ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

Department of Electrical and Computer Engineering

# Feasibility Study of Small Hydro/PV/Wind Hybrid System for Off-Grid Rural Electrification in Ethiopia

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In partial Fulfillment of the Requirement for the Degree of
**MASTER OF SCIENCE IN ELECTRICAL ENGINEERING (ELECTRICAL POWER ENGINEERING)**

By
Getnet Tadesse
Advisor: Getachew Bekele (PhD)
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BY

GETNET TADESSE AYELE

**GSR/3197/02**

APPROVAL BY BOARD OF EXAMINERS

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## Declaration

I, the undersigned, declare that this thesis is my original work, has not been presented for a degree in this or any other university, and all sources of materials used for the thesis have been acknowledged.

All examiners' comments are duly incorporated.

Name: Getnet Tadesse Ayele

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Place: Addis Ababa

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This thesis has been submitted for examination with my approval as a university advisor.

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|---|---|
| Dr. Getachew Bekele | ______________________ |
| Advisor's Name | Signature |

# Dedication

*... to my beloved father*

***Ato Tadesse Ayele Belay***

*and*

*to my brother*

***Ashenif Tadesse Ayele (B.Sc.)***

*... for their incomparable support in all of my academic achievements!*

## Acknowledgement

Many thanks to Ministry of Education (MoE) for sponsoring my MSc program in Electrical Power Engineering. I would like to thank AAiT (Addis Ababa Institute of Technology) for facilitating the thesis work.

I will take this chance to thank my advisor Dr. Getachew Bekele for his indispensable, guidance and supervision of this thesis work from the motivation up to journal paper. He was very friendly and devoted his time without any constraint by being available at any time. I am glad to mention his saying from our discussion which impressed me.

> "Ethiopia is one of the poorest countries in the world which is an indication of having a lot of problems that should be solved in such thesis works. How could it be difficult to get a nice relevant thesis title while living in such a country? ... It will not be too long for the country to defeat poverty!"

All in all, I found Dr. Getachew much more than an academic advisor.

I want to acknowledge the former Ethiopian Ministry of Water Resource, National Metrological Agency and officials of Dejen district for their cooperation to provide the raw data. My special thanks go to my family for their indispensable support. Last, but not least, I want to acknowledge Ms Shela Zhung for her kind cooperation in giving the price list of the diesel generators.

A lot of thanks to the Almighty God for His willingness without which this thesis work is unthinkable.

**Getnet Tadesse**

# Abstract

Ethiopia is among the least developed countries on the globe with a total access to electricity not exceeding 16% (in 2007). About 85% of the population lives in places where access to electricity is less than 2%. One such a place, which is the subject of this study, is the Dejen district ($10^{0}13'24.03''$N, $38^{0}07'58''$E) having a total population of 107710 within 23 villages. About 14 villages (corresponding to 63000 people) are found in the upper Blue Nile river gorge and far remote areas, which makes the task of their electrification via grid system very difficult. Kerosene for lighting, diesel for milling and pumping, biomass for cooking and dry cells for radio are being used in the non-electrified villages. Nothing has been done so far in developing the renewable energy resources, such as small-scale hydro, solar, and wind energy in the district.

In this work, feasibility of small-scale hydro/PV/wind based hybrid electric supply system to the district is studied using HOMER (Hybrid Optimization Model for Electrical Renewables) software as optimization and sensitivity analysis tool. Six sites (two on Taba stream, one on Bechet stream, two on Muga stream and one on Suha stream) with small-scale hydropower potentials have been identified. The hydro potentials are analyzed with the help of GIS (Geographical Information System) and data obtained from the Ministry of Water Resource of Ethiopia (former). Meteorological data from National Meteorological Agency of Ethiopia and other sources, such as NASA, is used for the estimation of solar and wind energy potentials. Electric load for the basic needs of the community, such as, for lighting, radio, television, electric baker, water pumps and flour mills, is estimated. Primary schools and health posts are also considered for the community. Since HOMER can't handle six hydro resources at a time, the total load is shared to each of the six sites and analysed separately. As a result, many feasible hybrid system combinations are found having a cost of energy less than \$0.156/kWh which is much lower than diesel generators and previously studied PV/Wind hybrid systems.



**Key words:**

Small Hydropower, Wind, Solar, Hybrid, HOMER, GIS, Catchment Area, Load Estimation

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## Nomenclature

| | |
|---|---|
| $a$ | regression coefficient |
| $A$ | the diode quality/curve fitting factor |
| A | the swept area of wind turbine ($m^2$) |
| $A_c$ | the array area |
| $A_{gauge}$ | Catchment area of the gauged reference catchment ($m^2$) |
| $A_{site}$ | Catchment area of the study catchment ($m^2$) |
| ASTER-GDEM | Advanced Space-borne Thermal Emission and Reflection Radiometer Global Digital Elevation Model |
| $b$ | regression coefficients |
| $c$ | A scale parameter of Weibull distribution (m/s) |
| CC | Cyclic charge dispatch strategy |
| CFL | Compact fluorescent lamp |
| COE | Cost of energy ($/kWh) |
| $C_p$ | the power coefficient of wind turbines |
| $E_a$ | internal voltage generated by a generator (V) |
| EEPCo | Ethiopian Electric Power Corporation |
| ESRI | Environmental Systems Research Institute |
| $f(v)$ | Weibull probability density function of wind distribution |
| $f$ | system frequency |
| FAO | World Food Aid Organization |
| $g$ | gravitational acceleration (9.81 $m/s^2$) |
| $G_{SC}$ | The solar constant =1367 ($W/m^2$) |
| $G_0$ | extraterrestrial irradiance at any angle of incidence |
| $G_{on}$ | extraterrestrial irradiance at normal incidence |
| GDP | Gross Domestic Product |
| GIS | Geographical Information System |
| $G_T$ | the incident solar radiation on the array |
| $H$ | monthly average daily radiation on horizontal surface ($MJ/m^2$) |
| $H_{eff}$ | effective head ($m$) |

| | |
|---|---|
| $H_0$ | monthly average daily extraterrestrial radiation on a horizontal surface (MJ/m$^2$) |
| HOMER | Hybrid Optimization and Modeling of Electrical Renewables |
| $I$ | the load current (A) |
| $I_0$ | reverse saturation current of the diode (A) |
| $I_a$ | armature current (A) |
| $I_D$ | the diode current (A) |
| $I_L$ | current produced by the cell (A) |
| $I_{mp}$ | maximum power current (A) |
| $I_{sc}(G)$ | the short circuit current at radiation level G (A) |
| $I_{sh}$ | current through the shunt resistance (A) |
| $K$ | scale factor for flow rate estimation |
| $k$ | A constant known as shape factor of Weibull distribution |
| LF | Load follow dispatch strategy |
| LINGO | Optimization Modeling Software for Linear, Non Linear and Integer Programming |
| $m$ | the number of phases; m=3 for a 3-phase generator |
| $N$ | the maximum possible daily hours of bright sunshine given by equation |
| $n$ | monthly average daily number of hours of bright sunshine |
| NASA | National Aeronautics and Space Administration |
| NPC | Net present cost |
| $n_s$ | synchronous speed |
| $P_h$ | hydropower output in kilowatts (kW) |
| $P_{outs}$ | output power of synchronous generator (kW) |
| $P_w$ | power in the wind (W) |
| $P_{wout}$ | output power of wind turbine (W) |
| PDF | Probability Density Function of wind distribution |
| $P_{mp}$ | maximum power point (W) |
| $P_{pole}$ | number of pole pairs |
| $P_{pv}$ | power output of PV array |
| $prob(v \geq V)$ | Probability of instantaneous wind speed is greater than $V$ |

| | |
|---|---|
| $prob(v \leq V)$ | Probability of instantaneous wind speed is less than $V$ |
| PV | Photo Voltaic |
| $Q$ | charge on an electron(C) |
| $Q_h$ | quantity of water flow rate ($m^3/s$) |
| $Q_{gauge}$ | River flow rate at the gauge station ($m^3/s$) |
| $Q_{site}$ | River flow rate at the study point ($m^3/s$) |
| $R_a$ | winding/armature resistance (Ω) |
| SRTM | Shuttle Radar Topography Mission |
| SWERA | Solar and Wind Energy Resource Assessment |
| $t_L$ | local solar time in hours. |
| $V(z)$ | Wind velocity at height of Z m above ground (m/s) |
| $V$ | instantaneous wind velocity |
| V | output voltage of PV cell (V) |
| $V_a$ | output terminal voltage (V) |
| $V_{mp}$ | maximum power voltage (V) |
| $V_{oc}$ | open circuit voltage (V) |
| $v(z)$ | wind speed at height of Z m (m/s) |
| $v(z_r)$ | wind speed at the reference height (m/s) |
| $\bar{v}$ | mean wind speed |
| $X_a$ | winding/synchronous reactance |
| Z | height where wind speed is to be determined (m) |
| $Z_0$ | Surface Roughness length (m) |
| $Z_r$ | reference height (m) |
| δ | declination angle ($^0$) |
| $\eta_e$ | the efficiency of power conditioning equipment (≈90%) |
| $\eta_{mp}$ | the maximum power point efficiency of the array (≈14%) |
| $\omega_s$ | The sunset hour angle |
| $\alpha_s$ | solar altitude ($^0$) |
| $\gamma_s$ | solar azimuth ($^0$) |
| $\theta_z$ | zenith angle ($^0$) |
| $\theta_i$ | the angle between the solar beam and normal to the solar panel |

| | |
|---|---|
| $\Phi$ | the angle between the voltage *Va* and the current *Ia* |
| $\rho$ | density of air |
| $\phi$ | latitude ($^0$) |
| $\eta$ | turbo-generator efficiency |
| $\eta_t$ | Overall efficiency of the transmission system/power train of wind turbine |
| $\omega$ | solar hour angle ($^0$) |

# Introduction

## I. Background and Statement of the Problem

Ethiopia is a non-oil producing, land locked country with a population estimated to be over 80 million in 2007 [1]. In terms of gross domestic product (GDP) per capita, Ethiopia is ranked 174$^{th}$ of 179 and in terms of human development index, it is rated 169$^{th}$ of 177 [1]. 85% of the population lives in rural areas and the total access of electricity within the country was about 16% by the year of 2007 [2]. Most of the customers live in urban areas and consume less than 50 kWh per year, while rural area electricity coverage is negligible (about 2% [2, 3]).

Five years back the country has started an Accelerated Development Strategy and programs to End Poverty. By 2010/2011 budget year, it has also launched an "Accelerated Development and Transformation Plan" to bring the country as one of the middle income countries. For an economic growth rate of 7-10%, the resulting electric energy demand growth rate is about 17% [4]. But, Ethiopia is developing at an economic growth rate of 8-12% which indicates that the energy demand growth rate is more than 17%. Due to this high energy demand rate and the climatic impacts on the hydropower system the country has been in energy shortage for long time. Power shading of every other day had been practiced even in the capital, Addis Ababa as recently as the year 2010. The problem is worse in the rural areas far from the grid system and grid electrification of these areas is unthinkable in the near future. Furthermore, hydro dominated power plants have climatic, geological and political risks [5]. Hence, attention should be given to development and diversification of the power system with renewable energy sources which are cost effective in reaching the remote areas.

Ethiopia has a lot of small hydropower, solar and wind energy potentials convenient for rural electrification [1 - 12]. It is conceivable that a hybrid system has the advantage of improved reliability and therefore gives better energy service when compared to any particular (wind, solar, etc.) type of stand-alone supply system. What this means is that in the absence of one type of energy (example: solar energy during nighttime) another could be available (example: wind) to carry out the service. Hence, hybrid systems are found to be more appropriate than single stand-alone resources.

Dejen district is a place having rural villages without sufficient access to electricity, in spite of having significant renewable energy resources. According to the rural development office of the district, there are 23 villages in the district from which two are town villages electrified much earlier. Other four villages are on the way to be electrified. Additional three villages are in EEPCO's future electrification plan.

**Table-i: Electrification Status of Dejen district (source: Rural Development Office of Dejen district)**

| *Village* | **Population* | *Electrification Status* |
|---|---|---|
| *Koncher-Sasaberay* | *4561* | *no* |
| *Kurar* | *4107* | *partially* |
| *Mng Ybza* | *4325* | *no* |
| *Gelgele* | *5263* | *partially* |
| *Zemetn* | *4722* | *no* |
| *Borebor* | *4689* | *no* |
| *Yetnora* | *5755* | *partially* |
| *Tik* | *4974* | *In a plan* |
| *Alektam* | *4397* | *no* |
| *Sebshengo* | *5643* | *partially* |
| *Enagma* | *3895* | *no* |
| *Jeba* | *4068* | *no* |
| *Trch'* | *4658* | *In a plan* |
| *Muyan T/Mariam* | *4662* | *no* |
| *Berch W/Amba* | *4345* | *In a plan* |
| *Yenagnat Lagene* | *4153* | *no* |
| *Kok wuha yeqosqos* | *4584* | *no* |
| *Hagere-selam Tsdm* | *4210* | *no* |
| *Weblat Getem* | *4356* | *no* |
| *Engosh* | *4678* | *no* |
| *Kqol* | *4985* | *no* |
| *Dejen 01* | *5281* | *completely* |
| *Dejen 02* | *5402* | *completely* |
| *Total* | *107,713* | *< 6%* |

The remaining 14 villages (about 63000 people) may not be electrified any time soon due to their remoteness and uneasy geographical location. Table-i shows the electrification status of the district.

The aim of this thesis is to study the feasibility of hybrid electrification of those 14 remote villages which are not to be electrified via national grid system. The people in these villages use kerosene for lamp, diesel for water pumping and flour mills, fire wood for cooking and dry cells for radio and tape recorders. Desertification of the land is getting worse and worse due to deforestation and backward agriculture. Figure-i shows the geographical layout of the project area.

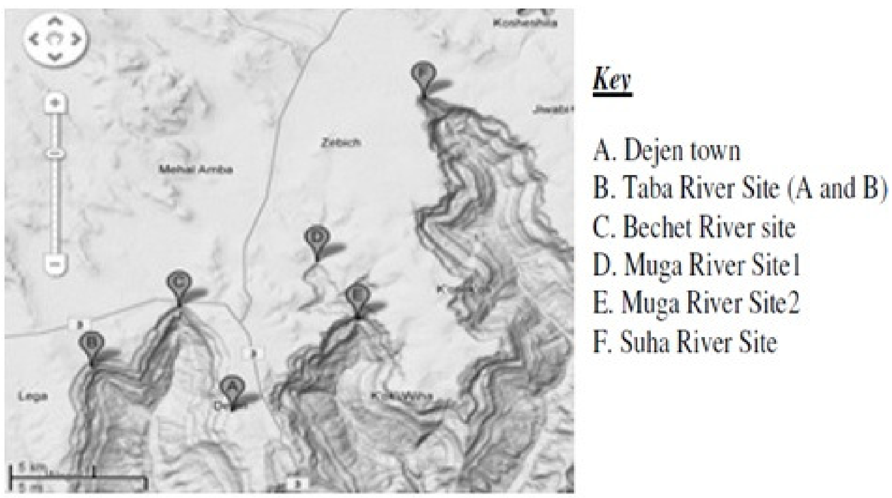


***Figure-i: Geographical layout of the project area (Source: Google Map, 2010)***

EEPCO, the sole authority for national electricity supply, has planned to electrify more and more villages time after time. However, due to capacity constraints and difficult geographical layout of the remote locations, grid connection of remote villages has not been possible. On the other hand, there are tributary rivers crossing the district and joining the Blue Nile basin. Out of these, Taba, Muga, Bechet and Suha are the main ones, with deep waterfalls. NASA (National Aeronautics and Space Administration) metrological estimation for the area shows a 6.05 kWh/m$^2$/day solar potential and a 3.1 m/s (at 10 m height) wind speed [13]. Combining these resources into hybrid off-grid system is appropriate in such remote areas.

## II. Objectives

The main objective of this thesis is to study the feasibility of small hydropower, wind and solar photovoltaic system for hybrid electrification of remote villages in Dejen district.

Specific objectives include the following goals:

- Estimation of the small hydropower potential
- Estimation of the solar Photo voltaic potential
- Estimation of the wind power generation potential
- Modeling an community load system
- Optimization and sensitivity analysis of the hydro/PV/wind hybrid system

## III. Methodology

***Site Identification***

Solar and wind distribution are assumed to be same throughout the district. The following six sites are identified for the potential assessment of small hydropower development by using Google Earth, Google Map and interviewing the local people.

- Taba A and Taba B (located at 10°12'25.68"N and 38° 3'3.00"E):
- Bechet (located at 10°14'31.00"N and 38° 5'37.11"E):
- Suha (located at 10°21'26.46"N and 38°14'45.21"E):
- Muga I (located at 10°16'11.05"N and 38°10'15.91"E):
- Muga II ( located at 10°14'11.11"N and 38°11'33.70"E):

***Data Collection and Literature Survey***

Relevant data is collected from three main sources. The first is from organizations and agencies like National Meteorological Agency and Ministry of Water Resources (former). Sunshine hour, wind speed and direction and flow rate of gauged rivers are collected from these offices and agencies. The second source is the sites themselves. Geographical layout, population distribution, surrounding environment in relation to the system design and geological characteristics are collected by visiting the sites. The third one is from different websites, especially related to cost of PV modules, wind turbines, diesel generator, converter and battery.

Related literatures on rural electrification inside Ethiopia as well as abroad are considered. These include papers and books related to rural load estimation, potential assessment techniques of hydro, wind and solar resources and for optimization of hybrid system components.

***Data Analysis and Feasibility Study***

The flow rate of streams is determined using GIS. The wind speed data is taken from NASA. The solar radiation is estimated from sunshine duration data taken from National Metrological Agency. These data are prepared in suitable format for input to HOMER. Then, feasibility study of wind, solar and small hydro systems is studied.

## IV. Related Works

Drake F. and Mulugeta Y. [6, 7] studied the solar and wind potential distribution of Ethiopia. Regression coefficients of the angstrom equation ($a$ and $b$) relating sunshine duration to daily solar radiation and Weibull parameters (shape factor, K, and the scale factor, c) are estimated throughout the country. Bekele G. [8, 9] determined solar and wind potentials of selected locations in Ethiopia and studied feasibility of Wind/PV hybrid system to electrify 200 model families using HOMER for optimization and sensitivity analysis. Tamirat B. [10] has made a feasibility comparison of independent electrification at Dillamo and Gode sites in Ethiopia by either of the wind, solar PV or micro hydropower system. But, he didn't consider the possibility of combining the resources into hybrid system and the analysis is done manually without any computer tool.

Sopian K. et al. [14] have discussed about the application of genetic algorithms in optimization of hybrid system consisting of Pico hydro system, solar photovoltaic modules, diesel generator and battery sets. Kenfack J. et al. [15] have proposed a micro hydro-PV hybrid system, at a site of Batocha, in Cameroon, using HOMER software for system optimization. Kanase-Patil A.B. et al. [16] studied off-grid electrification of seven villages in the Almora district of Uttarakhand state, India. In their study, biomass, solar, hydro and wind energy sources were considered and analysed using LINGO and HOMER software. Bakos G.C. [17] discussed feasibility of wind/hydro hybrid system to electrify remote islands in Greece. The system was simulated with the help of Monte Carlo simulation program. Connolly D. et al [18] have made a comparative study of 68 computer tools for integration of renewable resource in various energy systems. Accordingly, HOMER is best for optimization, feasibility and sensitivity analysis of both off-grid and grid connected micro power systems. Chapter 9 of a book on manual estimation of low run off [19] describes the different methods of estimating flow rates in ungauged sites. It describes the empirical method, statistical/regionalisation method, catchment modeling and use of local data as a means of estimating flow rates of ungauged rivers.

The main focus of this thesis work is to assess the solar, hydro and wind power potentials available at the Dejen district and propose optimal hybrid combinations for rural electrification of 10,500 families (with average of 6 members) using HOMER as optimization and simulation tool.

## V. Publication

A paper describing part of this thesis on community load and resource estimation together with optimization and sensitivity results of Taba B site is presented on peer reviewed "Third International Conference on Applied Energy - 16-18 May 2011 - Perugia, Italy". Furthermore, the paper is selected for publication in the special issue of Applied Energy and is on process. The paper presented on the conference looks the following:

Bekele G., Tadesse G., "Feasibility Study of Small Hydro-PV-Wind Hybrid System for Off-grid Rural Electrification in Ethiopia".

## VI. Organization of the Thesis

The introduction part discusses about the background, statement of the problem, objectives, publication and related works to this thesis. Chapter one covers the basic theory of solar PV system and the potential at Dejen district. Chapter two and chapter three present the basic theories of wind and hydropower systems together with their potential estimations at Dejen district respectively. Chapter four discusses the application of HOMER for hydro/PV/wind hybrid system, whereas, chapter five is all about the results of optimization and sensitivity analysis of the system. Chapter six summarises the main findings of the thesis work. Appendix A presents the full length overall optimization results for each of the six sites.

# CHAPTER 1

# 1. Solar PV System and Solar Potential in Ethiopia

## 1.1. Introduction

The source of energy can be broadly grouped into two: conventional and nonconventional energy resources. Conventional/renewable energy resources are those being generated by the same rate as they are being utilized. Hydro, wind, tidal, biomass, solar thermal, solar PV and geothermal resources are examples of renewable energy resources. Conventional or non-renewable energy resources are consumed without any replacement. They are depleted from time to time and are not generally environmental friendly. Fossil fuel based energy resources including oil, coal, and natural gas are examples of conventional energy resources.

## 1.2. Solar Energy

The sun, the source of solar radiation, is a sphere of intensely hot gaseous matter with a diameter of about 1.39 x $10^9$ m, a total mass of 1.99 x $10^{30}$ kg, and on the average 1.50 x $10^{11}$ m away from the earth. An atomic reaction taking place in the inner active part of the sun makes the outer surface to have a temperature of $5800^0$ k [20]. Solar radiation in the form of radio magnetic wave emanates from this surface and propagates spherically in space. Some part of the radiation reaches the earth surface after atmospheric effect (reflection, refraction, absorption, scattering etc.). Such radiation is called diffused radiation. There is also some part of radiation that reaches the earth's surface without such atmospheric effect which is called direct radiation [20, 21, 22]. The received solar radiation by Earth's surface can be used directly (in the form of solar PV and solar thermal) or indirectly (in the form of hydro, wind, biomass etc.). The basic principle of solar PV system will be studied in this chapter and that of hydro and wind systems is discussed in next chapters (chapter 2, 3).

## 1.3. PV Systems

Photovoltaic (PV) systems convert light energy directly into electricity using semiconductor technology in the form of solar/PV cells. The physics of the PV cell is very similar to the classical p-n junction diode (see Figure 1-1). When light is absorbed by the junction, the energy of the absorbed photons is transferred to the electron system of the material, resulting in the creation of charge carriers that are separated at the junction. The charge carriers may be electron-ion pairs in a liquid electrolyte or electron-hole pairs in a solid semiconducting material. The charge carriers in the junction region create a potential gradient, get accelerated under the electric field and circulate as the current through an external circuit. The current squared times the resistance of the circuit is the power converted into electricity. The remaining power of the photon elevates the temperature of the cell [20 - 23].

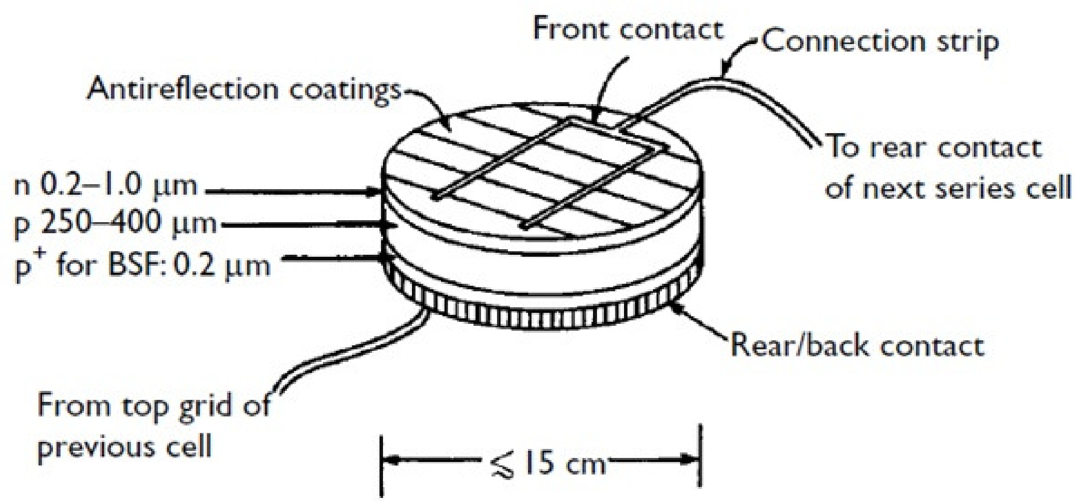


***Figure 1-1 Basic structure of p-n junction PV cell [23] (BSF=back surface field)***

The one diode model of a solar cell is shown in Figure 1-2.

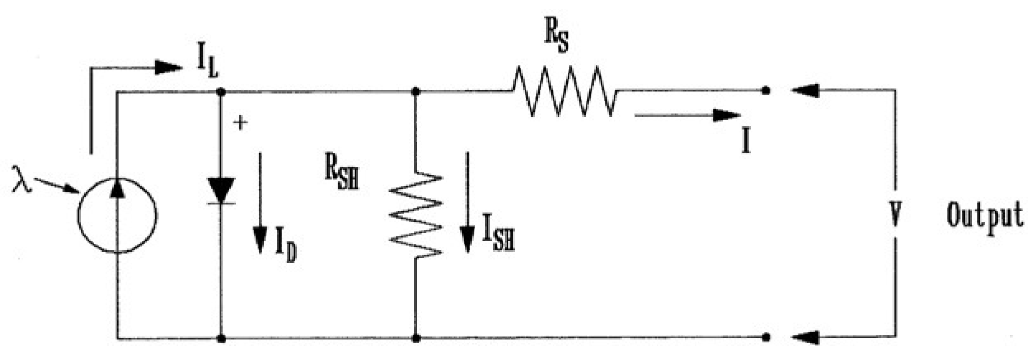


***Figure 1-2 Equivalent circuit for solar PV cell [22]***

The output-terminal current I is equal to the light-generated current $I_L$, less the diode-current $I_D$ and the shunt-leakage current $I_{SH}$. The series resistance $R_S$ represents the internal resistance to the current flow, and depends on the p-n junction depth, the impurities and the contact resistance. The shunt resistance $R_{SH}$ is inversely related with leakage current to the ground. In an ideal PV cell, $R_S$= 0 (no series loss), and $R_{SH}$=∞ (no leakage to ground). In a typical high quality one square inch silicon cell, $R_S$= 0.05 to 0.10 ohm and $R_{SH}$= 200 to 300 ohms. The PV conversion efficiency is sensitive to small variations in $R_S$, but is insensitive to variations in $R_{SH}$. A small increase in $R_S$ can decrease the PV output significantly [21 - 24].

The current at the output terminal is given by

$$I = I_L - I_D - I_{SH} \tag{1.1}$$

$$I = I_L - I_0\left[\exp\left(\frac{q(V + IR_s)}{AKT}\right) - 1\right] - \frac{V + IR_S}{R_{SH}} \tag{1.2}$$

where: *I*=the load current (A)

$I_D$=the diode current (A)

$I_L$=current produced by the cell (A)

$I_{SH}$=current through the shunt resistance (A)

$I_0$=reverse saturation current of the diode (A)

*q*=charge on an electron(C)

*V*=output voltage (V)

*K*=Boltzmann's constant

*T*=working temperature of the cell (K)

*A*=the diode quality/curve fitting factor

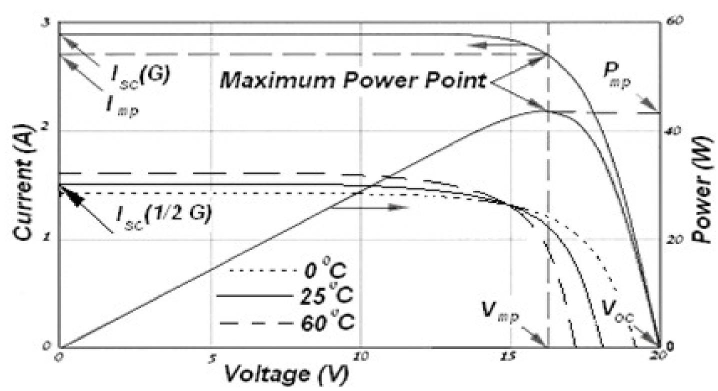


***Figure 1-3 V-I characteristics of PV cells against temperature [24]***

The current-voltage (I-V) and power-voltage (P-V) characteristics of a typical PV module are shown in Figure 1-3 with the short circuit current at radiation level G, $I_{sc}(G)$, the maximum power current ($I_{mp}$), maximum power point ($P_{mp}$), maximum power voltage ($V_{mp}$), and open circuit voltage ($V_{oc}$) labeled at their respective points [24]. $P_{mp}$ is the maximum power that can be obtained from the module and it corresponds to the maximum rectangular area under the I-V curve. $V_{oc}$ increases logarithmically, whereas $I_{sc}$ increases almost in proportion to the radiation as long as the current axis does not intersect the curved portion of the I-V characteristic [20, 24].

The power output of a PV system is determined by the type and area of the PV material and the incident solar radiation. Mathematically, it can be expressed by equation [20, 24].

$$P_{pv} = A_c \eta_{mp} \eta_e G_T \tag{1.3}$$

where: $P_{pv}$= power output of PV array
$A_c$=the array area
$\eta_{mp}$ =the maximum power point efficiency of the array (≈14%)
$\eta_e$ =the efficiency of power conditioning equipment (≈90%)
$G_T$=the incident solar radiation on the array

The solar cell described above is the basic building block of the PV power system. For obtaining high power, numerous such cells are connected in series and parallel circuits on a panel (module). The solar array or panel is then made from a group of several modules electrically connected in series-parallel combinations to generate the required current and voltage.

### 1.4. Solar Radiation Estimations

For any solar based system design, the most important factors are the position of the sun in the sky, the slope and orientation of a collecting surface, and obstruction and reflection properties of neighbouring structures. Figure 1-4 shows the geometry describing orientation of a collector and position of the sun in the sky.

A point on the earth's surface is expressed by its latitude and longitude. The angle between the collector surface and the horizontal is called slope, $\beta$ (with $0^0 < \beta < 90^0$ for a surface facing towards the equator; $90^0 < \beta < 180^0$ for a surface facing away from the equator). Surface azimuth angle, $\gamma$ is the angle between the normal to the surface and the local longitude meridian, projected on the horizontal plane. In either hemisphere, $\gamma$ equals $0^0$ for a surface facing due south, $180^0$ due north, $0^0$ to $180^0$ for a surface facing westward and $0^0$ to -$80^0$ eastward. For a horizontal surface, $\gamma$ is always $0^0$.

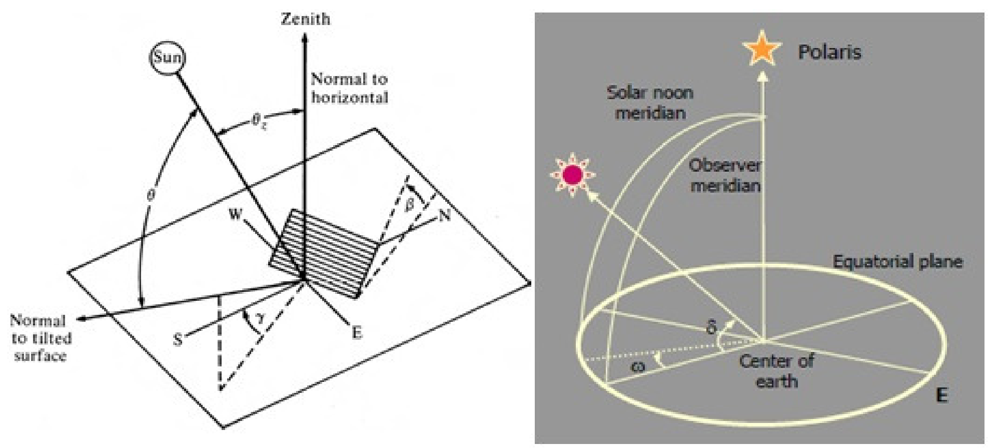


***Figure 1-4 Geometry of solar collector and location of sun relative to earth [23]***

Location of the sun in the sky, relative to a point on the ground, can be defined in terms of two angles, the solar altitude, $\alpha_s$ (or its complement the solar zenith angle, $\theta_z$) and the solar azimuth $\gamma_s$. Solar altitude, $\alpha_s$, angle of solar beam to the horizontal. Solar azimuth, $\gamma_s$ is the angle between the solar beam and the longitude meridian projected on the horizontal plane. Sign convention is the same as for surface azimuth angle ($\gamma$). Solar altitude and solar azimuth are functions of location (latitude, $\phi$), time of the year (declination angle, $\delta$ ) and time of the day (hour angle, $\omega$ ). Solar declination angle ($\delta$) is the angle between the earth's equatorial plane and the earth sun line. Solar hour angle $\omega$ is the angle Earth has rotated since solar noon. The relation between these angles is given below [6, 20 - 23].

$$\delta = 23.45 \sin\left(360 \frac{248 + n_d}{365}\right) \tag{1.4}$$

where $\delta$=solar declination angle ($^0$)

$n_d$=day number of the year starting at January 1st as 1

$$\omega = (12 - t_L)15^0 \quad (1.5)$$

where $t_L$=local solar time in hours.

