,2}} \tag{6-47}$$

$$DR_4 = \overline{DC_4} + 4\overline{DC_1} \;.\; DR_3 - 6DR_2 \;.\; \overline{DC_1}^{\,2} + 3\overline{DC_1}^{\,4} \tag{6-48}$$

The error between the distribution's theoretical moment and the calculated moment of the Monte-Carlo generated PV power is set such that it does not exceed 0.1% as indicated below:

The first central moment error (e_{c1}) and the second central moment error (e_{c2}) are shown below:

$$e_{c1} = 100.\frac{\left|WC_1 - \overline{DC_1}\right|}{\left|WC_1\right|} \tag{6-49}$$

$$e_{c2} = 100.\frac{\left|WC_2 - \overline{DC_2}\right|}{\left|WC_2\right|} \tag{6-50}$$

The third raw moment error (e_{R3}) and the fourth raw moment error (e_{R4}) are given below:

$$e_{R3} = 100.\frac{\left|WR_3 - \overline{DR_3}\right|}{\left|WR_3\right|} \tag{6-51}$$

$$e_{R4} = 100.\frac{\left|WR_4 - \overline{DR_4}\right|}{\left|WR_4\right|} \tag{6-52}$$

When it is hard to apply the wakeby stopping criteria in the Monte-Carlo simulation, the general extreme value distribution is a substitute for wakeby distribution. The stopping criteria in such cases can be described by the error between the central moments describing the distribution and those of the Monte-Carlo generated PV power data. The error is specified not to exceed 0.1% as a tolerance. GC_1 and GC_2 indicate the general extreme value distribution's first central moment [184] and second central moment, respectively. GC_1 and GC_2 are valid for $\hat{K} < 0.5$ according to [185] where $\Gamma(\,)$ in (6-57) is the gamma function [186].

$$e_{ec1} = 100.\frac{\left|GC_1 - DC_1\right|}{\left|GC_1\right|} \tag{6-53}$$

$$e_{ec2} = 100.\frac{|GC_2 - DC_2|}{|GC_2|} \quad \textbf{(6-54)}$$

$$GC_1 = \mu + \hat{\sigma}\frac{-1+\Gamma(1-\hat{k})}{\hat{k}} \quad \textbf{(6-55)}$$

$$GC_2 = \frac{\hat{\sigma}^2}{\hat{k}^2}\left(\Gamma(1-2\hat{k}) - \Gamma^2(1-\hat{k})\right) \quad \textbf{(6-56)}$$

$$\Gamma(t) = \int_0^\infty x^{t-1}\ e^{-x}dx \quad \textbf{(6-57)}$$

6.4.2.5 Proof of Method

A sample of the found results displaying PV power wakeby distribution and the PV power Monte-Carlo generated data following the earlier presented stopping criteria are shown in Figure 6.3. The displayed results are for 9am in the month of April utilizing seven years hourly calculated PV power. The top figure represents the wakeby distribution fitting the PV power data histogram. On the other hand, the second figure displays the PV power wakeby distribution fitting the PV power Monte-Carlo generated data. The third figure presents a comparison of the wakeby graph plotted for the original PV power data and the wakeby graph plotted for the Monte-Carlo simulation data on the histogram of the original data. The cumulative distribution functions for both cases are shown in the bottom figure. Table 6.2 compares the parameters determined for both cases.

Table 6.2: Wakeby distribution parameters

Parameter	$\bar{e}$	$\bar{a}$	$\bar{c}$	$\bar{b}$	$\bar{d}$
Data of PV output power	0.4171	0.2900	-0.0876	10.2870	-0.5222
MC of PV output power	0.4166	0.2905	-0.0873	10.3450	-0.5295
Error %	0.1061	0.1656	0.3014	0.5607	1.3786

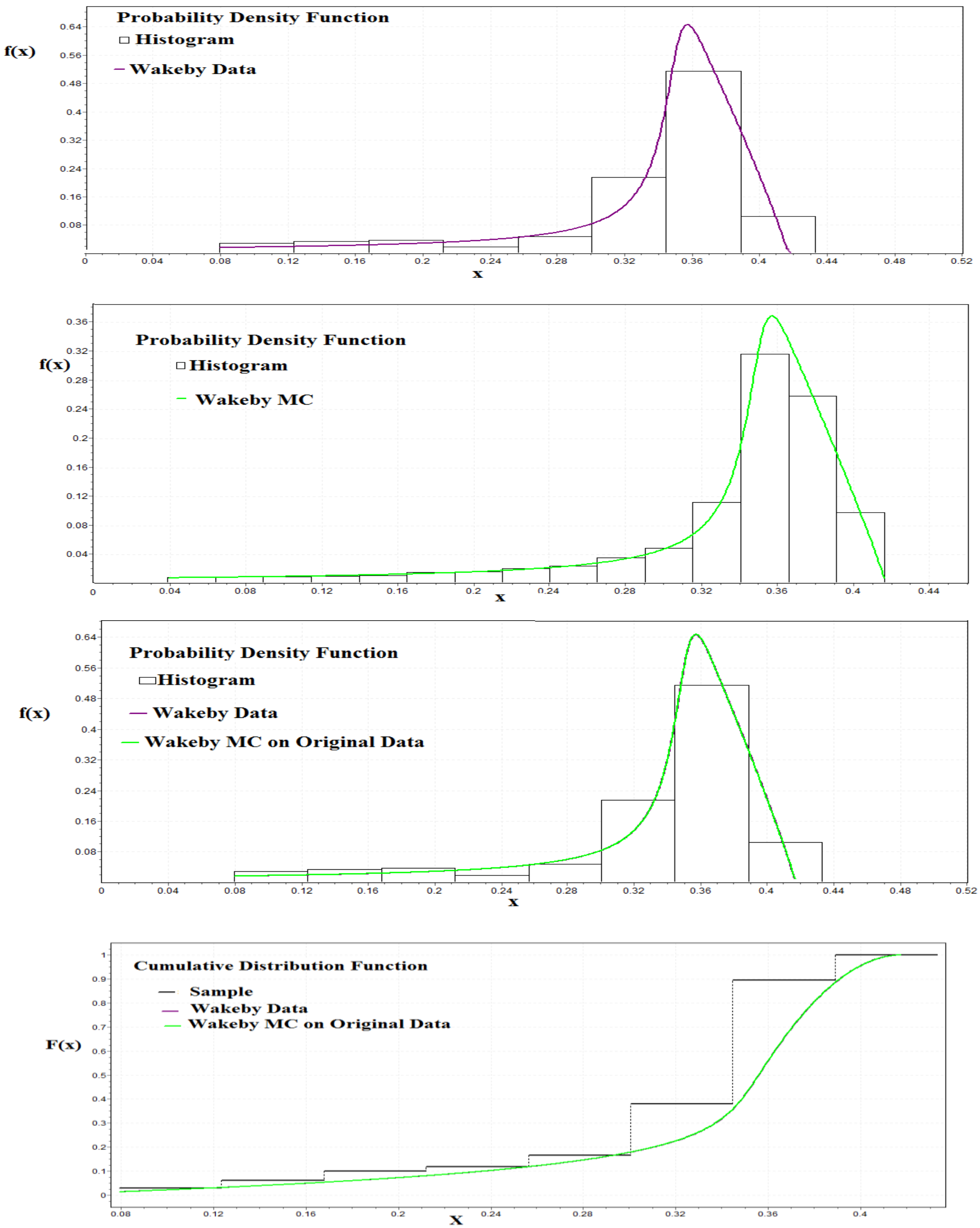


Figure 6.3: Wakeby distribution for 9am of the month of April

It is possible to validate the results by applying the following steps: 1) Evaluating the inverse of the cumulative distribution function at alternative probabilities for the original calculated PV power data and the Monte-Carlo simulation generated PV power data. 2) Calculating the error between them. The validation of the result is shown in Table 6.3. It can be noticed from Table 6.3 that the calculated error is found to be very small. This small error validates the proposed stopping criteria for the Monte-Carlo simulation. This method will be beneficial for accurate modeling of the PV power random data when targeting scheduling problems.

Table 6.3: Validating the results

	Wakeby at 9am in April			General Extreme at 1pm in January		
Probability	x(P) using data	x(P) using MC	Error %	x(P) using data	x(P) using MC	Error %
1	0.4166	0.4170	0.1032	0.5481	0.5480	0.0000
0.9	0.3908	0.3907	0.0205	0.5413	0.5413	0.0018
0.8	0.3794	0.3793	0.0316	0.5313	0.5314	0.0132
0.7	0.3705	0.3703	0.0297	0.5186	0.5187	0.0251
0.6	0.3628	0.3627	0.0248	0.5026	0.5028	0.0398
0.5	0.3559	0.3558	0.0169	0.4824	0.4827	0.0560
0.4	0.3485	0.3485	0.0172	0.4562	0.4566	0.0789
0.3	0.3371	0.3370	0.0326	0.4205	0.4209	0.1118
0.2	0.3101	0.3099	0.0806	0.3670	0.3677	0.1689
0.1	0.2363	0.2360	0.1312	0.2694	0.2702	0.3081
0.05	0.1607	0.1607	0.0436	0.1655	0.1665	0.6165
0.025	0.1069	0.1071	0.1965	0.0564	0.0576	2.0907
0.02	0.0945	0.0948	0.3069	0.0204	0.0216	6.0814

6.4.2.6 Estimated PV Energy

This section shows the results of modeling the PV power output accounting for both solar irradiance and ambient air temperature. Such a model is more useful than using a probabilistic model of solar irradiance only and then reutilizing it to estimate the PV power output with no emphasis on the probabilistic nature of ambient air temperature.

Figure 6.4 displays the PV energy for different months in the year involving seven years worth of data from 2002 to 2008. The energy graphed in this figure involves the realistic hourly solar radiation and ambient air temperature data. Figure 6.5 summarizes how PV power can be estimated by accounting for ambient air temperature differently. The energy found in each case shown in Figure 6.5 is plotted in Figure 6.6. The realistic solar energy that is a function of the realistic hourly solar radiation and ambient air temperature data is specified by the reference line that is the zero axis. When the PV power is estimated using the solar irradiance model and after that using one of the analysis techniques for the ambient air temperature as has been done in literature, these techniques will lead to either under or over prediction of the realistic PV power. These techniques make the consideration of the solar irradiance model to find the PV power in [144, 151] not effective when the objective is to consider the optimal utilization of the PV system to schedule power interruption. In developing countries where power generation shortage is an issue, these techniques will affect classifying the power cuts' zones and assigning power interruption durations to these zones. In some situations such as the case of lesser estimated PV energy than the actual energy, tracking the maximum power of the PV system can cause an under estimation. This is well described by Figure 6.7.

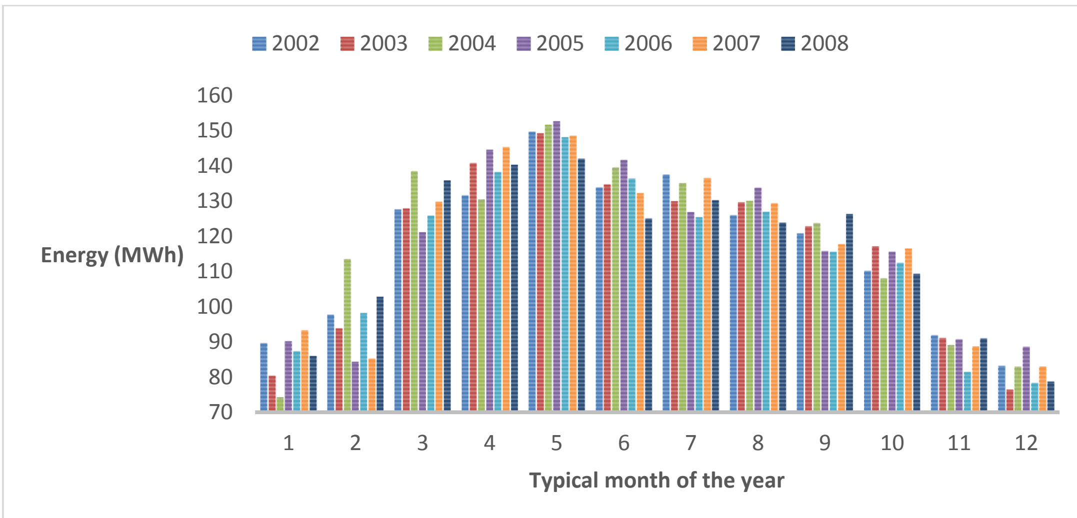


Figure 6.4: PV energy characterizing different months of the year

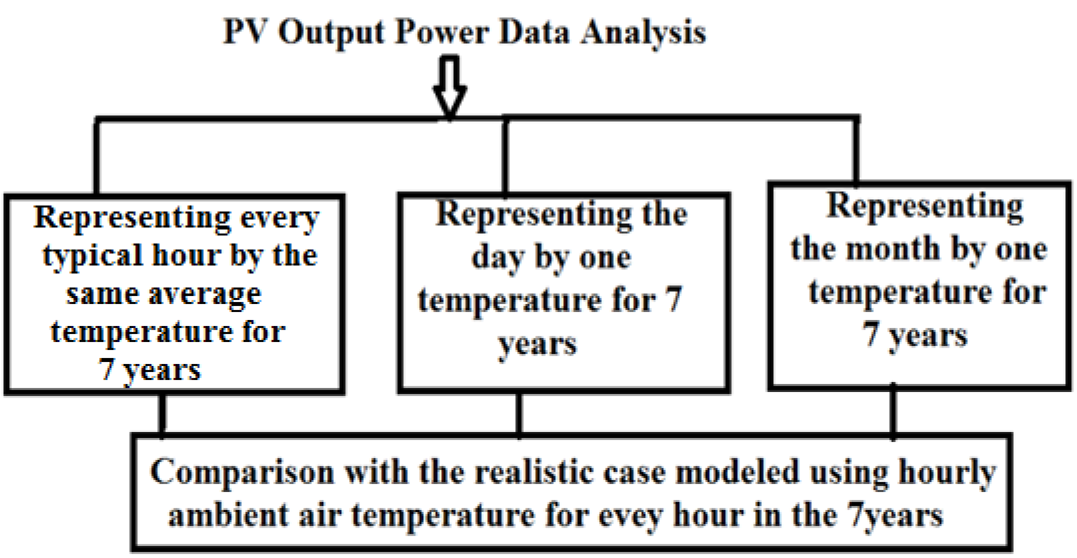


Figure 6.5: PV power data analysis

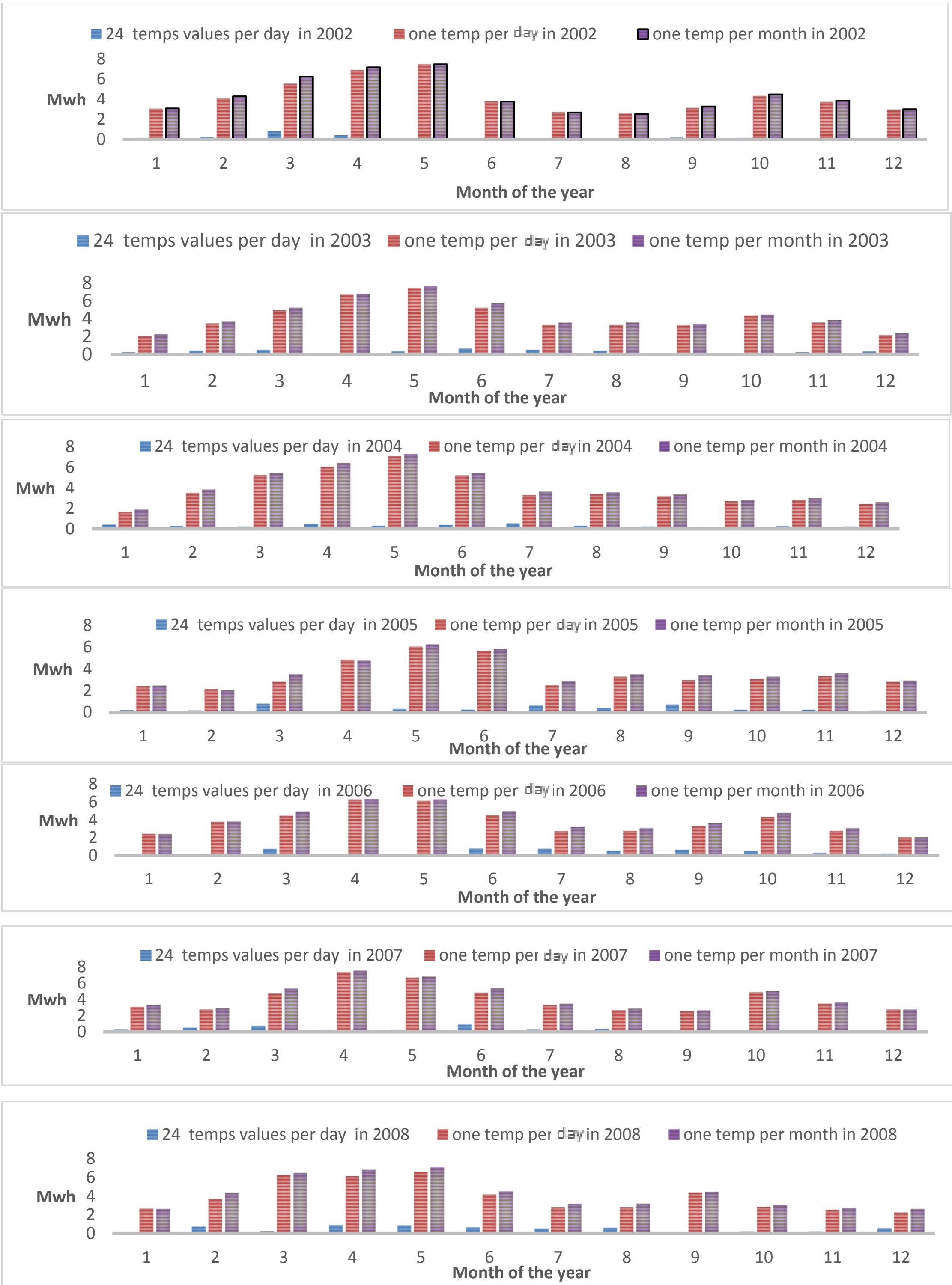


Figure 6.6: PV Energy for seven years following PV power data analysis system

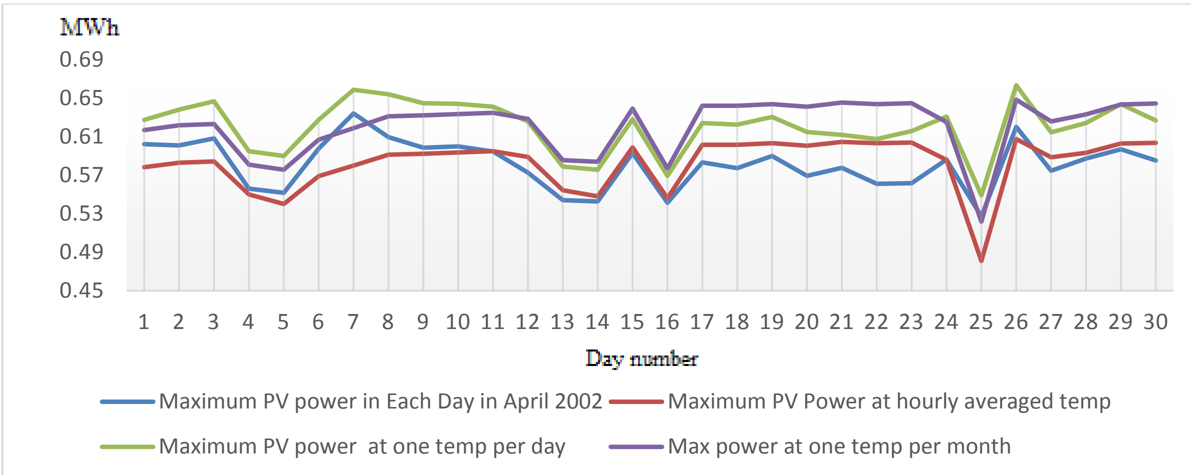


Figure 6.7: PV Energy per day accounting for air temperature differently in the month of April considering 7years data

6.4.3 .The 5kW Solar PV System Power Output

The PV power output as a percentage of the the assumed 5kW PV system discussed in section 6.2 is shown in Figure 6.8. The PV power output is determined for typical winter and summer days in selected months in these seasons. The PV power output is calculated as an expected value of the clustered data generated from the MCS as has been emphasized earlier in section 6.2.