$\omega$ =solar hour angle ($^0$)

$$\sin(\alpha_s) = \sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\cos(\omega) \quad (1.6)$$

where: $\alpha_s$ = solar altitude ($^0$)

$\phi$ =latitude ($^0$)

$$\sin(\gamma_s) = \frac{\cos(\delta)\sin(\omega)}{\cos(\alpha_s)} \quad (1.7)$$

where: $\gamma_s$= solar azimuth ($^0$)

The sunset/sunrise angle is given by

$$\omega_S = \cos^{-1}(-\tan\phi\tan\delta) \quad (1.8)$$

The angle of incident $\theta_i$ is the angle between the solar beam and normal to the solar panel which is given by:

$$\cos(\theta_i) = \sin(\delta)\sin(\phi)\cos(\beta) - \sin(\delta)\cos(\phi)\sin(\beta)\cos(\gamma) + \cos(\delta)\cos(\phi)\cos(\beta)\cos(\omega) + \cos(\delta)\sin(\phi)\sin(\beta)\cos(\gamma)\cos(\omega) + \cos(\delta)\sin(\beta)\sin(\gamma)\sin(\omega) \quad (1.9)$$

The intensity of solar radiation incident per unit area exposed normally to the sun's rays at the average sun-earth distance (about $1.5 \times 10^{11}$m), measured outside the earth's atmosphere is called the solar constant, $G_{sc}$ (1367 W/m$^2$) [20, 22, 23]. The intensity of radiation received outside the earth's atmosphere varies as the inverse square of the earth-sun distance and can be expressed in relation to time of the year. The extraterrestrial irradiance on a surface at normal incidence ($G_{on}$) may be expressed as:

$$G_{on} = G_{sc}\left[1 + 0.033\cos\frac{2\pi n_d}{365}\right] \quad (1.10)$$

The extraterrestrial irradiance incident on a horizontal plane at an arbitrary angle of incidence is given by,

$$G_o = G_{on}\cos(\theta_Z) \tag{1.11}$$

Where $\theta_z$=zenith angle (angle between the sun and the vertical line from a point on earth) which equals to the incident angle of a horizontal surface at the point of interest.

By integrating the solar constant (extraterrestrial irradiance) over the day length gives us the daily solar radiation on the horizontal surface.

$$H_0 = \frac{24*3600*G_{sc}}{\pi}\left(1+0.033*\cos\left(\frac{360\,n_d}{365}\right)\right)*\left(\cos\phi\cos\delta\sin\omega_s + \frac{\pi\omega_s}{180}\sin\phi\sin\delta\right) \tag{1.12}$$

where: $n_d \rightarrow$ Day number starting from January 1st as 1,

$G_{SC} \rightarrow$1367 W/m$^2$, the solar constant,

$\phi \rightarrow$Latitude of the location (10.25$^0$),

$\delta \rightarrow$ Declination angle ($^0$) given by equation 5.

$\omega_s \rightarrow$ Sunset hour angle ($^0$)

Ideally, the data required to predict the solar potential of any site are several years of measurements of irradiance on the proposed collector plane. These are rarely available, so the required data have to be estimated from meteorological data available either (i) from the site, or (ii) from some nearby site having similar irradiance, or (iii) from an official solar atlas or database [23]. Here, the sunshine duration data from the nearby station is used to estimate the monthly average solar radiation using the following angstrom type equation [7, 8, 10, and 20].

$$H = H_0(a + b\frac{n}{N}) \tag{1.13}$$

where: $H\rightarrow$ monthly average daily radiation on horizontal surface (MJ/m$^2$)

$H_0 \rightarrow$ monthly average daily extraterrestrial radiation on a horizontal surface (MJ/m$^2$)

$N \rightarrow$ the maximum possible daily hours of bright sunshine given by equation

$n \rightarrow$monthly average daily number of hours of bright sunshine

$a$ and $b$ are regression coefficients having average value of $a$ =0.33 and $b$=0.43 [7].

The day length, N, is the maximum possible daily sunshine hour is given by equation 1.13.

$$N = \frac{2}{15}\omega_s \qquad (1.14)$$

## 1.5. Solar Energy Resource in Ethiopia

Ethiopia receives 4.55 to 6.5 kWh/m$^2$/day annual average of solar insolation throughout the country [1 - 6, 10]. This varies significantly during the year, ranging from a minimum of 4.55 kWh/m$^2$ in July to a maximum of 6.55 kWh/m$^2$ in February and March. Other literatures describe the yearly average radiation to be in the range from 4.25 kWh/m$^2$ in the areas of Itang in the Gambella regional state (western Ethiopia), to 6.25 kWh/m$^2$ around Adigrat in the Tigray regional state (northern Ethiopia) [2, 11, 12].

### *1.5.1. Solar Energy Assessment of Dejen District*

There is only sunshine duration data recorded at the nearby stations (Debre Markoss). By using equations, (1.12 to 1.14), the solar radiation of the district is estimated as shown in Table 1-1. The last column of Table 1-1 shows solar radiation data obtained from NASA in (kWh/m$^2$/day).

**Table 1-1 Monthly solar radiation at the project site**

| Mid of month | $n_d$ | $\delta(°)$ | $\omega_s(°)$ | N (hours) | n | $H_0$ (kWh/m$^2$/d) | n/N | H(kWh/m$^2$/d) | NASA |
|---|---|---|---|---|---|---|---|---|---|
| Ja 15 | 15 | -21.3 | 86.01 | 11.47 | 9.90 | 8.82 | 0.86 | 5.87 | 6.15 |
| Fe 14 | 45 | -13.7 | 87.53 | 11.67 | 10.10 | 9.53 | 0.87 | 6.35 | 6.49 |
| Ma 15 | 74 | -2.89 | 89.52 | 11.94 | 8.40 | 10.22 | 0.70 | 6.57 | 6.57 |
| Ap 15 | 105 | 9.34 | 91.75 | 12.23 | 8.00 | 10.54 | 0.65 | 6.63 | 6.48 |
| Ma 15 | 135 | 18.74 | 93.56 | 12.47 | 8.10 | 10.45 | 0.65 | 6.56 | 6.35 |
| Ju 15 | 166 | 23.30 | 94.51 | 12.60 | 7.30 | 10.29 | 0.58 | 6.18 | 5.80 |
| Jul 15 | 196 | 21.56 | 94.14 | 12.55 | 5.80 | 10.32 | 0.46 | 5.59 | 5.24 |
| Au 15 | 227 | 13.87 | 92.60 | 12.35 | 4.90 | 10.44 | 0.40 | 5.22 | 5.26 |
| Se 15 | 258 | 2.33 | 90.47 | 12.06 | 7.90 | 10.30 | 0.65 | 6.48 | 5.87 |
| Oc 15 | 288 | -9.49 | 88.31 | 11.78 | 9.10 | 9.74 | 0.77 | 6.40 | 6.28 |
| No 15 | 319 | -19.1 | 86.46 | 11.53 | 9.50 | 8.99 | 0.82 | 5.96 | 6.11 |
| De 15 | 349 | -23.3 | 85.58 | 11.41 | 9.70 | 8.58 | 0.85 | 5.71 | 6.00 |
| Average | | | | | | | | 6.13 | 6.05 |

Data from SWERA (Solar and Wind Energy Resource Assessment) shows that the area has a solar radiation potential of 6.4 kWh/m$^2$/d. For this study the calculated monthly averaged daily radiation summarized in Table 1-1 (9$^{th}$ column) is used.

# CHAPTER 2

# 2. Wind Resource in Ethiopia

## 2.1. Introduction

Wind energy is another potential source of renewable energy. Winds are the motion of air caused by uneven heating of the earth's surface by the sun and rotation of the earth. It generates due to various global phenomena such as air-temperature difference associated with different rates of solar heating. Since the earth's surface is made up of land, desert, water, and forest areas, the surface absorbs the sun's radiation differently. Locally, the strong winds are created by sharp temperature difference between the land and the sea [10, 22, 25].

## 2.2. Distribution of Wind Speed

The distribution of wind is expressed by Weibull distribution which is called a Raleigh distribution for K=2 [7, 9, 22 - 24]. It is given by equations (2.1 to 2.3).

$$f(v) = \frac{\pi \cdot v}{2\bar{v}^2} \exp\left[-\frac{\pi}{4}\left(\frac{v}{\bar{v}}\right)^2\right] \tag{2.1}$$

$$prob(v \le V) = 1 - \exp\left[-\frac{\pi}{4}\left(\frac{v}{\bar{v}}\right)^2\right] \tag{2.2}$$

$$prob(v \ge V) = \exp\left[-\frac{\pi}{4}\left(\frac{v}{\bar{v}}\right)^2\right] \tag{2.3}$$

where, $f(v)$= Weibull probability density function of wind distribution

$\bar{v}$ = mean wind speed (m/s)

$v$=instantaneous wind speed (m/s)

$prob(v \le V)$ =probability of instantaneous wind speed is less than $V$

$prob(v \ge V)$ = probability of instantaneous wind speed is greater than $V$

Wind speeds are always measured at 10 m height anemometer. But, wind turbines are installed at higher elevations at which the wind speed is completely different from the 10 m measurement. This variation of wind speed with height can be expressed with equation 2.4 [7, 9].

$$v(z)\cdot \ln\left(\frac{z_r}{z_0}\right) = v(z_r)\cdot \ln\left(\frac{z}{z_0}\right) \qquad (2.4)$$

where, $Z_r \rightarrow$ Reference height (m)

$Z \rightarrow$ Height where wind speed is to be determined (m)

$Z_0 \rightarrow$ Measure of surface roughness (0.1 to 0.25 for crop land)

$v(z) \rightarrow$ Wind speed at height of Z m (m/s)

$v(z_r) \rightarrow$ Wind speed at the reference height (m/s)

## 2.3. Wind Turbine Types and Blade Aerodynamics

There are several wind turbine configurations including, drag-type, lift-type, Magnus effect wind plants and Vortex wind plants. Essentially all present day wind turbines are of the lift type and, over 90% of these are of the horizontal axis type. Magnus effect and vortex plants have never played a serious practical role. Lift type wind turbines can be horizontal axis and vertical axis based on the rotation of blades relative to the direction of wind [21].

The most common type of lift-force wind turbines is the horizontal axis wind turbine - HAWT. The rotor axis lies horizontally, parallel to the air flow. The blades sweep a circular (or slightly conical) plane normal to the air flow, situated upwind (in front of the tower) or downwind (behind the tower).The main advantage of HAWTs is the good aerodynamic efficiency (if blades are properly designed) and versatility of applications. Their main disadvantage is that the tower must support the rotor and all gearing and electrical generator standing on top of it, plus the necessity of yawing to face the wind.

Another type of lift-force wind turbines is the vertical axis wind turbine - VAWT. The rotor axis is perpendicular to the air flow (usually vertical). The blades sweep a cylindrical, conical or elliptical plane, perpendicular to the air flow and parallel to the rotor axis. All main power train components (gearbox, generator, brakes and main bearing) are placed on the ground, allowing for easy access for maintenance and lower stress on the tower. Yaw mechanism for facing the wind is not needed as the turbine accepts wind from any direction. All these features result in a simple machine, easily scalable to large dimensions, at lower costs than a horizontal axis one. Their main disadvantage is their requirement of starting torque which may be a critical issue for stand-alone applications.

Wind turbines are used as a means of extracting the wind energy. Their output is greatly affected by their aerodynamics. Their aerodynamics is mainly determined by the geometry of the turbine blade (see Figure 2-1).

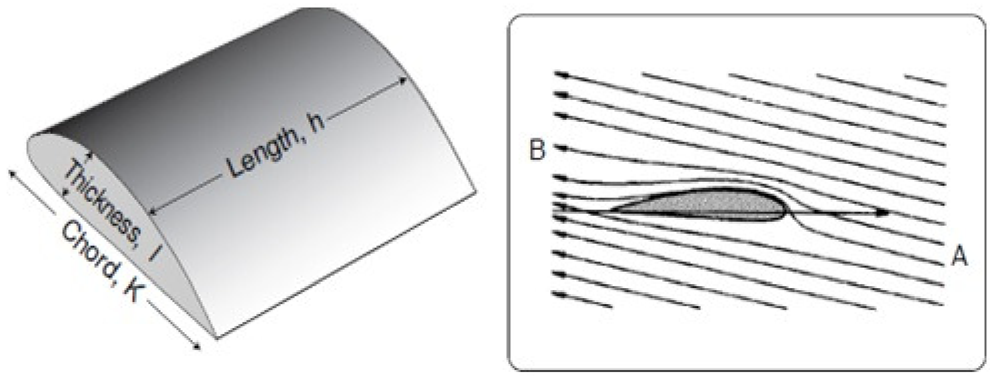


***Figure 2-1 Cross section of wind turbine blade [26]***

If a blade were sawn in half, the cross section has a streamlined asymmetrical shape, with the flattest side facing the oncoming air flow or wind. This shape is called the blade's aerodynamic profile. The shape of the aerodynamic profile is decisive for blade performance. The aerodynamic profile is formed with a rear side that is much more curved than the front side facing the wind. Two portions of air molecules side by side in the air flow moving towards the profile at point A will separate and pass around the profile and will once again be side by side at point B after passing the profile's trailing edge. As the rear side is more curved than the front side on a wind turbine blade, this means that the air flowing over the rear side has to travel a longer distance from point A to B than the air flowing over the front side. Therefore this air flow over the rear side must have a higher velocity if these two different portions of air shall be reunited at point B. Greater velocity produces a pressure drop on the rear side of the blade, and it is this pressure drop that produces the lift [26]. And this lift force is the source of torque to rotate horizontal axis wind turbines.

## 2.4. Wind Energy Extraction by HAWT

The energy of wind is extracted by using appropriate wind turbine. The wind energy is tapped by the wind turbine which converts the kinetic energy of the wind into mechanical shaft energy. The rotational energy is converted into electrical energy through the transmission system. The transmission system consists of the rotor shaft with bearings, brake(s), an optional gearbox, as well as a generator and optional clutches. The energy available in the wind can be expressed using equation (2.5).

$$P_w = \frac{1}{2}\rho A V^3 \qquad (2.5)$$

where: $\rho$ =Density of air (kg/m$^3$)

$A$=the swept area (m$^2$)

$P_w$= power in the wind (W)

$V$=instantaneous wind velocity (m$^3$)

Energy conversion from free-flowing fluid streams is limited because full energy extraction implies decrease of fluid velocity (decrease of kinetic energy of the stream), down to zero which is impossible. Some fluid may not pass through the turbine and may simply flow around it (bypass it). This limitation is expressed in terms of Betz limit defined by the power coefficient $C_p$ as given by equation (2.6).

$$C_p = \frac{Rotor - Power}{Power - in - the - wind} \qquad (2.6)$$

The power coefficient, $C_{P,}$ is a function of the axial induction factor. The optimum of this function (which is a maximum value for $C_P$) is 0.5926 (=16/27) [21 - 23]. Thus the electrical power output from the wind turbine can be expressed by equation 2.7.

$$Pwout = \eta_t C_p \tfrac{1}{2} \rho A V^3 \qquad (2.7)$$

where: $P_{wout}$= output power of wind turbine

$\eta_t$ =Overall efficiency of the transmission system/power train

$C_p$=the power coefficient

The power coefficient and efficiency of wind turbines vary greatly from manufactures to manufacturers. As a result, the power output of wind turbines vary from turbine to turbine and is given by power curve which plots the output power of a turbine against wind speed (see Figure 2-2).

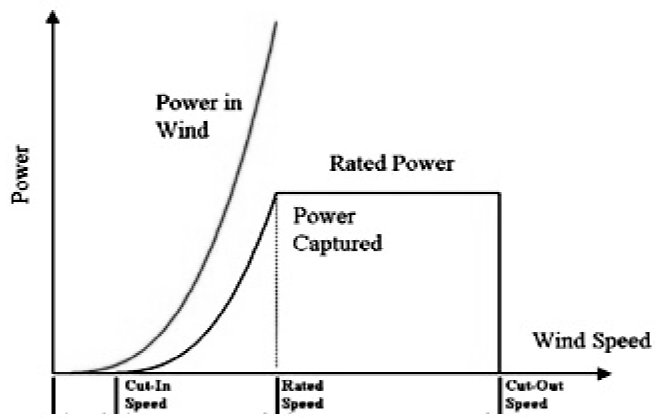


***Figure 2-2 General power curve of wind turbine [22]***

The wind speed at which wind turbine starts generating electrical power is called the cut-in speed. The rated wind speed is the wind speed at which the turbine operates at its maximum efficiency of energy conversion. Rated power is the power output at the wind speed which is equal to, or above, the rated speed. The cut-out speed is the wind speed at which the turbine may be shut down to protect the rotor and drive train machinery from damage, or high wind stalling characteristics.

### *2.4.1. Power Control mechanism*

Power output from the rotor can be decreased at high winds by decreasing the power coefficient through aggravated aerodynamic conditions, implying decreased lift forces. Such regulation helps the turbine operating nearly at its rated capacity during high wind speeds. There are three commonly used types of power control in the industry [24].

- Stall Control
- Pitch Control
- Active stall regulation

In stall controlling method, the wind is allowed to meet the blade at very big angle of attack. This makes the wind flow to separate and swirl on the suction side which increases the drag force and decrease the lift force. Firmly fixed blades to the hub have made such stall control mechanisms simple and less costly. But, it is not possible to maintain stable output and turbines with such control mechanism should be able to sustain large thrust forces at high winds.

In the Pitch control mechanism, the blade turns around its longitudinal axis, thus being able to maintain a given angle of attack (i.e. a given maximum lift force and power output) at changing wind speed without increasing much the trust on the rotor. Such control mechanism results in a smooth power output. Their demerit is their complicated arrangement (pitch motor and blade bearings) which adds cost and decreases reliability of the machine.

With an active stall regulation mechanism the machine is usually programmed to pitch the blades much like a pitch-controlled machine at low wind speeds, so as to get a reasonably large torque at low wind speeds. If the generator is about to be over loaded, then the machine also pitches its blades to increase the angle of attack of the rotor blades forcing the blades to go into a deeper stall thus wasting the excess energy in the wind [24]. In this control mechanism the machine can be run almost exactly at rated power at all high wind speeds.

## 2.5. Wind Resource in Ethiopia

Ethiopia has exploitable reserve of 10,000 MW wind energy with an average speed of 3.5 – 5.5 m/s, flowing for 6 hours/day. There are two basic zones with homogenous periodicity separated by the rift valley. In the first of these, covering most of the highland plateaus, there are two well-defined wind speed maximal occurring, respectively, between March and May and between September and November. In the second zone, covering most of the Ogaden and the eastern lowlands, average wind velocity reaches maximum values between May and August [1, 7, 9, 10, 11, 24]. Currently two projects are being constructed, one Ashegoda wind park (near Mekele) of 120MW and the other Adama Wind Park of nearly 40MW.

### *2.5.1. Wind Potential Assessment in Dejen District*

Annual average wind speed at a nearby station (Debre Markos) is calculated as 3.5 m/s based on anemometer data collected at 10 m height [7]. NASA has estimated the annual average wind speed of the location to be 3.1 m/s at the same 10 m height [13]. NMA has changed its anemometer measurement height from 10 m to a data logger measurement at 2 m height. 10 m extrapolation of the wind speed data obtained from the NMA is observed to be 2.4 m/s which is very far below from its previous 10 m measurement [7]. Generally, 10 m height is the one where most standard measurements are taken and measurements at 2 m height are error prone due to vegetation, shading and obstacles in the vicinity. Furthermore, the geographical layout of the studied area is different from the nearby stations where the measurements are taken. It is believed that the unevenness nature of the upper Blue Nile gorge is a good resource of wind, although there was no enough time to collect data and prove this. Hence, the minimum of the 3.5 m/s and the 3.1 m/s mentioned above is considered for this study and that is data obtained from NASA. This data can be extrapolated to the selected wind turbine height using equation 2.4 [7, 8]. The value of $Z_0$ is taken as 0.1; Weibull parameters are estimated to be K=2 and c=3.9 m/s [7]. Table 2-1 summarizes the wind speed at 10 m and 25 m heights.

**Table 2-1 Monthly average wind speed (m/s) at the site from NASA**

| | Ja | Fe | Ma | Ap | Ma | Ju | Jul | Au | Se | Oc | No | De | Av. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NASA(10 m) | 3.4 | 3.4 | 3.2 | 3.0 | 3 | 3.4 | 3.5 | 2.9 | 2.5 | 2.5 | 2.9 | 3.2 | 3.1 |
| At 25 m | 4.1 | 4.1 | 3.8 | 3.6 | 3.6 | 4.2 | 4.1 | 3.5 | 3.0 | 3.0 | 3.5 | 3.8 | 3.7 |

# CHAPTER 3

# 3. Hydropower Potentials in Ethiopia

## 3.1. Introduction

The water of the oceans and water bodies on land are evaporated by the energy of the sun's heat and come down back to earth surface. Much of the energy of flowing water in a river gets dissipated due to friction encountered with its banks or through loss of energy through internal turbulence. Nevertheless, the energy of water always gets replenished by the solar energy which is responsible for the eternal circulation of the hydrologic cycle. There is another form of water energy that is used for hydropower development: the variation of the ocean water with time due to the moon's pull, which is termed as the tide. Hydropower engineering deals with the two forms of energy and suggests method of converting it into electricity. To make the flowing water do useful work it is necessary to create a head at a point of the stream and to convey the water through the head to the turbines.

## 3.2. Classification of Hydropower Plants

There are a number of criteria for classification of hydropower plants, such as head, flow rate, hydraulic nature, purpose, size and the likes. Although there is no standard classification of hydropower plants, the more widely used classification is summarized below (based on size) [25 - 30].

- Large-hydro (> 100 MW feeding into a large electricity grid)
- Medium-hydro (15 - 100 MW usually feeding a grid)
- Small-hydro (1 - 15 MW usually feeding into a grid)
- Mini-hydro (0.1 - 1 MW used either stand alone schemes or grid connected)
- Micro-hydro (From 5 - 100 kW used for a small community or rural industry in remote areas far away from the grid.)
- Pico-hydro (< 5 kW used for remote areas far away from the grid.)

Some time, hydropower plants below 15 MW are referred to as small hydro plants. This definition is adopted in this thesis work.

### *3.2.1. Principle of Small Hydropower*

The water accumulated at higher elevation has a potential energy due to gravity. When this water is allowed to fall down a given height, its potential energy is converted into kinetic and pressure energy. Using hydro turbines, the kinetic and pressure energy can be converted into mechanical shaft energy. By coupling appropriate generator to the shaft of the hydro turbine, the energy can be converted into electrical energy. The theoretical potential of a flow stream with available head is given by:

$$P_h = g \times \eta \times Q_h \times H_{eff} \tag{3.1}$$

where: $P_h$ = power in kilowatts (kW)

$g$ = gravitational acceleration (9.81 $m/s^2$)

$\eta$ = turbo-generator efficiency (0<$n$<1)

$Q_h$ = quantity of water flow rate ($m^3$/sec)

$H_{eff}$ = effective head ($m$)

Most of small hydropower systems are run-of-river type which requires available head and flow rate determination. Gross head is total elevation difference between the head water and tail water of hydropower system. Effective/net head is gross head minus head losses due to hydraulic losses in the trash rack, penstock, gate valves, canals, outlets and other civil structures. Head can be measured measured using either of altimeter, pressure gauges, clear hose method, satellite images, sighting meter method or level method [19]. Flow rate of a given river can be measured using gauge meters, area-velocity, bucket method and others. Flow records of at least one year are necessary for determination of hydropower potentials. In the absence of such long records, hydrological estimations may be adapted.

Flow duration curve can be used for selection of design flow rate and estimation of annual energy production. For hybrid system analysis, the design flow rate is optimize together with other components from overall cost point of view.

## 3.3. Main Components of Small Hydropower System

Figure 3-1 shows the main components of small hydropower plants the design of which mainly depends on the type of scheme, local conditions, access to construction material and also local building traditions in the country or region.

**Dams:** are primarily intended to divert the river flow into the water conveyance system leading to the powerhouse. Dams also produce additional head and provide storage capacity. The choice of dam type depends largely on local topographical and geotechnical conditions.

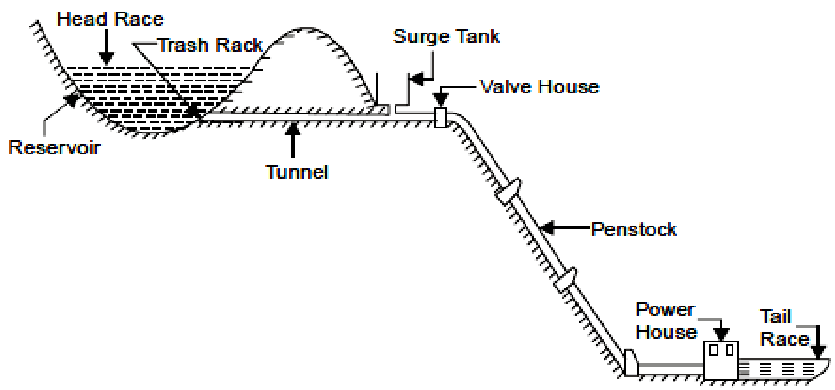


***Figure 3-1 Basic components of a small hydropower plant [25]***

**Spillways:** are structures at the top of dam (called crest) which allows excess water to flow out of the dam. Energy dissipating mechanisms are usually provided. They can be over flow type, side channel, shaft spillway/morning glory, siphon spillway and other types.

**Diversion Weir:** is a barrier built across the river used to divert water through an opening in the riverside (the 'Intake' opening) into a settling basin. These have opening which serves as a mechanism for over flowing of rivers. Their discharge characteristics are dependent on the geometry of their construction

**Intakes Structure:** is provided at the mouth of a water conveyance system for a hydropower project. Its design should be made in such a way that there should be minimum head loss, no formation of vortices, minimum entry of sediment and floating materials into the water conduit system. The location of the intake depends on a number of factors, such as submergence, geotechnical conditions, environmental considerations.

**Trash rack:** is required to protect the turbine runner from impinging objects. It is a structure made up of one or more panels, each generally fabricated of a series of evenly spaced parallel metal bars. Minimization of head loss with effective blocking of debris and floating objects is a design criterion.

**Sediment/Sand Trap:** The main objective of such a trap is to avoid sedimentation of downstream structures (canals, shafts, etc.) as well as to limit the possible damage of sediments on the hydro mechanical equipment to prevent suspended sediments. Their efficiency is measured by size of sediment they can trap. The design of length and width of the trap should be carefully designed against the minimum allowable sediment size.

**Gates and Valves:** are used to stop water flow for maintenance of components. Some of them are stop logs, sliding gates, flap gates, globe, rotary, sleeve-type, butterfly and sphere valves. Their head loss and ability to operate effectively for the system full gate discharge must be considered carefully

**Open Channel/Canal:** The flow conveyed by a canal is a function of its cross-sectional profile, its slope, and its roughness. Flume is a special form of open canal which is suspended above earth's surface with a support

**Tunnel:** It is a closed water passage under a natural hilly obstacle. It includes headrace tunnel, tail race tunnel and by pass tunnels.

**Pressure relief tank/ surge tank:** is a structure used to damp water hammering waves generated from sudden valve opening and closing.

**Penstock:** is the conduit that is used to carry water from the supply sources to the turbine. This conveyance is usually from a canal or reservoir to the turbine located at the power house. They can be pressure and siphon penstock types based on their principle of operation. For purposes of engineering feasibility and preliminary design, attention should be given to head loss through the penstock, thickness of the penstock, economical length and the routing of the penstock.

**Power House:** is a place where electromechanical equipments are to be sited and mechanical energy is converted into electrical energy. The main components are the hydraulic turbine and the electrical generator. Depending on the geographical layout of the project site, the power house can be constructed underground or on the surface of earth.

**Tailrace:** After passing through the turbine the water returns to the river through a short canal called a tailrace. Impulse turbines can have relatively high exit velocities, so the tailrace should be designed to ensure that the powerhouse would not be undermined. The design should also ensure that during relatively high flows the water in the tailrace does not rise so far that it interferes with the turbine runner. With a reaction turbine the level of the water in the tailrace influences the operation of the turbine and more specifically the onset of cavitations. This level also determines the available net head and in low head systems may have a decisive influence on the economic results.

### *3.3.1. Hydraulic Turbines and their Selection*

Commonly used hydraulic turbines are reaction and impulse turbines. Reaction turbines are the totally embedded in the fluid and powered from the pressure drop across the device. Angular and linear motions are converted into shaft power. Francis, Kaplan and propeller turbines are some of reaction turbines. Impulse turbines are not immersed into the fluid. Instead, water is provided to the turbine after passing through nozzles. The potential energy of the water is converted into kinetic energy and hits the turbine as a jet in an open environment. Pelton, Crossflow and Turgo turbines are some of impulse type hydraulic turbines.

The type of hydraulic turbine to be used is site specific. The operation mode (base load, peak load), head and flow rate of the system determines which type of turbine to be used. Most widely used method of turbine selection is specific speed method. Specific speed of a turbine is the speed at which a turbine of homologous design would operate, if the runner diameter was reduced to a size that would develop 1 kW power under one meter head. It is the maximum operating point of a turbine [25, 29, 30].

The performance of a turbine is ideal at the design head. Fall of efficiency with head variation in case of Pelton, Kaplan and Bulb turbines is much less in comparison to Francis-and Propeller types. Fall of efficiency at part load for Francis and Propeller is much steeper in comparison to that for Kaplan and Pelton turbines. A turbine with higher specific speed results in higher speed of rotation for generator which consequently reduces in cost of generator. Figure 3-2 shows application range of hydraulic turbines.

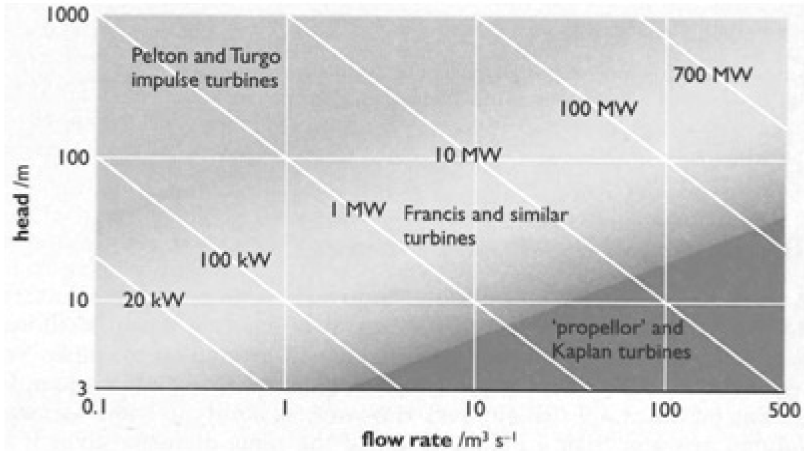


*Figure 3-2 Ranges of application of different types of turbine [37]*

### *3.3.2. Electrical Generators*

An electrical generator is an electromechanical system that converts mechanical energy into electrical energy through the interaction of electromagnetic and electrostatic fields within the system. Depending on their output voltage, generators can be AC type or DC type. DC generators have unidirectional voltage output and are used for very small systems (<1.6 kW). AC generators are, now, widely used for their easy connection to AC load. AC generators are further classified as synchronous and asynchronous generators [30].

**Asynchronous generators:** They can be wound rotor or squirrel-cage type which operates by principle of electromagnetic induction. They need to be connected to grid system before they start-up. The synchronous speed (speed of rotating flux) is determined by the main supply. The rotor runs at speed slightly higher than this synchronous speed. They draw their excitation current from the grid, absorbing reactive energy by their own magnetism. Adding a bank of capacitors can compensate for the absorbed reactive energy. Due to this, voltage regulation in induction generators is difficult [30].

On the other hand, induction generators are simple, rugged and cheap as compared to synchronous generators. They can be used in very small stand-alone applications as a cheap solution when the required quality of the electricity supply is not very high. Otherwise, their application is limited for wind application where their source of prime mover is highly variable [30].

**Synchronous generators:** They have a separate field excitation associated with a voltage regulator. They run at synchronous speed and can supply the reactive energy required by the power system when the generator is connected to the grid. Synchronous generators can be used for both grid connected and isolated systems [30].

Below 1 MW, synchronous generators are more expensive than asynchronous generators and are used in power systems where the output of the generator represents a substantial proportion of the power system load. Asynchronous generators are cheaper and are used in stable grids where their output is an insignificant proportion of the power system load. Variable-speed constant frequency systems (VSG), in which turbine speed is permitted to fluctuate widely, while the voltage and frequency are kept constant and undistorted, have become available. Frequency converters are used to connect and synchronize the generators with the grid [29].

Although the prime mover varies from system to system (such as hydro, wind, diesel, steam), the equivalent circuit of a synchronous generator is same and can be represented as shown in Figure 3-3. T is the mechanical torque of the prime move.

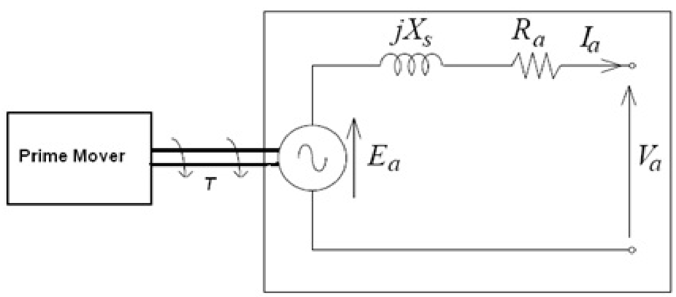


***Figure 3-3 The per-phase equivalent circuit of a synchronous generator driven by a prime mover [24]***

The per-phase equivalent circuit of synchronous generator is shown in Figure 3-3. Its synchronous speed is given by equation 3.2.

$$n_s = \frac{60f}{P_{pole}} \qquad (3.2)$$

Where, $n_s$=synchronous speed

$P_{pole}$=number of pole pairs

$f$=system frequency

The output voltage is given by equation 3.3.

$$V_a = E_a - I_a(R_a + jX_s) \tag{3.3}$$

where, $V_a$=output terminal voltage (V)

$E_a$=internal voltage generated (V)

$I_a$=armature current (A)

$R_a$=winding/armature resistance (Ω)

$X_a$=winding/synchronous reactance ($X_s >> R_a$)

All terms in the equation above are per phase parameters. The total electrical power output is given by equation 3.4.

$$P_{outs} = mV_a I_a \cos\Phi \tag{3.4}$$

where, $P_{outs}$= output power of synchronous generator (W)

$m$ = the number of phases; m=3 for a 3-phase generator

$\cos\Phi$ = the cosine of the angle between the voltage $V_a$ and the current $I_a$.

### 3.4. Hydropower Development Phases/Cycle

The most crucial steps undertaken while developing any hydropower development are project planning, project implementation and project operation [29, 30]. Project planning stage is the first stage of hydropower development cycle. The major activities are: selection of potential sites, site reconnaissance, planning of the potential site and formulation of the development plan. Several potential sites will be considered in this stage. It requires detailed study about topography, demand/load, geomorphology, water resource, environmental impact, head measurement, economic analysis and preliminary design of electro mechanical components.

Project implementation stage is the second phases of hydropower development cycle in which the detailed design and construction of the particular site is finalized including design of civil structures, design of electro-mechanical components and construction of each component. After finishing the construction phase, the hydropower plant enters into operation phase which is the third stage in the development cycle. Plant management, operation, control and maintenance are the main activities in the operation phase.

### 3.5. Hydropower Potential in Ethiopia

The national power system is dominated by large hydropower systems. From the total capacity of 30GW to 40GW hydropower potential, only about 2GW is developed and planned to develop about 14GW by end of 2030 [5]. All of this generation concentrates on large hydropower plants. Although not developed as such, there is plenty of small hydropower resources in Ethiopia. The average annual potential (exploitable with small slope plants without reservoir) is estimated to be about 20 TWh/year. The electric energy generated from small slope plants, being smaller in capacity and geographically dispersed, is of great importance for rural electrification [3]. Table 3-1 summarizes regional distribution of small hydropower potentials.

**Table 3-1 Regional estimation of small hydropower potentials [10, 28]**

| Region | Approximate small hydropower potential |
|---|---|
| Oromia | 35 MW |
| Amhara | 33 MW |
| Benishangul-Gumuz | 12MW |
| Gambella | 2MW |
| SNNP | 18MW |

### 3.6. Head and Flow Rate Measurements at Selected Sites

The proposed hydropower system is runoff the river type which requires the determination of available head and flow rate at the pour points. Head can be measured using either of altimeter, pressure gauges, clear hose method, satellite images, sighting meter or level method [27]. In the case of this study, the selected sites have steep waterfalls so that their head is measured using rope (see Figure 3-4). Table 3-2 summarizes head measurement of each site and non electrified villages in the neighborhood.

**Table 3-2 Head measurement results at the sites and villages in the neighborhood**

| Site | Head (m) | Non electrified small villages in the vicinity |
|---|---|---|
| Taba A | 50.5 | Gudy, Anqraq, G/Mariam, Dengel, Muamit, Amaya, Hlgie, Chifar, Wejel, Chuhetma, Shlemuk, Mizan, Sieko |
| Taba B | 62 | |
| Muga 1 | 47 | Hagere Selam, Buhach, Gafasob, Emebuga, Esmaya Dejen, Dgtma, Burabur, Buaba, Musial, Kolem, Kodem, Yeshencha, Lit't, Gady, Enambur, Borebor, Sentayt, Gelgele, Sengrer, Worka, Alektam |
| Muga 2 | 113 | |
| Bechet | 74 | Dbab Zib, Yegurtina, Omarit, Byan, Ybza, Ming, Jrie, Gentay |
| Suha | 92.1 | Suha, Kokwuha, Mehal Amba, Zebich |

***Figure 3-4 Sample photos taken during head measurement***

Although there are gauge stations at Muga and Suha streams, there are no gauging stations at the selected sites. The flow rate at the point of interest is estimated using hydrological estimation techniques. According to World Meteorological Organization (WMO), the flow rate at ungauged sites can be estimated using one of the three methods [19] - Empirical, Statistical and Rainfall-Runoff modeling.

An empirical method establishes a simple mathematical relation between flow rates of a given catchment with flow rate of another catchment having similar hydrological response. The reference catchment is better to be within the same catchment or very near to it. The equations do not explicitly describe physical and causal relationships.

The statistical method applies multiple regression techniques. Although this method is direct, objective and easy to handle, the method estimates the specific low flow indices rather than the full time series of river flows.

Rainfall runoff models establishes a relation between catchment structure, rainfall inputs, evaporative outputs and stream flow by representing hydrological processes with a mathematical equations. These models ranges from simple to complex lumped to distributed and small to large area coverage. A large amount of data regarding physical characteristics and meteorological data of the catchment area are required.

Regional methods and rainfall runoff models require plenty of data, such as evapo-transpiration, humidity, temperature, rainfall, vegetation coverage, soil type and property, underground flow characteristics etc., which are not available in the study area. Each of the six sites has a catchment area that lies in the same Northern Gojjam sub-basin of Upper Blue Nile [28, 31]. They are located close to each other and have similar landscape, soil type and land coverage. The catchments start from the same source known as mount Choke. Data from the FAO soil map also shows the similarity of the soil type and vegetation coverage of all the sites (see Figure 3-5).

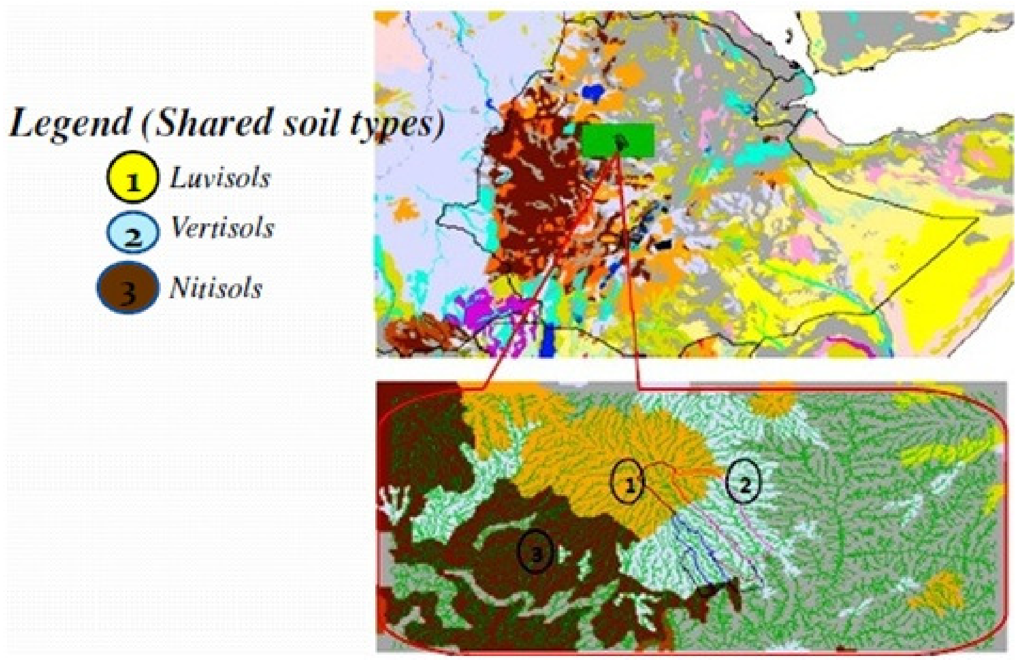


***Figure 3-5 Soil type of the study area***. *(Source: Harmonized world soil database)*

Because of such geographical similarity and insufficient hydrological data, the simple empirical estimation methods are adopted instead of the more complex statistical and rainfall runoff [19, 28, 31, 32] methods. The gauge stations at Muga and Suha streams are taken as reference for empirical formulation given by equation 3.5 [19, 28].

$$Q_{site} = K\left[\frac{A_{site}}{A_{gauge}}\right]Q_{gauge} \qquad (3.5)$$

where, $A_{site}$→ Catchment area of the power plant site (m$^2$)

$A_{gauge}$→ Catchment area of the gauge (m$^2$)

$Q_{site}$→ Discharge at site (m$^3$/s)

$Q_{gauge}$ $\rightarrow$ Discharge at gauge ($m^3/s$)

K$\rightarrow$ represents a scaling constant or function.

For simplicity, the scaling factor, K, can be taken as the ratio of average annual rainfall of the site and the gauged area. Since there are only two rain gauge stations randomly placed (assumed to be equally shared), the value of K is taken as 1.

Thus, to determine the flow rate at these pour points, the contributing area to the volume flow rate at these points should be known. For stream line identification and catchment area extraction, ArcGIS 9.3 Desktop is used together with DEM (Digital Elevation Model) data found from ASTER GDEM (Advanced Space-borne Thermal Emission and Reflection Radiometer Global Digital Elevation Model).

### *3.6.1. Application of ArcGIS 9.3 Desktop for Catchment Area Extraction*

ArcGIS 9.3 Desktop is software released by Environmental Systems Research Institute, Inc. (ESRI). It includes a suite of integrated applications that enables to perform GIS tasks, including mapping, geographic analysis, data editing and compilation, data management, visualization, and geo-processing. ArcGIS Desktop is the framework that provides the user interaction for the three ESRI software products: ArcView, ArcEditor, ArcInfo. It is structured with ArcMap, ArcCatalog, and ArcToolbox applications for each product (ArcView, ArcEditor and ArcInfo). ArcMap represents geographic information as a collection of layers and other elements in a map view. Common map elements include the data frame containing map layers for a given extent plus a scale bar, north arrow, title, descriptive text, and a symbol legend. There are two primary map display panels in ArcMap: the data frame and the layout view. The data frame provides a geographic map frame, in which geographic information is displayed as a series of map layers. The layout view provides a page view where map elements (such as the data frame, a scale bar, and a map title) are arranged on a page [32].

The ArcCatalog application is used to manage GIS information, such as, GIS datasets, map documents, layer files. There are geo-processing functions for spatial analysis operations, for converting data from one format to another, for simple data management operations, for data integration operations such as appending map sheets, and many other operations. These geo-processing functions are collected as tools in ArcToolbox, grouped by category in toolboxes and toolsets.

ArcGIS Desktop extensions add specialized functionality for data compilation, cartographic production, and advanced geographic analysis. Spatial analyst, 3D analyst, geo-statistical analyst, data interoperability, network analyst and few others are available extensions for ArcGIS Desktop. Spatial analyst extension helps to use density, distance, extraction, surface, ground water, hydrology, raster creation, solar radiation and other toolsets. Hydrology toolset is used for this study.

*3.6.1.1. Digital Elevation Model (DEM)*

DEM is a digital representation of geographical feature in the form of matrices. Hydrological information such as flow direction, flow accumulation, flow length, stream network, and catchment area can be derived from DEM with the help of hydrology toolsets released by Environmental Systems Research Institute, Inc. (ESRI) with the ArcGIS 9.3. Worldwide DEM data can be downloaded free of charge from the two well-known sources. These are SRTM (Shuttle Radar Topography Mission) and ASTER-GDEM.

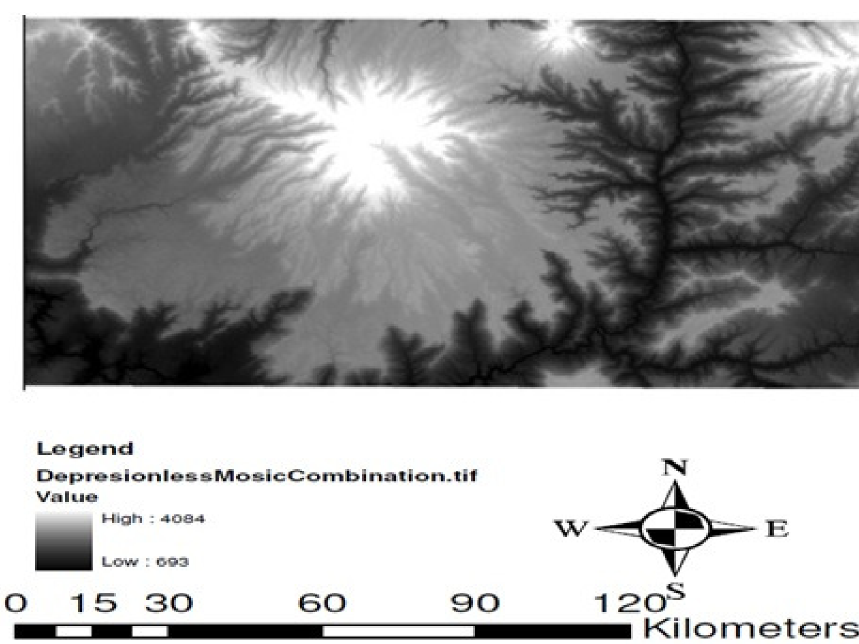


***Figure 3-6 ASTGTM_N10E37 and ASTGGTM_N10E38 cocombined into mosaic and filled***

The study area is small and is free of permanent cloud coverage. ASTER-GDEM is convenient for such places as it has fine resolution (30 m) and better accuracy (7 m). The data used for this analysis are ASTGTM_N10E37 and ASTGGTM_N10E38. The two tile DEM data were merged together. After applying the Fill Tool on the merged tiles, the result of Figure 3-6 is obtained. Using the filled DEM as input, the flow direction is computed using Flow Direction Tool. Flow Accumulation performs a cumulative count of the number of pixels that naturally drain into a given cell using Flow Direction as input.

The drainage network can be extracted from the flow accumulation using Raster Calculator tool. The threshold value of 1000 (~ 900,000 $m^2$) is used for stream network identification. Thus, cells with a contributing area of greater than 0.9 $km^2$ are included in the network. Stream link tool was used to assign values to segments of stream network.

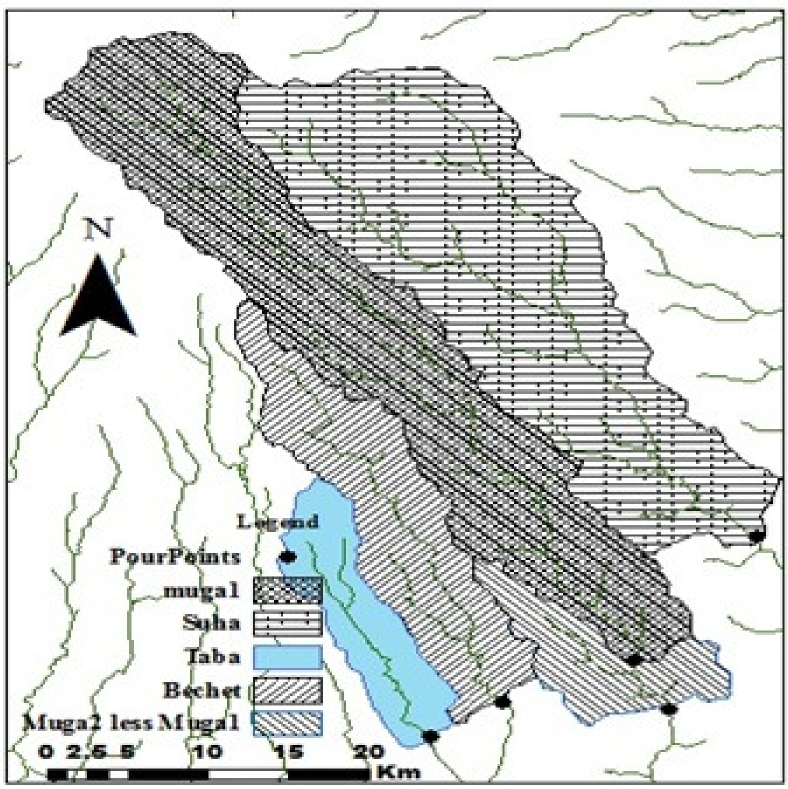


***Figure 3-7 Sub basin delineation for the selected sites***

The pour points are prepared on point shape file. Then, Watershed Tool is used to delineate the contributing catchments at the pour points. Each catchment area is converted to polygon feature (see Figure 3-7) to be able to calculate their area. Table 3-3 shows the result of area measurement for each site. Taba (A) and Taba (B) are found very near to each other so that their catchment area is taken to be equal for simplicity.

**Table 3-3: Results of catchment area extraction**

| Site | Location | | Catchment area (km$^2$) | Reference Area (km$^2$) | $\left[\frac{A_{site}}{A_{gauge}}\right]$ |
|---|---|---|---|---|---|
| | Latitude | Longitude | | | |
| Taba | 10°12'25.68"N | 38° 3'3.00"E | 93.963 | 375 | 0.25 |
| Bechet | 10°14'31.00"N | 38° 5'37.11"E | 193.545 | 375 | 0.516 |
| Muga1 | 10°16'11.05"N | 38°10'15.91"E | 479.58 | 375 | 1.28 |
| Muga2 | 10°14'11.11"N | 38°11'33.70"E | 562.172 | 375 | 1.5 |
| Suha | 10°21'26.46"N | 38°14'45.21"E | 529.621 | 359 | 1.475 |

Based on their geographical locations, gauge station at Muga River is taken as a reference catchment for Muga site I, Muga Site II, Bechet Site and Taba site. The gauged catchment at Suha River is taken as a reference for Suha site. The value of the catchment area ratio of each site to its corresponding reference catchment is given in Table 3-3. The value of K is taken to be 1 by assuming the same rainfall distribution over the sites.

A 25 years (1980 – 2005) recorded flow rate data of the two reference gauge stations at Muga stream and Suha streams is taken from MoWR (former). After filling missed data using average of vertically and horizontally neighboring data sets, monthly average flow rate for 2004 is calculated using equation (3.5) and is summarized in Table 3-4. Year to year variation is observed to occur mainly from rainfall variation in the rainy seasons. Since the determinant flow rate for runoff hydropower system is one available in the dry seasons, the hydro system is less sensitive to year to year variation.

**Table 3-4: Mean monthly flow rate at gauged points and at the selected sites**

| **Mean monthly flow rate in m$^3$/s** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site | Ja | Fe | Ma | Ap | Ma | Ju | Ju | Au | Sep | Oc | No | De |
| ***Muga river flow*** | | | | | | | | | | | | |
| gauged | 0.25 | 0.05 | 0.42 | 0.24 | 0.61 | 0.85 | 26.27 | 18.80 | 14.40 | 2.20 | 0.64 | 0.40 |
| Muga I | 0.32 | 0.06 | 0.54 | 0.31 | 0.78 | 1.08 | 33.63 | 24.10 | 18.40 | 2.90 | 0.80 | 0.50 |
| Muga II | 0.37 | 0.08 | 0.63 | 0.36 | 0.92 | 1.27 | 39.41 | 28.20 | 21.60 | 3.30 | 0.97 | 0.54 |
| Bechet | 0.13 | 0.03 | 0.22 | 0.12 | 0.32 | 0.44 | 13.55 | 9.71 | 7.44 | 1.20 | 0.33 | 0.19 |
| Taba | 0.06 | 0.01 | 0.11 | 0.06 | 0.15 | 0.21 | 6.57 | 4.71 | 3.61 | 0.60 | 0.16 | 0.09 |
| ***Suha river flow*** | | | | | | | | | | | | |
| gauged | 0.06 | 0.03 | 0.04 | 0.26 | 0.22 | 0.30 | 6.87 | 9.81 | 3.20 | 2.90 | 0.24 | 0.15 |
| Suha | 0.09 | 0.05 | 0.06 | 0.39 | 0.32 | 0.44 | 10.13 | 14.50 | 4.72 | 4.30 | 0.35 | 0.23 |

# CHAPTER 4

# 4. Hybrid System Optimization using HOMER

## 4.1. Introduction

With efficient, reliable and cost-effective renewable energy resources, off-grid supply can be used as an alternative to the power supplied by diesel generator for rural electrification. However, due to intermittency nature of renewable resources, use of any particular renewable energy resource based system may lead to component over-sizing and unnecessary operational and lifecycle costs. Such limitations can be overcome by combining one or more renewable energy resources in a form of a hybrid system. Hybrid systems improve load factors plants and save maintenance and replacement costs, as the renewable resource components complement each other [14]. For optimal combination of different renewables, various types of hybrid systems and methods of techno-economic analysis are used. Excel based, linear programming, artificial intelligence, LINGO and HOMER are the most commonly used methods of hybrid system optimization techniques [14-18].

## 4.2. Basic Components and Model of Hybrid System

The basic components of the hybrid system are the hydro system, the wind plant and the PV system. Others are additional/auxiliary components which help for full time functioning of the hybrid system. The principle of operation of the basic components has been covered before. The principle of operation for diesel generator is same as generators used for hydro (see section 3.3.2.) except the prime mover, in this case, is diesel engine. Figure 4-1 shows schematic of the hybrid system.

The power conditioners are set of power electronics converters which enable to handle the variability of wind and solar resources. They are composed of DC/DC, AC/DC, DC/AC converters. The AC output of the hydropower, diesel and generator are integrated and controlled in such a way that the output can be directly supplied to the connected AC load. When there is excess of energy (mainly from the wind, PV and hydro), it is directed to the battery through the converter and DC center. In addition, frequency and voltage regulation control circuitry is to be included in the operation and control center. Similarly, the DC output of the PV panel is connected to the system via the DC center. The DC center is integrated with the system through DC/AC and AC/DC converters. As well as, it is connected to PV and battery components. Since the scope of this study is limited to the feasibility assessment of energy resources, detailed analysis of each component of the hybrid system are not covered.

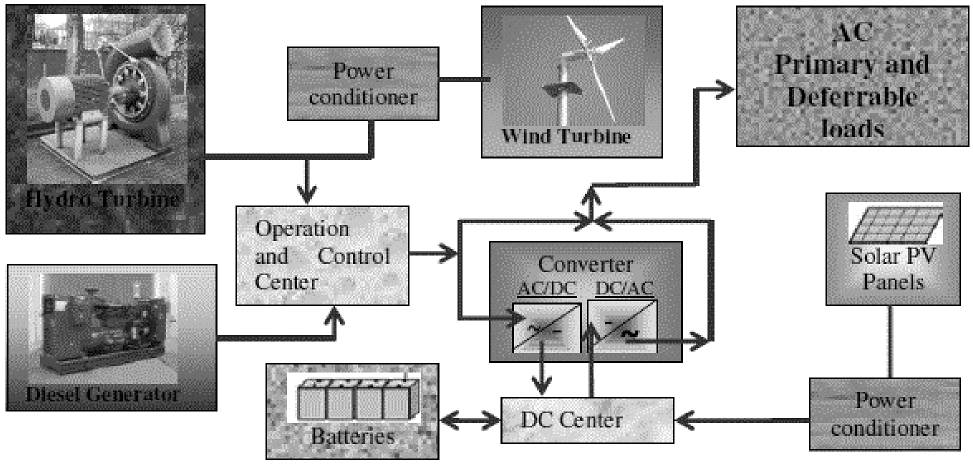


***Figure 4-1 General scheme of Small Hydro/PV/Wind hybrid system***

### *4.2.1. Converter*

Converters are generally four types: DC/DC, DC/AC, AC/DC and AC/AC. Power electronics devices (such as IGBT, power MOSFET, power Transistor, Thyristors, etc.) are used as a switching gate in different pattern of arrangement to achieve the required conversion output. DC/DC converters are classified as boost, buck and buck-boost converters based on their output voltage relative to their input (possibility of “step-up”, “step-down” or both respectively). They convert a given DC voltage level to the required voltage level. DC/AC converters (also called, inverters) can be classified based on the triggering signal as square wave, sine wave or modified sine wave. These devices use a given DC voltage as input and output the required voltage of a given amplitude and frequency. AC/DC converters (also called rectifiers) operate in the reverse principle of inverters. AC voltage source is used as input which passes through half or full bridge circuit (with a firing angle control) to result a rectified DC voltage output. AC/AC converters are used for conversion of AC voltage of a given frequency and amplitude to another AC voltage of the required amplitude and frequency.

### *4.2.2. Battery*

The one important reason of a hybrid system is to reduce component over-sizing by storing the excess energy available at one time for usage during shortage time. There are different types of storage mechanism such as batteries, pumped storage, hydrogen, fly wheels etc. Rechargeable batteries are widely used for implementation of hybrid energy systems because of their cheapness and easy operation.

Battery is a device in which the chemical energy of an electrolyte is converted into electrical energy through electrodes by the process of electrolysis. They are referred to as secondary cells (which can be recharged). The main parameters of selecting batteries are maximum throughput and minimum state of charge. Maximum throughput is measured by the output of the battery (in ampere-hour) that can be delivered throughout its life time. Minimum state of charge is the measure of how low the battery can be discharged as a percentage of its full capacity without losing its performance. There are very deep cycle batteries which can be discharged up to 40% such as Surrette6CS25P [33].

### 4.3. Simulation using HOMER

HOMER is a user-friendly micro-power design tool developed in 1992 by the National Renewable Energy Laboratory in the USA. The software can simulate and optimize stand-alone and grid-connected power systems with any combination of wind turbines, PV arrays, run-of-river hydro power, biomass power, internal combustion engine generators, fuel cells, batteries, and hydrogen storage, serving both electric and thermal loads [15, 33].

HOMER has three main windows which are used to enter necessary data to the software. The first is Add/Remove window where technologies to be considered are selected. The second window is Resource window which shows the type of energy source that are to be used corresponding to the equipments selected in the Add/Remove window. The third one is the Others window where economics, emission, constraints and system controls are defined. Details of each element in these windows should be defined.

In this study, wind turbine (type, cost, hub height, life time and number), hydro (cost, head, design flow rate, efficiency, minimum and maximum flow rate ratio, life time and head loss), PV (size, cost, slope, ground reflectance, derrating factor, life time), converter (cost, efficiency, size and life time), diesel generator (cost, size, minimum load ratio, fuel curve, type of fuel and life time), battery (type, cost and number of strings, life time), primary load (hourly data for the year, daily and hourly noise) and deferrable load (monthly average daily load, minimum ratio and storage capacity) are added to the system.

Details of solar, wind, hydro and diesel resources are defined. In the solar resource window, monthly averaged daily solar radiation data, location and time zones are defined which are used by the software to calculate the hourly incident solar radiation on the PV panel. In the wind resource window, monthly averaged wind speed data, altitude, anemometer height, variation with height, Weibull k, autocorrelation factors, diurnal pattern strength, hour of peak wind speed are defined which are used by HOMER to estimate the wind distribution and output power. In the hydro resource window, the monthly average stream flow and residual flow are defined. The diesel cost is defined in the diesel resource window.

Interest rate and project life time are defined in the economics window. Dispatch strategy (load follow and/or cycle charging) and generators control options are defined in the system control window. Greenhouse gas emission penalty are defined in the emission window. Maximum annual capacity shortage, minimum renewable fraction and operating reserves are defined in the constraint window.

The main objective of the overall project is to propose the optimal combination of the six small hydropower potentials together with wind and PV systems in a form of a hybrid system, which will improve the system reliability and investment costs. But, there is a limitation of the HOMER software to handle more than one hydro resource at the same time. Hence, modular analysis is opted for and the nominal hydropower potential of each site is roughly estimated as a percentage of the sum total. Based on the percentage contribution, the primary and the deferrable loads are allocated to each site. A hybrid system at each site can be then analyzed and finally the results will be combined into single overall system. Accordingly, Muga I, Muga II, Suha, Bechet, Taba (B) and Taba (A) share the community load in the 21.7, 56.3, 7.5, 8.3, 3.45 and 2.35 percentages respectively.

HOMER simulates all the possible system configurations based on the combinations of the components specified to it as input data and discards the infeasible system configurations that do not adequately meet the suggested load with the available resource and/or specified constraints [33]. Hence, only feasible combinations are displayed according to the total net present cost (NPC) in an increasing order. The optimization results are given out in an overall form and in a categorized form. For a particular set of sensitivity variables (solar radiation, average wind speed, diesel price, etc.), the overall table displays all feasible system configurations according to cost effectiveness. The categorized table displays only the most cost effective configuration from each possible hybrid system types.

It is to be noted that the results can further be refined with the refinement of the component sizes, but at a cost of much longer running time of the software. In this work a step by step repeated simulation is carried out by varying the input variables from coarse to fine and a practically applicable results have been achieved.

Since the price for diesel and for PV panels are more dynamic than other types of components, a range of diesel price and a PV capital and replacement cost multipliers are used as sensitivity parameters. HOMER displays the sensitivity analysis both in tabular and graphical form.

### 4.4. Load Estimation

One of the basic inputs to HOMER is the load profile of the system. According to Bekele G. et al. [24], electric load in the rural villages of Ethiopia can be assumed to be composed of lighting, radio and television, water pumps, health post and primary schools load. Tamrat B. [10] considered only lighting, radio and television as a community load. In this study, electricity for cooking and for flour mills is added to the load together with home radio and a TV set. Water pumps are considered as deferrable loads while the others as primary loads. As indicated previously, there are about 63,000 people without electricity now or even in the near future. Assuming an average of 6 members in a family, there would be a total of 10,500 families. Assuming one elementary school and one health center per 420 families, a total of 25 primary schools and 25 health centers are required for the community.

Each primary school consists of 8 classrooms and each classroom will be installed with four 11W CFLs (compact fluorescent lamps) and a radio receiver. An 11 W CFL has an equivalent lumens effect of a 60 W incandescent lamp. Additional 4 CFLs (of 11W) for external lighting are also considered. Evening classes are conducted from 18:00 to 21:00 and the receivers are used for radio lessons. Similarly for the 25 health centers, having 3 rooms each, one 11W CFL per room and one 20W CFL for external lighting are considered. A vaccine refrigerator of 80W working for 24 hours; a 20W capacity microscope and a 5 W radio receiver for the office hours; and a 1 kW water heater operational for 3 hours per day are also suggested for each health centers. One ceiling fan (75W) per room is also to be installed for air conditioning purpose between 10:00 and 15:00.

For the community a total of 25 flour mills of 12.5 kW working from 9:00 to 12:00 and 14:00 to 18:00 are assumed. Each family is assumed to use electric stove of 3 kW rating for baking a local bread, "Injera", for 40 minutes once every fourth day. Baking takes place side by side with either of preparation of breakfast (6:00-9:000, lunch (11:00-14:00) or 15:00-18:00. Each household is to be installed with 3 CFLs of 11W rating to be lit from 18:00 to 23:00. Additionally a CFL of 11W is also considered for external lighting. A radio receiver (5W) and a TV set (70W) are to be used in the time 18:00 to 23:00.

Water pumping system is required for the households, the schools and health care centers. A minimum of 100 l of water per day per family and 2400 l/day for each pair of one health center and one primary school is suggested [8, 24]. To accomplish this, 110 pumps of 450 W (with a capacity of 30 l/m) operating for 6 hours/day are to be installed to supply water for the community. Another 25 pumps of 150W (with a capacity of 10 l/m) for the 25 schools and health centers operating for 4 hours/day are assumed. A water storage capacity of 4 days is suggested requiring a storage capacity of 1188 kWh for the community and 60 kWh for primary school and health centers. The peak deferrable load is 3.75 kW for primary school and health center and 49.5 kW for the community.

**Exceptions:** The following exceptions to what is discussed above for weekend days, January, June July August and September. Because of religious concern, peoples are not on their regular activities in the weekend (i.e. religious holydays). Flour mills are not operational also for the same reason. And evening classes can be conducted at day time. Similarly, TV and radio may be enjoyed from 10:00 to 17:00 (all the day after church, in addition to 18:00 to 23:00 stated above in paragraph 2). Up to 30% deferrable load decreases can be expected in the rainy season [24]. 15% load decrease for June and September while 30% for July and August are assumed. There are no classes in July and August (annual break) and in January (semester break).