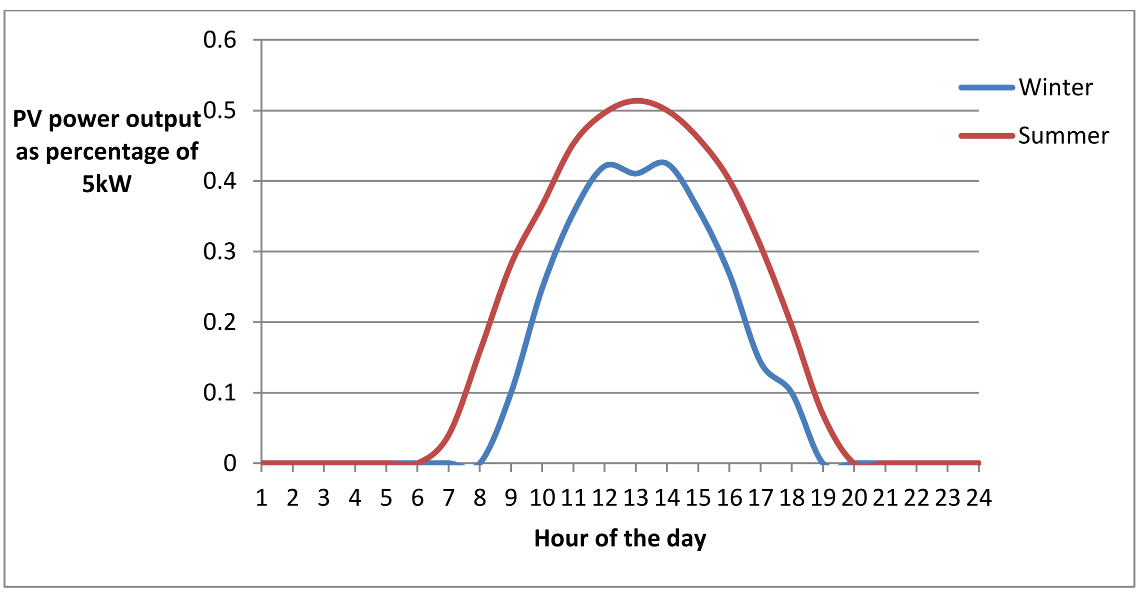


Figure 6.8: PV power output as a percentage of typical PV system size

6.5 Sizing Wind Turbines and PV Systems to Address Power generation shortage

Sizing wind turbines and solar PV systems to address the power generation problem in developing countries can be looked at from three perspectives. The first perspective is the utility aspect of finding the number of wind turbines considering the hourly available power generation and expected demand. The second perspective is based on minimizing the size of wind turbines and solar PV systems accounting for certain houses' full power interruption. The third perspective is based on sizing the wind turbines and solar PV systems considering residential devices' scheduling to minimize the size of such systems while maximizing the consumers' access to electricity. These aspects are discussed below.

6.5.1 Sizing Wind Turbines and Solar PV Systems based on Generation-Expected Demand Status

The utility company can consider the generation-demand status to address the power generation shortage by utilizing wind turbines or solar PV systems. In order to clarify the typical approach in sizing wind turbines and solar PV systems required to address the power generation shortage in developing countries, it is necessary to understand the current status of power generation and expected demand of the system under study (previously shown in Chapter 4). It can be seen from Figure 4.13 and Figure 4.14 that the available power is not sufficient to meet the expected demand of the new feeder to be connected to the grid to accommodate population growth. This problem can be addressedd by considering an alternative source of supply such as wind turbines or solar PV systems . By considering the energy gap between the expected demand and avaliable utility electricity supply, and the possible power generation from wind turbine modeled in section 6.3, the number of wind turbine systems demanded can be found as given in Table 6.4 where each wind turbine is rated at 10kW. In this case, a maximum of 24.9 wind turbines are needed in winter and a maximum of 6.14 wind turbines are needed in summer. If solar PV system modeled in section 6.4 is to be considered, then a maximum of 5.4 PV systems each rated at 5kW are needed to solve the shortage completely during the hours of solar radiation (9am-6pm) in winter. On the other hand, a maximum of 8.1 PV systems each rated at 5kW are needed to solve the shortage completely during the hours of solar radiation (7am-7pm) in summer. This is further clarified by Table 6.5. These number of wind turbines or solar PV systems will solve the power generation shortage completely during the hours characterized by wind speed generating power or solar radiation, respectively. The number of such systems (*number*) is obtained by considering the following optimization problem Where *Pg* is the maximum available power generation, *t* is the time of the day, *PQ* is the maximum available reactive power generation, *Pwind* is the 10kW wind turbine power output, *Transformer Rating* is the rating of the transformer that is 100kVA and $P_{total\text{-}demand}$ is the expected total demand of the new feeder to be connected to the grid. $Pwind_{t,s}$ is replaced with the term ($Psolar_{t,s}*5kW$) when the utility is to consider solar PV system instead of wind turbines system. In this case *Psolar* is the PV power output as a ratio of the used PV system rating (5kW) and *number* is the number of PV systems needed instead of the number of wind turbines.

$$\max_{over\ all\ t}(\min \quad number_{t,s}) \tag{6-58}$$

Subject to

$$\sqrt{(Pg_{t,s} + number_{t,s} * Pwind_{t,s})^2 + PQ_{t,s}{}^2} \leq Transformer\ Rating \tag{6-59}$$

$$Pg_{t,s} + number_{t,s} * Pwind_{t,s} - P_{total-demandt,s} = 0 \tag{6-60}$$

The number of wind turbines or solar PV systems needed to address the power generation shortage during the effective wind speed hours generating power or solar radiation is determined from the utility aspect to meet most of the demand as is without controlling the behaviour of the load as will be proposed later on in this chapter to minimize the size of the wind turbines' farm or the solar PV system. Even though the numbers in the table below are displayed as positive real numbers rather than integers, this display can be clarified as follows: In the case of utilizing wind turbines, the utility can select installing the integer number of wind turbines and adjust for any difference with respect to the number dsiplayed in the table by installing other types of wind turbines that can output the difference in power or the utility can decide to go for the next integer number of wind turbines at an extra cost while controlling the power output of the wind turbine to account for this difference or it can stay at a smaller integer number while incorporating power interruption at wind speed hours generating power. On the other hand, when solar PV systems are utilized, the display of real numbers of demanded PV systems can be clarified from two aspects. First, the PV system is assumed to control its output based on demand. Second, PV system is composed of modules that can be added or removed based on the utility decision toward residential load power interruption and according to the available funds supporting such projects to maximize the penetration of the PV system in the grid. In other words, by considering 5.4 PV systems each rated at 5kW in winter, the utility can solve the power interruption problem completely during the hours of the available solar radiation or it can decide to go for a smaller number (1.4) by incorporating the load power interruption at 9am and 18pm due to low solar radiation levels and at 5pm due to high energy demand. On the other hand, the solar power is low at 7am in summer. The power interruption might be allowed at this hour to reduce the system size to the next possible size, which is 2.6 PV systems.

Table 6.4: Sizing wind turbines from power generation-expected demand aspect of the utility

Hour of a typical winter day	1	2	3	4	5	6
Available utility generation (kW)	22.774058	20.794918	30.246004	19.469673	19.653496	33.983365
Total expected demand with system losses (kW)	22.941651	20.830162	32.354923	19.504127	19.725204	36.814067
Number of wind turbine systems	**0**	**5.5**	**0**	**0.4**	**14.7**	**20.1**
Wind power output of 10kW turbine (kW)	0	0.0064355	0	0.096831	0.0048844	0.1407486
Generation-expected demand gap (kW)	-0.1675933	0	-2.1089185	0	0	0
Hour of a typical winter day	7	8	9	10	11	12
Available utility generation (kW)	37.820767	49.906741	42.614716	32.450633	44.463681	33.420964
Total expected demand with system losses (kW)	40.480352	54.063421	44.830476	32.62347	46.966137	33.852238
Number of wind turbine systems	**0**	**24.9**	**3.1**	**0.2**	**2.7**	**0.5**
Wind power output of 10kW turbine	4.43E-05	0.1668845	0.7059022	1.1276939	0.9314608	0.9452074
Generation-expected demand gap (kw)	-2.6595853	0	0	0	0	0
Hour of a typical winter day	13	14	15	16	17	18
Available utility generation (kW)	40.638469	39.909494	40.528077	39.555106	52.853256	36.657465
Total expected demand with system losses (kW)	42.476057	41.606842	42.474484	41.249312	56.728526	37.395474
Number of wind turbine systems	**2.1**	**1.8**	**2.9**	**1.4**	**63.0**	**0**
Wind power output of 10kW turbine	0.8767388	0.9393805	0.6622242	1.2240421	0.0614806	0
Generation-expected demand gap (kW)	0	0	0	0	0	0
Hour of a typical winter day	19	20	21	22	23	24
Available utility generation (kW)	35.9986	33.909561	33.243165	41.168711	27.313886	21.478941
Total expected demand with system losses (kW)	36.607374	34.371183	33.903746	43.884688	27.991158	21.65241
Number of wind turbine systems	**0**	**0**	**0**	**0**	**0**	**0**
Wind power output of 10kW turbine	0	0	0	0	0	0
Generation-expected demand gap (kW)	-0.6087743	-0.4616226	-0.6605806	-2.7159766	-0.6772712	-0.1734693
Hour of a typical summer day	1	2	3	4	5	6
Available utility generation (kW)	21.9078	19.76894	19.47411662	18.45123	18.93818	21.55437
Total expected demand with system losses (kW)	22.027054	19.786327	19.537207	18.468911	19.016825	21.876615
Number of wind turbine systems	**0.15**	**0.02**	**0.13**	**0.04**	**0.38**	**2.32**
Wind power output of 10kW turbine	0.80304	0.769687	0.504540486	0.473227	0.205129	0.139083
Generation-expected demand gap (kW)	0	0	0	0	0	0
Hour of a typical summer day	7	8	9	10	11	12
Available utility generation (kW)	34.20147951	35.76384679	39.56590506	32.2287389	34.07275462	34.79080669
Total expected demand with system losses (kW)	35.819271	37.085254	40.897909	32.349294	34.255262	35.020090
Number of wind turbine systems	**6.14**	**3.17**	**2.43**	**0.18**	**0.38**	**0.37**
Wind power output of 10kW turbine	0.263664	0.416997	0.547819	0.682419	0.47569	0.613489
Generation-expected demand gap (kW)	0	0	0	0	0	0
Hour of a typical summer day	13	14	15	16	17	18
Available utility generation (kW)	42.26933171	42.48859036	43.37284048	41.45960328	41.50462451	34.0278973
Total expected demand with system losses (kW)	43.439779	43.644833	44.633991	42.614307	42.704966	34.327631
Number of wind turbine systems	**2.64**	**2.48**	**1.97**	**2.33**	**1.76**	**0.51**
Wind power output of 10kW turbine	0.442739	0.46587	0.641174	0.495782	0.683912	0.585359
Generation-expected demand gap (kW)	0	0	0	0	0	0
Hour of a typical summer day	19	20	21	22	23	24
Available utility generation (kW)	33.32378	32.48081	33.16985	33.07152	31.5633	24.46938
Total expected demand with system losses (kW)	33.660192	32.755120	33.528339	33.377141	31.929903	24.577510
Number of wind turbine systems	**0.62**	**0.34**	**0.41**	**0.38**	**0.40**	**0.10**
Wind power output of 10kW turbine	0.541977	0.811816	0.872256	0.808845	0.914144	1.120951
Generation-expected demand gap (kW)	0	0	0	0	0	0

Table 6.5: Sizing solar PV system considering power generation-expected demand status

Hour of a typical winter day	1	2	3	4	5	6
Total generation (kW)	22.774058	20.794918	30.246004	19.469673	19.653496	33.983365
Total demand with feeder losses (kW)	22.941651	20.830162	32.354923	19.504127	19.725204	36.814067
Number of PV systems	**0**	**0**	**0**	**0**	**0**	**0**
PV output power as percentage of 5kW	0	0	0	0	0	0
Generation-expected demand gap (kW)	-0.1675933	-0.0352447	-2.1089185	-0.0344543	-0.0717076	-2.8307015
Hour of a typical winter day	7	8	9	10	11	12
Total generation (kW)	37.820767	49.906741	42.614716	32.450633	44.463681	33.420964
Total demand with feeder losses (kW)	40.480352	54.063421	44.830476	32.62347	46.966137	33.852238
Number of PV systems	**0**	**0**	**4.4**	**0.1**	**1.4**	**0.2**
PV power output as percentage of 5kW	0	0	0.0998	0.2481	0.3549	0.421
Generation-expected demand gap (kW)	-2.6595853	-4.1566799	0	0	0	0
Hour of a typical winter day	13	14	15	16	17	18
Total generation (kW)	40.638469	39.909494	40.528077	39.555106	52.853256	36.657465
Total demand with feeder losses (kW)	42.476057	41.606842	42.474484	41.249312	56.728526	37.395474
Number of PV systems	**0.9**	**0.8**	**1.1**	**1.3**	**5.4**	**1.5**
PV power output as percentage of 5kW	0.4105	0.4246	0.3602	0.2684	0.1433	0.0998
Generation-expected demand gap (kW)	0	0	0	0	0	0
Hour of a typical winter day	19	20	21	22	23	24
Total generation (kW)	35.9986	33.909561	33.243165	41.168711	27.313886	21.478941
Total demand with feeder losses (kW)	36.607374	34.371183	33.903746	43.884688	27.991158	21.65241
Number of PV systems	**0**	**0**	**0**	**0**	**0**	**0**
PV power output as percentage of 5kW	0	0	0	0	0	0
Generation-expected demand gap (kW)	-0.6087743	-0.4616226	-0.6605806	-2.7159766	-0.6772712	-0.1734693
Hour of a typical summer day	1	2	3	4	5	6
Total generation (kW)	21.90779862	19.76893821	19.47411662	18.45123275	18.93818439	21.55436928
Total demand with feeder losses (kW)	22.027054	19.786327	19.537207	18.468911	19.016825	21.876615
Number of PV systems	**0**	**0**	**0**	**0**	**0**	**0**
PV output power as percentage of 5kW	0	0	0	0	0	0
Generation-expected demand gap (kW)	-0.119255696	-0.017388456	-0.063090228	-0.017678278	-0.078640633	-0.32224557
Hour of a typical summer day	7	8	9	10	11	12
Total generation (kW)	34.20147951	35.76384679	39.56590506	32.2287389	34.07275462	34.79080669
Total demand with feeder losses (kW)	35.819271	37.085254	40.897909	32.349294	34.255262	35.020090
Number of PV systems	**8.1**	**1.7**	**0.9**	**0.07**	**0.08**	**0.09**
PV power output as percentage of 5kW	0.0399	0.1583	0.2819	0.3659	0.4528	0.4966
Generation-expected demand gap (kW)	0	0	0	0	0	0
Hour of a typical summer day	13	14	15	16	17	18
Total generation (kW)	42.26933171	42.48859036	43.37284048	41.45960328	41.50462451	34.0278973
Total demand with feeder losses (kW)	43.439779	43.644833	44.633991	42.614307	42.704966	34.327631
Number of PV systems	**0.5**	**0.5**	**0.5**	**0.6**	**0.8**	**0.3**
PV output power as percentage of 5kW	0.5137	0.5001	0.4609	0.4013	0.3083	0.1949
Generation-expected demand gap (kW)	0	0	0	0	0	0
Hour of a typical summer day	19	20	21	22	23	24
Total generation (kW)	33.3237763	32.48080803	33.16984639	33.07152478	31.56330354	24.46938019
Total demand with feeder losses (kW)	33.660192	32.755120	33.528339	33.377141	31.929903	24.577510
Number of PV systems	**1.0**	**0**	**0**	**0**	**0**	**0**
PV power output as percentage of 5kW	0.0691	0	0	0	0	0
Generation-expected demand gap (kW)	0	-0.274311797	-0.358492443	-0.305615962	-0.366599734	-0.108129418

6.5.2 Sizing Wind Turbines and Solar PV Systems Considering House Full Power Interruption

In the normal case when no power interruption is assumed, the total expected residential houses' energy demand is 199.5839kWh in a typical winter day and is 117.7454kWh in a typical summer day as has been emphasized in section 4.2.7. Power interruption applied to the individual houses rather than a feeder is one proposed solution to address the power generation shortage in developing countries where there is a demand to expand the current grid to accommodate population growth. Along with this solution, utilizing alternative sources of supply such as wind turbines during effective wind speed hours and solar PV system during solar radiation hours can reduce the severity of the power interruption problem resulting from the deficiency in power generation. To find the number of wind turbines or solar PV systems needed to address this problem, the optimization problem formulation below is used where *objj* is the objective function to be maximized, *o* is a binary variable that is one when the current expected demand at time *t* for house *n* is met and that is zero otherwise, *af* and *bf* are weights assigned to different variables of the objective function that targets maximizing the demand that can be met and minimizing the number of renewable energy systems (wind turbines or PV systems). Even though the optimization problem formulation is shown when utilizing wind turbines, it can be adjusted to reflect the utilization of solar PV systems by replacing ($Pwind_{t,s}$) by ($Psolar_{t,s}*5kW$).

$$. \max \quad objj_s = af_s * (\sum_{t=1}^{24}\sum_{n=1}^{8} o_{n,t,s}) - bf_s * number_s \tag{6-61}$$