Based on the above analysis, the community will have a primary peak demand of 1423 kW, average primary load of 684 kW, annually averaged daily load of 16413 kWh/day and a load factor of 0.48 is found. A deferrable peak demand of 52.25 kW, annually averaged daily load of 289 kWh/day and a storage capacity of 1248 kWh are found. The variation of the deferrable load and the daily primary load (for week days) throughout the year is shown in Table 4-1. HOMER generated load data is depicted in Figures (4-2 & 4-3)

**Table 4-1 Monthly variation of daily primary and deferrable loads for the week days**

| Load Type Category | | Demand (kWh/day) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Jan | Feb-May | June | Jul & Aug | Sep | Oct-Dec |
| Deferrable | | 312 | 312 | 265.2 | 218.4 | 265.2 | 312 |
| Primary | Household | 13093.5 | 13093.5 | 13093.5 | 13093.5 | 13093.5 | 13093.5 |
| | Health Posts | 119.9 | 119.9 | 119.9 | 119.9 | 119.9 | 119.9 |
| | Primary Schools | 13.2 | 135.6 | 135.6 | 13.2 | 135.6 | 135.6 |
| | Mills | 2187.5 | 2187.5 | 2187.5 | 2187.5 | 2187.5 | 2187.5 |
| Total | | 15726.1 | 15848.5 | 15801.7 | 15632.5 | 15801.7 | 15848.5 |

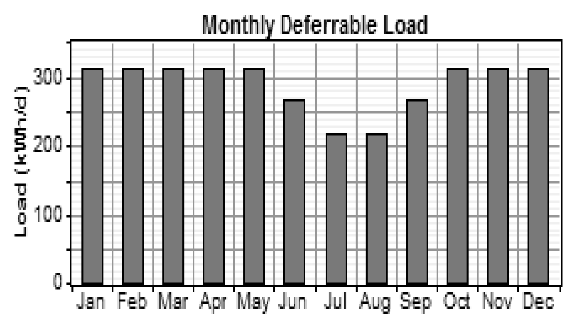


*Figure 4-2 Overall system deferrable load*

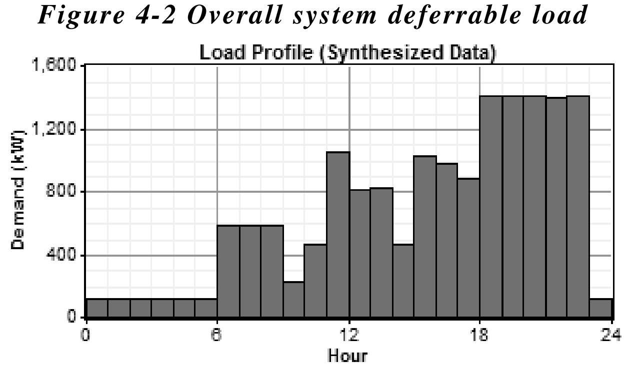


*Figure 4-3 Overall system daily primary load*

To account for randomness of load variation, a 5% daily and hourly noises are considered.

## 4.5. Summary of Input Data to HOMER

### *4.5.1. Common inputs to all sites*

Although each of the six sites, therefore six hybrid systems, is to be separately treated, there are common elements to all systems. Wind and solar radiation variations for such small range study areas can be neglected [7-9, 13]. The type of PV panel, wind turbine, diesel generator, converter and battery components are same for all systems, except their size and number. In addition, the sensitivity variables, constraints and system control strategies are similar. Cost information of small hydropower, solar PV module, battery, converter, diesel generator and wind turbine is collected from local suppliers, manufacturers and from different websites [34-38].

The HOMER synthesized wind speed probability density function (PDF) at 10 m height is shown in Figure 4-4. The type of wind turbine to be used is HY-5 kW which has a good cut-in speed of 2.5 m/s and its power curve is shown in Figure 4-5 [35]. The solar radiation data is also shown in Figure 4-6.

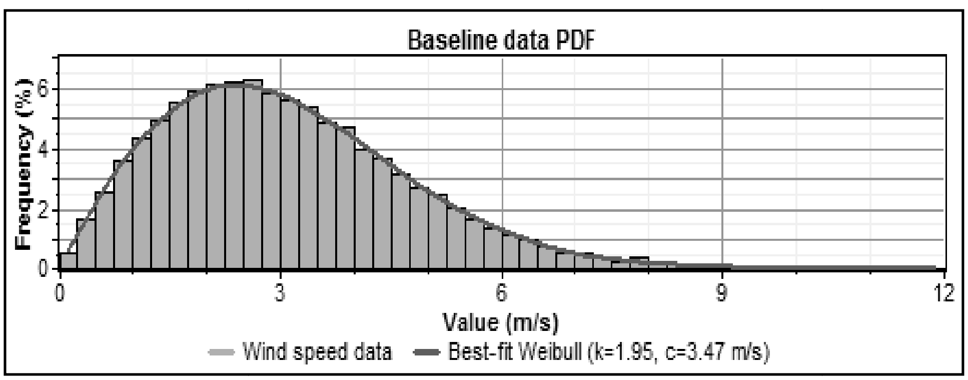


***Figure 4-4 Probability density function of wind speed (at 10 m height)***

The hydropower system pipe head loss of 15 % is assumed with 10 l/s reserve flow rate for all sites. Hydropower efficiency of 75% with 35% minimum flow ratio and 100% maximum flow ratio is taken. Derating factor of 90% and 20% ground reflectance PV system without tracking system is considered. PV panels are to be mounted at slope of $10.25^0$ (latitude of the site). Inverter and converter efficiencies are assumed to be 90%.

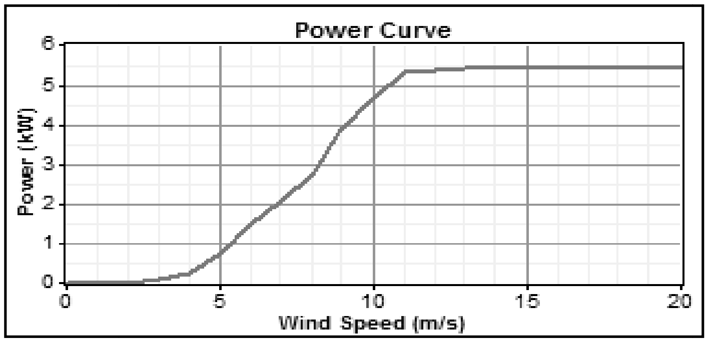


*Figure 4-5 Power curve of HY-5 kW wind turbine*

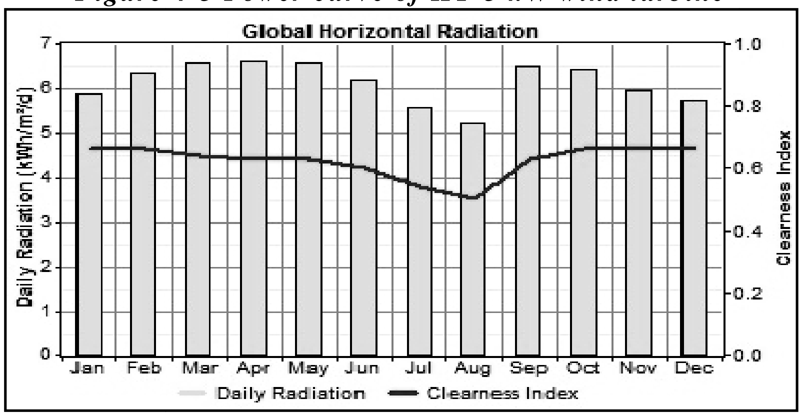


*Figure 4-6 Monthly solar radiation (kW/m$^2$)*

Diesel generator is allowed to operate under a minimum load ratio of 70%. Its fuel curve characteristics are calculated using HOMER and an intercept coefficient of 0.02 l/hr/kW and slope of 0.23 l/hr/kW are found using data from manufacturer's website [34]. The generator efficiency against its percentage loading is shown in Figure 4-7.

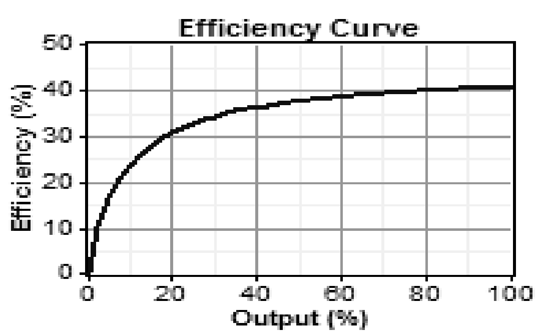


*Figure 4-7 Cummins diesel generator efficiency curve*

Both cyclic charge (CC) and load follow (LF) dispatch strategies are considered. The load following strategy is a dispatch strategy whereby whenever a generator operates; it produces only enough power to meet the primary load. Lower-priority objectives such as charging the battery bank or serving the deferrable load are left to the renewable power sources. The cycle charging strategy is a dispatch strategy whereby whenever a generator needs to operate to serve the primary load, it operates at full output power. Surplus electrical production goes toward the lower-priority objectives such as, in order of decreasing priority: serving the deferrable load and charging the battery bank [33].

Daily and hourly primary load noise is taken to be about 5%. An operating reserve of 10% of hourly load, 25% of solar output power and 50 % wind power output respectively is suggested. To account greenhouse effect, a \$20/t of penalty for $CO_2$ emission is considered. Maximum annual energy shortage and minimum renewable fraction are set to 5% and 0% respectively. Interest rate of 6.7% and 25 years project life time is used for present cost analysis.

A diesel price of \$0.6/l, \$0.9/l and \$1.2/l and a PV capital and replacement cost multipliers of 0.6, 0.8 and 1 are taken for sensitivity analysis.

### *4.5.2. Specific Inputs for Taba A*

The monthly average flow rate is shown in Figure 4-8. The design flow rate is repeatedly simulated and an about 80 l/s design flow rate is found to be more economical. This site has a gross head of 50.5 m. Table 4-2 shows the summary of the data input to HOMER for Taba A. Some of the components are expressed in kW while others in quantities. The life time of battery is indicated by its maximum throughput. This site shares about 2.35% of the total primary and deferrable loads as shown in Figures (4-9 & 4-10).

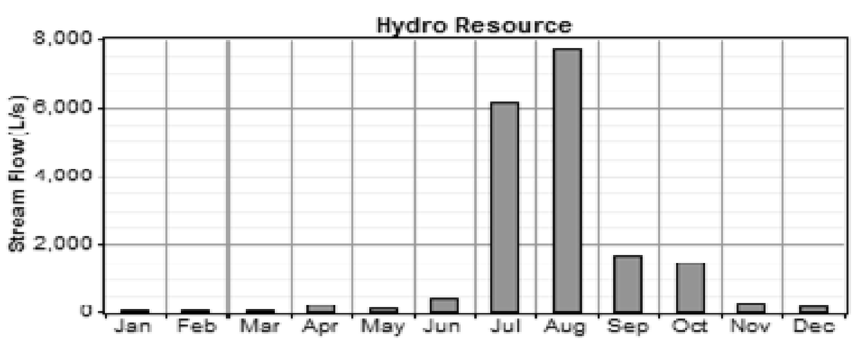


***Figure 4-8 Annual stream flow at Taba A.***

It has a primary peak demand of 39.1 kW, average primary load of 18.8 kW, annually averaged daily load of 451 kWh/day and a load factor of 0.48. A deferrable peak demand of 1.46 kW, annually averaged daily load of 7.94 kWh/day and a storage capacity of

34.32 kWh are found. The hybrid system set up developed using HOMER is shown in the Figure 4-11 (including 5% daily and hourly noise).

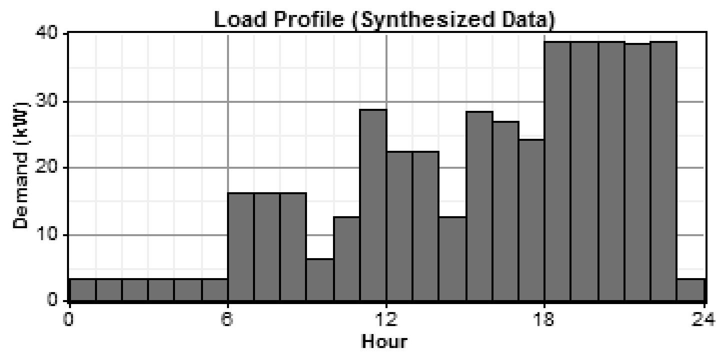


***Figure 4-9 Primary load for Taba A site***

**Table 4-2 Inputs to HOMER software Taba A**

| | PV Module | Wind turbine | Hydro System | Diesel Generator | Battery S6cs25p | Converter |
|---|---|---|---|---|---|---|
| Size (kW) | 1 | 5 | 29.7 | 0 - 77 | 1156 Ah | 1 |
| Capital ($) | 1800-3000 | 4990 | 65000 | 0 - 9000 | 833 | 700 |
| Replacement Cost($) | 1800-3000 | 3327 | 30000 | 0 - 6000 | 555 | 700 |
| O & M cost($/yr) | 25 | 100 | 1000 | 0.4/hr | 15 | 10 |
| Sizes (kW) considered | 0, 5, 10, 15, 20, 25, 30, 35, 40 | ------ | 29.7 | 0, 22, 26, 33, 35, 44, 53, 77 | ------ | 0, 10, 20, 25, 30, 35 |
| Quantities | ------ | 0, 1, 2, 3, 4, 5 | ------ | ------- | 0, 20, 40, 60, 80, 100, 120, 140 | ----- |
| Life Time | 20 yrs | 20 yrs | >25 yrs | 40000 hrs | 9645 kWh | 15 yr |

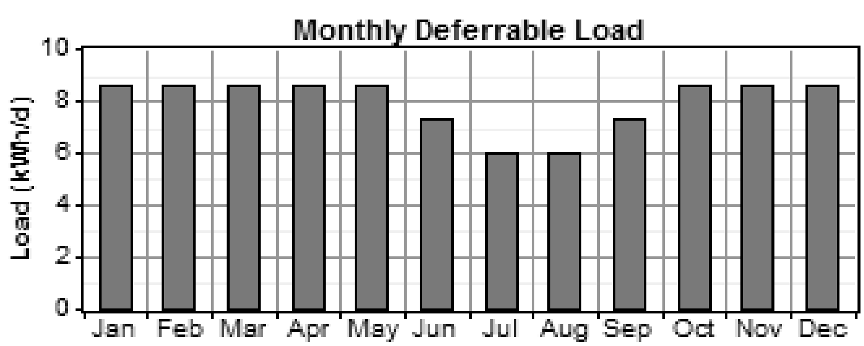


***Figure 4-10 Deferrable load for Taba A site***

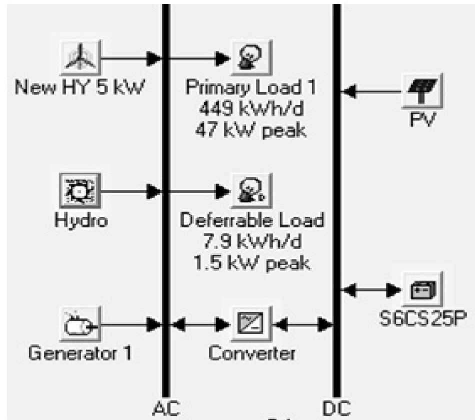


***Figure 4-11 Hydro/PV/Wind hybrid setup for Taba A***

### *4.5.3. Specific Inputs for Taba B*

The monthly average flow rate at this site is same as Taba A shown in Figure 4-8. The design flow rate is repeatedly simulated and 80 l/s is found to be more economical. This site has a gross head of 62 m and shares about 3.45% of the total primary and deferrable loads as shown in Figures (4-12 & 4-13). It has a primary peak demand of 49.1 kW, average primary load of 23.6 kW, annually averaged daily load of 566 kWh/day and a load factor of 0.48. A deferrable peak demand of 1.84 kW, annually averaged daily load of 9.96 kWh/day and a storage capacity of 43.06 kWh are found.

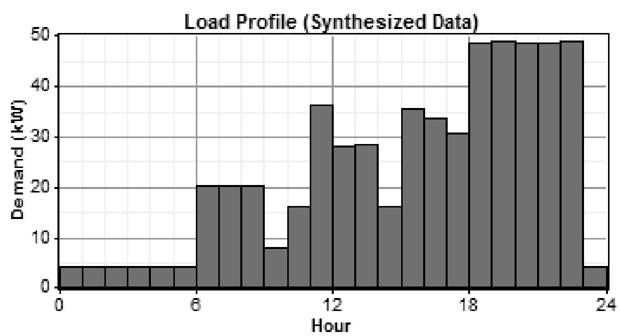


***Figure 4-12 Primary load for Taba B***

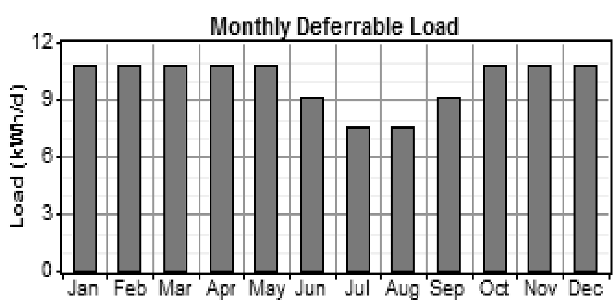


***Figure 4-13 Deferrable load for Taba B***

The hybrid system set up developed using HOMER is shown in the Figure 4-14 (including 5% daily and hourly noise). Table 4-3 shows the summary of the data input to HOMER for Taba B.

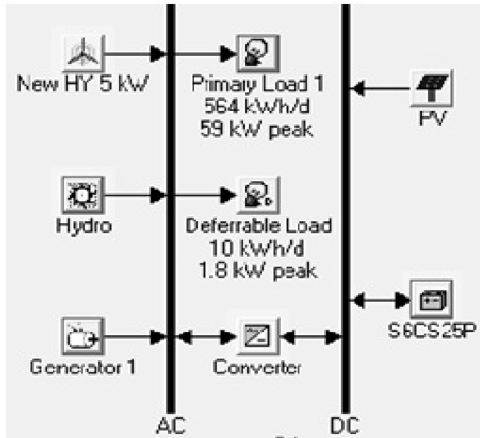


*Figure 4-14 Hydro/PV/Wind hybrid setup for Taba B*

**Table 4-3 Inputs to HOMER software for Taba B**

| | PV Module | Wind turbine | Hydro System | Diesel Generator | Battery S6cs25p | Converter |
|---|---|---|---|---|---|---|
| Size (kW) | 1 | 5 | 36.5 | 0-77 | 1156 Ah | 1 |
| Capital ($) | 1800-3000 | 4990 | 70000 | 0-9000 | 833 | 700 |
| Replacement Cost($) | 1800-3000 | 3327 | 30000 | 0-6000 | 555 | 700 |
| O & M cost($/yr) | 25 | 100 | 1400 | 0.4/hr | 15 | 10 |
| Sizes (kW) considered | 0, 5, 10, 15, 20, 25, 30, 35, 40 | ------ | 36.5 | 0, 22, 26, 33, 35, 44, 53, 77 | ------ | 0, 10, 20, 30, 40, 50 |
| Quantities | ------ | 0, 1, 2, 3, 4, 5 | ------ | ------- | 0, 20, 40, 60, 80, 100, 120, 140 | ----- |
| Life Time | 20 yrs | 20 yrs | >25 yrs | 40000 hrs | 9645 kWh | 15 yr |

### *4.5.4. Specific Inputs for Bechet*

The monthly average flow rate at this site is shown in Figure 4-15. The design flow rate is repeatedly simulated and about 200 l/s is found to be more economical. This site has a gross head of 74 m. This site shares about 8.3% of the total primary and deferrable loads as shown in Figures (4-16 & 4-17). It has a primary peak demand of 118 kW, average primary load of 56.8 kW, annually averaged daily load of 1362 kWh/day and a load factor of 0.48. A deferrable peak demand of 4.42 kW, annually averaged daily load of 24 kWh/day and a storage capacity of 103.8 kWh are found. The hybrid system set up developed using HOMER is shown in the Figure 4-18 (including 5% daily and hourly noise). Table 4-4 shows the summary of the data input to HOMER for Bechet.

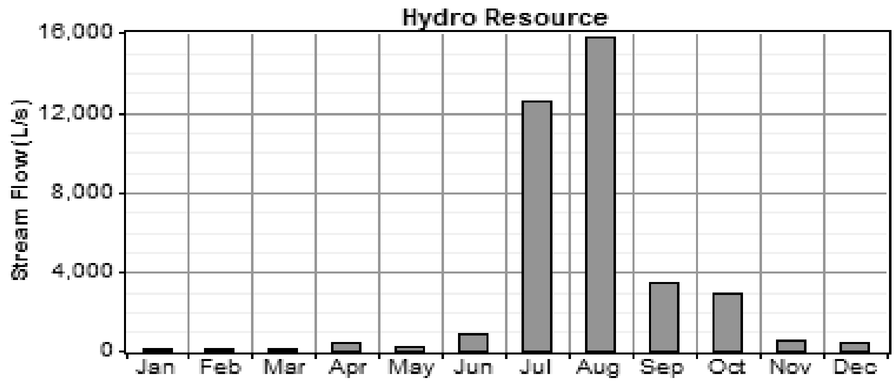


***Figure 4-15 Annual stream flow at Bechet site.***

**Table 4-4 Inputs to HOMER software for Bechet**

| | PV Module | Wind turbine | Hydro System | Diesel Generator | Battery Surrette6cs25p | Converter |
|---|---|---|---|---|---|---|
| Size (kW) | 1 | 5 | 109 | 0 - 77 | 1156 Ah | 1 |
| Capital ($) | 1800-3000 | 4990 | 180000 | 0 - 9000 | 833 | 700 |
| Replacement Cost($) | 1800-3000 | 3327 | 60000 | 0 - 6000 | 555 | 700 |
| O & M cost($/yr) | 25 | 100 | 4800 | 0.4/hr | 15 | 10 |
| Sizes (kW) considered | 0, 5, 10, 15, 20, 25, 30, 35, 40 | ------ | 109 | 0, 22, 26, 33, 35, 44, 53, 77 | ------ | 0, 10, 20, 30, 40, 50, 60 |
| Quantities | ------ | 0, 1, 2, 3, 4, 5 | ------ | ------- | 0, 20, 40, 60, 80, 100, 120, 140 | ----- |
| Life Time | 20 yrs | 20 yrs | >25 yrs | 40000 hrs | 9645 kWh | 15 yr |

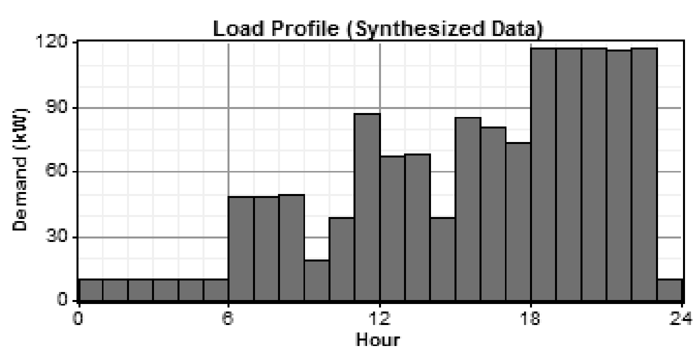


***Figure 4-16 Primary load at Bechet site***

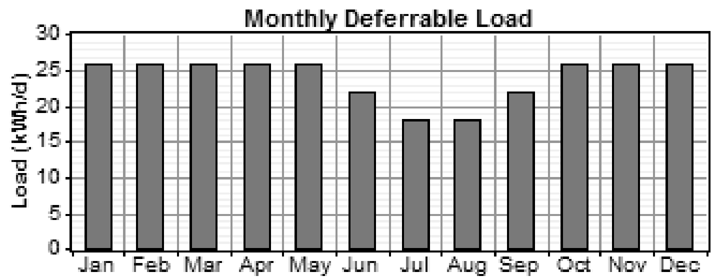


***Figure 4-17 Deferrable load at Bechet site***

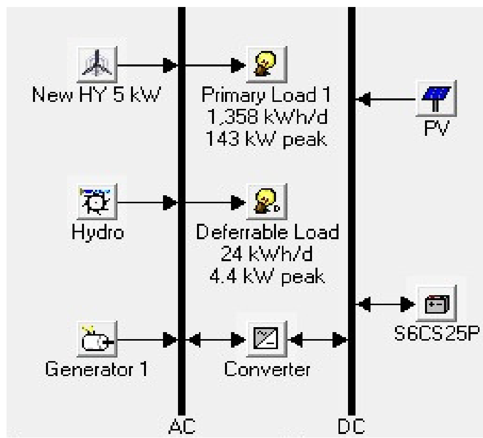


***Figure 4-18 Hydro/PV/Wind hybrid setup for Bechet***

### *4.5.5. Specific Inputs for Suha*

The monthly average flow rate at this site is shown in Figure 4-19. The design flow rate is repeatedly simulated and 120 l/s is found to be more economical. This site has a gross head of 92 m.

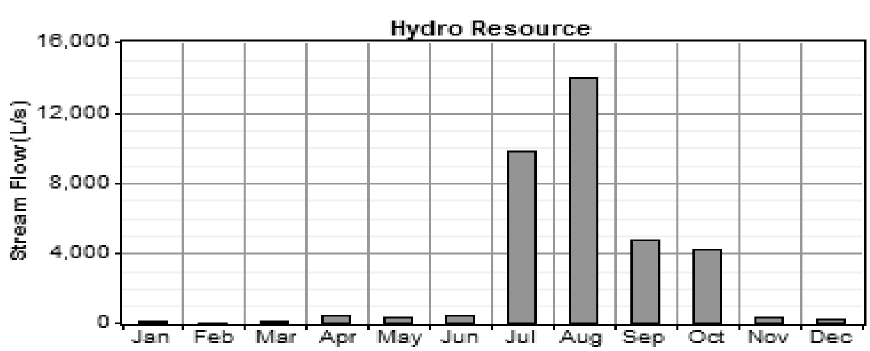


***Figure 4-19 Annual stream flow at Suha***

This site shares about 7.5% of the total primary and deferrable loads as shown in Figures (4-20 & 4-21). It has a primary peak demand of 107 kW, average primary load of 51.3

kW, annually averaged daily load of 1231 kWh/day and a load factor of 0.48. A deferrable peak demand of 4 kW, annually averaged daily load of 21.6 kWh/day and a storage capacity of 93.6 kWh are found. The hybrid system set up developed using HOMER is shown in the Figure 22 (including 5% daily and hourly noise). Table 4-5 shows the summary of the data input to HOMER for Suha.

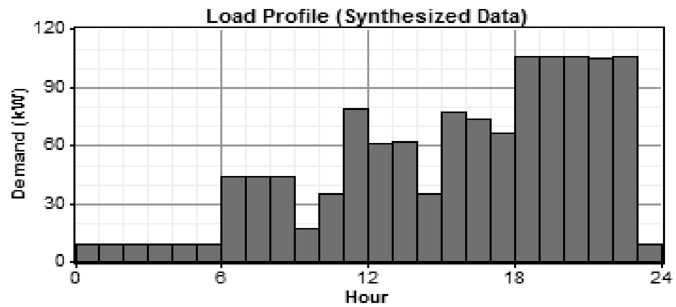


*Figure 4-20 Primary load at Suha site*

**Table 4-5 Inputs to HOMER software for Suha site**

| | PV Module | Wind turbine | Hydro System | Diesel Generator | Battery S6cs25p | Converter |
|---|---|---|---|---|---|---|
| Size (kW) | 1 | 5 | 81.2 | 0 - 77 | 1156 Ah | 1 |
| Capital ($) | 1800-3000 | 4990 | 160000 | 0 - 9000 | 833 | 700 |
| Replacement Cost($) | 1800-3000 | 3327 | 60000 | 0 - 6000 | 555 | 700 |
| O & M cost($/yr) | 25 | 100 | 4700 | 0.4/hr | 15 | 10 |
| Sizes (kW) considered | 0, 5, 10, 15, 20, 25, 30 | ------ | 81.2 | 0, 22, 26, 33, 35, 44, 53, 77 | ------ | 0, 10, 20, 40, 50, 60, 70, 80 |
| Quantities | ------ | 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 | ------ | ------- | 0, 20, 40, 60, 80, 100, 120, 140 | ----- |
| Life Time | 20 yrs | 20 yrs | >25 yrs | 40000 hrs | 9645 kWh | 15 yr |

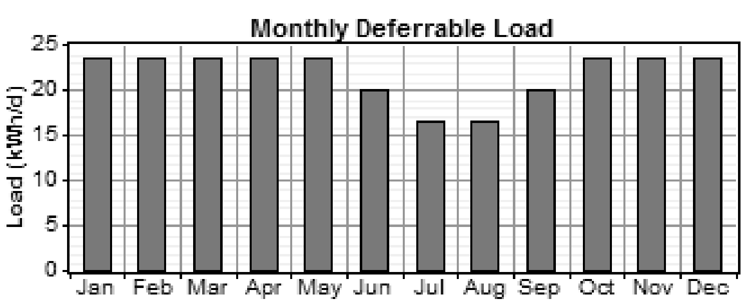


*Figure 4-21 Deferrable load at Suha site*

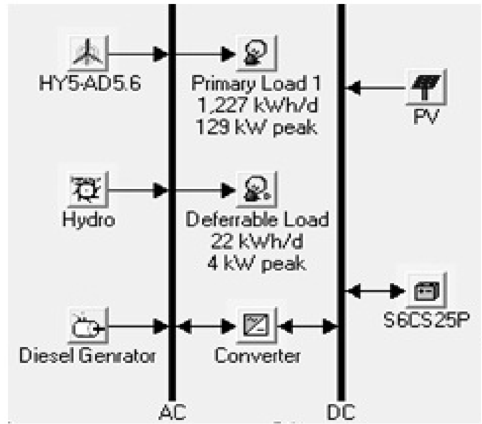


***Figure 4-22 Hydro/PV/Wind hybrid setup at Suha site***

### *4.5.6. Specific Inputs for Muga I*

The monthly average flow rate at this site is shown in Figure 4-23. The design flow rate is repeatedly simulated and 547 l/s is found to be more economical. This site has a gross head of 48 m.

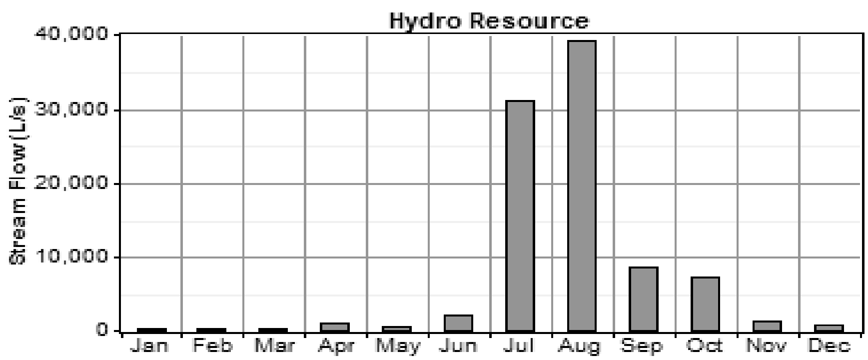


***Figure 4-23 Annual stream flow at Muga I site***

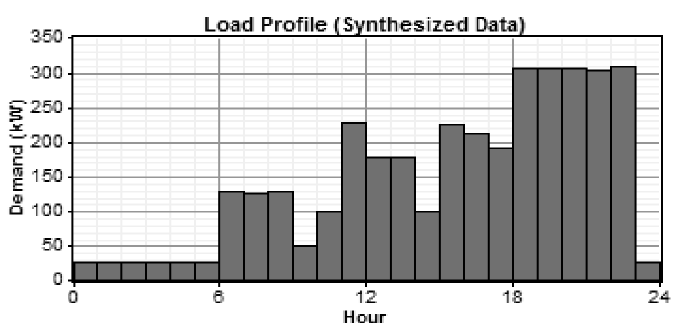


***Figure 4-24 Primary load at Muga I site***

This site shares about 21.7% of the total primary and deferrable loads as shown in Figures (4-24 & 4-25). It has a primary peak demand of 349 kW, average primary load of 148 kW, annually averaged daily load of 3562 kWh/day and a load factor of 0.48. A deferrable peak demand of 11.56 kW, annually averaged daily load of 62.6 kWh/day and a storage capacity of 270.76 kWh are found. The hybrid system set up developed using HOMER is shown in the Figure 4-26 (including 5% daily and hourly noise). Table 4-6 shows the summary of the data input to HOMER for Muga I.

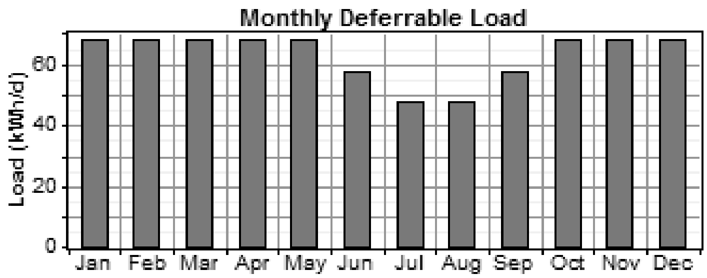


***Figure 4-25 Deferrable load at Muga I site***

**Table 4-6 Inputs to HOMER software for Muga I**

| | PV Module | Wind turbine | Hydro System | Diesel Generator | Battery S6cs25p | Converter |
|---|---|---|---|---|---|---|
| Size (kW) | 1 | 5 | 193 | 0 - 176 | 1156 Ah | 1 |
| Capital ($) | 1800-3000 | 4990 | 380000 | 0 - 17986 | 833 | 700 |
| Replacement Cost($) | 1800-3000 | 3327 | 175000 | 0 - 12050 | 555 | 700 |
| O & M cost($/yr) | 25 | 100 | 7000 | 0.4 – 0.5($/hr) | 15 | 10 |
| Sizes (kW) considered | 0,10,20,30,40, 50, 60, 70, 80, 90, 100, 110 | ------ | 193 | 0, 22, 44, 53, 74, 99, 114, 132, 154, 176 | ------ | 0 ,50, 100, 120, 140, 155, 170, 180, 190, 200 |
| Quantities | ------ | 0, 1, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20 | ----- | ------- | 0, 120, 180, 280, 320, 360, 400, 440, 480 | ----- |
| Life Time | 20 yrs | 20 yrs | >25 yrs | 40000 hrs | 9645 kWh | 15 yr |

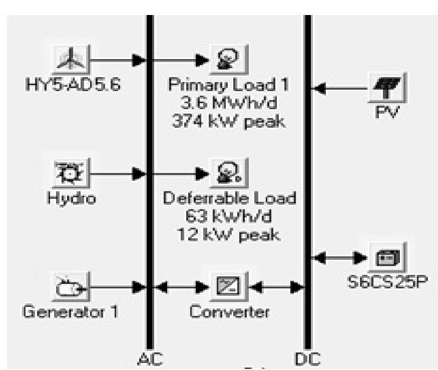


***Figure 4-26 Hydro/PV/Wind hybrid setup at Muga I site***

### *4.5.7. Specific Inputs for Muga II*

The monthly average flow rate at this site is shown in Figure 4-27. The design flow rate is repeatedly simulated and 1000 l/s is found to be more economical. This site has a gross head of 113 m and shares about 56.3% of the total primary and deferrable loads as shown in Figures (4-28 & 4-29). It has a primary peak demand of 801 kW, average primary load of 385 kW, annually averaged daily load of 9242 kWh/day and a load factor of 0.48. A deferrable peak demand of 30 kW, annually averaged daily load of 289 kWh/day and a storage capacity of 712 kWh are found. The hybrid system set up developed using HOMER is shown in the Figure 4-30 (including 5% daily and hourly noise). Table 4-7 shows the summary of the data input to HOMER for Muga II.

**Table 4-7 Inputs to HOMER software for Muga II**

| | PV Module | Wind turbine | Hydro System | Diesel Generator | Battery S6cs25p | Converter |
|---|---|---|---|---|---|---|
| Size (kW) | 1 | 5 | 831 | 0 - 396 | 1156 Ah | 1 |
| Capital ($) | 1800-3000 | 4990 | 1100000 | 0 - 33245 | 833 | 700 |
| Replacement Cost($) | 1800-3000 | 3327 | 500000 | 0 - 22279 | 555 | 700 |
| O & M cost($/yr) | 25 | 100 | 33000 | 0.4 – 0.5($/hr) | 15 | 10 |
| Sizes (kW) considered | 0, 5, 10, 15, 20, 25, 30, 35, 40 | ------ | 831 | 0, 53, 154, 200, 294, 354, 360, 374, 382, 396 | ------ | 0, 50, 100, 150, 200, 250, 260, 270, 280, 290, 300, 310, 320 |
| Quantities | ------ | 0,1,2,3 | ----- | ------- | 0, 120, 200, 280, 320, 360, 400, 440 | ----- |
| Life Time | 20 yrs | 20 yrs | >25 yrs | 40000 hrs | 9645 kWh | 15 yr |

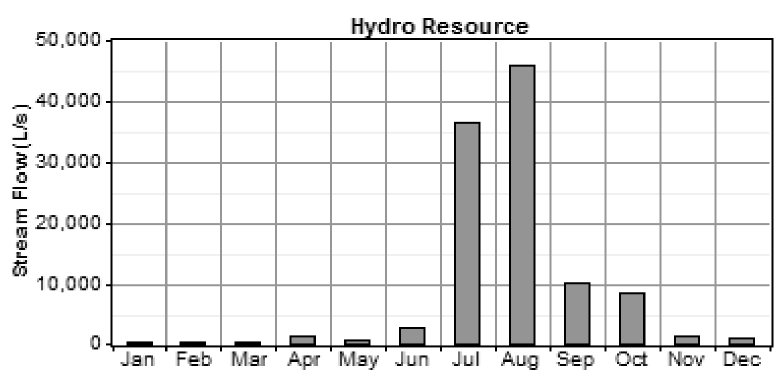


***Figure 4-27 Annual stream flow at Muga II***

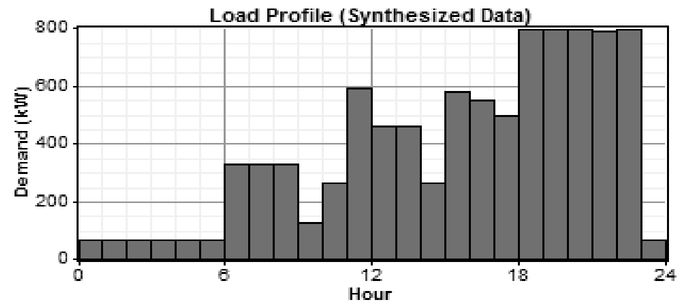


*Figure 4-28 Primary load at Muga II*

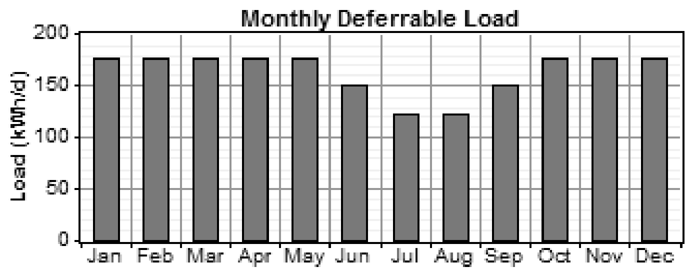


*Figure 4-29 Deferrable load at Muga II*

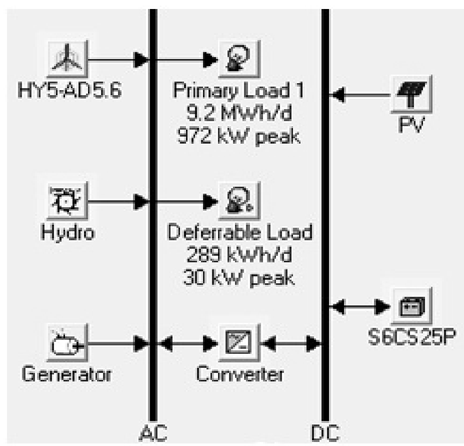


*Figure 4-30 Hydro/PV/Wind hybrid setup for Muga II*

# CHAPTER 5

# 5. Simulation Results and Discussion

## 5.1. Introduction

The feasibility study is carried out in two ways: optimization and sensitivity analysis. The optimization results are given out in an overall form and in a categorized form which represents feasible system configurations capable of meeting the system load and constraints. The results are displayed in an increasing order of the total net present cost (NPC). A given system type may have many different configurations based on the size combination of constituent elements. The categorized table displays only the most cost effective configuration from each system type. The overall optimization table displays all feasible system configurations (for any possible system type) ranked in their cost effectiveness. From the details of the optimization analysis the following can be observed: size of different components in each system, electric production of each component, capital, replacement and operating and maintenance cost of each system, annualized cost, excess and shortage of capacity, cost of energy (COE), renewable fraction, unmet load, amount of emission for each of green house gas, consumption of diesel, operating hour and number of starting of diesel generator, life time of generator and battery, throughput of battery and fuel cost. Renewable fraction cost of energy (COE), unmet load and total NPC values can be used as a parameter of selecting a given configuration among the many candidates.

The sensitivity analysis explains the "what if..." problem for input variables having dynamic nature. It takes the most cost effective system configuration for each combination of sensitivity variable values. Since the price for diesel and for PV panels are more dynamic than other types of components, a range of diesel price ($0.6/l to $1.2/l) and a PV capital cost multipliers (0.6 to 1) are used as sensitivity parameters. The PV capital and replacement cost multipliers are linked together. HOMER displays the sensitivity analysis both in tabular and graphical form. For each combination of the sensitivity variables, the sensitivity analysis takes the least cost (ranked $1^{st}$) and extrapolates it for the intermediate sensitivity variables. The possibility of other system types can be observed by clicking on the sensitivity graph.

Systems excluding hydro turbines are observed to have very high COE, low renewable fraction and needs large simulation time corresponding to the large size of components required. Therefore, the simulation and optimization analysis is made to include hydropower systems.

### 5.2. Results for Taba A Site

The results obtained are based on the current price of diesel ($0.9/l) and PV capital of $2400/kW. From Table 5-1, the levelized COE is observed to be in the range of $0.109/kWh to $0.179/kWh. Both of LF and CC dispatch strategies are feasible. Presence of plenty of renewable resource is indicated by the level of the renewable fraction ranging from 77% to 100% in the renewable fractions column of Tables (5-1 & 5-2). Although capacity shortage is allowed to a maximum of 5%, the unmet load is limited to a maximum of 4%. This is due to the system reserve (see section 4.5.1.). There are feasible combinations without any diesel generator (a renewable fraction of 100%). There are also system types which do not require battery and converter. It can be seen from the two Tables (5-1 & 5-2) that the hydro/wind/PV/battery system is the most cost effective which is followed by hydro/PV/battery and hydro/diesel/battery system types with increasing total NPC and COE.

The current energy tariff of Ethiopia is below $0.04/kWh. A previous study of Wind/PV hybrid system in Ethiopia (without hydropower resource) [9, 24] has suggested an optimal system with a levelized COE of $0.3/kWh to $0.4/kWh. Global electricity tariff varies in a wide range. For instance Canada has an energy tariff of $0.0618/kWh while Denmark has $0.43/kWh [39]. All feasible system types shown in both tables here have a levelized COE slightly higher than the national tariff. However, they are within the range of global tariff and much lower than what a previously studied result showed.

The listed outputs of the overall optimization table (see Table 5-2) have little variation in the COE ($0.101/kWh to $0.12/kWh). The system ranked first has a good renewable fraction (100%) and lowest COE ($0.109/kWh) but, with 4% unmet load. System setups ranked 29th and 49th have renewable fraction of 95% and unmet load of 1% for an additional COE of $0.003/kWh and $0.004/kW respectively over the top ranked system. These systems are better than the top ranked in meeting the system load. 49$^{th}$ ranked system configuration consumes less diesel and is more diversified than the 29th ranked system configuration. The system report for this particular setup is summarised in Table 5-3. Also, the monthly electricity production of each component is given in Table 5-4.

**Table 5-1 Taba A optimization results in a categorized form**

| Rank | PV (kW) | HY-5 turbine | Hydro (kW) | Gen (kW) | S6CS25P | Converter (kW) | Dispatch strategy | Total NPC ($) | COE ($/kWh) | Renewable fraction | Unmet load fraction | Diesel (L/yr) | Gen (hrs/yr) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 15 | 2 | 29.7 | 0 | 40 | 25 | CC | 209,921 | 0.109 | 1 | 0.04 | 0 | 0 |
| 2 | 20 | 0 | 29.7 | 0 | 40 | 25 | CC | 212,348 | 0.11 | 1 | 0.04 | 0 | 0 |
| 3 | 0 | 0 | 29.7 | 22 | 40 | 25 | LF | 220,357 | 0.111 | 0.93 | 0.01 | 5,129 | 839 |
| 4 | 0 | 1 | 29.7 | 22 | 40 | 25 | LF | 222,135 | 0.112 | 0.94 | 0.01 | 4,752 | 776 |
| 5 | 5 | 0 | 29.7 | 22 | 40 | 25 | LF | 222,638 | 0.112 | 0.95 | 0.01 | 4,051 | 663 |
| 6 | 5 | 1 | 29.7 | 22 | 40 | 25 | LF | 225,660 | 0.113 | 0.95 | 0.01 | 3,786 | 621 |
| 7 | 0 | 0 | 29.7 | 22 | 0 | 0 | LF | 351,939 | 0.177 | 0.77 | 0.01 | 21,691 | 3,700 |
| 8 | 0 | 1 | 29.7 | 22 | 0 | 0 | LF | 352,758 | 0.178 | 0.77 | 0.01 | 21,223 | 3,628 |
| 9 | 10 | 0 | 29.7 | 22 | 0 | 10 | LF | 353,542 | 0.178 | 0.81 | 0.01 | 18,682 | 3,185 |
| 10 | 5 | 1 | 29.7 | 22 | 0 | 10 | LF | 356,169 | 0.179 | 0.79 | 0.01 | 19,560 | 3,343 |

**Table 5-2 Extracts from overall optimization table for Taba A**

| Rank | PV (kW) | HY-5 kW | Hydro (kW) | Gen (kW) | S6CS25P | Converter (kW) | Dispatch strategy | Total NPC ($) | COE ($/kWh) | Renewable fraction | Unmet load fraction | Diesel (L/yr) | Gen (hrs/yr) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | **15** | **2** | **29.7** | **0** | **40** | **25** | **CC** | **209,921** | **0.109** | **1** | **0.04** | **0** | **0** |
| 2 | 15 | 2 | 29.7 | 0 | 40 | 25 | LF | 209,921 | 0.109 | 1 | 0.04 | 0 | 0 |
| 20 | 10 | 2 | 29.7 | 0 | 60 | 25 | LF | 220,351 | 0.115 | 1 | 0.04 | 0 | 0 |
| 21 | 0 | 0 | 29.7 | 22 | 40 | 25 | LF | 220,357 | 0.111 | 0.93 | 0.01 | 5,129 | 839 |
| **29** | **5** | **0** | **29.7** | **22** | **40** | **25** | **LF** | **222,638** | **0.112** | **0.95** | **0.01** | **4,051** | **663** |
| 30 | 25 | 0 | 29.7 | 0 | 40 | 20 | CC | 222,654 | 0.115 | 1 | 0.03 | 0 | 0 |
| 48 | 15 | 3 | 29.7 | 0 | 40 | 35 | LF | 225,452 | 0.117 | 1 | 0.04 | 0 | 0 |
| **49** | **5** | **1** | **29.7** | **22** | **40** | **25** | **LF** | **225,660** | **0.113** | **0.95** | **0.01** | **3,786** | **621** |
| 50 | 0 | 0 | 29.7 | 26 | 40 | 25 | LF | 225,730 | 0.113 | 0.93 | 0 | 5,580 | 790 |
| 121 | 10 | 3 | 29.7 | 0 | 60 | 30 | LF | 231,556 | 0.12 | 1 | 0.04 | 0 | 0 |

Sensitivity analysis is also carried out and Figure 5-1 shows the variation of PV capital cost multiplier against diesel price. At higher price of PV modules, hydro/diesel/battery and hydro/wind/PV/battery systems are favoured with lower and slightly higher price of diesel respectively. As PV module price decrease just below $1950/kW, hydro/PV/battery system is more economical and the system becomes less sensitive to variation of diesel price.

**Table 5-3 System report for 95% renewable fraction for Taba A**

| System architecture | |
|---|---|
| PV | 5 kW |
| Wind turbine | 1 HY5 kW |
| Hydro | 29.7 kW |
| Gen | 22 kW |
| Battery | 40 Surr6CS25P |
| Inverter | 25 kW |
| Rectifier | 25 kW |
| Disp. strategy | LF |

| Sensitivity case | |
|---|---|
| Design flow rate | 80 l/s |
| Stream flow rate | 1540 l/s |
| PV replacement cost multiplier | 0.8 |
| wind data | 3.1 m/s |
| PV capital cost multiplier | 0.8 |
| Solar data | 6.12 $kWh/m^2/d$ |

| Annual electric production ( kWh/yr) | | |
|---|---|---|
| PV array | 9,091 | 4% |
| Wind turbine | 3,363 | 1.5% |
| Hydro turbine | 199,461 | 89.5% |
| Gen | 10,771 | 5% |
| Excess electricity | 40,991 | 18.4% |
| Unmet load | 847 | 0.5% |
| Capacity shortage | 1,569 | 0.9% |
| Renewable ratio | 0.95 | 95% |

| Annual electric consumption (kWh/yr) | | |
|---|---|---|
| AC primary load | 163,037 | 98% |
| Deferrable load | 2,895 | 2% |
| Total | 165,292 | 100% |

| Cost summary | |
|---|---|
| Total NPC | $225,660 |
| Levelized COE | $ 0.113/kWh |
| Operating cost | $ 7,199/yr |

| Emission (kg/yr) | |
|---|---|
| $CO_2$ | 9,969 |
| CO | 24.6 |
| Unburned $CH_4$ | 2.73 |
| Particulate matter | 1.86 |
| $SO_2$ | 20 |
| $NO_x$ | 220 |

**Table 5-4 Monthly Average electric production from Taba A (kW)**

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PV | 1.0757 | 1.1289 | 1.1195 | 1.0793 | 1.0321 | 0.9597 | 0.879 | 0.8399 | 1.0819 | 1.1207 | 1.0911 | 1.0571 |
| Wind | 0.50519 | 0.50543 | 0.42262 | 0.34824 | 0.348 | 0.54826 | 0.50547 | 0.31273 | 0.19026 | 0.19132 | 0.3126 | 0.42359 |
| Diesel generator | 3.1052 | 7.8939 | 2.2277 | 0.2994 | 0.2277 | 0.2567 | 0.1656 | 0.2898 | 0.2781 | 0.1656 | 0.0856 | 0.276 |
| Hydro | 16.424 | 9.16 | 19.267 | 25.266 | 25.266 | 25.266 | 25.266 | 25.266 | 25.266 | 25.266 | 25.266 | 25.266 |

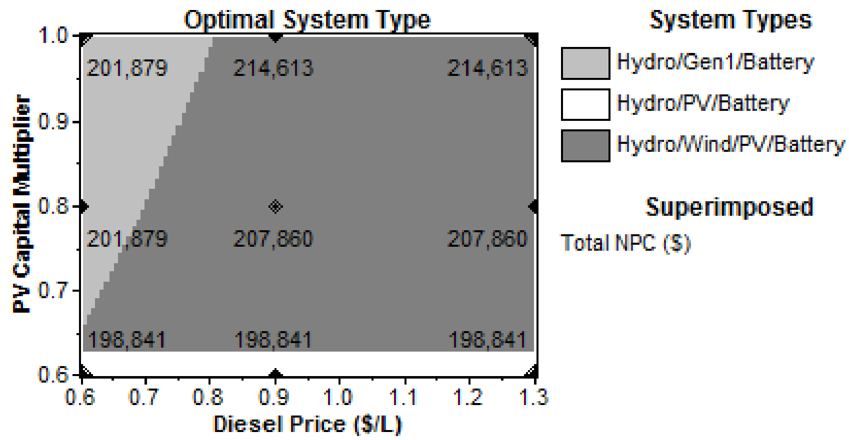


***Figure 5-1 Sensitivity result for diesel and PV module price variation at Taba A***

### 5.3. Results for Taba B Site

The results obtained are based on the current price of diesel ($0.9/l) and PV capital of $2400/kW. From Table (5-5 & 5-6), the levelized COE is observed to be in the range of $0.099/kWh to $0.129/kWh, which are within the range of global tariff and much lower than what previously studied result showed. Both of LF and CC dispatch strategies are feasible. The renewable fraction ranges from 79% to 100%. The unmet load is limited to a maximum of 4%. There are resources with 100% renewables. It can be seen from the two tables, that the hydro/diesel/battery system is the most cost effective which is followed by hydro/wind/diesel/battery and hydro/PV/wind/battery system types with increasing total NPC and COE (see Tables 5-5 & 5-6).

The listed outputs of the overall optimization table (see Table 5-6) have little variation in the COE ($0.099/kWh to $0.111/kWh). The system ranked first has a renewable fraction of 94% and lowest COE ($0.109/kWh) but, with 2% unmet load. A system setup ranked 4$^{th}$ has a better renewable fraction of 95% and unmet load of 1% for an additional COE of $0.001/kWh over the top ranked system. There are also systems with 0% unmet load, but with higher COE, such as 27$^{th}$ and 101$^{st}$. The system report for 4$^{th}$ ranked setup is summarised in Table 5-7. Also, the monthly electricity production of each component is given in Table 5-8.

Sensitivity analysis is also carried out and Figure 5-2 shows the variation of PV capital cost multiplier against diesel price. At higher price of PV modules, hydro/diesel/battery system is cost effective. In decreasing the PV module price and increasing the diesel price, hydro/wind/PV/battery systems get favoured. As PV module price decrease more, hydro/PV/battery system becomes more economical at higher diesel price. At lower diesel price (< $0.8/l), hydro/diesel/battery systems are cost effective and are less sensitive for PV module price variation.

**Table 5-5 Categorized optimization result for Taba B**

| Rank | PV (kW) | HY-5 | Hydro (kW) | Gen (kW) | S6CS25P | Converter (kW) | Dispatch strategy | Total NPC ($) | COE ($/kWh) | Renewable fraction | Unmet load fraction | Diesel (L/yr) | Gen (hrs/yr) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 36.5 | 22 | 60 | 30 | LF | 244,683 | 0.099 | 0.94 | 0.02 | 3,753 | 814 |
| 2 | 0 | 1 | 36.5 | 22 | 60 | 30 | LF | 247,569 | 0.1 | 0.95 | 0.01 | 3,456 | 752 |
| 3 | 15 | 2 | 36.5 | 0 | 60 | 30 | CC | 250,191 | 0.104 | 1 | 0.04 | 0 | 0 |
| 4 | 5 | 0 | 36.5 | 22 | 40 | 30 | LF | 250,726 | 0.101 | 0.93 | 0.01 | 4,834 | 1,089 |
| 5 | 20 | 0 | 36.5 | 0 | 60 | 30 | CC | 251,981 | 0.105 | 1 | 0.04 | 0 | 0 |
| 6 | 5 | 1 | 36.5 | 22 | 40 | 30 | LF | 253,488 | 0.102 | 0.94 | 0.01 | 4,530 | 1,024 |
| 7 | 0 | 0 | 36.5 | 22 | 0 | 0 | LF | 304,016 | 0.124 | 0.79 | 0.02 | 16,922 | 3,770 |
| 8 | 0 | 1 | 36.5 | 22 | 0 | 0 | LF | 306,613 | 0.125 | 0.79 | 0.02 | 16,598 | 3,720 |
| 9 | 5 | 0 | 36.5 | 22 | 0 | 10 | LF | 315,025 | 0.128 | 0.8 | 0.02 | 15,794 | 3,525 |
| 10 | 5 | 1 | 36.5 | 22 | 0 | 10 | LF | 318,267 | 0.129 | 0.81 | 0.02 | 15,521 | 3,485 |

**Table 5-6 Extracts from overall optimization table for Taba B**

| Rank | PV (kW) | HY-5 kW | Hydro (kW) | Gen (kW) | S6CS25P | Converter (kW) | Dispatch strategy | Total NPC ($) | COE ($/kWh) | Renewable fraction | Unmet load fraction | Diesel (L) | Gen (hrs) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | **0** | **0** | **36.5** | **22** | **60** | **30** | **LF** | **244,683** | **0.099** | **0.94** | **0.02** | **3,753** | **814** |
| 1 | 0 | 0 | 36.5 | 22 | 60 | 30 | LF | 244,683 | 0.099 | 0.94 | 0.02 | 3,753 | 814 |
| 2 | 0 | 0 | 36.5 | 22 | 40 | 30 | LF | 245,630 | 0.1 | 0.92 | 0.02 | 5,673 | 1,265 |
| 3 | 0 | 0 | 36.5 | 22 | 60 | 30 | CC | 247,169 | 0.1 | 0.94 | 0.01 | 3,968 | 820 |
| **4** | **0** | **1** | **36.5** | **22** | **60** | **30** | **LF** | **247,569** | **0.1** | **0.95** | **0.01** | **3,456** | **752** |
| 7 | 15 | 2 | 36.5 | 0 | 60 | 30 | CC | 250,191 | 0.104 | 1 | 0.04 | 0 | 0 |
| 24 | 0 | 3 | 36.5 | 22 | 60 | 30 | LF | 255,018 | 0.103 | 0.96 | 0.01 | 2,996 | 655 |
| 25 | 5 | 1 | 36.5 | 22 | 60 | 30 | LF | 255,324 | 0.103 | 0.96 | 0.01 | 2,875 | 635 |
| 26 | 0 | 0 | 36.5 | 22 | 60 | 40 | CC | 255,779 | 0.104 | 0.94 | 0.02 | 3,834 | 774 |
| **27** | **0** | **0** | **36.5** | **33** | **60** | **30** | **LF** | **255,823** | **0.102** | **0.93** | **0** | **4,731** | **731** |
| 92 | 0 | 0 | 36.5 | 22 | 20 | 20 | CC | 264,041 | 0.107 | 0.86 | 0.02 | 10,109 | 2,246 |
| **101** | **5** | **0** | **36.5** | **33** | **60** | **30** | **CC** | **264,995** | **0.106** | **0.94** | **0** | **4,276** | **614** |
| 102 | 20 | 2 | 36.5 | 0 | 60 | 30 | CC | 265,189 | 0.109 | 1 | 0.03 | 0 | 0 |
| 108 | 5 | 1 | 36.5 | 33 | 60 | 30 | LF | 265,918 | 0.106 | 0.95 | 0 | 3,791 | 586 |
| 115 | 0 | 0 | 36.5 | 22 | 60 | 50 | CC | 266,162 | 0.108 | 0.94 | 0.02 | 3,834 | 774 |

**Table 5-7 System report for 95% renewable fraction for Taba B**

| System architecture | |
|---|---|
| PV | 0 |
| Wind turbine | 1 HY5 kW |
| Hydro | 36.5 kW |
| Gen | 22 kW |
| Battery | 60 Surr6CS25P |
| Inverter | 30 kW |
| Rectifier | 30 kW |
| Disp. strategy | LF |

| Sensitivity case | |
|---|---|
| Design flow rate | 80 l/s |
| Stream flow rate | 1540 l/s |
| PV replacement cost multiplier | 0.8 |
| wind data | 3.1 m/s |
| PV capital cost multiplier | 0.8 |
| Solar data | 6.12 $kWh/m^2/d$ |

| Annual electric production ( kWh/yr) | | |
|---|---|---|
| PV array | 0 | 0 |
| Wind turbine | 3,978 | 2% |
| Hydro turbine | 244,864 | 93% |
| Gen | 13,586 | 5% |
| Excess electricity | 36,655 | 14% |
| Unmet load | 2895 | 1.4% |
| Capacity shortage | 4,395 | 2.1% |
| Renewable ratio | 0.95 | 95% |

| Annual electric consumption (kWh/yr) | | |
|---|---|---|
| AC primary load | 202,964 | 98% |
| Deferrable load | 3,632 | 2% |
| Total | 206,596 | 100% |

| Cost summary | |
|---|---|
| Total NPC | $247,569 |
| Levelized COE | $ 0.1/kWh |
| Operating cost | $ 7,950/yr |

| Emission (kg/yr) | |
|---|---|
| $CO_2$ | 9,100 |
| CO | 22.5 |
| Unburned hydrocarbon | 2.49 |
| Particulate matter | 1.69 |
| $SO_2$ | 18.3 |
| $NO_x$ | 200 |

**Table 5-8 Monthly Average electric production at Taba B (kW)**

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wind | 0.59186 | 0.59306 | 0.49882 | 0.41439 | 0.41426 | 0.64073 | 0.59302 | 0.37377 | 0.23126 | 0.23237 | 0.37358 | 0.50043 |
| Diesel generator | 4.1582 | 9.2618 | 3.1379 | 0.4064 | 0.2823 | 0.2567 | 0.207 | 0.3978 | 0.3422 | 0.2577 | 0.1711 | 0.3164 |
| Hydro | 20.164 | 11.246 | 23.654 | 31.019 | 31.019 | 31.019 | 31.019 | 31.019 | 31.019 | 31.019 | 31.019 | 31.019 |

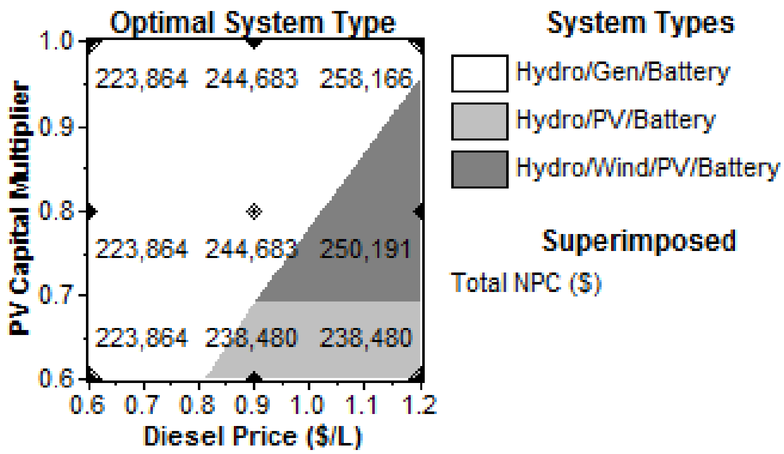


***Figure 5-2 Sensitivity result for diesel and PV module price variation at Taba B***

## 5.4. Results for Bechet Site

The results obtained are based on the current price of diesel ($0.9/l) and PV capital of $2400/kW. From Table (5-9 & 5-10), the levelized COE is observed to be in the range of $0.068/kWh to $0.072/kWh, which are within the range of global tariff and much lower than what a previously studied result showed. Both of LF and CC dispatch strategies are feasible. The renewable fraction ranges from 94% to 98%. The unmet load is limited to a maximum of 4%. There are no systems with 100% renewables. It can be seen from the two tables, that the hydro/diesel/battery system is the most cost effective which is followed by hydro/wind/diesel/battery, hydro/PV/diesel/battery and hydro/PV/wind/diesel/battery system types with increasing total NPC and COE (see Tables 5-9 & 5-10). Only these four system types are feasible.

The listed outputs of the overall optimization table (see Table 5-10) have little variation in the COE ($0.068/kWh to $0.072/kWh). The system ranked first has a renewable fraction of 97% and lowest COE ($0.068/kWh) but, with 4% unmet load. A system setup ranked 5$^{th}$ has a better renewable fraction of 97% and unmet load of 3% with same COE as the top ranked system. The system report for 5$^{th}$ ranked setup is summarised in Table 5-11. Also, the monthly electricity production of each component is given in Table 5-12.

Sensitivity analysis is also carried out and Figure 5-3 shows the variation of PV capital cost multiplier against diesel price. At lower price of diesel (<$1.01/l), hydro/diesel/battery system is cost effective and insensitive to to PV module price. When the diesel price is slightly increased, the system becomes sensitive to PV module price.

In this case, hydro/PV/diesel/battery and hydro/wind/diesel/battery systems become more favoured at lower and higher price of PV modules respectively.