This problem is subject to power flow constraints as given below:

$$Pg_{i,t,s} + R * Pwind_{t,s} * number_s - Pd_i * RTS_{t,s} = \sum_{j=1}^{4} [V_{i,t,s} * V_{j,t,s} * Y_{i,j} * \cos(-\theta_{i,j} - \delta_{j,t,s} + \delta_{i,t,s})]) \qquad \forall i = 1 \tag{6-62}$$

$$Pg_{i,t,s} - Pd_i * RTS_{t,s} = \sum_{j=1}^{4} [V_{i,t,s} * V_{j,t,s} * Y_{i,j} * \cos(-\theta_{i,j} - \delta_{j,t,s} + \delta_{i,t,s})]) \quad \forall i \neq 1,4 \tag{6-63}$$

$$Qg_{i,t,s} - Qd_i * RTS_{t,s} = \sum_{j=1}^{4} [V_{i,t,s} * V_{j,t,s} * Y_{i,j} * \sin(-\theta_{i,j} - \delta_{j,t,s} + \delta_{i,t,s})]) \quad \forall i \neq 4 \tag{6-64}$$

$$Pg_{i,t,s} - \sum_{n=1}^{8} o_{n,t,s} * R * P_{residentid-house\,n,t,s} = \sum_{j=1}^{4} [V_{i,t,s} * V_{j,t,s} * Y_{i,j} * \cos(-\theta_{i,j} - \delta_{j,t,s} + \delta_{i,t,s})]) \quad \forall i = 4 \tag{6-65}$$

$$Qg_{i,t,s} - \sum_{n=1}^{8} o_{n,t,s} * R * Q_{residentid-house\,n,t,s} = \sum_{j=1}^{4} [V_{i,t,s} * V_{j,t,s} * Y_{i,j} * \sin(-\theta_{i,j} - \delta_{j,t,s} + \delta_{i,t,s})]) \; \forall i = 4 \tag{6-66}$$

The power generation and expected demand are related as given by the equations below:

$$Pg_{i=1,t,s} + R * Pwind_{t,s} * number_s - Pd_{i=2} * RTS_{t,s} - Pd_{i=3} * RTS_{t,s} - Ploss_{t,s} = \sum_{n=1}^{8} o_{n,t,s} * R * P_{residentid-house\,n,t,s} \quad \textbf{(6-67)}$$

$$Qg_{i=1,t,s} - Qd_{i=2} * RTS_{t,s} - Qd_{i=3} * RTS_{t,s} - Qloss_{t,s} = \sum_{n=1}^{8} o_{n,t,s} * R * Q_{residentid-house\,n,t,s} \quad \textbf{(6-68)}$$

$$Ploss_{t,s} = \sum_{i=1}^{4} \sum_{j=1}^{4} (0.5 * gg_{i,j} * [V^2{}_{i,t,s} + V^2{}_{j,t,s} - 2 * V_{i,t,s} * V_{j,t,s} * \cos(\delta_{j,t,s} - \delta_{i,t,s})]) \quad \textbf{(6-69)}$$

$$Qloss_{t,s} = -\sum_{i=1}^{4} \sum_{j=1}^{4} (0.5 * bb_{i,j} * [V^2{}_{i,t,s} + V^2{}_{j,t,s} - 2 * V_{i,t,s} * V_{j,t,s} * \cos(\delta_{j,t,s} - \delta_{i,t,s})]) \quad \textbf{(6-70)}$$

The voltage level at system busses should be within a range as given by the following constraints:

$$0.95pu \le V_{i,t,s} \le 1.05pu \quad \textbf{(6-71)}$$

$$-\pi \le \delta_{i,t,s} \le \pi \quad \textbf{(6-72)}$$

The power is supplied through bus 1 only and it is within limits as indicated below:

$$Pg_{i \ne 1,t,s} = 0 \quad \textbf{(6-73)}$$

$$Qg_{i \ne 1,t,s} = 0 \quad \textbf{(6-74)}$$

$$Plow_{t,s} \le Pg_{i=1,t,s} \le Pup_{t,s} \quad \textbf{(6-75)}$$

$$Qlow_{t,s} \le Qg_{i=1,t,s} \le Qup_{t,s} \quad \textbf{(6-76)}$$

In order to ensure that most of the power supplied to the demand is obtained from the available power generation rather than the renewable energy systems such that this condition will result in a minimum renewable energy system size, the following constraint is added:

$$Pg_{i=1,t,s} \ge R * Pwind_{t,s} * number_s \quad \textbf{(6-77)}$$

In order to ensure that the power supplied does not exceed the transformer rating, the constraint below is used:

$$\sqrt{(Pg_{i=1,t,s} + R * Pwind_{t,s} * number_s)^2 + (Qg_{i=1,t,s}\ )^2} \le R * Transformer\ Rating \quad \textbf{(6-78)}$$

In winter, power interruption is taking place during hours of no effective wind speed, while the available utility supply is prioritized over the wind power. This prioritizing is to reduce the size of the wind turbine system. In this case, the residential houses' energy demand that can be met is 175.3522kWh in winter and is 117.7454kWh in summer. It can be seen that the enrgy in winter is much less than the actual demand in that season. This difference is due to the fact that in this case house's power interruption is assumed during hours of no wind power or during hours where power from wind is to exceed the available generation to solve the problem. In this case no control is applied on the house devices but rather house's full power interruption is encountered. The number of wind turbines determined in this case is 14.3 in winter and is 6.2 in summer each rated at 10kW. The number of wind turbines determined in summer season will solve the power generation shortage completely as wind speed is considered to be effective for power production over the 24 hours in comparison to the case in winter season where there are some hours with no effective wind speed. For the summer season, GAMS' execution time was 0.031 seconds. Table 6.6 presents the results of the power generation and expected supplied demand when utilizing wind turbines. On the other hand, when solar PV systems are utilized and the above optimization problem is applied, the expected residential houses' energy demand that can be met is 175.9761kWh in winter considering 5.2 PV systems and is 112.627987kWh in summer considering 1.7 PV systems. Each PV system is rated at 5kW. It can be seen that the determined energy is much less than the actual expected energy demand because in this case the house total power interruption is anticipated during hours of no PV supply. For the summer season, GAMS' execution time was 0.031 seconds, while it was 0.015 seconds when considering the winter season. Similarly to the case when wind turbines are utilized, this case does not involve any control on the house's devices. It is important to emphasize that power interruption is encountred at 7am in summer when PV systems are utilized. This is because the optimization problem formulation forces the power obtained from the available generation to be greater than that of PV systems. If this condition is ignored, then the number of PV systems needed such that no power interruption exists at 7am is 8.3 PV systems. In this case 113.7071kWh residential demand is met. Table 6.7 shows the results of the power generation and expected supplied demand when utilizing solar PV systems

Table 6.6: Power generation and expected supplied demand utilizing 14.3 wind turbines in winter and 6.2 wind turbines in summer

Hour of typical winter day	Power produced by 10kw wind turbine (kW)	Power produced by all wind turbines (kW)	Demand of (bus2+bus3 in Figure 4.1) (kW)	Real losses (kW)	Available utility power (kW)	Total power generation (kW)	Expected supplied demand of bus 4 that is shown in Figure 4.1 (kW)	Difference between total power generation and total expected supplied demand (kW)
1	0	0	21.72407	0.2712	22.377	22.377	0.3817	0.0
2	0.006435463	0.092021	20.42711	0.236	20.7751	20.86712	0.204	0.0
3	0	0	19.45439	0.5311	29.1427	29.1427	9.1572	0.0
4	0.096831004	1.384584	19.13015	0.2072	18.152	19.53658	0.1992	0.0
5	0.0048844	0.069842	19.13015	0.178	19.6535	19.72334	0.4152	0.0
6	0.140748609	2.012561	19.45439	0.7541	31.5958	33.60836	13.3999	0.0
7	4.43E-05	0.000633	23.99375	0.9054	35.7838	35.78443	10.8853	0.0
8	0.166884488	2.386278	27.88463	1.7825	48.2018	50.58808	20.921	0.0
9	0.705902226	10.09368	30.80279	1.3614	34.8987	44.99238	12.8282	0.0
10	1.127693872	16.12487	31.12703	0.573	16.5757	32.70057	1.0006	0.0
11	0.931460815	13.31894	31.12703	1.3406	33.6366	46.95554	14.4879	0.0
12	0.94520736	13.5155	30.80279	0.6229	20.407	33.9225	2.4968	0.0
13	0.876738849	12.53647	30.80279	1.2155	30.1203	42.65677	10.6384	0.0
14	0.939380464	13.43218	30.80279	1.1646	28.3617	41.79388	9.8265	0.0
15	0.662224153	9.469129	30.15431	1.2239	33.1779	42.64703	11.2688	0.0
16	1.224042096	17.50255	30.47855	1.1478	23.9326	41.43515	9.8088	0.0
17	0.061480571	0.879109	32.09975	1.917	52.4297	53.30881	19.2921	0.0
18	0	0	32.42399	0.7214	36.4587	36.4587	3.3133	0.0
19	0	0	32.42399	0.6964	35.8937	35.8937	2.7733	0.0
20	0	0	31.12703	0.6139	33.7455	33.7455	2.0046	0.0
21	0	0	29.50583	0.5915	32.9608	32.9608	2.8635	0.0
22	0	0	26.91191	0.9939	41.1687	41.1687	13.2629	0.0
23	0	0	23.66951	0.4122	27.2517	27.2517	3.17	0.0
24	0	0	20.42711	0.25	21.4302	21.4302	0.753	0.0

Hour of typical summer day	Power produced by 10kw wind turbine (kW)	Power produced by all wind turbines (kW)	Demand of (bus2+bus3 in Figure 4.1) (kW)	Real losses (kW)	Available utility power (kW)	Total power generation (kW)	Expected supplied demand of bus 4 that is shown in Figure 4.1 (kW)	Difference between total power generation and total expected supplied demand (kW)
1	0.80304	5.001271	20.75135	0.2688	17.0657	22.06697	1.0468	0.0
2	0.769687	4.793553	19.45439	0.2131	15.0266	19.82015	0.152632	0.0
3	0.50454	3.142239	18.80591	0.2116	16.429	19.57124	0.553792	0.0
4	0.473227	2.947223	18.15744	0.186	15.5514	18.49862	0.155176	0.0
5	0.205129	1.277526	18.15744	0.201	17.7712	19.04873	0.69029	0.0
6	0.139083	0.866198	18.80591	0.2697	21.0381	21.9043	2.8286	0.0
7	0.263664	1.642077	20.75135	0.8916	34.2015	35.84358	14.20062	0.0
8	0.416997	2.597023	24.64223	0.994	34.6383	37.23532	11.59902	0.0
9	0.547819	3.411777	28.20887	1.1561	37.6452	41.05698	11.69204	0.0
10	0.682419	4.25005	30.80279	0.5684	28.1794	32.42945	1.058202	0.0
11	0.47569	2.962561	32.09975	0.6328	31.372	34.33456	1.602011	0.0
12	0.613489	3.820761	32.42399	0.6674	31.2832	35.10396	2.012599	0.0
13	0.442739	2.757347	32.09975	1.2571	40.8734	43.63075	10.27393	0.0
14	0.46587	2.901403	32.42399	1.2745	40.9463	43.8477	10.14924	0.0
15	0.641174	3.993181	32.42399	1.3348	40.8357	44.82888	11.0701	0.0
16	0.495782	3.087691	31.45127	1.2246	39.724	42.81169	10.13574	0.0
17	0.683912	4.259352	31.12703	1.2339	38.6379	42.89725	10.53634	0.0
18	0.585359	3.64557	31.12703	0.6454	30.7578	34.40337	2.631	0.0
19	0.541977	3.375391	30.15431	0.6233	30.3552	33.73059	2.95298	0.0
20	0.811816	5.055929	29.83007	0.5884	27.7704	32.82633	2.407848	0.0
21	0.872256	5.432345	29.83007	0.6199	28.1643	33.59665	3.146767	0.0
22	0.808845	5.037424	30.15431	0.6072	28.4067	33.44412	2.682629	0.0
23	0.914144	5.693216	28.20887	0.5649	26.2985	31.99172	3.217931	0.0
24	1.120951	6.981194	23.34527	0.329	17.6422	24.62339	0.949136	0.0

Table 6.7: Power generation and expected supplied demand utilizing 5.2 solar PV systems in winter and 1.7 solar PV systems in summer

Hour of a typical winter day	PV power as percentage of 5kW	PV power output (kW)	Demand of (bus2 +bus3 in Figure 4.1) (kW)	Real losses (kW)	Pg (kW)	Total power generation (Supply+PV) in (kW)	Expected supplied demand of bus 4 that is shown in Figure 4.1 (kW)	Difference between total generation and expected demand (kW)
1	0	0	21.72407	0.2712	22.377	22.377	0.3817	0
2	0	0	20.42711	0.2148	20.7949	20.7949	0.153	0
3	0	0	19.45439	0.5311	29.1427	29.1427	9.1572	0
4	0	0	19.13015	0.1901	19.4697	19.4697	0.1494	0
5	0	0	19.13015	0.2068	19.5176	19.5176	0.1806	0
6	0	0	19.45439	0.7541	33.6084	33.6084	13.3999	0
7	0	0	23.99375	0.9054	35.7845	35.7845	10.8853	0
8	0	0	27.88463	1.5271	47.1889	47.1889	17.7772	0
9	0.0998	2.5742911	30.80279	1.3614	42.4181	44.992391	12.8282	0
10	0.2481	6.3996155	31.12703	0.573	26.301	32.700615	1.0006	0
11	0.3549	9.1544681	31.12703	1.3406	37.8011	46.955568	14.4879	0
12	0.421	10.859485	30.80279	0.6229	23.063	33.922485	2.4968	0
13	0.4105	10.588642	30.80279	1.2155	32.0681	42.656742	10.6384	0
14	0.4246	10.952345	30.80279	1.1646	30.8416	41.793945	9.8265	0
15	0.3602	9.2911789	30.15431	1.2239	33.3558	42.646979	11.2688	0
16	0.2684	6.9232438	30.47855	1.1478	34.5119	41.435144	9.8088	0
17	0.1433	3.6963519	32.09975	2.0141	52.8533	56.549652	22.4358	0
18	0.0998	2.5742911	32.42399	0.7676	34.89	37.464291	4.2727	0
19	0	0	32.42399	0.6964	35.8937	35.8937	2.7733	0
20	0	0	31.12703	0.6139	33.7455	33.7455	2.0046	0
21	0	0	29.50583	0.5915	32.9608	32.9608	2.8635	0
22	0	0	26.91191	0.9939	41.1687	41.1687	13.2629	0
23	0	0	23.66951	0.4122	27.2517	27.2517	3.17	0
24	0	0	20.42711	0.25	21.4302	21.4302	0.753	0
Hour of a typical summer day	PV power as percentage of 5kW	PV power output (kW)	Demand of bus2 +bus3 (kW)	Real losses (kW)	Pg (kW)	Total power power generation (utility supply+PV) in (kW)	Bus 4 expected supplied demand (KW)	Difference between total generation and expected demand
1	0	0	20.751354	0.2629	21.8584	21.8584	0.844162	0
2	0	0	19.454395	0.181	19.7689	19.7689	0.133553	0
3	0	0	18.805915	0.1836	19.4741	19.4741	0.484568	0
4	0	0	18.157435	0.158	18.4512	18.4512	0.135779	0
5	0	0	18.157435	0.1959	18.8405	18.8405	0.487144	0
6	0	0	18.805915	0.2425	20.9224	20.9224	1.874036	0
7	0.0399	0.3387496	20.751354	0.8856	33.7254	34.06415	12.427209	0
8	0.1583	1.3439615	24.642233	0.8666	35.7638	37.107761	11.599021	0
9	0.2819	2.3933211	28.208872	1.1561	38.6637	41.057021	11.692037	0
10	0.3659	3.1064782	30.802792	0.5684	29.323	32.429478	1.058202	0
11	0.4528	3.8442562	32.099751	0.6328	30.4903	34.334556	1.602011	0
12	0.4966	4.2161166	32.423991	0.6674	30.8879	35.104017	2.012599	0
13	0.5137	4.361295	32.099751	1.2571	39.2695	43.630795	10.273928	0
14	0.5001	4.2458315	32.423991	1.2745	39.6019	43.847731	10.149242	0
15	0.4609	3.9130249	32.423991	1.3348	40.9159	44.828925	11.0701	0
16	0.4013	3.407023	31.451271	1.2246	39.4046	42.811623	10.135736	0
17	0.3083	2.6174562	31.127031	1.2339	40.2798	42.897256	10.536335	0
18	0.1949	1.6546942	31.127031	0.6454	32.7487	34.403394	2.631	0
19	0.0691	0.5866566	30.154312	0.6233	33.144	33.730657	2.95298	0
20	0	0	29.830072	0.5439	32.4808	32.4808	2.106867	0
21	0	0	29.830072	0.5613	33.1698	33.1698	2.778454	0
22	0	0	30.154312	0.5799	32.7644	32.7644	2.030217	0
23	0	0	28.208872	0.5464	31.5376	31.5376	2.782313	0
24	0	0	23.345274	0.2936	24.4694	24.4694	0.830494	0

6.5.3 Sizing Renewable Energy Systems Considering Scheduling Houses' Devices

The objective of this section is to minimize the size of renewable energy systems (wind turbines and PV systems) that are to be connected to the grid such that the expected met energy demand of residential houses is maximized by considering scheduling houses' devices. The problem is solved as two interconnected problems. In the first problem, the problem is treated as an optimization problem for finding the number of renewable energy systems and maximizing the demand met subject to the available power generation-expected demand relationship while accounting for customers' comfort, working hours of individuals, customers' preferences, stochastic weather condition and the effect of the current decisions of devices' power interruption on future decisions. The latter has an advantage of predicting future decisions if consumers have no control on devices, or of providing more comfort level as a subsequent prediction of customers' actions in the case of no control of devices. In this optimization problem, the power flow constraints are not involved. The output of decisions made on devices power interruptions is inputted into a second optimization problem targeting maximizing the demand that can be met and minimizing the number of renewable energy systems demanded while maintaining the power flow under no violation of the system's voltage levels. It is important to emphasize that the first optimization problem will provide an estimate of the number of renewable energy systems demanded but this is not necessarily the optimal number of renewable energy systems. The main reason behind that is that the system losses set in the first optimization problem are approximate as determined from an optimal minimum system losses problem treated under no power interruption where utility power supply is assumed to be capable of meeting the total expected demand. In the second optimization problem, this size is to be re-determined such that no violations of power flow constraints are encountered accounting for the realistic calculated losses under the determined schedule of devices obtained from the first optimization problem. If power interruption exists in the second case, the problem is reconsidered to reduce the size of renewable energy systems by rescheduling of devices not met in the second problem and utilizing feeder's losses determined from the second problem. Such an approach is considered iteratively until no power interruption exists and the appropriate number of renewable energy systems is determined. This approach is further clarified by the following flow chart. The next two sections are dedicated to discussing the two optimizations problems.

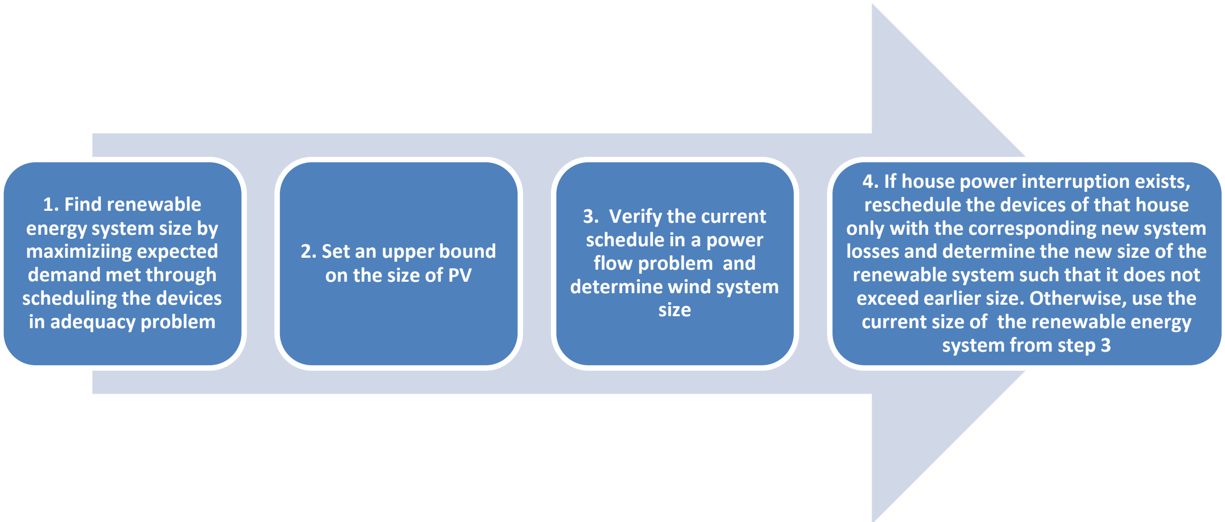


Figure 6.9: Proposed solution to determine renewable energy systems' size

6.5.3.1 First Optimization Problem Sizing Renewable Energy Systems and Scheduling Houses' Devices

The objective of the problem is to reduce house devices' power interruption by maximizing the expected demand that can be met by utilizing the hours during which wind speed is producing power or solar radiation is available. The objective and the constraints are shown below:

$$In\ winter: \max\ \ obj = \sum_{t=1}^{24}\sum_{n=1}^{8} P_{heat\,n,t}\ hour\ \ wnew_{n,t} + zwh_{n,t}\ hour + P_{washing\text{-}machine_{n,t}}\ hour\ \ washing_{n,t} + P_{well-pump_{n,t}}\ hour\ \ well_{n,t}$$

(6-79)

$$In\ summer: \max\ \ obj = \sum_{t=1}^{24}\sum_{n=1}^{8} P_{fan_{n,t}}\ hour\ \ MfanM_{n,t} + zwh_{n,t}\ hour + P_{washing\text{-}machine_{n,t}}\ hour\ \ washing_{n,t} + P_{well-pump_{n,t}}\ hour\ \ well_{n,t}$$

(6-80)

Subject to:

1. Devices' operational models described in Chapter 4.

2. Power generation-expected demand constraints given below:

   In winter, the constraint below applies when utilizing wind turbines; while in summer, the term ($P_{sh\ n,t}\ wnew_{n,t}$) is replaced with ($P_{fan\ n,t}\ MfanM_{n,t}$). $Pwind_{t,s}$ is to be replaced with ($P_{solar\ t,s}$ *$5kW$) when utilizing solar PV system.

$$Pg_{i=1,t,s} + R * Pwind_{t,s} * Number_s - Pd_{i=2} * RTS_{t,s} - Pd_{i=3} * RTS_{t,s} - R * \sum_{n=1}^{8} light_{n,t,s} - [R * \sum_{n=1}^{8} (P_{sh_{n.t}} \; wnew_{n,t} + zwh_{n,t,s} + P_{washing-machine_{n.t,s}} \; washing_{n,t,s} + P_{well-pump_{n.t,s}} \; well_{n,t,s})] - Ploss_{t,s} = 0$$

(6-81)

In winter, the constraint below is applied; while in summer, the term ($-P_{fan\ n,t}$ $MfanM_{n,t}*PF_{fan}$) is added to the left hand side of the constraint and specifically in the bracket.

$$Qg_{i=1,t,s} - Qd_{i=2} * RTS_{t,s} - Qd_{i=3} * RTS_{t,s} - [R * \sum_{n=1}^{8} (P_{washing-machine_{n.t,s}} \; washing_{n,t,s} \; PF_{washing-machine} + P_{well-pump_{n.t,s}} \; well_{n,t,s} \; PF_{well-pump})] - Qloss_{t,s} = 0$$

(6-82)

The available power generation available is though bus 1 in Figure 4.1 and it should not exceed an upper bound based on the corresponding season as given by the following equations.

$$Pg_{i \neq 1,t,s} = 0 \tag{6-83}$$

$$Qg_{i \neq 1,t,s} = 0 \tag{6-84}$$

$$Plow_{t,s} \leq Pg_{i=1,t,s} \leq Pup_{t,s} \tag{6-85}$$

$$Qlow_{t,s} \leq Qg_{i=1,t,s} \leq Qup_{t,s} \tag{6-86}$$

In order to ensure that most of the power is obtained from the available power generation rather than wind power such that the number of wind turbines is reduced, the following constraint is added:

$$Pg_{i=1,t,s} \geq R * Pwind_{t,s} * number_s \tag{6-87}$$

In order to ensure that the power supplied does not exceed the transformer rating, the constraint below is verified aside from the optimization problem to maintain the linearity of the problem:

$$\sqrt{(Pg_{i=1,t,s} + R * Pwind_{t,s} * number_s)^2 + (Qg_{i=1,t,s})^2} \leq R * Transformer\ Rating \tag{6-88}$$

The number of wind turbines needed is set to be less than that determined when addressing the power generation shortage accounting for the size determined from a utility aspect as given below:

$$number_s \leq number_{s\,utility}$$

(6-89)

The number of wind turbine systems needed as determined from scheduling devices in this problem is 13.8 in winter and is 2.23 in summer. In this case, GAMS execution time is 1.077 seconds for the winter season and it is 0.032 seconds for the summer season. On the other hand, the number of PV systems needed in this case is 5.3 PV systems in winter and is 0.9 PV system (rounded from 0.86) in summer. The next step is to determine the size of renewable energy systems accounting for power flow constraints.

6.5.3.2 Second Optimization Problem to Validate the Schedule of Houses' Devices

The objective of the second optimization problem is to validate the schedule of supplied houses' devices in the first optimization problem and to find the minimum size of renewable energy systems demanded to achieve this objective while accounting for system losses under such a schedule. The objective function and the constraints are shown below:

$$\max \quad objj_s = \sum_{t=1}^{24}\sum_{n=1}^{8} o_{n,t,s} \tag{6-90}$$

where *objj* is the objective function to be maximized, *o* is a binary variable that is one when the schedule determined at time *t* for house *n* can be met and that is zero otherwise.

This problem is subject to power flow constraints as given by the following equations accounting for the corresponding season. $Pwind_{t,s}$ is replaced with ($Psolar_{t,s}$*5kW) when solar PV systems are utilized instead of wind turbines.

$$Pg_{i,t,s} + R * Pwind_{t,s} * number_s - Pd_i * RTS_{t,s} = \sum_{j=1}^{4} [V_{i,t,s} * V_{j,t,s} * Y_{i,j} * \cos(-\theta_{i,j} - \delta_{j,t,s} + \delta_{i,t,s})]) \quad \forall i = 1 \tag{6-91}$$

$$Pg_{i,t,s} - Pd_i * RTS_{t,s} = \sum_{j=1}^{4} [V_{i,t,s} * V_{j,t,s} * Y_{i,j} * \cos(-\theta_{i,j} - \delta_{j,t,s} + \delta_{i,t,s})]) \quad \forall i \neq 1,4 \tag{6-92}$$

$$Qg_{i,t,s} - Qd_i * RTS_{t,s} = \sum_{j=1}^{4} [V_{i,t,s} * V_{j,t,s} * Y_{i,j} * \sin(-\theta_{i,j} - \delta_{j,t,s} + \delta_{i,t,s})]) \quad \forall i \neq 4 \tag{6-93}$$

$$Pg_{i,t,s} - \sum_{n=1}^{8} o_{n,t,s} * R * P_{residentid-house\,n,t,s} = \sum_{j=1}^{4} [V_{i,t,s} * V_{j,t,s} * Y_{i,j} * \cos(-\theta_{i,j} - \delta_{j,t,s} + \delta_{i,t,s})]) \quad \forall i = 4 \tag{6-94}$$

$$Qg_{i,t,s} - \sum_{n=1}^{8} o_{n,t,s} * R * Q_{residentid-house\,n,t,s} = \sum_{j=1}^{4} [V_{i,t,s} * V_{j,t,s} * Y_{i,j} * \sin(-\theta_{i,j} - \delta_{j,t,s} + \delta_{i,t,s})]) \quad \forall i = 4 \tag{6-95}$$

The power generation-expected demand relationships are given by the equations below:

$$Pg_{i=1,t,s} + R * Pwind_{t,s} * number_s - Pd_{i=2} * RTS_{t,s} - Pd_{i=3} * RTS_{t,s} - Ploss_{t,s} = \sum_{n=1}^{8} o_{n,t,s} * R * P_{residentid-house\, n,t,s}$$

(6-96)

$$Qg_{i=1,t,s} - Qd_{i=2} * RTS_{t,s} - Qd_{i=3} * RTS_{t,s} - Qloss_{t,s} = \sum_{n=1}^{8} o_{n,t,s} * R * Q_{residentid-house\, n,t,s} \quad \textbf{(6-97)}$$

$$Ploss_{t,s} = \sum_{i=1}^{4} \sum_{j=1}^{4} (0.5 * gg_{i,j} * [V^2{}_{i,t,s} + V^2{}_{j,t,s} - 2 * V_{i,t,s} * V_{j,t,s} * \cos(\delta_{j,t,s} - \delta_{i,t,s})]) \quad \textbf{(6-98)}$$

$$Qloss_{t,s} = -\sum_{i=1}^{4} \sum_{j=1}^{4} (0.5 * bb_{i,j} * [V^2{}_{i,t,s} + V^2{}_{j,t,s} - 2 * V_{i,t,s} * V_{j,t,s} * \cos(\delta_{j,t,s} - \delta_{i,t,s})]) \quad \textbf{(6-99)}$$

The voltage level at system busses should be within a range as given by the following constraints:

$$0.95pu \le V_{i,t,s} \le 1.05pu \quad \textbf{(6-100)}$$

$$-\pi \le \delta_{i,t,s} \le \pi \quad \textbf{(6-101)}$$

The available power generation, excluding wind turbine and solar PV power, that can be supplied to the new system through bus 1 are as given by the following constraints:

$$Pg_{i\ne1,t,s} = 0 \quad \textbf{(6-102)}$$

$$Qg_{i\ne1,t,s} = 0 \quad \textbf{(6-103)}$$

$$Plow_{t,s} \le Pg_{i=1,t,s} \le Pup_{t,s} \quad \textbf{(6-104)}$$

$$Qlow_{t,s} \le Qg_{i=1,t,s} \le Qup_{t,s} \quad \textbf{(6-105)}$$

In order to ensure that most of the power supplied to the expected demand is obtained from the available power generation rather than renewable energy system to reduce the number of wind turbine systems, the following constraint is added:

$$Pg_{i=1,t,s} \ge R * Pwind_{t,s} * number_s \quad \textbf{(6-106)}$$

The power supplied to the new feeder is not to exceed the transformer rating as indicated by the constraint below:

$$\sqrt{(Pg_{i=1,t,s} + R * Pwind_{t,s} * number_s)^2 + (Qg_{i=1,t,s})^2} \le R * Transformer\ Rating \quad \textbf{(6-107)}$$

The number of wind turbines determined from the second optimization problem that maximizes expected demand supplied is 14.5 in winter and is 2.7 in summer. On the other hand, 5.6 PV systems in winter and is 0.9 PV systems in summer are needed when utilizing PV systems. It can be seen that these numbers are higher than the numbers determined from the first optimization problem. This difference is due to the fact that the losses used in the first optimtization are the minimum losses determined from an optimization problem targeting minimizing system losses under no power generation deficiency to provide a rough estimate of such losses such that utility power can be reserved to it when considering devices' scheduling. Furthermore, these number of renewable energy systems do not violate the power flow constraints. The next step is to redefine the objective function to minimize the number of renewable energy systems needed as shown below such that the number is less than the number determined when considering house full power interruption:

$$\max \quad objj_s = af * \sum_{t=1}^{24} \sum_{n=1}^{8} o_{n,t} - bf * number \qquad \textbf{(6-108)}$$

Where *af* and *bf* are weighting factors. It is important to emphasize that this objective function is a simplified version of the multi-objective function that incorporates the following objectives and the problem is subject to the same constraints of the second optimization problem.

$$\max \quad \sum_{t=1}^{24} \sum_{n=1}^{8} o_{n,t,s} \qquad \textbf{(6-109)}$$

$$\min \quad number \qquad \textbf{(6-110)}$$

If *af* and *bf* are set to be a ratio of 1: 1 as explained in [187] and the constraints of the second optimization problem presented in Section 6.5.3.2, the system is to require 5.5 wind turbines system in winter while incorporating power interruptions and 2.3 wind turbines system with no power interruptions in summer.The houses whose devices will undergo power interruption in winter are house 4 at 7am, houses 5 and 7 at 10am and houses 1 and 6 at 11am. The next step is to consider rescheduling the devices of houses with power interruptions in winter following the first optimization problem while incorporating system losses from the second optimization problem. This consideration reveals 8.7 wind turbine systems guaranteeing no power interruption during hours of utilized wind power in winter. If *af* and *bf* are set such that their sum is one, no rescheduling is needed and the wind turbine systems is 14.1 in winter. Further clarification of the expected energy met in the different cases investigated is given in the table below.

Another way of addressing the problem is to set the objective function to minimize the number of wind turbines in the first optimization problem and to maximize ($\sum_{t=1}^{24}\sum_{n=1}^{8} o_{n,t,s}$ *-number$_s$*); while setting the following variables *(LSupplied*, *yyy$_{sh}$*, *PumpSupply* and *MachineSupply*) to one. Such a consideration is only possible when power production from wind turbines is possible over all hours of the day. This consideration is presented here as a special case, resulting in less than 2.5 wind turbines to be demanded.

Table 6.8: Results of sizing wind turbines system considering houses' devices scheduling

Comparison in winter	Normal case of full house power interruption	Scheduling Houses' devices with power interruption during wind power hours	Scheduling house devices with no power interruption during wind power hours	Rescheduling Houses' devices to minimize wind size with no power interruptions during wind power
Energy met kWh	175.3522	175.8768	188.1093	186.962
Number of wind turbines systems given that each is 10kW	14.3	5.5	14.1	8.7
Comparison in summer	Normal case of full house power interruption (No interruption exists in this case)	Scheduling house devices with no power interruption during wind power hours Objective =max $\sum_{t=1}^{24}\sum_{n=1}^{8} o_{n,t,s}$	Scheduling Houses' devices to minimize wind size with no power interruptions during wind power Objective =max $\sum_{t=1}^{24}\sum_{n=1}^{8} o_{n,t,s}$ -number$_s$	If *Lsupplied*=fancanbesupplied= MachineSupply=PumpSupply =1 in first optimization problem. Objective of 1st optimization problem=min number$_s$
Energy met kWh	117.7454	116.0628	116.0628	116.0628
Number of wind turbines systems given that each is 10kW	6.2	2.7	2.3	2.5

It can be seen from the above table that the energy met in the fourth column from the left is more than that in the fifth column in winter only. This variation is due to the difference in the energy consumed by the water heater due to tank losses that is a function of the internal air temperature of the house, which depends on what time the space heater is operated.

The next table shows a detailed comparison between the devices met in the normal case where the certain houses undergo full power interruption and the case where devices of residential houses are rescheduled such that the best number of wind turbine systems is determined while maintaining no power interruption during hours of effective wind speeds given that the priority of supply is from the available power generation rather than the wind turbines such that wind system size is minimized. It is important to emphasize that the number of water heaters supplied in summer is 103 in both case studies displayed in the table; however, the energy supplied is not the same.This difference is due to the temperature effect on losses and device operation as well as the fact that losses are uncontrollable in the case of house full power interruption compared to the second case where devices are scheduled to address the power generation shortage problem in developing countries.

Table 6.9: Devices supplied when wind turbines system are grid connected

Number of devices supplied during 24 hours of a typical winter day	Normal case of full house power interruption	Rescheduling house devices to minimize wind system size with no power interruptions during wind power hours
Heater	42	46
Well pump	60	64
Water heater energy daily demand KWh	31.5	33.6
Washing machine	6	8
Light	45 x (2 lights)	56 x (2 lights)
Number of devices supplied during 24 hours of a typical summer day	Normal case of full house power interruption (No power interruption exists in this case)	Scheduling House devices to minimize wind system size with no power interruptions during wind power hours
Electric fan	120	120
Well pump	64	64
Water heater energy daily demand kWh	103 times supplying 27.74541kWh	103 times supplying 26.062838kWh
Washing machine	8	8
Light	48 x (2 lights)	48 x (2 lights)

When solar PV systems are to be sized, applying the objective function given in (6-108) where *af* and *bf* are set to be a ratio of 1:1 and the constraints of the second optimization problem reveals that one house devices will undergo full power interruption in winter and that reflects the use of 4.5 PV systems. When the same objective function as well as the same constraints of the second optimization problem are involved and rescheduling of this house's devices was carried out following the first optimization problem, 4.8 PV systems are needed in winter. On the other hand, 0.9 PV system is needed only in summer to meet the scheduled demand. Table 6.10 provides an emphasis on the energy met of various scenarios studied. Furthermore, Table 6.11 provides a comparison between the devices supplied when specific houses will encounter full power interruption and the devices supplied when they are rescheduled such that the best size of PV system is found while assuring the residential consumers no power interruption during hours of solar radiation.