**Table 5-9 Categorized optimization result for Bechet**

| Rank | PV (kW) | HY-5 | Hydro (kW) | Gen (kW) | S6CS25P | Converter (kW) | Dispatch strategy | Total NPC ($) | COE ($/kWh) | Renewable fraction | Unmet load fraction | Diesel (L/yr) | Gen (hrs/yr) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 109 | 26 | 80 | 50 | LF | 394,245 | 0.068 | 0.97 | 0.04 | 4,976 | 866 |
| 2 | 0 | 1 | 109 | 22 | 80 | 50 | CC | 395,523 | 0.068 | 0.98 | 0.04 | 4,514 | 881 |
| 3 | 5 | 0 | 109 | 22 | 80 | 50 | LF | 398,951 | 0.069 | 0.98 | 0.04 | 4,099 | 837 |
| 4 | 5 | 1 | 109 | 22 | 80 | 50 | LF | 403,900 | 0.069 | 0.98 | 0.04 | 3,995 | 815 |

**Table 5-10 Extracts from overall optimization results table for Bechet**

| Rank | PV (kW) | HY-5 kW | Hydro (kW) | Gen (kW) | S6CS25P | Converter (kW) | Dispatch strategy | Total NPC ($) | COE ($/kWh) | Renewable fraction | Unmet load fraction | Diesel (L/yr) | Gen (hrs/yr) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | **0** | **0** | **109** | **26** | **80** | **50** | **LF** | **394,245** | **0.068** | **0.97** | **0.04** | **4,976** | **866** |
| 2 | 0 | 1 | 109 | 22 | 80 | 50 | CC | 395,523 | 0.068 | 0.98 | 0.04 | 4,514 | 881 |
| 3 | 0 | 2 | 109 | 22 | 80 | 50 | LF | 397,149 | 0.068 | 0.98 | 0.04 | 4,127 | 840 |
| 4 | 5 | 0 | 109 | 22 | 80 | 50 | LF | 398,951 | 0.069 | 0.98 | 0.04 | 4,099 | 837 |
| **5** | **0** | **1** | **109** | **26** | **80** | **50** | **LF** | **399,133** | **0.068** | **0.97** | **0.03** | **4,856** | **844** |
| 15 | 0 | 1 | 109 | 26 | 80 | 50 | CC | 403,767 | 0.069 | 0.97 | 0.03 | 5,230 | 877 |
| 16 | 5 | 1 | 109 | 22 | 80 | 50 | LF | 403,900 | 0.069 | 0.98 | 0.04 | 3,995 | 815 |
| 49 | 5 | 0 | 109 | 26 | 60 | 40 | CC | 410,403 | 0.07 | 0.96 | 0.04 | 7,743 | 1,361 |
| 50 | 0 | 1 | 109 | 26 | 80 | 60 | CC | 410,602 | 0.07 | 0.97 | 0.03 | 4,975 | 821 |
| 81 | 0 | 0 | 109 | 35 | 60 | 40 | LF | 414,256 | 0.071 | 0.95 | 0.03 | 9,574 | 1,321 |
| 121 | 5 | 3 | 109 | 26 | 60 | 50 | LF | 417,569 | 0.071 | 0.97 | 0.03 | 5,782 | 1,031 |
| 122 | 0 | 2 | 109 | 22 | 100 | 50 | LF | 417,927 | 0.072 | 0.98 | 0.03 | 3,731 | 769 |
| 150 | 10 | 1 | 109 | 26 | 60 | 40 | LF | 420,163 | 0.072 | 0.97 | 0.03 | 6,807 | 1,256 |

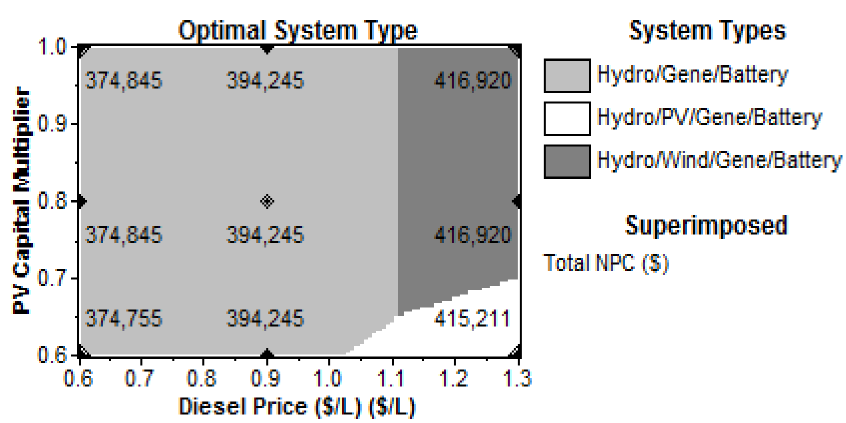


***Figure 5-3 Sensitivity result for diesel and PV module price variation at Bechet***

**Table 5-11: System report for 97.4% renewable fraction for Bechet**

| System architecture | |
|---|---|
| PV | 0 |
| Wind turbine | 1 HY5 kW |
| Hydro | 109 kW |
| Gen | 26 kW |
| Battery | 80 Surr6CS25P |
| Inverter | 50 kW |
| Rectifier | 50 kW |
| Disp. strategy | LF |

| Sensitivity case | |
|---|---|
| Design flow rate | 200 l/s |
| Stream flow rate | 3172 l/s |
| PV replacement cost multiplier | 0.8 |
| wind data | 3.1 m/s |
| PV capital cost multiplier | 0.8 |
| Solar data | 6.12 kWh/m$^2$/d |

| Annual electric production ( kWh/yr) | | |
|---|---|---|
| PV array | 0 | 0 |
| Wind turbine | 3,978 | 0.5% |
| Hydro turbine | 720,110 | 96.9% |
| Gen | 19,204 | 2.6% |
| Excess electricity | 228,135 | 30.7% |
| Unmet load | 17,095 | 3.4% |
| Capacity shortage | 22,874 | 4.5% |
| Renewable ratio | 0.974 | 97.4% |

| Annual electric consumption (kWh/yr) | | |
|---|---|---|
| AC primary load | 478,574 | 98% |
| Deferrable load | 8,750 | 2% |
| Total | 487,324 | 100% |

| Cost summary | |
|---|---|
| Total NPC | $399,133 |
| Levelized COE | $ 0.068/kWh |
| Operating cost | $ 8,837/yr |

| Emission (kg/yr) | |
|---|---|
| $CO_2$ | 12,787 |
| CO | 31.6 |
| Unburned hydrocarbons | 3.5 |
| Particulate matter | 2.38 |
| $SO_2$ | 25.7 |
| $NO_x$ | 282 |

**Table 5-12 Monthly Average electric production for Bechet (kW)**

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wind | 0.59186 | 0.59306 | 0.49882 | 0.41439 | 0.41426 | 0.64073 | 0.59302 | 0.37377 | 0.23126 | 0.23237 | 0.37358 | 0.50043 |
| Diesel generator | 6.404 | 10.786 | 5.863 | 0.536 | 0.388 | 0.43 | 0.342 | 0.657 | 0.46 | 0.319 | 0.278 | 0.447 |
| Hydro | 53.688 | 32.861 | 63.407 | 92.558 | 92.558 | 92.558 | 92.558 | 92.558 | 92.558 | 92.558 | 92.558 | 92.558 |

### 5.5. Results for Suha site

The results obtained are based on the current price of diesel ($0.9/l) and PV capital of $2400/kW. From Table (5-13 & 5-14), the levelized COE is observed to be in the range of $0.106/kWh to $0.157/kWh, which are within the range of global tariff and much lower than what a previously studied result showed. Both of LF and CC dispatch strategies are feasible. The renewable fraction ranges from 77% to 95%. The unmet load is limited to a maximum of 4%. The hydro/wind/diesel/battery system type is most economical which is followed by hydro/PV/wind/diesel/battery and hydro/PV/diesel/battery systems with increasing total NPC (see Tables 5-13 & 5-14). The listed outputs of the overall optimization table (see Table 5-14) have little variation in the COE ($0.106/kWh to $0.109/kWh).

**Table 5-13 Categorized optimization result for Suha**

| Rank | PV (kW) | HY-5 turbine | Hydro (kW) | Gen (kW) | S6CS25P | Converter (kW) | Dispatch strategy | Total NPC ($) | COE ($/kWh) | Renewable fraction | Unmet load fraction | Diesel (L/yr) | Gen (hrs/yr) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 6 | 81 | 35 | 100 | 60 | LF | 558,597 | 0.106 | 0.95 | 0.04 | 10,684 | 1,038 |
| 2 | 5 | 4 | 81 | 35 | 100 | 60 | LF | 559,534 | 0.106 | 0.95 | 0.04 | 10,538 | 1,025 |
| 3 | 15 | 0 | 81 | 35 | 100 | 60 | LF | 562,189 | 0.107 | 0.95 | 0.04 | 10,336 | 1,008 |
| 4 | 0 | 0 | 81 | 44 | 100 | 60 | LF | 566,447 | 0.107 | 0.92 | 0.03 | 14,928 | 1,173 |
| 5 | 0 | 0 | 81.2 | 53 | 0 | 0 | LF | 830,311 | 0.156 | 0.77 | 0.02 | 54,923 | 3,804 |
| 6 | 0 | 1 | 81.2 | 53 | 0 | 0 | LF | 831,738 | 0.156 | 0.78 | 0.02 | 54,458 | 3,778 |
| 7 | 10 | 0 | 81.2 | 53 | 0 | 10 | LF | 833,835 | 0.156 | 0.79 | 0.02 | 51,746 | 3,586 |
| 8 | 10 | 1 | 81.2 | 53 | 0 | 10 | LF | 836,613 | 0.157 | 0.79 | 0.02 | 51,401 | 3,568 |

**Table 5-14 Extracts from overall optimization results table for Suha**

| Rank | PV (kW) | HY-5 kW | Hydro (kW) | Gen (kW) | S6CS25P | Converter (kW) | Dispatch strategy | Total NPC ($) | COE ($/kWh) | Renewable fraction | Unmet load fraction | Diesel (L/yr) | Gen (hrs/yr) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | **0** | **6** | **81.2** | **35** | **100** | **60** | **LF** | **558,597** | **0.106** | **0.95** | **0.04** | **10,684** | **1,038** |
| 2 | 5 | 4 | 81.2 | 35 | 100 | 60 | LF | 559,534 | 0.106 | 0.95 | 0.04 | 10,538 | 1,025 |
| 9 | 5 | 2 | 81.2 | 35 | 120 | 60 | LF | 562,334 | 0.107 | 0.95 | 0.04 | 9,772 | 941 |
| **10** | **5** | **5** | **81.2** | **35** | **100** | **60** | **LF** | **562,584** | **0.107** | **0.95** | **0.03** | **10,231** | **996** |
| 11 | 0 | 7 | 81.2 | 35 | 100 | 60 | LF | 562,682 | 0.107 | 0.95 | 0.03 | 10,476 | 1,019 |
| 42 | 15 | 3 | 81.2 | 33 | 100 | 60 | LF | 567,106 | 0.108 | 0.96 | 0.04 | 9,039 | 935 |
| 43 | 10 | 1 | 81.2 | 35 | 120 | 60 | LF | 567,141 | 0.108 | 0.95 | 0.04 | 9,452 | 916 |
| 101 | 5 | 0 | 81.2 | 44 | 100 | 60 | LF | 571,293 | 0.108 | 0.93 | 0.03 | 13,987 | 1,100 |
| 116 | 0 | 0 | 81.2 | 44 | 100 | 60 | CC | 572,301 | 0.108 | 0.92 | 0.03 | 15,389 | 1,160 |

**Table 5-15 System report for 95% renewable fraction for Suha**

| System architecture | |
|---|---|
| PV | 5 kW |
| Wind turbine | 5 HY-5 kW |
| Hydro | 81.2 kW |
| Gen | 35 kW |
| Battery | 100 Surr6CS25P |
| Inverter | 60 kW |
| Rectifier | 60 kW |
| Disp. strategy | LF |

| Sensitivity case | |
|---|---|
| Design flow rate | 120 l/s |
| Stream flow rate | 2928 l/s |
| PV replacement cost multiplier | 0.8 |
| wind data | 3.1 m/s |
| PV capital cost multiplier | 0.8 |
| Solar data | 6.12 kWh/m$^2$/d |

| Annual electric production ( kWh/yr) | | |
|---|---|---|
| PV array | 9,091 | 1.5% |
| Wind turbine | 19,889 | 3.4% |
| Hydro turbine | 528,782 | 90% |
| Gen | 29,770 | 5.1% |
| Excess electricity | 112,711 | 19.2% |
| Unmet load | 15,732 | 3% |
| Capacity shortage | 21,676 | 4.8% |
| Renewable ratio | 0.95 | 95% |

| Annual electric consumption (kWh/yr) | | |
|---|---|---|
| AC primary load | 432,124 | 98% |
| Deferrable load | 7,876 | 2% |
| Total | 440,000 | 100% |

| Cost summary | |
|---|---|
| Total NPC | $562,584 |
| Levelized COE | $ 0.107/kWh |
| Operating cost | $ 19,493/yr |

| Emission (kg/yr) | |
|---|---|
| $CO_2$ | 26,942 |
| CO | 66.5 |
| Unburned hydrocarbon | 7.37 |
| Particulate matter | 5.01 |
| $SO_2$ | 54.1 |
| $NO_x$ | 593 |

**Table 5-16 Monthly Average electric production from Suha (kW)**

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PV | 1.0757 | 1.1289 | 1.1195 | 1.0793 | 1.0321 | 0.9597 | 0.879 | 0.8399 | 1.0819 | 1.1207 | 1.0911 | 1.0571 |
| Wind | 2.9593 | 2.9653 | 2.4941 | 2.072 | 2.0713 | 3.2037 | 2.9651 | 1.8688 | 1.1563 | 1.1619 | 1.8679 | 2.5021 |
| Diesel generator | 6.499 | 14.305 | 12.687 | 0.997 | 0.84 | 0.774 | 0.742 | 1.036 | 1.137 | 0.799 | 0.699 | 1.002 |
| Hydro | 46.609 | 24.743 | 29.347 | 69.043 | 69.043 | 69.043 | 69.043 | 69.043 | 69.043 | 69.043 | 69.043 | 69.043 |

The system ranked first has a renewable fraction of 95% and a COE of $0.106/kWh but, with 4% unmet load. A system setup ranked 10$^{th}$ has a better renewable fraction of 95% and unmet load of 3% for an additional COE of $0.001/kWh over the top ranked system. The system report for this 10$^{th}$ ranked setup is summarised in Table 5-15. Also, the monthly electricity production of each component is given in Table 5-16.

Sensitivity analysis is also carried out and Figure 5-4 shows the variation of PV capital cost multiplier against diesel price. At lower price of diesel (< $0.65/l), hydro/diesel/battery system is cost effective and insensitive to PV module price. When the diesel price is slightly increased, the system becomes sensitive to PV module price. In this case, hydro/PV/diesel/battery, hydro/wind/PV/diesel/battery and hydro/wind/diesel/battery systems become more favoured as PV modules cost multipliers increases from 0.6 to 1 as shown in the figure.

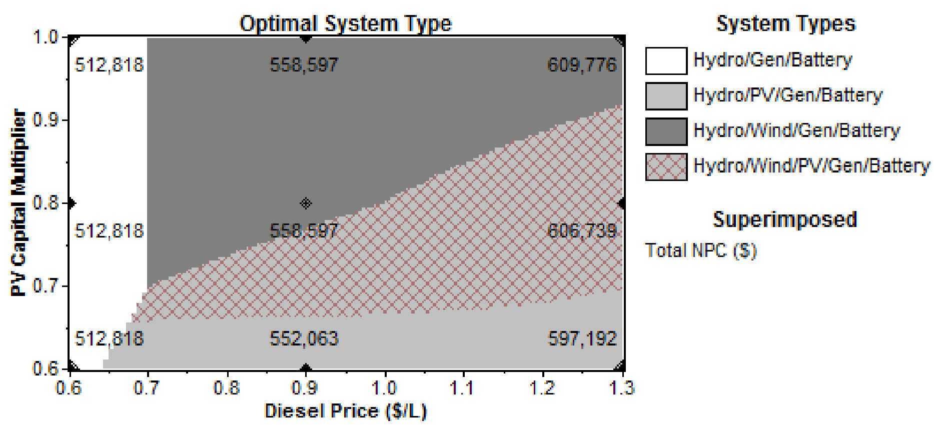


***Figure 5-4 Sensitivity results for diesel and PV module price variation at Suha***

### 5.6. Results for Muga I site

The results obtained are based on the current price of diesel ($0.9/l) and PV capital of $2400/kW. From Table (5-17 & 5-18), the levelized COE is observed to be in the range of $0.11/kWh to $0.143/kWh, which are within the range of global tariff and much lower than what a previously studied result showed. LF dispatch strategy is more dominant over CC dispatch strategies. The renewable fraction ranges from 69% to 93%. The unmet load is limited to a maximum of 4%. The hydro/PV/wind/diesel/battery system type is most economical which is followed by hydro/PV/diesel/battery and hydro/wind/diesel/battery systems with increasing total NPC (see Table 17 & 18).

The listed outputs of the overall optimization table (see Table 5-18) have little variation in the COE ($0.11/kWh to $0.111/kWh). The system ranked first has COE of $0.11/kWh and 3% unmet load but, a renewable fraction of 88%. A system setup ranked 13th has a better renewable fraction of 93% and unmet load of 3% for additional COE of $0.001/kWh over the top ranked system. The system report for this 13th ranked setup is summarised in Table 5-19. Also, the monthly electricity production of each component is given in Table 5-20.

**Table 5-17 Categorized optimization result for Muga I**

| Rank | PV (kW) | HY-5 | Hydro (kW) | Gen (kW) | S6CS25P | Converter (kW) | Dispatch strategy | Total NPC ($) | COE ($/kWh) | Renewable fraction | Unmet load fraction | Diesel (L/yr) | Gen (hrs/yr) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 20 | 2 | 193 | 132 | 320 | 190 | LF | 1,681,425 | 0.11 | 0.88 | 0.03 | 46,459 | 1,668 |
| 2 | 30 | 0 | 193 | 132 | 320 | 190 | LF | 1,683,941 | 0.11 | 0.88 | 0.03 | 45,136 | 1,624 |
| 3 | 0 | 10 | 193 | 132 | 320 | 180 | LF | 1,687,587 | 0.11 | 0.87 | 0.03 | 48,539 | 1,768 |
| 4 | 0 | 0 | 193 | 154 | 320 | 180 | LF | 1,731,378 | 0.112 | 0.85 | 0.02 | 58,071 | 1,850 |
| 5 | 0 | 0 | 193 | 173 | 0 | 0 | LF | 2,128,687 | 0.138 | 0.69 | 0.02 | 143,446 | 4,085 |
| 6 | 0 | 2 | 193 | 173 | 0 | 0 | LF | 2,138,062 | 0.138 | 0.69 | 0.02 | 143,111 | 4,084 |
| 7 | 10 | 0 | 193 | 173 | 0 | 50 | LF | 2,203,157 | 0.142 | 0.7 | 0.02 | 142,799 | 4,078 |
| 8 | 10 | 2 | 193 | 173 | 0 | 50 | LF | 2,212,636 | 0.143 | 0.7 | 0.02 | 142,473 | 4,077 |

**Table 5-18 Extracts from overall optimization results table for Muga I**

| Rank | PV (kW) | HY-5 kW | Hydro (kW) | Gen (kW) | S6CS25P | Converter (kW) | Dispatch strategy | Total NPC ($) | COE ($/kWh) | Renewable fraction | Unmet load fraction | Diesel (L) | Gen (hrs) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | **20** | **2** | **193** | **132** | **320** | **190** | **LF** | **1,681,425** | **0.11** | **0.88** | **0.03** | **46,459** | **1,668** |
| 2 | 20 | 2 | 193 | 132 | 320 | 180 | LF | 1,682,372 | 0.11 | 0.88 | 0.03 | 47,482 | 1,728 |
| 3 | 30 | 0 | 193 | 132 | 320 | 190 | LF | 1,683,941 | 0.11 | 0.88 | 0.03 | 45,136 | 1,624 |
| 4 | 20 | 2 | 193 | 132 | 360 | 200 | LF | 1,684,171 | 0.11 | 0.89 | 0.03 | 41,478 | 1,463 |
| 12 | 10 | 6 | 193 | 132 | 360 | 190 | LF | 1,686,862 | 0.11 | 0.89 | 0.03 | 42,902 | 1,531 |
| **13** | **40** | **16** | **193** | **114** | **360** | **200** | **LF** | **1,687,001** | **0.111** | **0.93** | **0.03** | **28,731** | **1,165** |
| 14 | 10 | 8 | 193 | 132 | 320 | 180 | LF | 1,687,056 | 0.11 | 0.88 | 0.03 | 47,057 | 1,716 |
| 15 | 20 | 2 | 193 | 132 | 320 | 200 | LF | 1,687,351 | 0.11 | 0.88 | 0.03 | 45,970 | 1,640 |
| 16 | 0 | 10 | 193 | 132 | 320 | 180 | LF | 1,687,587 | 0.11 | 0.87 | 0.03 | 48,539 | 1,768 |
| 62 | 10 | 8 | 193 | 132 | 280 | 170 | LF | 1,693,791 | 0.111 | 0.86 | 0.03 | 52,791 | 1,959 |
| 63 | 20 | 4 | 193 | 132 | 280 | 190 | LF | 1,693,890 | 0.111 | 0.87 | 0.03 | 50,182 | 1,819 |
| 64 | 10 | 10 | 193 | 132 | 280 | 180 | LF | 1,693,923 | 0.111 | 0.87 | 0.03 | 50,393 | 1,843 |
| 125 | 20 | 4 | 193 | 132 | 320 | 210 | LF | 1,697,598 | 0.111 | 0.88 | 0.03 | 44,742 | 1,590 |

**Table 5-19 System report for 93% renewable fraction for Muga I**

| System architecture | |
|---|---|
| PV | 40 kW |
| Wind turbine | 16 HY5 kW |
| Hydro | 193 kW |
| Gen | 114 kW |
| Battery | 360 Surr6CS25P |
| Inverter | 200 kW |
| Rectifier | 200 kW |
| Disp. strategy | LF |

| Sensitivity case | |
|---|---|
| Design flow rate | 547 l/s |
| Stream flow rate | 7870 l/s |
| PV replacement cost multiplier | 0.8 |
| wind data | 3.1 m/s |
| PV capital cost multiplier | 0.8 |
| Solar data | 6.12 $kWh/m^2/d$ |

| Annual electric production ( kWh/yr) | | |
|---|---|---|
| PV array | 81,823 | 5.3% |
| Wind turbine | 63,646 | 4.2% |
| Hydro turbine | 1,269,464 | 83.1% |
| Gen | 113,367 | 7.4% |
| Excess electricity | 130,957 | 8.57% |
| Unmet load | 44,361 | 3.36% |
| Capacity shortage | 64,824 | 4.92% |
| Renewable ratio | 0.93 | 93% |

| Annual electric consumption (kWh/yr) | | |
|---|---|---|
| AC primary load | 1,251,390 | 98% |
| Deferrable load | 22,817 | 2% |
| Total | 1,274,207 | 100% |

| Cost summary | |
|---|---|
| Total NPC | $1,687,001 |
| Levelized COE | $ 0.111/kWh |
| Operating cost | $ 56,726/yr |

| Emission (kg/yr) | |
|---|---|
| $CO_2$ | 75,658 |
| CO | 187 |
| Unburned hydrocarbon | 20.7 |
| Particulate matter | 14.1 |
| $SO_2$ | 152 |
| $NO_x$ | 1,666 |

**Table 5-20 Monthly average electric production from Muga I (kW)**

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PV | 9.681 | 10.161 | 10.076 | 9.714 | 9.289 | 8.637 | 7.911 | 7.559 | 9.737 | 10.086 | 9.82 | 9.514 |
| Wind | 9.47 | 9.489 | 7.981 | 6.63 | 6.628 | 10.252 | 9.488 | 5.98 | 3.7 | 3.718 | 5.977 | 8.007 |
| Diesel generator | 30.486 | 48.454 | 27.681 | 6.324 | 5.364 | 4.729 | 4.931 | 6.127 | 7.582 | 5.174 | 5.161 | 5.82 |
| Hydro | 90.98 | 57.65 | 106.59 | 164.2 | 164.2 | 164.2 | 164.2 | 164.2 | 164.2 | 164.2 | 164.2 | 164.2 |

Sensitivity analysis is also carried out and Figure 5-5 shows the variation of PV capital cost multiplier against diesel price. At lower diesel price (< $0.625/l), hydro/diesel/battery system is cost effective and insensitive to PV module price. When the diesel price is slightly increased ($0.625/l to $0.8/l), hydro/PV/diesel/battery and hydro/wind/diesel/battery are more cost effective at lower and higher PV module prices, respectively. When the diesel price is increased more (>$0.8/l), hydro/PV/diesel/battery and hydro/wind/PV/diesel/battery systems become more favoured with lower and higher PV modules cost multipliers, respectively.

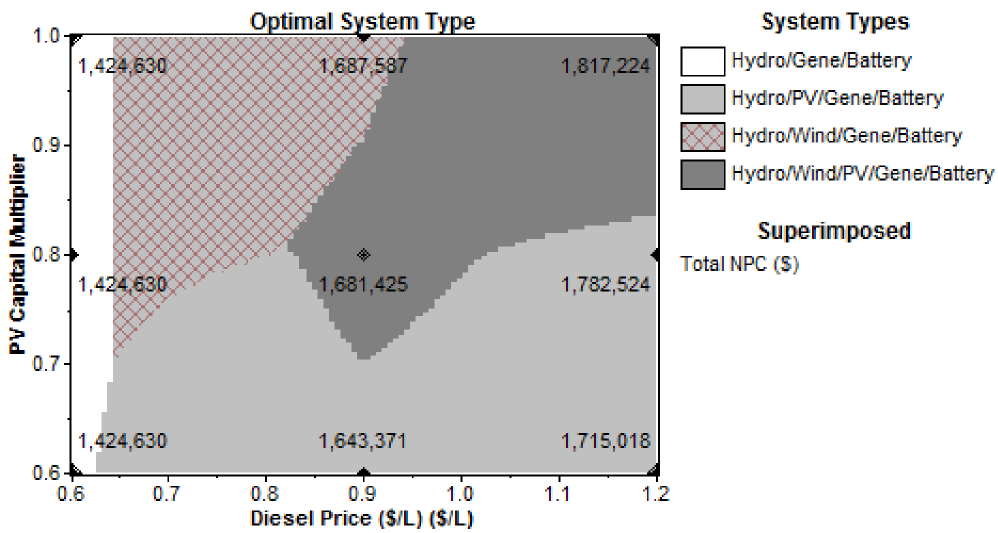


***Figure 5-5 Sensitivity result for diesel and PV module price variation at Muga I***

### 5.7. Results for Muga II site

The results obtained are based on the current price of diesel ($0.9/l) and PV capital of $2400/kW. From Table (5-21 & 5-22), the levelized COE is observed to be in the range of $0.088/kWh to $0.118/kWh, which are within the range of global tariff and much lower than what a previously studied result showed. LF dispatch strategy is more dominant over CC dispatch strategies. The renewable fraction ranges from 83% to 92%. The unmet load is limited to a maximum of 4%. The hydro/diesel/battery system type is most economical which is followed by hydro/wind/diesel/battery system and hydro/PV/diesel/battery system types with increasing total NPC ( Tables 5-21 & 5-22).

The listed outputs of the overall optimization table (see Table 5-22) have little variation in the COE ($0.088/kWh to $0.889/kWh). The system ranked first has COE of

$0.11/kWh and 4% unmet load but, a renewable fraction of 88%. System configurations ranked 37th, 45th, 48th and 50th have a better renewable fraction of 92% and same unmet load of 4% for additional COE of $0.001/kWh over the top ranked system. The 50th ranked system is more preferable for its less consumption of diesel (see Table 5-22). The system report for this 50th ranked setup is summarised in Table 5-23. Also, the monthly electricity production of each component is given in Table 5-24.

Sensitivity analysis is also carried out and Figure 5-6 shows the variation of PV capital cost multiplier against diesel price. At lower diesel price (< $0.78/l), hydro/diesel/battery system is cost effective and insensitive to to PV module price. When the diesel price is slightly increased (> $0.78/l), the system becomes sensitive to price of PV module. In this case, hydro/PV/diesel/battery systems are more favoured at lower PV module price, whereas, hydro/diesel/battery systems are still more economical at higher price of PV module.

**Table 5-21 Categorized optimization result for Muga II**

| Rank | PV (kW) | HY-5 turbine | Hydro (kW) | Gen (kW) | S6CS25P | Converter (kW) | Dispatch strategy | Total NPC ($) | COE ($/kWh) | Renewable fraction | Unmet load fraction | Diesel (L/yr) | Gen (hrs/yr) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 831 | 382 | 320 | 280 | LF | 3,529,068 | 0.088 | 0.91 | 0.04 | 120,634 | 1,474 |
| 2 | 0 | 1 | 831 | 382 | 320 | 280 | LF | 3,530,627 | 0.088 | 0.91 | 0.04 | 120,195 | 1,468 |
| 3 | 5 | 0 | 831 | 382 | 320 | 280 | LF | 3,530,666 | 0.088 | 0.91 | 0.04 | 119,470 | 1,458 |
| 4 | 5 | 1 | 831 | 382 | 320 | 280 | LF | 3,536,484 | 0.088 | 0.91 | 0.04 | 119,401 | 1,458 |
| 5 | 35 | 3 | 831 | 396 | 0 | 50 | LF | 4,715,947 | 0.118 | 0.83 | 0.04 | 266,318 | 3,419 |

**Table 5-22 Extracts from overall optimization results table for Muga II**

| Rank | PV (kW) | HY-5 kW | Hydro (kW) | Gen (kW) | S6CS25P | Converter (kW) | Dispatch strategy | Total NPC ($) | COE ($/kWh) | Renewable fraction | Unmet load fraction | Diesel (L/yr) | Gen (hrs/yr) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | **0** | **0** | **831** | **382** | **320** | **280** | **LF** | **3,529,068** | **0.088** | **0.91** | **0.04** | **120,634** | **1,474** |
| 2 | 0 | 0 | 831 | 382 | 320 | 270 | LF | 3,529,095 | 0.088 | 0.91 | 0.04 | 121,433 | 1,486 |
| 3 | 0 | 1 | 831 | 382 | 320 | 280 | LF | 3,530,627 | 0.088 | 0.91 | 0.04 | 120,195 | 1,468 |
| 4 | 5 | 0 | 831 | 382 | 320 | 280 | LF | 3,530,666 | 0.088 | 0.91 | 0.04 | 119,470 | 1,458 |
| **37** | **0** | **0** | **831** | **382** | **360** | **300** | **LF** | **3,542,416** | **0.089** | **0.91** | **0.04** | **115,737** | **1,404** |
| **45** | **5** | **0** | **831** | **382** | **360** | **290** | **LF** | **3,544,730** | **0.089** | **0.92** | **0.04** | **115,434** | **1,399** |
| 44 | 0 | 1 | 831 | 382 | 320 | 250 | LF | 3,544,368 | 0.089 | 0.91 | 0.04 | 123,780 | 1,522 |
| **48** | **5** | **0** | **831** | **382** | **360** | **300** | **LF** | **3,545,192** | **0.089** | **0.92** | **0.04** | **114,677** | **1,388** |
| **50** | **5** | **0** | **831** | **382** | **360** | **310** | **LF** | **3,545,245** | **0.089** | **0.92** | **0.04** | **113,883** | **1,377** |
| 89 | 0 | 2 | 831 | 382 | 360 | 300 | LF | 3,551,280 | 0.089 | 0.92 | 0.04 | 115,360 | 1,399 |
| 90 | 0 | 2 | 831 | 382 | 360 | 310 | LF | 3,551,376 | 0.089 | 0.92 | 0.04 | 114,570 | 1,388 |

**Table 5-23 System report for 92% renewable fraction for Muga II**

| System architecture | |
|---|---|
| PV | 5 kW |
| Wind turbine | 0 |
| Hydro | 831 kW |
| Gen | 382 kW |
| Battery | 360 Surr6CS25P |
| Inverter | 310 kW |
| Rectifier | 310 kW |
| Disp. strategy | LF |

| Sensitivity case | |
|---|---|
| Design flow rate | 1000 l/s |
| Stream flow rate | 9221 l/s |
| PV replacement cost multiplier | 0.8 |
| wind data | 3.1 m/s |
| PV capital cost multiplier | 0.8 |
| Solar data | 6.12 $kWh/m^2/d$ |

| Annual electric production ( kWh/yr) | | |
|---|---|---|
| PV array | 9,091 | 0.2% |
| Wind turbine | 0 | 0 |
| Hydro turbine | 4,900,787 | 92.4% |
| Gen | 449,410 | 7.4% |
| Excess electricity | 130,957 | 8.57% |
| Unmet load | 44,361 | 3.36% |
| Capacity shortage | 64,824 | 4.92% |
| Renewable ratio | 0.916 | 92% |

| Annual electric consumption (kWh/yr) | | |
|---|---|---|
| AC primary load | 3,238,472 | 97% |
| Deferrable load | 103,261 | 3% |
| Total | 3,341,733 | 100% |

| Cost summary | |
|---|---|
| Total NPC | $3,545,245 |
| Levelized COE | $ 0.089/kWh |
| Operating cost | $ 157,332/yr |

| Emission (kg/yr) | |
|---|---|
| $CO_2$ | 299,892 |
| CO | 740 |
| Unburned hydro-carbon | 82 |
| Particulate matter | 55.8 |
| $SO_2$ | 602 |
| $NO_x$ | 6,605 |

**Table 5-24 Monthly Average electric production from Muga II (kW)**

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PV | 1.2101 | 1.2701 | 1.2594 | 1.2142 | 1.1611 | 1.0796 | 0.9889 | 0.9448 | 1.2171 | 1.2608 | 1.2275 | 1.1892 |
| Diesel generator | 138.64 | 288.63 | 126.71 | 2.6 | 60.38 | 3.34 | 1.44 | 4.67 | 1.49 | 1.08 | 1.11 | 2.16 |
| Hydro | 251.57 | 0 | 295.38 | 706.69 | 477.7 | 706.69 | 706.69 | 706.69 | 706.69 | 706.69 | 706.69 | 706.69 |

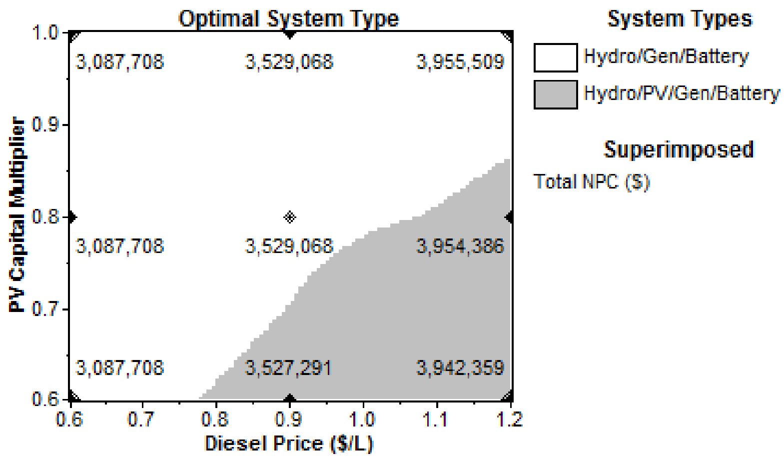


***Figure 5-6 Sensitivity result for diesel and PV module price variation at Muga II***

## 5.8. Overall System Results

Although the modular approach is considered due to the limitation of HOMER software, the results of each site can be combined for the total system. As all optimization results of each site have COE close to the lower boundary of international energy tariff and much lower than previously studied solar/PV/diesel systems, the overall system can be any combination of these feasible system configurations. Here, the combination of the system configurations whose system report is discussed in the previous section is presented.

Component size and electricity production total NPC and annualized costs are the sum of the individual systems. Excess electricity, capacity shortage, unmet load and emission of the overall system is calculated by adding corresponding values of each system. The renewable fraction of the system is calculated by adding non-diesel generation and taking the ratio to the total electricity production. The load supplied can be taken directly from load estimation (section 4.4.) with additional 5% hourly and daily noise or by adding the load supplied at each system report. COE of the system is calculated as the ratio of its annualized capital cost to its total annualized electricity consumption. Table 5-25 summarizes the results of these calculations. The excess electricity, unmet load and capacity shortage are calculated by assuming shortage and excess of electricity occur on the individual sites at the same time. But, there are possibilities of excess electricity in one site while there is shortage on another site. So the values indicated in the table are the possible maximum.