Table 6.10: Results of sizing solar PV system considering house's devices scheduling

Comparison in winter	Normal case of house full power interruption	1. Scheduling house devices with power interruption during solar radiation hours	2. Scheduling house devices with no power interruption during solar radiation hours	3. Rescheduling house devices to minimize PV size with no power interruption during solar radiation hours
Energy met (kWh)	175.9761	184.7541	187.898	187.898
Number of PV systems given that each is rated at 5kW	5.2	4.5	5.6	4.8
Comparison in summer	Normal case of house full power interruption	Scheduling house devices		
Energy met (kWh)	112.627987	114.3751		
Number of PV systems given that each is rated at 5kW	1.7	0.9		

Table 6.11: Devices supplied when solar PV systems are utilized

Number of devices supplied during 24 hours in a typical winter day	Full house interruption	Rescheduling house devices to minimize PV size
Heater	42	45
Well pump	60	64
Water heater based on hot water demand	91	93
Washing machine	6	8
Light	48 x (2 lights)	56 x (2 lights)
Number of devices supplied during 24 hours in a typical summer day	Full house interruption	Scheduling house devices to minimize PV size
Electric fan	114	103
Well pump	63	64
Water heater based on hot water demand	95	101
Washing machine	7	8
Light	43 x (2 lights)	48 x (2 lights)

Considering both seasons, the selected number of PV systems or wind turbines that will maximize consumer access to electricity is 4.8 PV systems such that each is rated at 5kW or 8.7 wind turbines each rated at 10kW, respectively.

6.6 Scheduling Residential Demand Considering Renewable Energy Uncertainty

The objective of this section is to address the effect of the uncertainty in the power production from renwable energy systems, wind turbines and solar PV systems due to the corresponding wind speed and solar power variabilities, in managing residential demand. To achieve this, representative states of wind speed or solar power obtained when clustering the wind speed data or solar power data, generated from the Monte-Carlo simulation, are used. The clustering of data is supervised. This utilization of states is considered rather than dealing with the expected value of the variable that has been determined earlier in this cahpter as the result of adding all values found when multiplying a state's probability by its corresponding variable value. The power corresponding to each variable state is determined for every hour such that *24 hours* x *St* states are obtained. Scheduling residential demand in summer will be presented here and this can be modified to account for the winter season.

When dealing with wind turbines system, the objective function is maximizing the expected demand that can be met during effective wind speed hours as shown below where *PP* is the probability of a wind speed state corresponding to an hour, *state* indicates the corresponding state, *St* in the number of states. In the case of availability of PV systems, *PP* will represent the probability of a solar power state.

$$\max \; obj = \sum_{t=1}^{24}\sum_{state=1}^{St}\sum_{n=1}^{8}(P_{fan_{n.t,s,state}}\; hour \;\; MfanM_{fan_{n,t,state}} + zwh_{n,t,s,state} + P_{washing-machine_{n.t,s,state}}\; hour \;\; washing_{n,t,s,state} + P_{well-pump_{n.t,s,state}}\; hour \;\; well_{n,t,s,state} + light_{n,t,s,state}\; hour \;) * PP_{state,t}$$

(6-111)

The optimization problem is subject to the following constraints:

1. Devices' operational models described in Chapter 4.
2. Power generation-expected demand constraints as given by (6-112) to (6-119).
3. Number of wind turbines: The number of wind turbines needed is set to be less than a specified number (*Specified)* as given by (6-120).

$$Pg_{i=1,t,s,state} + R * Pwind_{t,s,state} * Number_s - Pd_{i=2} * RTS_{t,s} - Pd_{i=3} * RTS_{t,s} - R * \sum_{n=1}^{8} light_{n,t,s,state} - [R * \sum_{n=1}^{8}(P_{fan_{n,t,s,state}}\;\; MfanM_{fan\; n,t,s,state} + zwh_{n,t,s,state} + P_{washing-machine_{n.t,s,state}}\;\; washing_{n,t,s,state} + P_{well-pump_{n.t,s,state}}\;\; well_{n,t,s,state})] - Ploss_{t,s,state} = 0$$

(6-112)

$$Qg_{i=1,t,s,state} - Qd_{i=2} * RTS_{t,s} - Qd_{i=3} * RTS_{t,s} - [R * \sum_{n=1}^{8}(P_{fan_{n,t,s,state}}\;\; MfanM_{fan\; n,t,s,state}\; PF_n + P_{washing-machine_{n.t,s,state}}\;\; washing_{n,t,s,state}\; PF_n + P_{well-pump_{n.t,s,state}}\;\; well_{n,t,s,state}\; PF_n)] - Qloss_{t,s,state} = 0$$

(6-113)

The available power generation available is though bus 1 in Figure 4.1 and it should not exceed an upper bound based on the corresponding season as given by the following equations.

$$Pg_{i\neq 1,t,s,state} = 0 \quad \textbf{(6-114)}$$

$$Qg_{i\neq 1,t,s,state} = 0 \quad \textbf{(6-115)}$$

$$Plow_{t,s} \leq Pg_{i=1,t,s,state} \leq Pup_{t,s} \quad \textbf{(6-116)}$$

$$Qlow_{t,s} \leq Qg_{i=1,t,s,state} \leq Qup_{t,s} \quad \textbf{(6-117)}$$

In order to ensure that most of the power is obtained from the available power generation rather than wind power such that the number of wind turbines is reduced, the following constraint is added:

$$Pg_{i=1,t,s,state} \geq R * Pwind_{t,s,state} * number_s \quad \textbf{(6-118)}$$

In order to ensure that the power supplied does not exceed the transformer rating, the constraint below is verified aside from the optimization problem to maintain the linearity of the problem:

$$\sqrt{(Pg_{i=1,t,s,state} + R * Pwind_{t,s,state} * number_s)^2 + (Qg_{i=1,t,s,state})^2} \leq R * Transformer\ Rating \quad \textbf{(6-119)}$$

The number of wind turbines needed is set not to exceed a specified number as given below:

$$number_s \leq Specified \quad \textbf{(6-120)}$$

The determined schedules from this problem are verified not to violate power flow constraints as given by the optimization problem below:

$$\max \quad objj_{state} = \sum_{t=1}^{24}\sum_{n=1}^{8}(o_{fan\,n,t,s,state} + o_{wh\,n,t,s,state} + o_{wm\,n,t,s,state} + o_{well-pump\,n,t,s,state} + o_{light\,n,t,s,state}) \forall state \in \{1,...St\}$$

(6-121)

Subject to:

$$Pg_{i,t,s,state} + R * Pwind_{t,s,state} * number_s - Pd_i * RTS_{t,s} = \sum_{j=1}^{4} [V_{i,t,s,state} * V_{j,t,s,state} * Y_{i,j} * \cos(-\theta_{i,j} - \delta_{j,t,s,state} + \delta_{i,t,s,state})]) \quad \forall i = 1$$

(6-122)

$$Pg_{i,t,s,state} - Pd_i * RTS_{t,s} = \sum_{j=1}^{4} [V_{i,t,s,state} * V_{j,t,s,state} * Y_{i,j} * \cos(-\theta_{i,j} - \delta_{j,t,s,state} + \delta_{i,t,s,state})]) \quad \forall i \neq 1,4$$

(6-123)

$$Qg_{i,t,s,state} - Qd_i * RTS_{t,s} = \sum_{j=1}^{4} [V_{i,t,s,state} * V_{j,t,s,state} * Y_{i,j} * \sin(-\theta_{i,j} - \delta_{j,t,s,state} + \delta_{i,t,s,state})]) \quad \forall i \neq 4 \qquad \textbf{(6-124)}$$

$$Pg_{i,t,s,state} - \sum_{n=1}^{8} (o_{n,t,s,state} * R * PD_{light\ n,t,s,state} + o_{fan\ n,t,s,state} * R * PD_{fan\ n,t,s,state} + o_{washing-machine\ n,t,s,state} * R * PD_{washing-machine\ n,t,s,state} + o_{wh\ n,t,s,state} * R * PD_{wh\ n,t,s,state} + o_{well,n,t,s,state} * R * PD_{well\ n,t,s,state}) = \sum_{j=1}^{4} [V_{i,t,s,state} * V_{j,t,s,state} * Y_{i,j} * \cos(-\theta_{i,j} - \delta_{j,t,s,state} + \delta_{i,t,s,state})])$$

$$\forall i = 4 \qquad \textbf{(6-125)}$$

where *PD* is the active power demand of the corresponding device that is supplied in the first optimization problem in kW.

$$Qg_{i,t,s,state} - \sum_{n=1}^{8} (o_{fan\ n,t,s,state} * R * QD_{fan\ n,t,s,state} + o_{washing-machine\ n,t,s,state} * R * QD_{washing-machine\ n,t,s,state} + o_{well,n,t,s,state} * R * QD_{well\ n,t,s,state}) = \sum_{j=1}^{4} [V_{i,t,s,state} * V_{j,t,s,state} * Y_{i,j} * \sin(-\theta_{i,j} - \delta_{j,t,s,state} + \delta_{i,t,s,state})])$$

$$\forall i = 4 \qquad \textbf{(6-126)}$$

where *QD* is the reactive power demand of the corresponding device that is supplied in the first optimization problem in kVAR.

The power generation-expected demand relationships are given by the constraints below.

$$Pg_{i=1,t,s,state} + R * Pwind_{t,s,state} * number_s - Pd_{i=2} * RTS_{t,s} - Pd_{i=3} * RTS_{t,s} - Ploss_{t,s,state} = \sum_{n=1}^{8} (o_{n,t,s,state} * R * PD_{light\ n,t,s,state} + o_{fan\ n,t,s,state} * R * PD_{fan\ n,t,s,state} + o_{washing-machine\ n,t,s,state} * R * PD_{washing-machine\ n,t,s,state} + o_{wh\ n,t,s,state} * R * PD_{wh\ n,t,s,state} + o_{well,n,t,s,state} * R * PD_{well\ n,t,s,state})$$

(6-127)

$$Qg_{i=1,t,s,state} - Qd_{i=2} * RTS_{t,s} - Qd_{i=3} * RTS_{t,s} - Qloss_{t,s,state} = \sum_{n=1}^{8} (o_{fan\ n,t,s,state} * R * QD_{fan\ n,t,s,state} + o_{washing-machine\ n,t,s,state} * R * QD_{washing-machine\ n,t,s,state} + o_{well,n,t,s,state} * R * QD_{well\ n,t,s,state})`$$

(6-128)

$$Ploss_{t,s,state} = \sum_{i=1}^{4} \sum_{j=1}^{4} (0.5 * gg_{i,j} * [V^2_{i,t,s,state} + V^2_{j,t,s,state} - 2 * V_{i,t,s,state} * V_{j,t,s,state} * \cos(\delta_{j,t,s,state} - \delta_{i,t,s,state})])$$

(6-129)

$$Qloss_{t,s,state} = -\sum_{i=1}^{4} \sum_{j=1}^{4} (0.5 * bb_{i,j} * [V^2_{i,t,s,state} + V^2_{j,t,s,state} - 2 * V_{i,t,s,state} * V_{j,t,s,state} * \cos(\delta_{j,t,s,state} - \delta_{i,t,s,state})])$$

(6-130)

The voltage level at system busses should be within a range as given by the following constraints:

$$0.95pu \le V_{i,t,s,state} \le 1.05pu \quad \textbf{(6-131)}$$

$$-\pi \le \delta_{i,t,s,state} \le \pi \quad \textbf{(6-132)}$$

The utility possible power supply dedicated to bus 1 only should be within a limit as indicated by the following constraints:

$$Pg_{i\ne 1,t,s,state} = 0 \quad \textbf{(6-133)}$$

$$Qg_{i\ne 1,t,s,state} = 0 \quad \textbf{(6-134)}$$

$$Plow \le Pg_{i=1,t,s,state} \le Pup \quad \textbf{(6-135)}$$

$$Qlow \le Qg_{i=1,t,s,state} \le Qup \quad \textbf{(6-136)}$$

The number of wind turbine systems demanded is set to be below a specified number as given below:

$$number_s \le Specified \quad \textbf{(6-137)}$$

In order to ensure that the power supplied does not exceed the transformer rating, the following constraint is to be used:

$$\sqrt{(Pg_{i=1,t,s,state} + R * Pwind_{t,s,state} * number_s)^2 + (Qg_{i=1,t,s,state})^2} \le R * Transformer\ Rating \quad \textbf{(6-138)}$$

The expected energy that can be met is 117.42kWh subject to the availability of 1.9 wind turbine systems. ON/OFF schedules of devices are shown in the Figure 6-10.

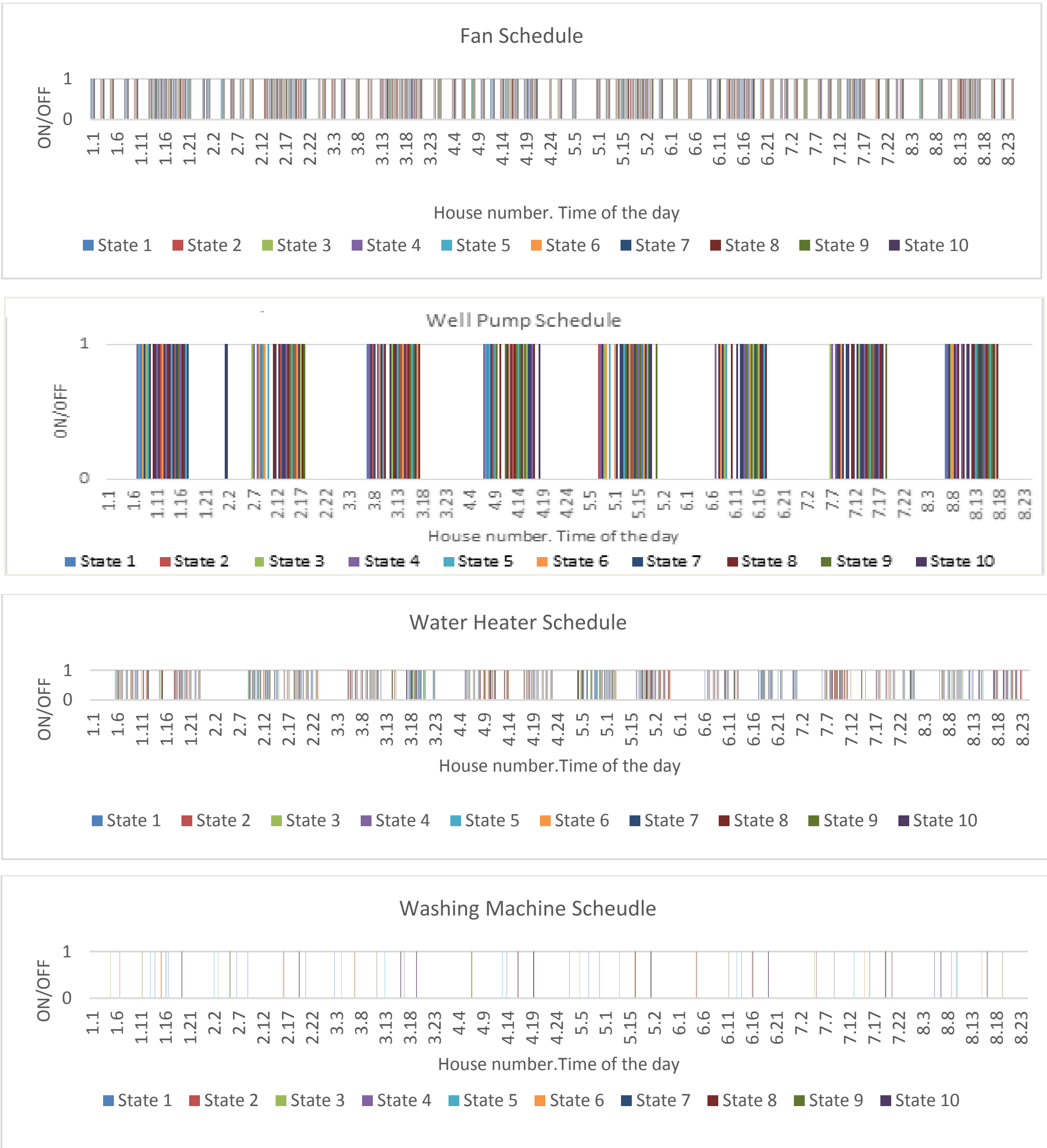


Figure 6.10: Devices' scheduling in summer considering wind speed uncertainty

When solar PV systems are utilized, the first optimization problem utilizied when wind turbines are used is considered. In this case, $P_{wind\ t,s,state}$ is replaced with ($P_{solar\ t,s,state}$*$5kW$). It has been decided here to set the number of solar PV systems to as specific number as a case study as given below where $\underline{A}$ is a specified number of PV systems.

$$Number = \underline{A} \quad \textbf{(6-139)}$$

The determined schedules from this problem are verified not to violate power flow constraints. Two approaches are considered. The first approach is to verify the schedule for every state individually by considering rescheduling if needed and setting *Number* to be variable in this case to account for system losses as shown below.The second approach is to verify the problem accounting for all determined schedules to be verified in one optimization problem as will be shown later.

$$\max \quad objj_{state} = \sum_{t=1}^{24}\sum_{n=1}^{8} o_{fan\,n,t,s,state} + o_{wh\,n,t,s,state} + o_{wm\,n,t,s,state} + o_{well-pump\,n,t,s,state} + o_{light\,n,t,s,state} - number_{s,state}$$

$$\forall state \in \{1,...St\} \qquad \textbf{(6-140)}$$

The amount of energy to be supplied to residential houses accounting for the uncertainty in solar power production is 99.01253kWh. It can be seen that this number is less than the number determined in the previous section because the probability is set to be zero during no solar power production hours.

The second approach is based on verifying the second optimization problem carried for individual states separately in one optimization problem. In this case, the objective is to minimize the number of PV systems demanded and the following constraint is added to the previous constraints to ensure that the total demand determined from the first optimization problem is supplied all the time:

$$\sum_{n=1}^{8} o_{fan\,n,t,state} + o_{wh\,n,t,state} + o_{wm\,n,t,state} + o_{well-pump\,n,t,state} + o_{light\,n,t,state} = 5 \qquad \textbf{(6-141)}$$

6.7 Chapter Summary

This chapter was focused on sizing renewable energy systems (wind turbines and solar PV systems) to address the power generation shortage in a developing country by utilizing the power production from such resources during the effective wind speed hours and solar radiation hours. Furthermore, this chapter proposed a novel probabilistic PV power model that accounted for more than one factor governing the production of solar power. The probabilistic model proposed had the advantage of providing more accurate estimation of the power output than the models presented in the literature. The model was utilized to derive the output of a small scale solar PV system. Solar PV system was assumed to be located in high solar radiation areas, while wind turbines are located in wind farms. Wind turbines and solar PV systems are to be connected to the grid. The sized wind turbines system or solar PV system were based on the demand of the new feeder to be connected to the grid due to population growth and the demand for system expansion. The chapter proposed sizing the wind turbines system as well as the solar PV system accounting for house full power interruptions during the corresponding hours of no wind power production or solar power production and proposed sizing the wind turbines system as well as the solar PV system accounting for house devices' power interruption. The minimum number of renewable energy systems was determined while maximzing the expected demand that can be met. It can be concluded from the different case studies presented in this chapter that scheduling home devices to minimize power interruption experienced by expected residential customers is the best solution to address the power generation shortage in developing countries while utilizing the minimum number of renewable energy systems. Moreover, the chapter investigated the effect of wind speed and solar power uncertainty on sizing such a system and scheduling residential demand. This solution is more beneficial than the utility aspect in finding the number of renewable energy systems needed based on the gap between the available power generation and the expected demand.