**Table 5-25 Sample overall system report**

| System architecture | |
|---|---|
| PV | 55 kW |
| Wind turbine | 24 HY turbine |
| Hydro | 1280.4 kW |
| Gen | 601 kW |
| Battery | 1000 Surr6CS25P |
| Inverter | 675 kW |
| Rectifier | 310 kW |
| Disp. strategy | LF |

| Annual electric production ( kWh/yr) | | |
|---|---|---|
| PV array | 110,233 | 1.30% |
| Wind turbine | 95469 | 1.10% |
| Hydro turbine | 7,215,368 | 90.30% |
| Gen | 636,108 | 7.30% |
| Excess electricity | 680406 | 7.80% |
| Unmet load | 125,291 | 1.4% |
| Capacity shortage | 180,162 | 2.1% |
| Renewable ratio | 92.7 | 93% |

| Annual electric consumption (kWh/yr) | | |
|---|---|---|
| AC primary load | 5766461 | 97.5% |
| Deferrable load | 149231 | 2.5% |
| Total | 5915152 | 100% |

| Cost summary | |
|---|---|
| Total NPC | $6577192 |
| Levelized COE | $0.094/kWh |
| Operating cost | $257537/kWh |

| Emission (kg/yr) | |
|---|---|
| $CO_2$ | 434348 |
| CO | 1072.2 |
| Unburned hydro-carbon | 118.79 |
| Particulate matter | 80.84 |
| $SO_2$ | 872.1 |
| $NO_x$ | 9566 |

**Table 5-26 Monthly Average electric production from overall system (kW)**

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PV | 13.0425 | 13.6889 | 13.5744 | 13.0868 | 12.5143 | 11.636 | 10.6579 | 10.1836 | 13.1179 | 13.5882 | 13.2297 | 12.8174 |
| Wind | 14.1182 | 14.1459 | 11.8954 | 9.87902 | 9.87582 | 15.2854 | 14.1446 | 8.90907 | 5.50908 | 5.53596 | 8.90466 | 11.9336 |
| Diesel | 189.292 | 379.331 | 178.307 | 11.1628 | 67.482 | 9.7864 | 7.8276 | 13.1776 | 11.2893 | 7.7953 | 7.5047 | 10.0214 |
| Hydro | 479.435 | 135.66 | 537.645 | 1088.78 | 859.786 | 1088.78 | 1088.78 | 1088.78 | 1088.78 | 1088.78 | 1088.78 | 1088.78 |
| Total | 695.888 | 542.825 | 741.421 | 1122.9 | 949.658 | 1125.48 | 1121.41 | 1121.05 | 1118.69 | 1115.7 | 1118.42 | 1123.55 |

The daily average system load (primary + deferrable load with 5 % daily and hourly noise) on the system is 16361 kWh/day + 289 kWh/day which equals to 16.65 MWh/day. This gives an annual electricity demand of 6.1 GWh/yr and equals to annual average of 694 kW. The consumption indicated in the table is about 5.92 GWh/yr which indicates as there is unmet load (1.4%). On the other hand, the total production from hydro, wind, PV and diesel gives 8.06 GWh/yr which is an indication of excess electricity (7.8%). This indicates that there is still a mismatch between maximum demand and the maximum production which is not handled through storage system from economic point of view. The monthly averaged electric production ranges from 542 kW to 1125.5 kW as shown in Table 5-26 and Figure 5-7. It shows that there is maximum production from diesel on February where there is scarce stream flow. It can be seen from Figure 5-7 that there is some sort of complementariness between the hydro, wind and solar resources throughout the year.

Sensitivity analysis of the overall system can be predicted from the results of individual site. It can be seen that hydro/diesel/battery are more economical at lower diesel price and are not sensitive to PV module prices. When diesel price increases slightly, hydro/PV/diesel/battery and hydro/wind/diesel/battery systems become more favoured at lower and higher PV module price, respectively. When diesel price is increased more, hydro/PV/wind/diesel/battery systems become more economical.

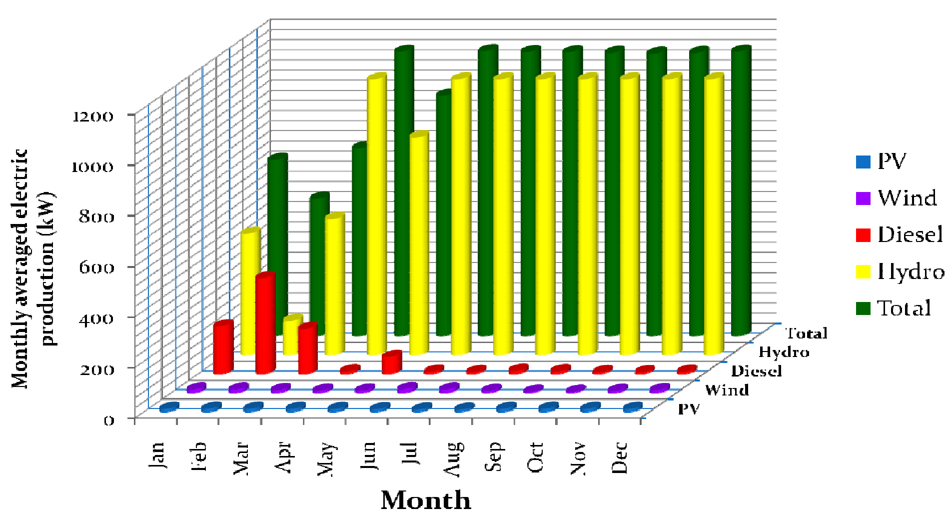


*Figure 5-7 Averaged monthly electricity production of sample overall system*

# CHAPTER 6

# 6. Conclusions, Recommendations and Suggestions for Future Work

## 6.1. Conclusions

In this thesis, feasibility study of small hydro/PV/wind hybrid system for electrification of 10,500 families in Dejen district is carried out. Six hydropower sites, wind resource and solar potentials in the district are analysed. HOMER is used for optimization and sensitivity analysis of the proposed hybrid system.

GIS based empirical estimation is used for flow rate determination of the six sites. Accordingly, the annual average flow rate is found to be 1540 l/s at Taba A and Taba B sites, 3172 l/s at Bechet site, 2928 l/s at Suha site, 7870 l/s at Muga I site and 9221 l/s at Muga II site. Head measurement of each site is done directly from field survey and 50.5 m, 62 m, 74 m, 92.5 m, 47 m and 113 m heads are found at Taba A, Taba B, Bechet, Suha, Muga I and Muga II sites, respectively. Their design flow rate is optimized from hybrid system point of view and is found to be 80 l/s, 80 l/s, 200 l/s, 120 l/s, 547 l/s, 1000 l/s respectively. Based on the flow rate determined, their hydropower potential are found to be 29.7 kW (Taba A), 36.5 kW (Taba B), 109 kW (Bechet), 81.2 kW (Suha), 193 kW (Muga I), and 831 kW (Muga II).

Monthly average wind speed data from NASA is used to synthesize hourly wind speed data using HOMER. The Weibull parameters k and c are determined (k=1.95 and c=3.47 m/s). Solar radiation is calculated from daily sunshine hour data using empirical formulas and is 6.13 kWh/m$^2$/day. This result is very close to what is obtained in the previous study [7], and also, to NASA and SWERA predictions.

Hourly electric load of the community consisting of lighting, TV set, radio receiver, stove, health post, clinic, water pumps and flour mills is determined. The total community (about 10,500 families) is estimated to have a primary peak demand of 1424 kW, a deferrable peak demand of 52.25 kW and a storage capacity of 1248 kWh. This load is shared to each site roughly based on their potential as 2.35% (Taba A) 3.45% (Taba B). 8.3% (Bechet), 7.5% (Suha), 21.7% (Muga I) and 56.3 %, (Muga II).

For each site, different optimum and feasible system configurations with different level of renewable fraction and total NPC are obtained. The levelized COE ranges from $0.068/kWh to $0.156/kWh. This cost is slightly higher than the current energy tariff within the country (< $0.04/kWh), but, is much less than previously studied PV/Wind based hybrid system (which does not include hydro). It can be said that the maximum COE determined here is at the lower range of global electricity tariff.

Taking the current diesel price of $0.9/l and a PV capital and replacement cost of $2400/kW, different system configurations/types are found as feasible options for each site. One feasible system from each site can be taken to makeup the overall system capable of supplying the whole community (63000 people). For the overall system, hydro/diesel/battery are more cost economical at lower diesel price and are not sensitive to PV module prices. When diesel price increases slightly, hydro/PV/diesel/battery and hydro/wind/diesel/battery systems become more favoured at lower and higher PV module price, respectively. When diesel price is increased more, hydro/PV/wind/diesel/battery systems become more economical.

One sample overall system shows a COE of $0.09/kWh and a renewable fraction of 93%. In this system an excess electricity of 7.8% and unmet load of 1.4% have been found. Although the proposed system has a relatively higher COE than the national tariff, in view of the energy shortage at the national level, resistance to deforestation, clean energy development, changing the life of the poor in remote regions and expansion of power generation it is a highly recommendable solution.

The hydropower system suggested is a run-off type and doesn't require extensive civil work. The head is naturally endowed. Consequently, all the civil structures and installation of electromechanical components are to be realized within a small area, which as a result wouldn't cause any significant social and environmental impacts.

This study, even though is specific for Dejen district, proves to be of high importance in its demonstrative character to the utilization of the resource potential of the country. Ethiopia has a lot of small hydropower potential. Due to the seasonal nature of these resources, wind and solar resources together with diesel generator and battery system as a backup can be used for better reliability of rural electrification.

## 6.2. Recommendations

The 2 m height installation and the calibration of wind speed measuring data logger at D/Markos should be cheeked as its data shows significant difference with what is previously studied (10 m height) and with that of NASA's prediction. Flow rate gauge stations are better installed at small rivers and their data should be updated. Solar radiation measuring equipments should be installed at selected towns, such as D/Markos.

In addition to what are covered in this thesis, there are potential sites suitable for storage based hydropower developments. There are also sites having much higher heads than what have been presented. Although these sites are close to what have been studied, accessing them is very difficult and may require more time and finance to study them in detail.

Currently, the national energy strategy is towards large hydropower, large wind farm and towards geothermal to some extent. Small hydropower developments and its hybrid combination with other sources such as wind and solar is not given attention. Such hybrid systems should be given attention as their capital investment is low and are convenient for rural electrification.

## 6.3. Suggestions for Future Work

This thesis work may be refined and expanded by considering

1. Exact measured flow rate, solar radiation, wind speed and residual flow rate data.
2. Possible demand growth rate with population and economic growth rate (load forecasting)
3. Solar thermal, biomass and storage based hydropower resources together with the possibility of grid extension
4. Detailed design of each component and steady state and dynamic performance of the overall system.

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# Appendix A

## Overall Optimization Results

**Table A-1 Overall optimization for Taba A**

| Rank | PV (kW) | HY-5 kW | Hydro (kW) | Gen (kW) | S6CS25P | Converter (kW) | Dispatch strategy | Total NPC ($) | COE ($/kWh) | Renewable fraction | Unmet load fraction | Diesel (L/yr) | Gen (hrs/yr) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 15 | 2 | 29.7 | 0 | 40 | 25 | CC | 209,921 | 0.109 | 1 | 0.04 | 0 | 0 |
| 2 | 15 | 2 | 29.7 | 0 | 40 | 25 | LF | 209,921 | 0.109 | 1 | 0.04 | 0 | 0 |
| 3 | 20 | 0 | 29.7 | 0 | 40 | 25 | CC | 212,348 | 0.11 | 1 | 0.04 | 0 | 0 |
| 4 | 20 | 0 | 29.7 | 0 | 40 | 25 | LF | 212,348 | 0.11 | 1 | 0.04 | 0 | 0 |
| 5 | 15 | 2 | 29.7 | 0 | 40 | 30 | CC | 214,518 | 0.111 | 1 | 0.04 | 0 | 0 |
| 6 | 15 | 2 | 29.7 | 0 | 40 | 30 | LF | 214,518 | 0.111 | 1 | 0.04 | 0 | 0 |
| 7 | 15 | 3 | 29.7 | 0 | 40 | 25 | CC | 216,259 | 0.112 | 1 | 0.04 | 0 | 0 |
| 8 | 15 | 3 | 29.7 | 0 | 40 | 25 | LF | 216,259 | 0.112 | 1 | 0.04 | 0 | 0 |
| 9 | 20 | 0 | 29.7 | 0 | 40 | 30 | CC | 216,945 | 0.113 | 1 | 0.04 | 0 | 0 |
| 10 | 20 | 0 | 29.7 | 0 | 40 | 30 | LF | 216,945 | 0.113 | 1 | 0.04 | 0 | 0 |
| 11 | 15 | 4 | 29.7 | 0 | 40 | 20 | CC | 218,272 | 0.113 | 1 | 0.03 | 0 | 0 |
| 12 | 15 | 4 | 29.7 | 0 | 40 | 20 | LF | 218,272 | 0.113 | 1 | 0.03 | 0 | 0 |
| 13 | 20 | 1 | 29.7 | 0 | 40 | 25 | CC | 218,557 | 0.113 | 1 | 0.04 | 0 | 0 |
| 14 | 20 | 1 | 29.7 | 0 | 40 | 25 | LF | 218,557 | 0.113 | 1 | 0.04 | 0 | 0 |
| 15 | 15 | 2 | 29.7 | 0 | 40 | 35 | CC | 219,114 | 0.114 | 1 | 0.04 | 0 | 0 |
| 16 | 15 | 2 | 29.7 | 0 | 40 | 35 | LF | 219,114 | 0.114 | 1 | 0.04 | 0 | 0 |
| 17 | 20 | 2 | 29.7 | 0 | 40 | 20 | CC | 220,121 | 0.114 | 1 | 0.03 | 0 | 0 |
| 18 | 20 | 2 | 29.7 | 0 | 40 | 20 | LF | 220,121 | 0.114 | 1 | 0.03 | 0 | 0 |
| 19 | 10 | 2 | 29.7 | 0 | 60 | 25 | CC | 220,351 | 0.115 | 1 | 0.04 | 0 | 0 |
| 20 | 10 | 2 | 29.7 | 0 | 60 | 25 | LF | 220,351 | 0.115 | 1 | 0.04 | 0 | 0 |
| 21 | 0 | 0 | 29.7 | 22 | 40 | 25 | LF | 220,357 | 0.111 | 0.93 | 0.01 | 5,129 | 839 |
| 22 | 15 | 3 | 29.7 | 0 | 40 | 30 | CC | 220,856 | 0.114 | 1 | 0.04 | 0 | 0 |
| 23 | 15 | 3 | 29.7 | 0 | 40 | 30 | LF | 220,856 | 0.114 | 1 | 0.04 | 0 | 0 |
| 24 | 20 | 0 | 29.7 | 0 | 40 | 35 | CC | 221,542 | 0.115 | 1 | 0.04 | 0 | 0 |
| 25 | 20 | 0 | 29.7 | 0 | 40 | 35 | LF | 221,542 | 0.115 | 1 | 0.04 | 0 | 0 |
| 26 | 0 | 1 | 29.7 | 22 | 40 | 25 | LF | 222,135 | 0.112 | 0.94 | 0.01 | 4,752 | 776 |
| 27 | 15 | 0 | 29.7 | 0 | 60 | 25 | CC | 222,142 | 0.115 | 1 | 0.04 | 0 | 0 |
| 28 | 15 | 0 | 29.7 | 0 | 60 | 25 | LF | 222,142 | 0.115 | 1 | 0.04 | 0 | 0 |
| 29 | 5 | 0 | 29.7 | 22 | 40 | 25 | LF | 222,638 | 0.112 | 0.95 | 0.01 | 4,051 | 663 |
| 30 | 25 | 0 | 29.7 | 0 | 40 | 20 | CC | 222,654 | 0.115 | 1 | 0.03 | 0 | 0 |
| 31 | 25 | 0 | 29.7 | 0 | 40 | 20 | LF | 222,654 | 0.115 | 1 | 0.03 | 0 | 0 |
| 32 | 15 | 4 | 29.7 | 0 | 40 | 25 | CC | 222,868 | 0.115 | 1 | 0.03 | 0 | 0 |
| 33 | 15 | 4 | 29.7 | 0 | 40 | 25 | LF | 222,868 | 0.115 | 1 | 0.03 | 0 | 0 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 34 | 0 | 0 | 29.7 | 22 | 40 | 25 | CC | 222,953 | 0.112 | 0.93 | 0.01 | 5,320 | 810 |
| 35 | 20 | 1 | 29.7 | 0 | 40 | 30 | CC | 223,154 | 0.116 | 1 | 0.04 | 0 | 0 |
| 36 | 20 | 1 | 29.7 | 0 | 40 | 30 | LF | 223,154 | 0.116 | 1 | 0.04 | 0 | 0 |
| 37 | 5 | 4 | 29.7 | 0 | 60 | 30 | CC | 223,157 | 0.116 | 1 | 0.04 | 0 | 0 |
| 38 | 5 | 4 | 29.7 | 0 | 60 | 30 | LF | 223,157 | 0.116 | 1 | 0.04 | 0 | 0 |
| 39 | 0 | 2 | 29.7 | 22 | 40 | 25 | LF | 224,112 | 0.113 | 0.94 | 0.01 | 4,380 | 718 |
| 40 | 0 | 1 | 29.7 | 22 | 40 | 25 | CC | 224,359 | 0.113 | 0.93 | 0.01 | 4,909 | 747 |
| 41 | 0 | 0 | 29.7 | 22 | 40 | 30 | LF | 224,657 | 0.113 | 0.93 | 0.01 | 5,102 | 829 |
| 42 | 20 | 2 | 29.7 | 0 | 40 | 25 | CC | 224,745 | 0.116 | 1 | 0.03 | 0 | 0 |
| 43 | 20 | 2 | 29.7 | 0 | 40 | 25 | LF | 224,745 | 0.116 | 1 | 0.03 | 0 | 0 |
| 44 | 5 | 0 | 29.7 | 22 | 40 | 25 | CC | 224,929 | 0.113 | 0.94 | 0.01 | 4,231 | 651 |
| 45 | 10 | 2 | 29.7 | 0 | 60 | 30 | CC | 224,947 | 0.117 | 1 | 0.04 | 0 | 0 |
| 46 | 10 | 2 | 29.7 | 0 | 60 | 30 | LF | 224,947 | 0.117 | 1 | 0.04 | 0 | 0 |
| 47 | 15 | 3 | 29.7 | 0 | 40 | 35 | CC | 225,452 | 0.117 | 1 | 0.04 | 0 | 0 |
| 48 | 15 | 3 | 29.7 | 0 | 40 | 35 | LF | 225,452 | 0.117 | 1 | 0.04 | 0 | 0 |
| 49 | 5 | 1 | 29.7 | 22 | 40 | 25 | LF | 225,660 | 0.113 | 0.95 | 0.01 | 3,786 | 621 |
| 50 | 0 | 0 | 29.7 | 26 | 40 | 25 | LF | 225,730 | 0.113 | 0.93 | 0 | 5,580 | 790 |
| 51 | 0 | 1 | 29.7 | 22 | 40 | 30 | LF | 226,331 | 0.114 | 0.94 | 0.01 | 4,716 | 766 |
| 52 | 0 | 2 | 29.7 | 22 | 40 | 25 | CC | 226,577 | 0.114 | 0.94 | 0.01 | 4,564 | 700 |
| 53 | 20 | 3 | 29.7 | 0 | 40 | 20 | CC | 226,671 | 0.117 | 1 | 0.03 | 0 | 0 |
| 54 | 20 | 3 | 29.7 | 0 | 40 | 20 | LF | 226,671 | 0.117 | 1 | 0.03 | 0 | 0 |
| 55 | 0 | 3 | 29.7 | 22 | 40 | 25 | LF | 226,727 | 0.114 | 0.95 | 0 | 4,056 | 665 |
| 56 | 15 | 0 | 29.7 | 0 | 60 | 30 | CC | 226,738 | 0.118 | 1 | 0.04 | 0 | 0 |
| 57 | 15 | 0 | 29.7 | 0 | 60 | 30 | LF | 226,738 | 0.118 | 1 | 0.04 | 0 | 0 |
| 58 | 5 | 0 | 29.7 | 22 | 40 | 30 | LF | 226,739 | 0.114 | 0.95 | 0.01 | 4,008 | 650 |
| 59 | 10 | 3 | 29.7 | 0 | 60 | 25 | CC | 226,960 | 0.118 | 1 | 0.04 | 0 | 0 |
| 60 | 10 | 3 | 29.7 | 0 | 60 | 25 | LF | 226,960 | 0.118 | 1 | 0.04 | 0 | 0 |
| 61 | 0 | 1 | 29.7 | 26 | 40 | 25 | LF | 226,977 | 0.114 | 0.93 | 0 | 5,151 | 731 |
| 62 | 0 | 0 | 29.7 | 22 | 40 | 30 | CC | 227,271 | 0.114 | 0.93 | 0.01 | 5,294 | 800 |
| 63 | 25 | 0 | 29.7 | 0 | 40 | 25 | CC | 227,288 | 0.118 | 1 | 0.03 | 0 | 0 |
| 64 | 25 | 0 | 29.7 | 0 | 40 | 25 | LF | 227,288 | 0.118 | 1 | 0.03 | 0 | 0 |
| 65 | 5 | 0 | 29.7 | 26 | 40 | 25 | LF | 227,420 | 0.114 | 0.94 | 0 | 4,458 | 633 |
| 66 | 15 | 4 | 29.7 | 0 | 40 | 30 | CC | 227,465 | 0.117 | 1 | 0.03 | 0 | 0 |
| 67 | 15 | 4 | 29.7 | 0 | 40 | 30 | LF | 227,465 | 0.117 | 1 | 0.03 | 0 | 0 |
| 68 | 5 | 1 | 29.7 | 22 | 40 | 25 | CC | 227,495 | 0.114 | 0.95 | 0 | 3,924 | 606 |
| 69 | 20 | 1 | 29.7 | 0 | 40 | 35 | CC | 227,750 | 0.118 | 1 | 0.04 | 0 | 0 |
| 70 | 20 | 1 | 29.7 | 0 | 40 | 35 | LF | 227,750 | 0.118 | 1 | 0.04 | 0 | 0 |
| 71 | 5 | 4 | 29.7 | 0 | 60 | 35 | CC | 227,753 | 0.119 | 1 | 0.04 | 0 | 0 |
| 72 | 5 | 4 | 29.7 | 0 | 60 | 35 | LF | 227,753 | 0.119 | 1 | 0.04 | 0 | 0 |
| 73 | 0 | 2 | 29.7 | 22 | 40 | 30 | LF | 228,191 | 0.115 | 0.94 | 0.01 | 4,337 | 706 |
| 74 | 5 | 2 | 29.7 | 22 | 40 | 25 | LF | 228,202 | 0.114 | 0.96 | 0 | 3,478 | 570 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 75 | 0 | 3 | 29.7 | 22 | 40 | 25 | CC | 228,583 | 0.115 | 0.94 | 0 | 4,213 | 645 |
| 76 | 0 | 0 | 29.7 | 26 | 40 | 25 | CC | 228,728 | 0.114 | 0.92 | 0 | 5,790 | 746 |
| 77 | 15 | 1 | 29.7 | 0 | 60 | 25 | CC | 228,751 | 0.118 | 1 | 0.03 | 0 | 0 |
| 78 | 15 | 1 | 29.7 | 0 | 60 | 25 | LF | 228,751 | 0.118 | 1 | 0.03 | 0 | 0 |
| 79 | 0 | 2 | 29.7 | 26 | 40 | 25 | LF | 228,752 | 0.114 | 0.94 | 0 | 4,772 | 679 |
| 80 | 5 | 0 | 29.7 | 22 | 40 | 30 | CC | 228,794 | 0.115 | 0.94 | 0.01 | 4,168 | 634 |
| 81 | 25 | 1 | 29.7 | 0 | 40 | 20 | CC | 228,845 | 0.118 | 1 | 0.03 | 0 | 0 |
| 82 | 25 | 1 | 29.7 | 0 | 40 | 20 | LF | 228,845 | 0.118 | 1 | 0.03 | 0 | 0 |
| 83 | 0 | 1 | 29.7 | 26 | 40 | 25 | CC | 228,849 | 0.115 | 0.93 | 0 | 5,274 | 682 |
| 84 | 0 | 1 | 29.7 | 22 | 40 | 30 | CC | 228,911 | 0.115 | 0.93 | 0.01 | 4,901 | 741 |
| 85 | 0 | 0 | 29.7 | 22 | 40 | 20 | LF | 228,945 | 0.115 | 0.92 | 0.01 | 6,207 | 1,046 |
| 86 | 10 | 4 | 29.7 | 0 | 60 | 20 | CC | 228,972 | 0.118 | 1 | 0.03 | 0 | 0 |
| 87 | 10 | 4 | 29.7 | 0 | 60 | 20 | LF | 228,972 | 0.118 | 1 | 0.03 | 0 | 0 |
| 88 | 10 | 0 | 29.7 | 22 | 40 | 25 | LF | 229,112 | 0.115 | 0.96 | 0.01 | 3,362 | 554 |
| 89 | 0 | 0 | 29.7 | 22 | 40 | 35 | LF | 229,253 | 0.115 | 0.93 | 0.01 | 5,102 | 829 |
| 90 | 20 | 2 | 29.7 | 0 | 40 | 30 | CC | 229,342 | 0.118 | 1 | 0.03 | 0 | 0 |
| 91 | 20 | 2 | 29.7 | 0 | 40 | 30 | LF | 229,342 | 0.118 | 1 | 0.03 | 0 | 0 |
| 92 | 5 | 0 | 29.7 | 26 | 40 | 25 | CC | 229,395 | 0.115 | 0.94 | 0 | 4,608 | 604 |
| 93 | 5 | 1 | 29.7 | 26 | 40 | 25 | LF | 229,481 | 0.115 | 0.95 | 0 | 4,114 | 582 |
| 94 | 10 | 2 | 29.7 | 0 | 60 | 35 | CC | 229,544 | 0.119 | 1 | 0.04 | 0 | 0 |
| 95 | 10 | 2 | 29.7 | 0 | 60 | 35 | LF | 229,544 | 0.119 | 1 | 0.04 | 0 | 0 |
| 96 | 5 | 1 | 29.7 | 22 | 40 | 30 | LF | 229,570 | 0.115 | 0.95 | 0.01 | 3,722 | 605 |
| 97 | 0 | 4 | 29.7 | 22 | 40 | 25 | LF | 229,601 | 0.115 | 0.95 | 0 | 3,753 | 615 |
| 98 | 0 | 0 | 29.7 | 22 | 60 | 25 | LF | 229,889 | 0.116 | 0.95 | 0.01 | 3,842 | 613 |
| 99 | 0 | 0 | 29.7 | 26 | 40 | 30 | LF | 230,137 | 0.115 | 0.93 | 0 | 5,562 | 785 |
| 100 | 5 | 2 | 29.7 | 22 | 40 | 25 | CC | 230,414 | 0.116 | 0.95 | 0 | 3,646 | 568 |
| 101 | 0 | 2 | 29.7 | 22 | 40 | 30 | CC | 230,574 | 0.116 | 0.94 | 0.01 | 4,510 | 684 |
| 102 | 0 | 2 | 29.7 | 26 | 40 | 25 | CC | 230,753 | 0.115 | 0.93 | 0 | 4,911 | 638 |
| 103 | 15 | 2 | 29.7 | 0 | 60 | 20 | CC | 230,763 | 0.119 | 1 | 0.03 | 0 | 0 |
| 104 | 15 | 2 | 29.7 | 0 | 60 | 20 | LF | 230,763 | 0.119 | 1 | 0.03 | 0 | 0 |
| 105 | 0 | 3 | 29.7 | 22 | 40 | 30 | LF | 230,790 | 0.116 | 0.95 | 0 | 4,013 | 656 |
| 106 | 0 | 0 | 29.7 | 22 | 60 | 25 | CC | 230,885 | 0.116 | 0.95 | 0.01 | 3,937 | 596 |
| 107 | 10 | 0 | 29.7 | 22 | 40 | 25 | CC | 230,913 | 0.116 | 0.96 | 0.01 | 3,500 | 550 |
| 108 | 0 | 1 | 29.7 | 22 | 40 | 20 | LF | 230,922 | 0.116 | 0.93 | 0.01 | 5,830 | 986 |
| 109 | 0 | 1 | 29.7 | 22 | 40 | 35 | LF | 230,928 | 0.116 | 0.94 | 0.01 | 4,716 | 766 |
| 110 | 0 | 3 | 29.7 | 26 | 40 | 25 | LF | 231,092 | 0.116 | 0.94 | 0 | 4,432 | 630 |
| 111 | 0 | 1 | 29.7 | 26 | 40 | 30 | LF | 231,253 | 0.116 | 0.93 | 0 | 5,119 | 725 |
| 112 | 20 | 3 | 29.7 | 0 | 40 | 25 | CC | 231,268 | 0.119 | 1 | 0.03 | 0 | 0 |
| 113 | 20 | 3 | 29.7 | 0 | 40 | 25 | LF | 231,268 | 0.119 | 1 | 0.03 | 0 | 0 |
| 114 | 5 | 0 | 29.7 | 26 | 40 | 30 | LF | 231,332 | 0.116 | 0.94 | 0 | 4,389 | 619 |
| 115 | 15 | 0 | 29.7 | 0 | 60 | 35 | CC | 231,335 | 0.12 | 1 | 0.04 | 0 | 0 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 116 | 15 | 0 | 29.7 | 0 | 60 | 35 | LF | 231,335 | 0.12 | 1 | 0.04 | 0 | 0 |
| 117 | 5 | 0 | 29.7 | 22 | 40 | 35 | LF | 231,335 | 0.116 | 0.95 | 0.01 | 4,008 | 650 |
| 118 | 5 | 1 | 29.7 | 26 | 40 | 25 | CC | 231,422 | 0.116 | 0.94 | 0 | 4,253 | 561 |
| 119 | 5 | 1 | 29.7 | 22 | 40 | 30 | CC | 231,425 | 0.116 | 0.95 | 0.01 | 3,863 | 590 |
| 120 | 10 | 3 | 29.7 | 0 | 60 | 30 | CC | 231,556 | 0.12 | 1 | 0.04 | 0 | 0 |
| 121 | 10 | 3 | 29.7 | 0 | 60 | 30 | LF | 231,556 | 0.12 | 1 | 0.04 | 0 | 0 |
| 122 | 0 | 0 | 29.7 | 22 | 40 | 20 | CC | 231,590 | 0.116 | 0.92 | 0.01 | 6,443 | 1,035 |
| 123 | 5 | 3 | 29.7 | 22 | 40 | 25 | LF | 231,687 | 0.116 | 0.96 | 0 | 3,239 | 533 |
| 124 | 0 | 4 | 29.7 | 22 | 40 | 25 | CC | 231,725 | 0.116 | 0.95 | 0 | 3,942 | 608 |
| 125 | 0 | 0 | 29.7 | 22 | 40 | 35 | CC | 231,867 | 0.117 | 0.93 | 0.01 | 5,294 | 800 |