Chapter 7
Conclusion and Future Works

Developing countries are demanding continuous electricity supply to derive their evolving economies as well as to assist rising populations. Power interruption schedules attributable to underfunded power generation capacity have lead to the search for the alternative sources of supply such as renewable energy. With population growth, the power generation shortage will worsen the effects on consumers electricity supply. Even though some electricity customers have utilized individual PV systems to supply their houses with electricity, not all electricity customers are able to consider such a solution due to the high associated costs of such systems. This highlights the role that utility can play in addressing the power generation shortage.

This thesis proposed solutions to address the power generation shortage at a residential consumer level that were more beneficial than the current applied solutions in developing countries and more suitable to accommodate population growth. The current solution applied in developing countries is based on classifying the grids into zones where each zone can represent a feeder to undergo power interruptions for many hours daily that can last more than 10-12 hours. A feeder that is to be out of supply for such durations can affect the quality of life and thus economic production. A solution was needed to reduce the severity of the problem. This thesis proposed two solutions from a residential consumer aspect. The first solution was based on interrupting the full power of individual houses during the days of typical seasons at different hours as a mean of reducing the demand to be connected to the grid rather than isolating the feeder. The second solution was based on scheduling consumers' devices to reduce the severity of the power generation shortage by maximizing the number of devices that can be supplied while maximizing consumers' comfort level. To achieve this goal, house devices' load models were involved accounting for consumers' preferences, individuals' working hours, weather uncertainty and seasonality as major factors governing consumers' demand for electricity. Weather uncertainty was modeled using a probability paper plot and the Monte-Carlo simulation. The effects of major components of the devices' operational models on expected demand scheduling were investigated.

From the residential consumers' perspective, this proposal will not solve the problem but rather will reduce its severity. A need for investment in alternative sources of supply clearly exists. Since developing countries are characterized by wide renewable energy sources, there is a demand to search for the best candidate source of supply from the economic perspective due to limited funds. This thesis applied the incremental rate of return analysis following a general financial structure recognized in the literature with corrections and updates to some of the concepts governing the project funding and implementation. This thesis investigated the effect of depreciation on selecting the best economic project for an investment as there have been different definitions of this concept in the literature. It might be argued that with the current limited funds, a diesel generator project is to be a better alternative to investment in renewable energy projects, but in this thesis, it has been shown that wind energy is the best project for an investment as has been verified due to the increasing fuel cost of diesel generator for the size of the project under study. This thesis applied the concept of benefit to cost ratio as an alternative to incremental rate of return analysis when a demand exists for its application. After that, the thesis investigated the role that policy can play in project funding and implantation following the same approach. In this case, it has been clarified that the current policy supports solar PV projects as distinct from wind projects. Even though solar PV projects were in implementation, this consideration will not solve the power generation shortage due to population growth and the demand for more renewable energy projects. This necessitates a study to be recommended to governance institutions to update the current policy such that with limited income, investors are guaranteed reasonable profits over the long run. This thesis contributes by investigating how different regulations can function in policy reform. This contribution has been achieved by implementing a data management program capable of searching for that policy and by indicating the significant regulation impacting future project funding and implementation when there is a demand to accommodate more renewable energy projects.

This thesis proposed a novel probabilistic model of solar PV power profiles taking into account solar irradiance and ambient air temperature as factors governing the power production from the PV. The distribution used was a five parameter distribution which provides a better representation of the PV power behavior for every hour of the day. The uncertainty of this resource was modeled and involved in an optimization problem targeting residential houses' devices scheduling while maintaining power flow constraints. This thesis also utilized a probabilistic wind model for addressing the power generation shortage in developing countries by finding the minimum number of wind turbines meeting the maximum possible demand through houses' devices scheduling. The effect of the selected project resource uncertainty on the expected demand that can be met was also investigated.

Since smaller PV systems were found to be needed in summer compared to winter and if the size of PV system used in winter is to be considered to address the power generation shortage, the author proposes that future work involve using such a system and investigating the possibility of storing summer energy to be utilized in winter to accommodate populatio-n growth at the currently found sizes.

As a future work, the inter-hourly variation of PV power and wind speed will be accounted for using Markov-Chain model.

The implementation of both controllers and timers governing load operation online and offline is to be studied in the future.

Appendix A

Probability Paper Plot for House External Air Temperature

This appendix will summarize the concept of probability paper plot discussed in [46] and applied in [16]. It will also emphasizes on the stopping criteria in the Monte-Carlo simulation utilized when modeling the stochastic nature of weather condition.

The house external air temperature data (X) and their corresponding cumulative frequencies are plotted using the concept of probability paper plot based on a linear scale to estimate the cumulative distribution function (Y) as shown by the following equation where *mm* is the slope of the line and *bs* is the Y-intercept of the line.

$$Y = mm\ X\ +\ bs \tag{A-1}$$

Linearity and deficiency of linearity are the principles applied to test if the house external air temperature distribution is like the one of the probability paper. To develop a graph relating the external air temperature out of the house sample data and the probability distribution function, it is necessary to consign a probability for every single data point. This is achieved following rank exploration. The house external air temperature data are well-arranged by size and every data point is assigned a specific cumulative probability based on the median rank probability (P_L) as shown in the equation below where *LL* is the data point order and *nn* is the total number of data:

$$P_{LL} = \frac{LL}{nn+1} \tag{A-2}$$

Normal Probability Paper Plot

The uniform form of the normal distribution describing the external air temperature of the house is given by the equation below based on [16, 46] . $\overline{\sigma}$ is the slope of the curve and it indicates the standard deviation of the distribution and has a value greater than zero. $\hat{\mu}$ is the graph intercept and it refers to the mean of the distribution. *SV* represents the standard normal variate, *t* is the time *s* is the season and $T_{external}$ is the external air temperature of the house:

$$SV_{t,s} = \frac{T_{external\,t,s} - \hat{\mu}_{t,s}}{\sigma_{t,s}} \tag{A-3}$$

The equation above is rearranged to have the form of (A-1) as shown below. The the plot can be obtained by drawing $T_{external}$ data with respect to the parallel *S* value.

$$T_{external\,t,s} = \overline{\sigma}_{t,s} S_{t,s} + \hat{\mu}_{t,s} \tag{A-4}$$

Log-Normal Probability Paper Plot (LNPPP)

The log normal probability density function (*f(T*$_{external\ t,s}$*))* can be described by the equation below where λ is the intercept indicating the shape parameter of the log normal distribution and ζ is the slope indicating the scale parameter of the log normal distribution and has a value above zero, *l* indicates long normal distribution.

$$f_l(T_{external_{t,s}}) = \frac{1}{\sqrt{2\pi}\zeta_{t,s} T_{external_{t,s}}} e^{-\frac{1}{2}\left(\frac{\ln(T_{external_{t,s}})-\lambda_{l\,t,s}}{\zeta_{t,s}}\right)^2} \quad \textbf{(A-7)}$$

The cumulative distribution function $F_l(T_{external\ t,s})$ is shown below. It is found as a characteristic of every studied hour of the day considering seasonal data.

$$F_l(T_{out_j}) = Q\left(\frac{\ln(T_{out_j}) - \lambda_{l\,j}}{\zeta_j}\right) \quad \textbf{(A-6)}$$

The standard normal variate is shown below as it demonstrates the log normal distribution.

$$SV_{t,s} = \frac{\ln(T_{external_{t,s}}) - \lambda_{l\,t,s}}{\zeta_{t,s}} \quad \textbf{(A-7)}$$

The log normal probability paper plot can be drawn using logarithm of the external air temperature of the house at time *t* in season *s* with respect to the standard normal variate found by (A-7) that is arranged to take the linear form below:

$$\ln(T_{external_{t,s}}) = \zeta_{t,s} S_{t,s} + \lambda_{l\,t,s} \quad \textbf{(A-8)}$$

Exponential Probability Paper Plot

The exponential distribution probability density function defined as ($f_p(T_{external\ t,s})$) as well as the exponential cumulative distribution function defined as ($F_p(T_{external\ t,s})$) are presented in the following equations for every hour in a season:

$$f_p(T_{external_{t,s}}) = \lambda_{pt,s} e^{-\lambda_{pt,s}(T_{external_{t,s}} - \mu_{pt,s})} \quad \textbf{(A-9)}$$

$$F_p(T_{external_{t,s}}) = 1 - e^{-\lambda_{pt,s}(T_{external_{t,s}} - \mu_{pt,s})} \quad \textbf{(A-10)}$$

The quantile function is derived such that the graph can be plotted in the linear form shown below. This is by finding $T_{external\ t,sj}$ and considering $\mu_{pt,s}$ to have a zero value. $\lambda_{pt,s}$ is one divided by the slope of the linear curve and it defines the scale of the distribution.

$$T_{external_{t,s}} = \frac{1}{\lambda_{pt,s}}\left(-\ln(1-P_{t,s})\right) \quad \textbf{(A-11)}$$

Weibull Probability Paper Plot

The probability density function and cumulative distribution function describing the house external air temperature distribution are $f_{weibull}(T_{external_{t,s}})$ and $F_{weibull}(T_{external_{t,s}})$; respectively.

$$f_{weibull}(T_{external_{t,s}}) = \frac{\alpha_{weibull_{t,s}}}{\beta_{weibull_{t,s}}^{\alpha_{weibull_{t,s}}}}(T_{external_{t,s}} - \mu_{weibull_{t,s}})^{\alpha_{weibull_{t,s}}-1} e^{-\left(\frac{T_{external_{t,s}}-\mu_{weibull_{t,s}}}{\beta_{weibull_{t,s}}}\right)^{\alpha_{weibull_{t,s}}}}$$

(A-12)

$$F_{weibull}(T_{external_{t,s}}) = 1 - e^{-\left(\frac{T_{external_{t,s}}-\mu_{weibull_{t,s}}}{\beta_{weibull_{t,s}}}\right)^{\alpha_{weibull_{t,s}}}} \quad \textbf{(A-13)}$$

The quantile function is found to be in the linear form as derived from the cumulative distribution function after setting the location parameter of this distribution $\mu_{weibull_{t,s}}$ to have a zero value as shown below:

$$\ln(T_{external_{t,s}}) = \frac{1}{\alpha_{weibull_{t,s}}}\ln\left(-\ln(1-P_{t,s})\right) + \ln(\beta_{weibull_{t,s}})$$

(A-14)

To have the Weibull probability paper plot, $\ln(T_{external\ t,s})$ is drawn with resepect to $\ln(-\ln(1-P_{t,s}))$. From the above equation, it can be noticed that $\alpha_{weibull_{t,s}}$ represents one divided by the slope of the curve. $\alpha_{weibull_{t,s}}$ is recognized as the shape parameter of the Weibull distribution. On the other hand, $\beta_{weibull_{t,s}}$ is $e^{\text{curve intercept}}$. $\beta_{weibull_{t,s}}$ is recognized as the scale parameter of the Weibull distribution.

Stopping Criteria of Monte-Carlo Simulation

The Monte-Carlo simulation was considered to estimate the house external air temperature corresponding to every hour in the season under study utilizing the inverse of the quantile functions corresponding to each distribution. Two stopping criteria should be met to stop the Monte-Carlo simulation. The first depends on the error in the mean of the distribution in comparison to the mean of the house external air temperature generated data using the simulation platform in Matlab. The second depends on the error in the standard deviation of the distribution compared the standard deviation of the house external air temperature generated data using the Monte-Carlo simulation. Both errors are smaller than a predefined tolerance. In contrast; the stopping criterion used when the exponential distribution is considered follows both the error in (1/λ) in comparison to the mean of the house external air temperature data generated from the Monte-Carlo simulation to be less than a predefined tolerance. After that, it is necessary to adjust the exponential distribution house external air temperature data generated using the Monte-Carlo simulation by adding ($\mu_{p\,t,s}$) to it. The equations utilized to find the mean and the standard deviation of the different distributions are available in [46, 188-191]

Appendix B

Radiation Effect of Well's Water Temperature

This appendix is focused on linearizing the equation describing the heat transfer between two bodies. The water in a well exhibits heat loss or gain due to radiation. The equation describing the heat transfer between two bodies in [61] can be applied to show the effect of heat loss/gain from the water in a well due to radiation effect in a developing country. This effect is described by the fourth order equation as given below:

$$Q_{t,s} = \varepsilon\sigma A(T^4{}_{well-water_{t,s}} - T^4{}_{external_{t,s}}) \quad \textbf{(B-1)}$$

$$A = \pi\ r^2 \quad \textbf{(B-2)}$$

where

Q : Heat loss/gain (Watt) by radiation between water and air

ε : Emissivity factor of water [192]

σ: Stefan Boltzmann constant (Watt/m^2K^4) [193, 194]

A: Circular surface area of the well (m^2)

$T_{well\text{-}water\ t,s}$: Well's water temperature (°K)

$T_{external\ t,s}$: house external air temperature that surrounds water (°K).

For definite temperature range in India, the curve linking the radiation effect per area and the temperature of the well surface can be replaced by a linear equation. For this, Taylor series expansion is used. The general form of Tayler series expansion for a function f(t) is given below where higher order terms are neglected:

$$f(T) = f(T_o) + \frac{df}{dT}\bigg|_{T=T_o} \Delta T \quad \textbf{(B-3)}$$

where T_o is the seasonal operating point of the temperature in (°K) [62].

The linearization of (B-1) is performed as below:

$$Let\ C1 = \varepsilon\sigma A \quad \textbf{(B-4)}$$

$$\therefore Q = C1(T^4{}_{well-water_{t,s}} - T^4{}_{external_{t,s}}) \quad \textbf{(B-5)}$$

Let $\overline{B} = C1\ T^4{}_{external_{t,s}}$ **(B-6)**

$$\therefore Q_{t,s} = C1\ T^4{}_{welll-water_{t,s}} - \overline{B} \quad \textbf{(B-7)}$$

Using Taylor series expansion:

$$Q(T) = C1\ T_{o_s}{}^4 - \overline{B} + 4\ C1\ T_{o_s}{}^3 (T_{well-water_{t,s}} - T_{o_s}) \quad \textbf{(B-8)}$$

Thus:

$$Q_{t,s}(T) = \varepsilon\sigma A\ (-3\ T_{os}{}^4 - T^4{}_{external_{t,s}}\ + 4\ T_{os}{}^3\ T_{well-water_{t,s}}) \quad \textbf{(B-9)}$$

To find the hourly temperature variation between the well's water and the surrounding air, the heat loss radiation equation is to take in the time step (Δt = 1 hour) as given below:

$$Q_{t,s}\Delta t(watt - hour) = \varepsilon\sigma A(T^4{}_{well-water_{t,s}} - T^4{}_{external_{t,s}})\ \Delta t \quad \textbf{(B-10)}$$

At this instant, the hourly temperature variation between the water and the air around it can be found according to [195] which denotes the stored thermal heat energy in a well's water as given by the following equation where *EK* is Energy (kJ), C_p is specific heat capacity (kJ/kg ^oC) [195], *mass* is the mass of water (kg) and *dT* is the temperature variation between well's water and the surrounding in (^oK).

$$Ek_{t,s} = C_p\ mass\ dT_{t,s} \quad \textbf{(B-11)}$$

It is possible to measure the heat loss radiation in J as 1J represents $2.78*10^{-4}$Watt-hour:

$$\frac{Q_{t,s}\Delta t(Watt - hour)\ \ *1J}{2.78*10^{-4}} = Q(J) \quad \textbf{(B-12)}$$

The appropriate unit conversion of the heat loss radiation from J to kJ is considered and the result is relieved as in the equation below:

$$Q_{t,s}(kJ) = C_p\ mass\ dT_{t,s} \quad \textbf{(B-13)}$$

At this instant, dT can be determined as:

$$dT_{t,s}(^oC) = \frac{Q_{t,s}(KJ)}{4.2\ mass} \quad \textbf{(B-14)}$$

mass can be obtained from the equation shown below where ρ is the density of water that is 1000kg/m^3, *Volume* is water volume measured in m^3 and *D* is the depth of the water in the well measured in meter.

$$\rho = \frac{mass}{Volume} = \frac{mass}{A\,D} \tag{B-15}$$

Appendix C
Economic Consideration

C.1 The cash flow used to find equity internal rate of return

In indicates cash income, *Out* indicate cash outcome, *HR* is the number of hours in year *n*, *CUF* is the capacity utilization factor of the project under study, *RAT* is the project power rating, *k* is the price of electricity generated from the project (INR/kWh), *OM* is the operation and maintenance cost (INR), *COM* is the operation and maintenance contingency cost, *fuel* is the fuel cost if used (INR/Liter), *inf* is the inflation rate of the cost, *A* is the debt repayment, *DT* is the debt term, *C* is the capital cost of the project and *esc* is the escalation rate of the price of energy or fuel cost.

$$Pcash\ (n) = In\ (n) + Out\ (n) \tag{C-1}$$

$$In\ (n) = K\ x\ CUF\ x\ HR\ x\ RAT\ (1+esc)^n \tag{C-2}$$

$$Out\ (n) = \begin{cases} -[(OM+COM)\ x\ (1+\inf)^n + fuel(1+esc)^n + A] & \forall\ \ 0 < n \le DT \\ -C & \forall n = 0 \\ -[(OM+COM)\ x\ (1+\inf)^n + fuel(1+esc)^n] & \forall n > DT \end{cases} \tag{C-3}$$

C.2 Tax Estimation on Pretax Cash Flow

The effective tax rate (*Tax*) on taxable income is considered and applied as shown below. It is important to emphasize that in [80], the tax is applied at year zero as 10% of the project is assumed to be depreciated in this year; while in the analysis considered in this thesis, this tax is not considered because the project is to undergo 100% depreciation. A comparison on different assumptions including this has been shown in the thesis. *Pcash* is the pretax cash flow, *dep* is the amount of depreciation and *int* is the debt minus interest when calculating equity IRR and it has a negative value of the interest when calculating Project IRR.In the latter case, *Pcash* will ecxclude *A*.

$$Tax\ on\ Pcash(n) = Tax\ x \begin{cases} Pcash(n) - dep(n) & n > DT \\ Pcash(n) - dep(n) + \mathrm{int}(n) & \forall n \neq 0\ \ and\ \ \forall n \leq DT \end{cases}$$ **(C-4)**

C.3 After Tax Cash Flow

The after tax cash flow is determined applying **(C-5)** as in [80]:

$$Cash(n) = Pcash(n) - Tax\ on\ Pcash(n)$$ **(C-5)**

The deduction of the tax from the *Pcash* is determined as given in the figure below according to [80].

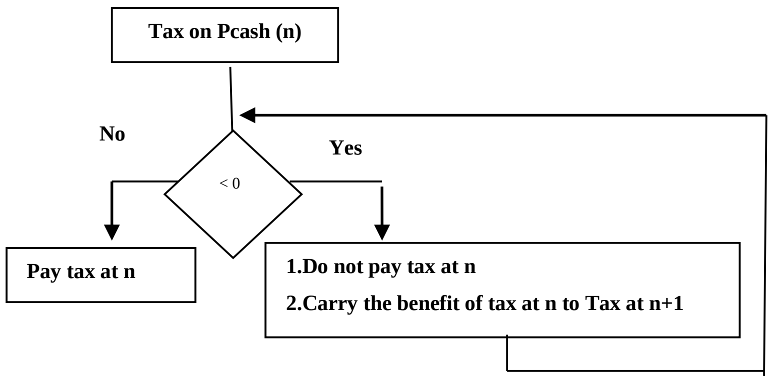


Figure AC. 1: Tax payment statement

C.4 *Interest*

The interest component of the debt repayment is not essentially to be repaid in equivalent amounts every year. It is possible to calculate this amount using Excel software. The function used in Excel is shown below based on [78, 90]:

$$IPMT\begin{pmatrix} \text{annual loan interest rate,} \\ \text{year number in which repayment is to be made,} \\ \text{loan repayment period} \\ \text{loan amount} \end{pmatrix}$$ **(C-6)**

C.5 *Depreciation Methods:*

The straight line depreciation is given by [80, 81]:

$$SLD = \begin{cases} \dfrac{(C - S)D}{N} & \forall n > 0 \\ C\ (1 - D) & \forall n = 0 \end{cases}$$ **(C-7)**

The declining balance depreciation is given by [80]:

$$DB_n = \begin{cases} U_{n-1}\ R & \forall 0 < n < N \\ U_{N-1} & \forall n = N \\ C(1 - D) & \forall n = 0 \end{cases}$$ **(C-8)**

The undepreciated capital cost is given by [80]:

$$\begin{cases} U_{n-1} = U_{n-2} - DB_{n-1} & \forall 0 < n < N \\ U_{N-1} = DB_N & \forall n = N \\ U_n = C - DB_n & \forall n = 0 \end{cases} \quad \textbf{(C-9)}$$

where S *LD* is straight line depreciation, *D* is depreciation tax basis, *N* is project life (25years), *S* is salvage value (zero), *DB* is declining balance depreciation, *n* is year of the project, *R* is depreciation rate and *U* is un-depreciated capital cost.

Permissions for Publications from the Thesis

- ✓ Reproduced by permission of the Institution of Engineering & Technology Full acknowledgment to the Ameena Al-Sumaiti and Magdy Salama, Review on issues related to electric energy demand in distribution system for developing countries, 2014:
  [3] A. Al-Sumaiti and M. M. A. Salama, "Review on issues related to electric energy demand in distribution system for developing countries," presented at the 3rd IET International Conference on Clean Energy and Technology, Kuching, Sarawak, Malaysia, 2014

- ✓ This is an Author's Original Manuscript of an article published by Taylor & Francis in [Electric Power Components and Systems] on [09 Sep 2014], available online: *http://wwww.tandfonline.com/*[Article DOI: 10.1080/15325008.2014.933375]."
  [16] A. S. Al-Sumaiti, M. A. Hassan, and M. M. A. Salama, "Residential load management under stochastic weather condition in a developing country," *Electric power components and Systems* vol. 42, pp. 1352-1473, 2014.

- ✓ This is an Author's Original Manuscript of an article published by Taylor & Francis in [Electric Power Components and Systems] on [05 Feb 2014], available online: *http://wwww.tandfonline.com/*[Article DOI: 10.1080/15325008.2013.832439]."
  [28] A. S. Al-Sumaiti, M. H. Ahmed, and M. M. A. Salama, "Smart home activities: a literature review," *Electric Power Components and Systems,* vol. 42, pp. 294-305, 2014.

- ✓ © 2013 IEEE. Reprinted, with permission, from [Ameena Al-Sumaiti, The role of regulation in the economical evaluation of renewable energy Investments in developing countries, 7th IEEE GCC Conference and Exhibition, November/2013]:
  [78] A. S. Al-Sumaiti, "The role of regulation in the economical evaluation of renewable energy investments in developing countries," presented at the 7th IEEE GCC, Doha, Qatar, 2013.

Other Permissions

Other permissions for some of the references requiring permission to be used in the thesis are obtained.

Bibliography

[1] C. Wolfram, O. Shelef, and P. Gertler, "How will energy demand develop in the developing world?," *Journal of Economic Perspectives,* vol. 26, pp. 119-138, January 2012.

[2] EnergyInformationAdministration. (2011). *2011 International Energy Outlook* Available: http://www.eia.gov/forecasts/ieo/index.cfm

[3] A. Al-Sumaiti and M. M. A. Salama, "Review on issues related to electric energy demand in distribution system for developing countries," presented at the 3rd IET International Conference on Clean Energy and Technology, Kuching, Sarawak, Malaysia, 2014.

[4] IEA. (2009). *Electrification rate by Indian states*. Available: http://www.iea.org/country/Poverty_India/Electrification.pdf

[5] Ministry of Power, Government of India "About rural electrification."

[6] Population Reference Bureau. (2009). *World population data sheet*. Available: http://www.prb.org/pdf09/09wpds_eng.pdf

[7] M. A. McNeil and V. E. Letschert, "Forecasting electricity demand in developing countries: A study of household income and appliance ownership," *European Council for an Energy Efficient Economy, Panel 6: Dynamics of Consumption,* vol. 6,259, 2005.

[8] B. Mohanty, "Standby power lessons in household electrical appliances and office equipment," *Regional symposium on energy efficiency standards and labeling,* vol. 20, May 2001.

[9] O. P. Sharma and C. Haub. (2012). *How people in India really live*. Available: http://www.prb.org/Articles/2008/howindianslive.aspx

[10] National Sample Surveys (India), "Housing condition in India: Household amenities and other characteristics, NSS Rep. 489," May 2005.

[11] Almohandes.org. (2011). *How many solar cells do you need for your house and what is the cost? (Translated version)*. Available: http://www.almohandes.org/vb/f133/t51725

[12] A. Wilson and J. Morill, *Consumer guide to home energy savings*: American council for an energy efficient economy, 1991.

[13] ABS.Alaskan. (2008). *Power consumption table*. Available: http://www.absak.com/library/power-consumption-table

[14] "Nat. Sample Surveys: 'Employment and unemployment situation in India 2004-05'. NSS Rep. 515(61/10/1), India, Sep. 2006 ".

[15] NIC. *Ahmednagar*. Available: http://ahmednagar.gov.in/html_docs/GEO-Main.htm

[16] A. S. Al-Sumaiti, M. A. Hassan, and M. M. A. Salama, "Residential load management under stochastic weather condition in a developing country," *Electric power components and Systems* vol. 42, pp. 1352-1473, 2014.

[17] B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, and L. A. Meyer, "Contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change," Cambridge, United Kingdom and New York, NY, USA.2007.

[18] C. More, S. J. Saikia, and R. Banerjee, "An analysis of Maharashtra's power situation," *Economic and Political Weekly,* pp. 3943-3951, March 20th 2007.

[19] M. CentralElectricityAuthority, " 17th electric power survey of India," India2007.

[20] ThereAreNoSunglasses. (2013). *Ordinary Pakistanis have no gas or electricity for 20 hours every day, while judges, politicians and generals are never without power!* . Available: https://therearenosunglasses.wordpress.com/2013/06/11/ordinary-pakistanis-have-no-gas-or-electricity-for-20-hours-every-day-while-judges-politicians-and-generals-are-never-without-power/

[21] National Institute of Hydrology, Roorkee, India. "Hydropower potential in India.". Available: http://www.nih.ernet.in/rbis/india_information/hydropower.htm
[22] ASAPP news bureau. (2012). *Maharashtra may not face power-cuts from Dec*. Available: http://www.infranews.in/News.aspx?nid=s2Bz422hgxmysmOhH2z3Dw==&news=Maharashtra-may-not-face-power-cuts-from-Dec-India-Sector
[23] IDFC, "Power distribution reforms in Maharashtra," October 2009. Available: http://www.idfc.com/pdf/publications/Maharashtra-Distribution-Reforms-Draft-Report.pdf
[24] Nepal Load Shedding Schedule Sponsered by Easy Nepali Typing. (2014). *Nepali load shedding schedule: Effective from 4 June 2014 (21st Jestha 2071) - 8 hrs Daily*. Available: http://www.easynepalityping.com/loadshedding-nepali
[25] Maharashtra State Electricity Distribution Co.Ltd. (2014). *Load sheduling cirular 46: Annexure A*. Available: http://mahadiscom.com/consumer/load-shedding-protocol-01.shtm
[26] World Energy Council-Indian Member Committee (WEC-IMC) and Power Grid Corporation of India Limited, "Tranmission and distribution in India: A report," india.
[27] CGIAR. *Smart solar pump' solution gains foothold in India*. Available: http://wle.cgiar.org/blog/2015/02/13/smart-solar-pump-solution-gains-foothold-india/
[28] A. S. Al-Sumaiti, M. H. Ahmed, and M. M. A. Salama, "Smart home activities: a literature review," *Electric Power Components and Systems,* vol. 42, pp. 294-305, 2014.
[29] Natural resources Canada. (2004). *Teacher's note: wind energy project (grid connected wind farm, Andhara Pradesh, India)*. Available: www.retscreen.net/download.php/ang/33/2/WIND04-B.pdf
[30] The MathWorks- nc. *MATLAB (the language of technical computing)*. Available: http://www.mathworks.com/products/matlab/
[31] *GAMS*. Available: www.gams.com
[32] T. Gonen, *Electric power distribution engineering*: McGraw-Hill Inc, 1986.
[33] Reliability Test System Task Force Of The Application Of Probability Methods Subcommittee, "IEEE Reliability Test System-1996," *IEEE transaction on Power Systems,* vol. 14, pp. 1010-1020, 1999.
[34] Makanaka. (2010). *Household income*. Available: http://makanaka.wordpress.com/tag/household-income/
[35] L. E. Hodge, "Demand side management of households in Bergen- A study of potential peak load reductions," Department of Ecology and Natural Resource Management, Norwegian University of Life Sciences, 2013.
[36] timeanddate.com. (2012). *Sunrise and sunset in Mumbai*. Available: http://www.timeanddate.com/worldclock/astronomy.html?n=44&month=1&year=2012&obj=sun&afl=-11&day=1
[37] worldwide-tax.com. (2012). *India businesses hours*. Available: http://www.worldwide-tax.com/india/indbusiness.asp
[38] Indian Human Development Survey, 2005.
[39] The Tata Power Company Limited, "Scedule of electricity tariff," September 1st 2010.
[40] A. Thakur. (2008). *33% of Indians live in less space than US prisoners*. Available: http://articles.timesofindia.indiatimes.com/2008-11-25/india/27912135_1_sq-ft-sq-feet-urban-areas
[41] M. A. A. Pedrasa, T. D. Spooner, and I. F. MacGill, "Coordinated scheduling of residential distributed energy resources to optimize smart home energy services," *IEEE Transactions on Smart Grid,,* vol. 1, pp. 134-143, 2010.

[42] H. Long Duy, S. Ploix, E. Zamai, and M. Jacomino, "Tabu search for the optimization of household energy consumption," in *IEEE International Conference on Information Reuse and Integration*, 2006, pp. 86-92.
[43] O. S. Pawaskar and S. S. More, "Time of Day Tariff Structure," *IE(I) 23rd National Convention of Electrical Engineers* pp. 129-123.
[44] Freemeteo. (January 2012). *weather forecasts for the entire planet*. Available: http://freemeteo.com/default.asp?pid=20&gid=1261481&sid=421810&la=1&lc=1&nDate=1/1/2012
[45] Freemeteo. (August 2012). *weather forecasts for the entire planet*. Available: http://freemeteo.com/default.asp?pid=20&gid=1261481&sid=421810&la=1&lc=1&nDate=1/8/2012
[46] M. D. Pandey, "CIVE 601 course notes: Engineering risk and reliability," ed: Department of Civil and Enviromental Engineering, University of Waterloo.
[47] indiamart. (1996). *Electric room heater from India*. Available: http://dir.indiamart.com/impcat/electric-room-heater.html
[48] M. A. Pedrasa, E. D. Spooner, and I. F. MacGill, "Improved energy services provision through the intelligent control of distributed energy resources," presented at the 2009 IEEE Bucharest PowerTech Conference, Bucharest, Romania, 2009.
[49] A. Hartley, "Fuel poverty," Birmingham, UK1 March 2006 2006.
[50] D. Ryder-Cook, "Thermal Modelling of Buildings," 2009.
[51] D. J. C. MacKay. (2009). *Sustainable energy – without the hot air*. Available: http://www.withouthotair.com
[52] *Discretization*. Available: http://en.wikipedia.org/wiki/Discretization
[53] J. Chew. *How to become a human windchill calculator*. Available: http://www.poslarchive.com/math/misc/windchill.html
[54] K. M. *How to convert RPM to MPH with a Calculator*. Available: http://www.ehow.com/how_8259717_convert-rpm-mph-calculator.html
[55] Magnequench. (2010). *Ceiling fan motor analysis (ed.)*. Available: http://www.mqitechnology.com/downloads/motor_design/MotorDesign-10-CeilingFanMotor.pdf
[56] M. Lubliner, J. Douglass, D. Parker, and D. Chasar, "Performance and applications of Gossamer Wind™ solar powered ceiling fans," presented at the The 25th Conference of the Air Infiltration and Ventilation Centre, Prague, Czech Republic 2004.
[57] J. C. Smith and Z. C. Taskın, "A tutorial guide to mixed-integer programming models and solution techniques," March 26 2007.
[58] C. Aguilar, D. J. White, and D. L. Ryan, "Domestic water heating and water heater energy consumption in Canada," CBEEDAC 2005–RP-02, April 2005.
[59] T. P. Wenzel, J. G. Koomey, G. J. Rosenquist, M. Sanchez, and J. W. Hanford, "Energy data sourcebook for the U.S. residential sector," Ernest Orlando Lawrence Berkeley National Laboratory Report LBNL-40297, 1997.
[60] GENRUI Technology Co., Ltd. (2013). Available: http://www.genrui.cc/aspcms/news/2013-4-15/296.html
[61] The Engineering ToolBox. *Radiation heat transfer*. Available: http://www.engineeringtoolbox.com/radiation-heat-transfer-d_431.html
[62] APEC. *Ground water and temperature*. Available: http://www.freedrinkingwater.com/water-education2/7-ground-water-temperature.htm
[63] Asknumbers.com. (2012). *Celsius to Kelvin conversion*. Available: http://www.asknumbers.com/celsius-to-kelvin.aspx

[64] J. D. Lutz, X. Liu, J. E. McMahon, C. Dunham, L. J. Shown, and Q. T. McGrue, "Modeling patterns of hot water use in households," Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California, USA1996.

[65] The School of Hard Knocks. (2011). *For an electric water heater*. Available: http://www.leaningpinesoftware.com/hot_water_heater_tank_insul.shtml

[66] AOSmith. *Residential electric water heaters*. Available: http://s3.pexsupply.com/manuals/1277918330238/33791_PROD_FILE.pdf

[67] *Water Heating* Available: http://en.wikipedia.org/wiki/Water_heating

[68] C. L. Thomas and M. K. Rice, *Taber's cyclopedic medical dictionary* 16 ed. Philadelphia: F. A. Davis, 1989.

[69] International Institute for Population Sciences (IIPS) and Macro International Inc, "National family health survey (NFHS-3), 2005-2006, India," Calverton, Maryland, USA 2007.

[70] Wikipedia. (2013). *Indian states ranking by household size*. Available: http://en.wikipedia.org/wiki/Indian_states_ranking_by_household_size

[71] *Please tell me the Power Factor!!?* Available: https://in.answers.yahoo.com/question/index?qid=20100416020333AAxa68L

[72] The Engineering ToolBox, "Power Factor for a Three-Phase Electrical Motor."

[73] M. Karandikar and Mahavitaran. (2011). *Akshay Prakesh Yojana*. Available: https://www.youtube.com/watch?v=m0czpyYk_-Q

[74] R. Singh, Y.R.Sood, and N.P.Padhy, "Development of renewable energy sources for Indian power sector moving towards competitive electricity market," presented at the IEEE power and energy society general meeting, 2009.

[75] Ministry of New and Renewable Energy Source. Available: http://www.mnes.nic.in

[76] H. Khatib, "Energy issues in developing countries," WEC cmmittiee on developing countries meeting April 1993.

[77] H. Khatib, "Renewable energy in developing countries," presented at the International conference on renewable energy clean power London, 1993.

[78] A. S. Al-Sumaiti, "The role of regulation in the economical evaluation of renewable energy Investments in developing countries," presented at the 7th IEEE GCC, Doha, Qatar, 2013.

[79] D. Kulkarni. (2012). *No load-shedding in Maharashtra from Dec?* Available: http://www.dnaindia.com/mumbai/report_no-load-shedding-in-maharashtra-from-dec_1753595

[80] Natural resources Canada, *Clean energy project analysis (RETScreen engineering & cases textbook)*, 3 ed.

[81] D. G. Newnan, T. G. Eschenbach, and J. P. Lavelle, *Engineering economic analysis*, 9 ed.: Oxford University Press, 2004.

[82] P. Deo, S. S.Jayaraman, S. V. S. Verma, and S. M. D. Dayalan, "In the matter of determination of generic levellised generation tariff for the FY2013-14 under Regulation 8 of the Central Electricity Regulatory Commission (Terms and Conditions for Tariff determination from Renewable Energy Sources) Regulations, 2012.," New Delhi, India2013.

[83] IRENA, "Renewable energy analysis: cost analysis series," *Power Sector*, vol. 1, 2012.

[84] H. Mitavachan, A. Gokhale, and J. Srinivasan, "A case study of 3MW scale grid connected solar photovoltaic power plant at Kolar, Karnataka : Performace assessment & recommendations," Indian Institute of Science, India2011.

[85] Shiv. (2013). *Cost of 1MW photovoltaic solar plant in India*. Available: http://www.linkedin.com/groups/COST-1-MW-PHOTOVOLTAIC-SOLAR-1874501.S.200396349

[86] R. Banerjee, "Comparison of options for distributed generation in India," *Elsevier:Energy policy*.
[87] D. Pauschert, "Study of equipment prices in the power sector," ESMAP2009.
[88] A. Mandal, "A report on design estimation of 1MW solar PV plant (utility scale)."
[89] Central Electricity Regulatory Commission, "Explanatory memrandom for tariff norms for solar power projects," 2009.
[90] TechOnTheNet.com. (2003-2013). *MS Excel: IPMT Function (WS, VBA)*. Available: http://www.techonthenet.com/excel/formulas/ipmt.php
[91] Milefoot.com. *The mathematics of MACRS depreciation*. Available: http://www.milefoot.com/math/businessmath/topics/macrs.htm
[92] M. O'Neill. *MACRS Depreciation*. Available: http://seattlecentral.edu/faculty/moneil/Lectures/macrs.htm
[93] H. Campbell and R. Brown, "Benifit cost analysis: Financial and economic appraisal using spreadsheets," ed: Cambridge University Press, 2003.
[94] C. S. Park, "Fundamentals of Engineering Economics: Project Cash Flow Analysis, Lecture No. 27," 2005.
[95] Maharashtra State Electricity Distribution Co.Ltd, "Tariff of non conventional energy (NCE) / renewable energy projects for FY 2010-11," Mumbai2010.
[96] Maharashtra Electricity Regulatory Commission, "Terms and conditions for determination of re-tariff," Mumbai2010.
[97] S. Raja and S. Sonavani, "In the matter of determination of generic tariff under regulation 8 of the Maharashtra electricity regulatory commission (terms and conditions for determination of renewable energy tariff) Regulations," 2010.
[98] K. Zweibel, "Cost comparison of PV with other electricity options," The George Washington University.
[99] Climate Connect Ltd. (2013). *Maharashtra confirms 19% cut in solar PV tariff; undercuts REC floor price, CERC tariff*. Available: http://www.climate-connect.co.uk/Home/?q=Maharashtra%20confirms%2019%25%20cut%20in%20solar%20PV%20tariff%3B%20undercuts%20REC%20floor%20price%2C%20CERC%20tariff
[100] Climate Connect Ltd. (2013). *Maharashtra proposes lowest solar PV tariff, undercuts solar REC floor price* Available: http://www.climate-connect.co.uk/Home/?q=Maharashtra%20proposes%20lowest%20solar%20PV%20tariff%2C%20undercuts%20solar%20REC%20floor%20price%20
[101] B. Trivedi. (2011). *Solar Power Becomes Cheaper than Diesel in India* Available: http://www.renewableenergyworld.com/rea/news/article/2011/12/solar-power-becomes-cheaper-than-diesel-in-india
[102] Vertex42.com. (2014). *Discount factor table for excel: Summary of discount factor formulas for TVM calculations in excel by Jon Wittwer*. Available: http://www.vertex42.com/ExcelArticles/discount-factors.html
[103] J. W. Wittwer, ""Calculating Discount Factors in Excel," From Vertex42.com."
[104] Natural resources Canada. (2012). *Power – photovoltaic – feed-in tariff – policy / Canada*. Available: http://www.retscreen.net/ang/case_studies_feed_in_tariff_policy_canada.php
[105] MaRS Discovery District, "Financing renewable energy: accelerating Ontario's green energy industry," 2010.
[106] G. Shively and M. Galopin. *An Overview of Benefit-Cost Analysis*. Available: http://www.agecon.purdue.edu/staff/shively/COURSES/AGEC406/reviews/bca.htm
[107] NPTEL. (Lecture 14 : Incremental benefit-cost ratio analysis). Available: http://nptel.ac.in/courses/105103023/22

[108] Maverik green tech pvt. ltd. *Solar project 5MW capacity*.
[109] S. Bahaskar, "Cashing on the sun: Financial attractiveness of on-grid solar PV and thermal projects in India," India2010.
[110] S. Vashishtha and S. Nair. (2013). *Understanding accelerated depreciation in solar projects*. Available: https://firstgreenconsulting.wordpress.com/2013/05/21/understanding-accelerated-depreciation-in-solar-projects/
[111] C. S. Park. (2005). *Fundamentals of Engineering Economics: Corporate Taxes (Lecture No.25)*. Available: http://faculty.kfupm.edu.sa/SE/atique/SE307_Engineering_Economics/
[112] R. Bales. (2006). *Chapter 9: Project cash flow analysis.* Available: https://eng.ucmerced.edu/people/rbales/Courses/ENGR155files
[113] M. G. Lipsett. (2010). *ENGM 401 & 620 – X1: Fundamentals of engineering finance, Lecture 28: After tax cash flow*. Available: http://www.ualberta.ca/~mlipsett/ENGM401_620/ENGM401_620.htm
[114] A. Mursau. (2012). *Depreciation accounting (MACRS vs GAAP book depreciation effect on taxable income)*. Available: https://www.youtube.com/watch?v=T2mkxmDqGhU
[115] Investopedia. (2015). *Depreciation*. Available: http://www.investopedia.com/terms/d/depreciation.asp
[116] Wind Energy America. (2009). *Frequently asked questions*. Available: http://www.windenergyamerica.com/faqs.html
[117] Secure Future, LLC. (2013). *Benifits*. Available: http://securefutures.us/services/benefits/
[118] CDM Executive Board (UNFCCC/CCNUCC), "Project design document form for CDM project activities," 2012.
[119] P. Westerman, M. Veal, J. Cheng, and K. Zering, "Carbon credits for Methane collection and combustion," College of Agrculture and Life Sciences, NC State University.
[120] M. A. Ajero. Estimating CO2 emissions reduction by example [Online].
[121] S. Bhawan and R.K.Puram, "Co2 baseline database for Indian power sector," Central Electricity Authority, Ministry of Power, Government on India, New Delhi, India2011.
[122] S. P. Pratt and R. J. Grabowski, *Cost of capital: Applications and examples*. Hoboken, New Jersey and Canada: Joh Wiley & Sons Inc, 2010.
[123] JustAnswer.LLC. Available: www.justanswer.com/uploads/.../2009-06-18_060823_pip_1.doc
[124] Income Tax Department, Ministry of Finance, Government of India. *Tax rates*. Available: http://www.incometaxindiapr.gov.in/incometaxindiacr/contents/taxrates/COMPANIES_2013_14.htm
[125] G. S. Patil. (2012). *Carbon credit fraud: How big firms faked green to mint gold*. Available: http://www.dnaindia.com/mumbai/1738940/report-carbon-credit-fraud-how-big-firms-faked-green-to-mint-gold
[126] N. Bothra, "Carbon Credits – Unravelling regulatory, taxation & accounting issues," Vinod Kothari & Company.
[127] P. C. Fishburn and G. A. Kochenberger, "Two-piece von neumann-morgenstern utility functions," *Decision Sciences* vol. 10, pp. 503-518, 1979.
[128] A. K. Hiranandai, "A sensitivity approach to the sizing of insulated power cables in low and medium voltage electrical power distribution systems," *IEEE Transaction on Power Delivery*, vol. 4, pp. 1521-1528, 1989.
[129] M. M. A. Salama, R. Hackam, and A. Y. Chikhani, "Instructional desing of multi-layer insulation of power cables," *Transaction on Power Systems*, vol. 7, pp. 377-382, February 1992.

[130] Canada Wind Energy Association (canwea), "Small wind turbine purchasing guide: offgrid, residential, farm & small business applications."
[131] WindPowerForums.com. HomeWindTurbines. (2008). *Specifications and details on 1KW wind turbine kit*. Available: http://windenergy7.com/forums/viewtopic.php?p=25
[132] ASOS Network. *ASOS-AWOS-METAR Data Download*. Available: http://mesonet.agron.iastate.edu/request/download.phtml?network=II_ASOS
[133] Tozzi nord. *Tozi nord Brochure: Winning with wind*. Available: http://www.tozzinord.com/source/Tozzi_Nord_en.pdf
[134] G. Howell. *Mech E443, Energy conversion*. Available: http://www.hme.ca/presentations/UA_Mech_E_443_--_Solar_PV_Design_Overview_2010_03_29.pdf
[135] M. Alotaibi, "Modeling of renewable resources in distribution system planning and operation," Master, Electrical and Computer Engineering, University of Waterloo, Waterloo, Canada, 2014.
[136] D. Sarkar. (2007). [R] *Histograms and Sturges' rule* . Available: https://stat.ethz.ch/pipermail/r-help/2007-November/146967.html
[137] J. F. Newman and P. M. Klein, "Extrapolation of wind speed data for wind energy applications," presented at the AMS 93RD Annual Meeting, Austin, Texas, 2013.
[138] *Power law analyses*. Available: www.deq.mt.gov/energy/wind_atlas/atlas/pdf/Chapter5.PDF
[139] E. W. Peterson and J. P. H. Jr, "On the use of power laws for estimates of wind power potential," *Journal of Applied Meteorology* vol. 17, pp. 390-394, 1978.
[140] M. Elnashar, "Enabling High Wind Penetration in Electrical Grids," PHD, ECE, University of Waterloo, Canada, 2011.
[141] M. H. Ahmed, "New models and analytical frameworks for power systems with wind generation penetration," PHD, Electrical and Computer Engineering, University of Waterloo, Waterloo, Ontario, Canada, 2012.
[142] NIST/SEMATECH. (2013). *e-Handbook of Statistical Methods: Weibull distribution*. Available: http://www.itl.nist.gov/div898/handbook/eda/section3/eda3668.htm
[143] D. L. Bricker. (2000). *Weibull distribution*. Available: http://user.engineering.uiowa.edu/~dbricker/active%20learning%20cases/Stochastic/Weibull_tables.PDF
[144] Y. Atwa, "Distribution system planning and reliability assessment under high DG penetration," PHD, Electrical and Computer Engineering, University of Waterloo, Canada, 2010.
[145] K. Divya and P. Rao, "Models for wind turbine generating systems and their application in load flow studies," *Electric Power Systems Research*, vol. 76, pp. 844-856, 2006.
[146] N. Hatziargyriou, T. Karakatsanis, and M. Papadopoulos, "Probabilistic load flow in distribution systems containingdispersed wind power generation," *IEEE Transactions on Power Systems*, vol. 8, pp. 59-165, 1993.
[147] P. Jeantya, M. Delsautb, L. Trovaleta, H. Ralambondrainyb, J. D. Lan-Sun-Luka, M. Bessafia, *et al.*, "Clustering daily solar radiation from Reunion Island using data analysis methods," presented at the International Conference on Renewable Energies and Power Quality (ICREPQ'13), Bilbao, Spain, 2013.
[148] P. Jeantya, M. Delsautb, L. Trovaleta, H. Ralambondrainyb, J. D. Lan-Sun-Luka, M. Bessafia, *et al.*, "Clustering daily solar radiation from Reunion Island using data analysis methods," *Renewable Energy and Power Quality Journal (RE&PQJ)*, vol. 11, pp. 1-6, March 2013 2013.

[149] A. Y. Dissou and O. F. Tabi, "Monthly cluster of hourly solar irradiation in Kumasi-Ghana," *International Journal of Business and Social Science,* vol. 3, pp. 123-131, October 2012 2012.

[150] A. Bracale, P. Caramia, G. Carpinelli, A. R. D. Fazio, and G. Ferruzzi, "A Bayesian method for short-term probabilistic forecasting of photovoltaic generation in smart grid operation and control," *energies,* vol. 6, pp. 733-747, 2013.

[151] Y. M. Atwa, E. F. El-Saadany, M. M. A. Salama, R. Seethapathy, M. Assam, and S. Conti, "Adequcy evaluation of distribution system including wind/solar DG during different modes of operation," *IEEE Trnsaction on Power Systems,* vol. 26, pp. 1945-1952, November 2011 2011.

[152] E. Koutroulis, D. Kolokotsa, A. Potirakis, and K. Kalaitzakis, "Methodology for optimal sizing of stand-alone photovoltaic/wind generator systems using genetic algorithms," *Solar Energy,* vol. 80, pp. 1072-1088, 2006.

[153] W. Omran, "Performance analysis of grid-connected photovoltaic systems," PHD, Electrical and Computer Engineering, University of Waterloo, Waterloo, Ontario, Canada, 2010.

[154] C.-J. Huang, M.-T. Huang, and C.-C. Chen, "A novel power output model for photovoltaic system," *Industrial Journal of Smart Grid and Clean Energy,* vol. 2, pp. 139-147, May 2013 2013.

[155] M. E. Ropp and M. Begovi, "Determination of the curvature derating factor for the Georgia Tech Aquatic Center photovoltaic array," presented at the Twenty-Sixth IEEE Photovoltaic Specialists Conference, Anaheim, CA, 1997.

[156] E. Skoplaki and J. A. Palyvos, "On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations," *Elsevier Solar Energy,* vol. 83, pp. 614-624, 2009.

[157] National Renewable Energy Laboratory. (2013). *Updated India solar resource Maps*. Available: http://www.nrel.gov/international/ra_india.html

[158] A. Verma and S. Singhal, "Solar PV performance parameter and recommendation for optimization of performance in large scale grid connected solar PV plant—Case Study," *Journal of Energy and Power Sources,* vol. 2, pp. 40-53, 2015.

[159] A.Q. Jakhrani, A. K. Othman, A. R. H. Rigit, and S. R. Samo, "Comparison of solar photovoltaic module temperature models," *World Applied Sciences Journal:Special Issue of Food and Environment (01-08, 2011),* vol. 14, pp. 1-8, 2011.

[160] Mike Holt Enterprises Inc, *Mike Holt's illustrated guide to understanding 2011 NEC requirements for Solar photovoltaic (PV) systems*, 2011.

[161] G. Marios. (2013). *PV voltage temperature coefficients*. Available: http://vimeo.com/67448086

[162] NC Clean Energy. Available: http://nccleantech.ncsu.edu/wp-content/uploads/3-Article-690-explored.pdf

[163] Y. Atwa, E. El-Saadany, M. Salama, and R. Seethapathy, "Optimal renewable resources mix for distribution system energy loss minimization," *IEEE Transaction on Power Systems,* vol. 25, pp. 360 - 370 2009.

[164] M. Walker. (2012). *10487 - How HOMER calculates the PV cell temperature*. Available: http://support.homerenergy.com/index.php?/Knowledgebase/Article/View/489/0/10487---how-homer-calculates-the-pv-cell-temperature

[165] Sargosis Solar & Electric (PV Solar Specialist:Information-Design-Maintenace-Repair-Consultation). *Calculating the IV and PV curves for a solar module*. Available: http://sargosis.com/articles/science/how-pv-modules-work/calculating-the-iv-and-pv-curves-for-a-solar-module/

[166] PVEducation.org. *Nominal operating cell temperature*. Available: http://www.pveducation.org/pvcdrom/modules/nominal-operating-cell-temperature
[167] Titan Energy Systems Ltd., "PV module TITAN S60-60."
[168] D. Waco. (2011). *How heat affects solar panel efficiency*. Available: http://www.civicsolar.com/resource/how-heat-affects-solar-panel-efficiency
[169] NIST/SEMATECH:e-Hand book of Statistical Methods. (2003). *Kolmogorov-Smirnov goodness-of-fit test*. Available: http://www.itl.nist.gov/div898/handbook/eda/section3/eda35g.htm
[170] A. Udas, "Road variability and its effect on vehicle dynamics simulation," Master, Mechanical Engineering, University of Iowa, Iowa Research Online, 2011.
[171] T. O. ztekin, "Wakeby distribution for representing annual extreme and partial duration rainfall series," *Meteorological Applications,* vol. 14, pp. 381-387, 2007.
[172] J. C. Houghton, "Birth of a parent: The wakeby distribution for modeling flood flows," PHD Candidate, Enviromental System Program in the Division of Applied Science, Harvard University, Harvard University, 1977.
[173] J. R. M. Hosking and J.R.Wallis, *Regional frequency analysis*. USA: Cambridge University Press, 1997.
[174] A. Heckert. (2007, April 25, 2014). *WAKPDF*. Available: http://www.itl.nist.gov/div898/software/dataplot/refman2/auxillar/wakpdf.htm
[175] Johnson, Kotz, and Balakrishnan, *Continuous univariate distribution*, 2 ed. vol. 1: Wiley, 1994.
[176] P. Friederichs, "An introduction to extreme value theory," Meteorological Institute, University of Bonn, COPS Summer Schooljuly-August 2007.
[177] J. A. Raynal-Villasenor, "Maximum likelihood parameter estimators for the two populations GEV distribution," *IJRRAS,* vol. 11, pp. 350-357, 2012.
[178] VoseSoftware. (2007, April 26, 2014). *Raw moments versus central moments*. Available: http://www.vosesoftware.com/ModelRiskHelp/Probability_theory_and_statistics/The_basics/Probability_parameters/Raw_moments_versus_central_moments.htm
[179] E. W. Weisstein. (2014, April 26). *Raw moment*. Available: http://mathworld.wolfram.com/RawMoment.html
[180] W. L. Martinez and A. R. Martinez, *Computational statistics handbook with MATLAB*. Florida, USA: Chapman & Hall/CRC, 2001.
[181] NIST/SEMATECH. (2003, April 26, 2014). *e-Handbook of Statistical Methods: Measures of Skewness and Kurtosis*. Available: http://itl.nist.gov/div898/handbook/eda/section3/eda35b.htm
[182] MathWorksInc. (2014, April 26). *Skewness*. Available: http://www.mathworks.com/help/stats/skewness.html
[183] MathWorksInc. (2014, April 26). *Kurtosis*. Available: http://www.mathworks.com/help/stats/kurtosis.html
[184] R. Carmona, *Statistical Analysis of Financial Data in R, Chapter 2: Heavy tail distributions*, second ed. USA: Springer Science & Business Media, 2013.
[185] Wikipedia. (2014, April 26, 2014). *Generalized extreme value distribution*. Available: http://en.wikipedia.org/wiki/Generalized_extreme_value_distribution
[186] W. F. Hammond, "About the gamma function: Notes for honors calculus II," University at Albany: State University of New York1995.
[187] B. A. McCarl and T. H. Spreen, *Applied mathematical programming using algebric systems*.
[188] S. W. Cheng. (2011). *Math 2810-Probability, Lecture 5: Continuous random variables*. Available:

http://www.stat.nthu.edu.tw/~swcheng/Teaching/math2810/lecture/05_ContinuousRV_1206.pdf
[189] C. W. Cheng. (2014). *Math 2810-Probability, Lecture 5: Continuous random variables (RV_1204)*. Available: http://www.stat.nthu.edu.tw/~swcheng/Teaching/math2810/lecture/06_ContinuousRV_1204.pdf
[190] S. W. Cheng. (2014). *Math 2810-Probability, Lecture 6: Continuous random variables (RV_1125)*. Available: http://www.stat.nthu.edu.tw/~swcheng/Teaching/math2810/lecture/06_ContinuousRV_1125.pdf
[191] S. W. Cheng. (2014). *Math 2810-Probability, Lecture 6: Continuous random variables*. Available: http://www.stat.nthu.edu.tw/~swcheng/Teaching/math2810/lecture/06_ContinuousRV_part4.pdf
[192] ThermoWorks. (2012). *Emissivity table*. Available: http://www.thermoworks.com/emissivity_table.html
[193] P. J. Mohr and B. N. Taylor, "CODATA recommended values of the fundamental physical constants:2002," *Rev. Mod. Phys*, vol. 77, pp. 1-107, 2005.
[194] Chemical Portal. *Fundamental physical constants* Available: http://www.webqc.org/constants.php
[195] The Engineering ToolBox. *Energy storage in water-KWh*. Available: http://www.engineeringtoolbox.com/energy-storage-water-d_1463.html