## Table A-2 Overall optimization for Taba B

| Rank | PV (kW) | HY-5 kW | Hydro (kW) | Gen (kW) | S6CS25P | Converter (kW) | Dispatch strategy | Total NPC ($) | COE ($/kWh) | Renewable fraction | Unmet load fraction | Diesel (L) | Gen (hrs) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 36.5 | 22 | 60 | 30 | LF | 244,683 | 0.099 | 0.94 | 0.02 | 3,753 | 814 |
| 2 | 0 | 0 | 36.5 | 22 | 40 | 30 | LF | 245,630 | 0.1 | 0.92 | 0.02 | 5,673 | 1,265 |
| 3 | 0 | 0 | 36.5 | 22 | 60 | 30 | CC | 247,169 | 0.1 | 0.94 | 0.01 | 3,968 | 820 |
| 4 | 0 | 1 | 36.5 | 22 | 60 | 30 | LF | 247,569 | 0.1 | 0.95 | 0.01 | 3,456 | 752 |
| 5 | 0 | 1 | 36.5 | 22 | 40 | 30 | LF | 247,794 | 0.1 | 0.92 | 0.02 | 5,320 | 1,193 |
| 6 | 0 | 1 | 36.5 | 22 | 60 | 30 | CC | 249,661 | 0.101 | 0.95 | 0.01 | 3,637 | 756 |
| 7 | 15 | 2 | 36.5 | 0 | 60 | 30 | CC | 250,191 | 0.104 | 1 | 0.04 | 0 | 0 |
| 8 | 15 | 2 | 36.5 | 0 | 60 | 30 | LF | 250,191 | 0.104 | 1 | 0.04 | 0 | 0 |
| 9 | 0 | 0 | 36.5 | 22 | 40 | 30 | CC | 250,213 | 0.101 | 0.91 | 0.02 | 6,037 | 1,273 |
| 10 | 0 | 2 | 36.5 | 22 | 40 | 30 | LF | 250,311 | 0.101 | 0.93 | 0.01 | 4,994 | 1,122 |
| 11 | 5 | 0 | 36.5 | 22 | 40 | 30 | LF | 250,726 | 0.101 | 0.93 | 0.01 | 4,834 | 1,089 |
| 12 | 0 | 2 | 36.5 | 22 | 60 | 30 | LF | 251,074 | 0.101 | 0.95 | 0.01 | 3,209 | 699 |
| 13 | 5 | 0 | 36.5 | 22 | 60 | 30 | LF | 251,496 | 0.102 | 0.95 | 0.01 | 3,096 | 683 |
| 14 | 0 | 1 | 36.5 | 22 | 40 | 30 | CC | 251,633 | 0.102 | 0.92 | 0.01 | 5,624 | 1,184 |
| 15 | 20 | 0 | 36.5 | 0 | 60 | 30 | CC | 251,981 | 0.105 | 1 | 0.04 | 0 | 0 |
| 16 | 20 | 0 | 36.5 | 0 | 60 | 30 | LF | 251,981 | 0.105 | 1 | 0.04 | 0 | 0 |
| 17 | 0 | 3 | 36.5 | 22 | 40 | 30 | LF | 252,802 | 0.102 | 0.93 | 0.01 | 4,662 | 1,051 |
| 18 | 0 | 2 | 36.5 | 22 | 60 | 30 | CC | 253,234 | 0.102 | 0.95 | 0.01 | 3,395 | 706 |
| 19 | 0 | 0 | 36.5 | 22 | 60 | 40 | LF | 253,260 | 0.103 | 0.94 | 0.02 | 3,617 | 765 |
| 20 | 5 | 0 | 36.5 | 22 | 60 | 30 | CC | 253,322 | 0.102 | 0.95 | 0.01 | 3,255 | 687 |
| 21 | 5 | 1 | 36.5 | 22 | 40 | 30 | LF | 253,488 | 0.102 | 0.94 | 0.01 | 4,530 | 1,024 |
| 22 | 5 | 0 | 36.5 | 22 | 40 | 30 | CC | 254,042 | 0.103 | 0.93 | 0.01 | 5,102 | 1,093 |
| 23 | 0 | 2 | 36.5 | 22 | 40 | 30 | CC | 254,234 | 0.103 | 0.92 | 0.01 | 5,304 | 1,120 |
| 24 | 0 | 3 | 36.5 | 22 | 60 | 30 | LF | 255,018 | 0.103 | 0.96 | 0.01 | 2,996 | 655 |
| 25 | 5 | 1 | 36.5 | 22 | 60 | 30 | LF | 255,324 | 0.103 | 0.96 | 0.01 | 2,875 | 635 |
| 26 | 0 | 0 | 36.5 | 22 | 60 | 40 | CC | 255,779 | 0.104 | 0.94 | 0.02 | 3,834 | 774 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 27 | 0 | 0 | 36.5 | 33 | 60 | 30 | LF | 255,823 | 0.102 | 0.93 | 0 | 4,731 | 731 |
| 28 | 0 | 0 | 36.5 | 22 | 40 | 40 | LF | 255,835 | 0.104 | 0.92 | 0.02 | 5,654 | 1,257 |
| 29 | 0 | 4 | 36.5 | 22 | 40 | 30 | LF | 255,984 | 0.103 | 0.94 | 0.01 | 4,399 | 995 |
| 30 | 0 | 1 | 36.5 | 22 | 60 | 40 | LF | 256,025 | 0.104 | 0.95 | 0.01 | 3,311 | 700 |
| 31 | 5 | 2 | 36.5 | 22 | 40 | 30 | LF | 256,460 | 0.103 | 0.94 | 0.01 | 4,248 | 961 |
| 32 | 0 | 3 | 36.5 | 22 | 40 | 30 | CC | 256,771 | 0.104 | 0.93 | 0.01 | 4,975 | 1,053 |
| 33 | 15 | 3 | 36.5 | 0 | 60 | 30 | CC | 256,794 | 0.106 | 1 | 0.04 | 0 | 0 |
| 34 | 15 | 3 | 36.5 | 0 | 60 | 30 | LF | 256,794 | 0.106 | 1 | 0.04 | 0 | 0 |
| 35 | 5 | 1 | 36.5 | 22 | 40 | 30 | CC | 256,821 | 0.104 | 0.93 | 0.01 | 4,797 | 1,027 |
| 36 | 0 | 3 | 36.5 | 22 | 60 | 30 | CC | 257,020 | 0.104 | 0.95 | 0.01 | 3,170 | 658 |
| 37 | 5 | 1 | 36.5 | 22 | 60 | 30 | CC | 257,326 | 0.104 | 0.96 | 0.01 | 3,047 | 643 |
| 38 | 0 | 1 | 36.5 | 22 | 40 | 40 | LF | 257,894 | 0.104 | 0.92 | 0.02 | 5,295 | 1,181 |
| 39 | 0 | 0 | 36.5 | 33 | 60 | 30 | CC | 258,081 | 0.103 | 0.93 | 0 | 4,945 | 698 |
| 40 | 0 | 1 | 36.5 | 33 | 60 | 30 | LF | 258,238 | 0.103 | 0.94 | 0 | 4,389 | 678 |
| 41 | 20 | 1 | 36.5 | 0 | 60 | 30 | CC | 258,585 | 0.107 | 1 | 0.04 | 0 | 0 |
| 42 | 20 | 1 | 36.5 | 0 | 60 | 30 | LF | 258,585 | 0.107 | 1 | 0.04 | 0 | 0 |
| 43 | 0 | 0 | 36.5 | 22 | 20 | 20 | LF | 258,599 | 0.105 | 0.87 | 0.02 | 9,668 | 2,238 |
| 44 | 10 | 0 | 36.5 | 22 | 40 | 30 | LF | 258,630 | 0.104 | 0.94 | 0.01 | 4,245 | 967 |
| 45 | 0 | 1 | 36.5 | 22 | 60 | 40 | CC | 258,739 | 0.105 | 0.95 | 0.01 | 3,541 | 717 |
| 46 | 10 | 4 | 36.5 | 0 | 60 | 40 | CC | 258,783 | 0.107 | 1 | 0.04 | 0 | 0 |
| 47 | 10 | 4 | 36.5 | 0 | 60 | 40 | LF | 258,783 | 0.107 | 1 | 0.04 | 0 | 0 |
| 48 | 5 | 0 | 36.5 | 22 | 60 | 40 | LF | 258,906 | 0.105 | 0.96 | 0.01 | 2,873 | 604 |
| 49 | 0 | 4 | 36.5 | 22 | 60 | 30 | LF | 259,086 | 0.104 | 0.96 | 0.01 | 2,793 | 614 |
| 50 | 5 | 2 | 36.5 | 22 | 40 | 30 | CC | 259,396 | 0.105 | 0.94 | 0.01 | 4,480 | 959 |
| 51 | 0 | 2 | 36.5 | 22 | 60 | 40 | LF | 259,451 | 0.105 | 0.95 | 0.01 | 3,058 | 646 |
| 52 | 5 | 2 | 36.5 | 22 | 60 | 30 | LF | 259,512 | 0.105 | 0.96 | 0.01 | 2,683 | 593 |
| 53 | 5 | 3 | 36.5 | 22 | 40 | 30 | LF | 259,539 | 0.105 | 0.95 | 0.01 | 3,971 | 902 |
| 54 | 0 | 4 | 36.5 | 22 | 40 | 30 | CC | 259,866 | 0.105 | 0.93 | 0.01 | 4,708 | 997 |
| 55 | 0 | 1 | 36.5 | 33 | 60 | 30 | CC | 260,016 | 0.104 | 0.93 | 0 | 4,561 | 644 |
| 56 | 0 | 0 | 36.5 | 33 | 40 | 30 | LF | 260,053 | 0.104 | 0.9 | 0 | 6,944 | 1,093 |
| 57 | 0 | 2 | 36.5 | 22 | 40 | 40 | LF | 260,410 | 0.105 | 0.93 | 0.01 | 4,969 | 1,111 |
| 58 | 0 | 0 | 36.5 | 22 | 40 | 40 | CC | 260,458 | 0.106 | 0.91 | 0.02 | 6,021 | 1,265 |
| 59 | 15 | 2 | 36.5 | 0 | 60 | 40 | CC | 260,573 | 0.108 | 1 | 0.04 | 0 | 0 |
| 60 | 15 | 2 | 36.5 | 0 | 60 | 40 | LF | 260,573 | 0.108 | 1 | 0.04 | 0 | 0 |
| 61 | 0 | 4 | 36.5 | 22 | 60 | 30 | CC | 260,721 | 0.105 | 0.96 | 0.01 | 2,937 | 613 |
| 62 | 5 | 0 | 36.5 | 22 | 40 | 40 | LF | 260,804 | 0.105 | 0.93 | 0.01 | 4,810 | 1,075 |
| 63 | 5 | 0 | 36.5 | 22 | 60 | 40 | CC | 260,833 | 0.105 | 0.95 | 0.01 | 3,038 | 612 |
| 64 | 5 | 2 | 36.5 | 22 | 60 | 30 | CC | 261,040 | 0.105 | 0.96 | 0.01 | 2,817 | 593 |
| 65 | 0 | 2 | 36.5 | 33 | 60 | 30 | LF | 261,141 | 0.104 | 0.94 | 0 | 4,085 | 635 |
| 66 | 10 | 0 | 36.5 | 22 | 40 | 30 | CC | 261,197 | 0.105 | 0.94 | 0.01 | 4,443 | 961 |
| 67 | 10 | 1 | 36.5 | 22 | 40 | 30 | LF | 261,253 | 0.105 | 0.95 | 0.01 | 3,929 | 896 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 68 | 0 | 1 | 36.5 | 22 | 20 | 20 | LF | 261,381 | 0.106 | 0.87 | 0.02 | 9,373 | 2,178 |
| 69 | 0 | 1 | 36.5 | 33 | 40 | 30 | LF | 261,469 | 0.104 | 0.91 | 0 | 6,522 | 1,032 |
| 70 | 0 | 1 | 36.5 | 22 | 40 | 40 | CC | 261,517 | 0.106 | 0.92 | 0.02 | 5,582 | 1,168 |
| 71 | 10 | 0 | 36.5 | 22 | 60 | 30 | LF | 261,745 | 0.105 | 0.96 | 0.01 | 2,714 | 611 |
| 72 | 0 | 2 | 36.5 | 22 | 60 | 40 | CC | 262,169 | 0.106 | 0.95 | 0.01 | 3,287 | 666 |
| 73 | 20 | 0 | 36.5 | 0 | 60 | 40 | CC | 262,364 | 0.109 | 1 | 0.04 | 0 | 0 |
| 74 | 20 | 0 | 36.5 | 0 | 60 | 40 | LF | 262,364 | 0.109 | 1 | 0.04 | 0 | 0 |
| 75 | 5 | 1 | 36.5 | 22 | 60 | 40 | LF | 262,634 | 0.106 | 0.96 | 0.01 | 2,643 | 556 |
| 76 | 5 | 3 | 36.5 | 22 | 40 | 30 | CC | 262,673 | 0.106 | 0.94 | 0.01 | 4,218 | 908 |
| 77 | 5 | 0 | 36.5 | 33 | 60 | 30 | LF | 262,707 | 0.105 | 0.94 | 0 | 4,067 | 630 |
| 78 | 0 | 3 | 36.5 | 22 | 40 | 40 | LF | 262,870 | 0.106 | 0.93 | 0.01 | 4,634 | 1,039 |
| 79 | 5 | 4 | 36.5 | 22 | 40 | 30 | LF | 262,945 | 0.106 | 0.95 | 0.01 | 3,733 | 851 |
| 80 | 0 | 2 | 36.5 | 33 | 60 | 30 | CC | 262,952 | 0.105 | 0.94 | 0 | 4,257 | 606 |
| 81 | 0 | 3 | 36.5 | 22 | 60 | 40 | LF | 263,094 | 0.106 | 0.96 | 0.01 | 2,822 | 596 |
| 82 | 10 | 0 | 36.5 | 22 | 60 | 30 | CC | 263,105 | 0.106 | 0.96 | 0.01 | 2,833 | 610 |
| 83 | 0 | 2 | 36.5 | 33 | 40 | 30 | LF | 263,232 | 0.105 | 0.91 | 0 | 6,132 | 971 |
| 84 | 5 | 1 | 36.5 | 22 | 40 | 40 | LF | 263,308 | 0.106 | 0.94 | 0.01 | 4,484 | 1,006 |
| 85 | 15 | 4 | 36.5 | 0 | 60 | 30 | CC | 263,398 | 0.109 | 1 | 0.03 | 0 | 0 |
| 86 | 15 | 4 | 36.5 | 0 | 60 | 30 | LF | 263,398 | 0.109 | 1 | 0.03 | 0 | 0 |
| 87 | 0 | 0 | 36.5 | 22 | 60 | 50 | LF | 263,643 | 0.107 | 0.94 | 0.02 | 3,617 | 765 |
| 88 | 0 | 0 | 36.5 | 33 | 60 | 40 | LF | 263,745 | 0.105 | 0.93 | 0 | 4,535 | 689 |
| 89 | 0 | 0 | 36.5 | 22 | 80 | 30 | LF | 263,923 | 0.107 | 0.95 | 0.01 | 3,243 | 696 |
| 90 | 10 | 1 | 36.5 | 22 | 40 | 30 | CC | 264,000 | 0.106 | 0.94 | 0.01 | 4,146 | 900 |
| 91 | 5 | 0 | 36.5 | 33 | 40 | 30 | LF | 264,032 | 0.105 | 0.92 | 0 | 6,032 | 957 |
| 92 | 0 | 0 | 36.5 | 22 | 20 | 20 | CC | 264,041 | 0.107 | 0.86 | 0.02 | 10,109 | 2,246 |
| 93 | 0 | 2 | 36.5 | 22 | 20 | 20 | LF | 264,246 | 0.107 | 0.88 | 0.02 | 9,078 | 2,117 |
| 94 | 5 | 3 | 36.5 | 22 | 60 | 30 | LF | 264,285 | 0.106 | 0.96 | 0.01 | 2,536 | 564 |
| 95 | 0 | 3 | 36.5 | 33 | 60 | 30 | LF | 264,305 | 0.106 | 0.95 | 0 | 3,804 | 591 |
| 96 | 0 | 0 | 36.5 | 44 | 60 | 30 | LF | 264,423 | 0.105 | 0.92 | 0 | 5,461 | 671 |
| 97 | 5 | 0 | 36.5 | 22 | 40 | 40 | CC | 264,424 | 0.107 | 0.93 | 0.01 | 5,100 | 1,085 |
| 98 | 10 | 2 | 36.5 | 22 | 40 | 30 | LF | 264,494 | 0.106 | 0.95 | 0.01 | 3,669 | 840 |
| 99 | 0 | 2 | 36.5 | 22 | 40 | 40 | CC | 264,580 | 0.107 | 0.92 | 0.01 | 5,298 | 1,114 |
| 100 | 5 | 1 | 36.5 | 22 | 60 | 40 | CC | 264,704 | 0.107 | 0.96 | 0.01 | 2,818 | 569 |
| 101 | 5 | 0 | 36.5 | 33 | 60 | 30 | CC | 264,995 | 0.106 | 0.94 | 0 | 4,276 | 614 |
| 102 | 20 | 2 | 36.5 | 0 | 60 | 30 | CC | 265,189 | 0.109 | 1 | 0.03 | 0 | 0 |
| 103 | 20 | 2 | 36.5 | 0 | 60 | 30 | LF | 265,189 | 0.109 | 1 | 0.03 | 0 | 0 |
| 104 | 0 | 3 | 36.5 | 22 | 60 | 40 | CC | 265,267 | 0.107 | 0.96 | 0.01 | 3,007 | 607 |
| 105 | 0 | 3 | 36.5 | 33 | 40 | 30 | LF | 265,449 | 0.106 | 0.92 | 0 | 5,792 | 919 |
| 106 | 0 | 0 | 36.5 | 22 | 80 | 30 | CC | 265,527 | 0.107 | 0.95 | 0.01 | 3,383 | 697 |
| 107 | 0 | 0 | 36.5 | 22 | 20 | 30 | LF | 265,774 | 0.108 | 0.87 | 0.02 | 9,317 | 2,144 |
| 108 | 5 | 1 | 36.5 | 33 | 60 | 30 | LF | 265,918 | 0.106 | 0.95 | 0 | 3,791 | 586 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 109 | 0 | 0 | 36.5 | 33 | 40 | 30 | CC | 265,952 | 0.106 | 0.89 | 0 | 7,384 | 1,030 |
| 110 | 0 | 4 | 36.5 | 22 | 40 | 40 | LF | 265,979 | 0.107 | 0.94 | 0.01 | 4,365 | 981 |
| 111 | 5 | 3 | 36.5 | 22 | 60 | 30 | CC | 265,997 | 0.107 | 0.96 | 0.01 | 2,682 | 573 |
| 112 | 0 | 1 | 36.5 | 33 | 60 | 40 | LF | 266,023 | 0.106 | 0.94 | 0 | 4,180 | 638 |
| 113 | 10 | 1 | 36.5 | 22 | 60 | 30 | LF | 266,027 | 0.107 | 0.96 | 0.01 | 2,530 | 568 |
| 114 | 5 | 4 | 36.5 | 22 | 40 | 30 | CC | 266,046 | 0.107 | 0.95 | 0.01 | 3,983 | 859 |
| 115 | 0 | 0 | 36.5 | 22 | 60 | 50 | CC | 266,162 | 0.108 | 0.94 | 0.02 | 3,834 | 774 |
| 116 | 0 | 1 | 36.5 | 44 | 60 | 30 | LF | 266,209 | 0.106 | 0.93 | 0 | 5,062 | 622 |
| 117 | 0 | 0 | 36.5 | 22 | 40 | 50 | LF | 266,217 | 0.108 | 0.92 | 0.02 | 5,654 | 1,257 |
| 118 | 5 | 2 | 36.5 | 22 | 40 | 40 | LF | 266,232 | 0.107 | 0.94 | 0.01 | 4,197 | 942 |
| 119 | 5 | 1 | 36.5 | 33 | 40 | 30 | LF | 266,269 | 0.106 | 0.92 | 0 | 5,692 | 902 |
| 120 | 0 | 0 | 36.5 | 33 | 60 | 40 | CC | 266,301 | 0.106 | 0.93 | 0 | 4,776 | 653 |
| 121 | 0 | 1 | 36.5 | 22 | 60 | 50 | LF | 266,408 | 0.108 | 0.95 | 0.01 | 3,311 | 700 |
| 122 | 0 | 3 | 36.5 | 33 | 60 | 30 | CC | 266,523 | 0.106 | 0.94 | 0 | 4,006 | 575 |
| 123 | 5 | 2 | 36.5 | 22 | 60 | 40 | LF | 266,581 | 0.107 | 0.96 | 0.01 | 2,431 | 511 |
| 124 | 5 | 1 | 36.5 | 22 | 40 | 40 | CC | 266,693 | 0.108 | 0.93 | 0.01 | 4,754 | 1,009 |
| 125 | 25 | 0 | 36.5 | 0 | 60 | 30 | CC | 266,980 | 0.11 | 1 | 0.03 | 0 | 0 |

## Table A-3 Overall optimization for Bechet

| Rank | PV (kW) | HY-5 kW | Hydro (kW) | Gen (kW) | S6CS25P | Converter (kW) | Dispatch strategy | Total NPC ($) | COE ($/kWh) | Renewable fraction | Unmet load fraction | Diesel (L/yr) | Gen (hrs/yr) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 109 | 26 | 80 | 50 | LF | 394,245 | 0.068 | 0.97 | 0.04 | 4,976 | 866 |
| 2 | 0 | 1 | 109 | 22 | 80 | 50 | CC | 395,523 | 0.068 | 0.98 | 0.04 | 4,514 | 881 |
| 3 | 0 | 2 | 109 | 22 | 80 | 50 | LF | 397,149 | 0.068 | 0.98 | 0.04 | 4,127 | 840 |
| 4 | 5 | 0 | 109 | 22 | 80 | 50 | LF | 398,951 | 0.069 | 0.98 | 0.04 | 4,099 | 837 |
| 5 | 0 | 1 | 109 | 26 | 80 | 50 | LF | 399,133 | 0.068 | 0.97 | 0.03 | 4,856 | 844 |
| 6 | 0 | 0 | 109 | 26 | 80 | 50 | CC | 399,608 | 0.069 | 0.97 | 0.03 | 5,402 | 908 |
| 7 | 0 | 0 | 109 | 26 | 80 | 60 | LF | 400,756 | 0.069 | 0.97 | 0.04 | 4,699 | 802 |
| 8 | 0 | 2 | 109 | 22 | 80 | 50 | CC | 401,136 | 0.069 | 0.98 | 0.04 | 4,462 | 873 |
| 9 | 0 | 2 | 109 | 26 | 60 | 40 | LF | 401,463 | 0.069 | 0.96 | 0.04 | 7,192 | 1,316 |
| 10 | 0 | 1 | 109 | 22 | 80 | 60 | CC | 402,200 | 0.069 | 0.98 | 0.04 | 4,261 | 819 |
| 11 | 0 | 2 | 109 | 26 | 60 | 50 | LF | 402,315 | 0.069 | 0.97 | 0.04 | 6,293 | 1,118 |
| 12 | 0 | 3 | 109 | 22 | 80 | 50 | LF | 402,422 | 0.069 | 0.98 | 0.04 | 4,021 | 818 |
| 13 | 5 | 0 | 109 | 22 | 80 | 50 | CC | 403,208 | 0.069 | 0.98 | 0.04 | 4,441 | 873 |
| 14 | 0 | 2 | 109 | 22 | 80 | 60 | LF | 403,511 | 0.069 | 0.98 | 0.04 | 3,873 | 773 |
| 15 | 0 | 1 | 109 | 26 | 80 | 50 | CC | 403,767 | 0.069 | 0.97 | 0.03 | 5,230 | 877 |
| 16 | 5 | 1 | 109 | 22 | 80 | 50 | LF | 403,900 | 0.069 | 0.98 | 0.04 | 3,995 | 815 |
| 17 | 5 | 0 | 109 | 26 | 60 | 40 | LF | 404,079 | 0.069 | 0.96 | 0.04 | 7,223 | 1,327 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 18 | 5 | 0 | 109 | 26 | 60 | 50 | LF | 404,582 | 0.069 | 0.97 | 0.04 | 6,296 | 1,124 |
| 19 | 0 | 2 | 109 | 26 | 80 | 50 | LF | 404,686 | 0.069 | 0.97 | 0.03 | 4,769 | 832 |
| 20 | 5 | 0 | 109 | 22 | 80 | 60 | LF | 405,363 | 0.07 | 0.98 | 0.04 | 3,823 | 764 |
| 21 | 0 | 1 | 109 | 26 | 80 | 60 | LF | 405,648 | 0.07 | 0.98 | 0.03 | 4,584 | 782 |
| 22 | 0 | 3 | 109 | 26 | 60 | 40 | LF | 405,871 | 0.07 | 0.96 | 0.03 | 7,032 | 1,287 |
| 23 | 0 | 0 | 109 | 26 | 80 | 60 | CC | 406,011 | 0.07 | 0.97 | 0.04 | 5,115 | 845 |
| 24 | 5 | 0 | 109 | 26 | 80 | 50 | LF | 406,081 | 0.07 | 0.98 | 0.03 | 4,727 | 828 |
| 25 | 0 | 3 | 109 | 22 | 80 | 50 | CC | 406,497 | 0.07 | 0.98 | 0.04 | 4,361 | 855 |
| 26 | 0 | 0 | 109 | 33 | 80 | 50 | LF | 406,755 | 0.069 | 0.97 | 0.03 | 6,086 | 848 |
| 27 | 0 | 0 | 109 | 22 | 100 | 50 | LF | 406,786 | 0.07 | 0.98 | 0.04 | 3,898 | 800 |
| 28 | 0 | 3 | 109 | 26 | 60 | 50 | LF | 406,795 | 0.07 | 0.97 | 0.03 | 6,135 | 1,091 |
| 29 | 0 | 1 | 109 | 22 | 80 | 40 | CC | 407,110 | 0.07 | 0.97 | 0.04 | 6,184 | 1,271 |
| 30 | 0 | 2 | 109 | 22 | 80 | 60 | CC | 407,330 | 0.07 | 0.98 | 0.04 | 4,177 | 804 |
| 31 | 0 | 2 | 109 | 26 | 60 | 40 | CC | 407,356 | 0.07 | 0.96 | 0.04 | 7,676 | 1,344 |
| 32 | 0 | 2 | 109 | 22 | 80 | 40 | LF | 407,472 | 0.07 | 0.97 | 0.04 | 5,659 | 1,222 |
| 33 | 0 | 0 | 109 | 33 | 60 | 50 | LF | 407,608 | 0.07 | 0.96 | 0.03 | 7,920 | 1,122 |
| 34 | 5 | 1 | 109 | 22 | 80 | 50 | CC | 407,853 | 0.07 | 0.98 | 0.04 | 4,315 | 848 |
| 35 | 0 | 0 | 109 | 26 | 80 | 40 | LF | 408,068 | 0.07 | 0.96 | 0.03 | 6,829 | 1,258 |
| 36 | 5 | 1 | 109 | 26 | 60 | 40 | LF | 408,331 | 0.07 | 0.96 | 0.03 | 7,048 | 1,295 |
| 37 | 0 | 2 | 109 | 26 | 60 | 50 | CC | 408,396 | 0.07 | 0.96 | 0.04 | 6,791 | 1,151 |
| 38 | 0 | 3 | 109 | 22 | 80 | 60 | LF | 408,551 | 0.07 | 0.98 | 0.04 | 3,781 | 754 |
| 39 | 5 | 1 | 109 | 26 | 60 | 50 | LF | 408,841 | 0.07 | 0.97 | 0.04 | 6,118 | 1,091 |
| 40 | 0 | 0 | 109 | 22 | 100 | 50 | CC | 409,189 | 0.07 | 0.98 | 0.04 | 4,105 | 807 |
| 41 | 0 | 2 | 109 | 26 | 80 | 50 | CC | 409,262 | 0.07 | 0.97 | 0.03 | 5,154 | 868 |
| 42 | 0 | 0 | 109 | 33 | 60 | 40 | LF | 409,279 | 0.07 | 0.95 | 0.03 | 9,136 | 1,332 |
| 43 | 5 | 0 | 109 | 22 | 80 | 60 | CC | 409,414 | 0.07 | 0.98 | 0.04 | 4,144 | 799 |
| 44 | 5 | 2 | 109 | 22 | 80 | 50 | LF | 409,767 | 0.07 | 0.98 | 0.03 | 3,935 | 806 |
| 45 | 0 | 3 | 109 | 26 | 80 | 50 | LF | 409,893 | 0.07 | 0.98 | 0.03 | 4,656 | 812 |
| 46 | 0 | 0 | 109 | 35 | 80 | 50 | LF | 410,229 | 0.07 | 0.97 | 0.03 | 6,389 | 844 |
| 47 | 5 | 1 | 109 | 22 | 80 | 60 | LF | 410,267 | 0.07 | 0.98 | 0.04 | 3,719 | 742 |
| 48 | 5 | 0 | 109 | 22 | 80 | 40 | LF | 410,307 | 0.07 | 0.97 | 0.04 | 5,741 | 1,243 |
| 49 | 5 | 0 | 109 | 26 | 60 | 40 | CC | 410,403 | 0.07 | 0.96 | 0.04 | 7,743 | 1,361 |
| 50 | 0 | 1 | 109 | 26 | 80 | 60 | CC | 410,602 | 0.07 | 0.97 | 0.03 | 4,975 | 821 |
| 51 | 0 | 2 | 109 | 26 | 80 | 60 | LF | 410,783 | 0.07 | 0.98 | 0.03 | 4,498 | 769 |
| 52 | 5 | 0 | 109 | 26 | 60 | 50 | CC | 410,809 | 0.071 | 0.96 | 0.04 | 6,807 | 1,158 |
| 53 | 0 | 2 | 109 | 26 | 60 | 60 | LF | 410,810 | 0.071 | 0.97 | 0.04 | 6,225 | 1,101 |
| 54 | 5 | 0 | 109 | 26 | 80 | 50 | CC | 410,818 | 0.07 | 0.97 | 0.03 | 5,108 | 863 |
| 55 | 0 | 0 | 109 | 22 | 100 | 60 | LF | 410,848 | 0.071 | 0.98 | 0.04 | 3,496 | 698 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 56 | 10 | 0 | 109 | 22 | 80 | 50 | LF | 411,292 | 0.071 | 0.98 | 0.03 | 3,909 | 805 |
| 57 | 5 | 1 | 109 | 26 | 80 | 50 | LF | 411,360 | 0.07 | 0.98 | 0.03 | 4,628 | 811 |
| 58 | 0 | 3 | 109 | 26 | 60 | 40 | CC | 411,474 | 0.071 | 0.96 | 0.03 | 7,495 | 1,313 |
| 59 | 0 | 1 | 109 | 33 | 80 | 50 | LF | 411,595 | 0.07 | 0.97 | 0.03 | 5,940 | 830 |
| 60 | 0 | 0 | 109 | 35 | 60 | 50 | LF | 411,702 | 0.07 | 0.96 | 0.03 | 8,298 | 1,114 |
| 61 | 0 | 1 | 109 | 33 | 60 | 50 | LF | 411,844 | 0.07 | 0.96 | 0.03 | 7,737 | 1,098 |
| 62 | 0 | 1 | 109 | 22 | 100 | 50 | LF | 412,253 | 0.071 | 0.98 | 0.03 | 3,806 | 782 |
| 63 | 5 | 0 | 109 | 26 | 80 | 60 | LF | 412,257 | 0.071 | 0.98 | 0.03 | 4,419 | 756 |
| 64 | 0 | 0 | 109 | 33 | 80 | 50 | CC | 412,436 | 0.07 | 0.97 | 0.03 | 6,553 | 883 |
| 65 | 0 | 0 | 109 | 22 | 100 | 60 | CC | 412,774 | 0.071 | 0.98 | 0.04 | 3,662 | 704 |
| 66 | 0 | 3 | 109 | 22 | 80 | 40 | LF | 412,787 | 0.071 | 0.97 | 0.04 | 5,555 | 1,203 |
| 67 | 0 | 0 | 109 | 33 | 80 | 60 | LF | 412,860 | 0.07 | 0.97 | 0.03 | 5,762 | 788 |
| 68 | 0 | 3 | 109 | 26 | 60 | 50 | CC | 412,869 | 0.071 | 0.97 | 0.03 | 6,632 | 1,125 |
| 69 | 5 | 0 | 109 | 26 | 60 | 60 | LF | 412,903 | 0.071 | 0.97 | 0.04 | 6,214 | 1,103 |
| 70 | 0 | 1 | 109 | 26 | 80 | 40 | LF | 412,950 | 0.071 | 0.96 | 0.03 | 6,690 | 1,233 |
| 71 | 0 | 2 | 109 | 22 | 80 | 40 | CC | 412,957 | 0.071 | 0.97 | 0.04 | 6,122 | 1,261 |
| 72 | 0 | 3 | 109 | 22 | 80 | 60 | CC | 412,997 | 0.071 | 0.98 | 0.04 | 4,133 | 799 |
| 73 | 5 | 2 | 109 | 26 | 60 | 40 | LF | 413,001 | 0.071 | 0.96 | 0.03 | 6,913 | 1,273 |
| 74 | 0 | 1 | 109 | 33 | 60 | 40 | LF | 413,069 | 0.07 | 0.95 | 0.03 | 8,905 | 1,299 |
| 75 | 5 | 2 | 109 | 26 | 60 | 50 | LF | 413,335 | 0.071 | 0.97 | 0.03 | 5,958 | 1,064 |
| 76 | 0 | 0 | 109 | 26 | 100 | 50 | LF | 413,936 | 0.071 | 0.98 | 0.03 | 4,506 | 791 |
| 77 | 5 | 1 | 109 | 22 | 80 | 60 | CC | 413,946 | 0.071 | 0.98 | 0.04 | 4,012 | 773 |
| 78 | 5 | 2 | 109 | 22 | 80 | 50 | CC | 413,971 | 0.071 | 0.98 | 0.03 | 4,284 | 847 |
| 79 | 0 | 0 | 109 | 26 | 80 | 40 | CC | 414,133 | 0.071 | 0.96 | 0.03 | 7,342 | 1,297 |
| 80 | 0 | 3 | 109 | 26 | 80 | 50 | CC | 414,139 | 0.071 | 0.97 | 0.03 | 5,013 | 845 |
| 81 | 0 | 0 | 109 | 35 | 60 | 40 | LF | 414,256 | 0.071 | 0.95 | 0.03 | 9,574 | 1,321 |
| 82 | 0 | 1 | 109 | 22 | 100 | 50 | CC | 414,593 | 0.071 | 0.98 | 0.03 | 4,009 | 788 |
| 83 | 5 | 1 | 109 | 26 | 60 | 40 | CC | 414,706 | 0.071 | 0.96 | 0.03 | 7,572 | 1,333 |
| 84 | 0 | 1 | 109 | 35 | 80 | 50 | LF | 414,911 | 0.07 | 0.97 | 0.02 | 6,230 | 825 |
| 85 | 10 | 0 | 109 | 22 | 80 | 50 | CC | 414,960 | 0.071 | 0.98 | 0.03 | 4,204 | 832 |
| 86 | 5 | 1 | 109 | 26 | 60 | 50 | CC | 414,995 | 0.071 | 0.97 | 0.03 | 6,621 | 1,125 |
| 87 | 0 | 0 | 109 | 33 | 60 | 50 | CC | 415,119 | 0.071 | 0.96 | 0.03 | 8,533 | 1,151 |
| 88 | 5 | 0 | 109 | 22 | 80 | 40 | CC | 415,161 | 0.071 | 0.97 | 0.04 | 6,154 | 1,270 |
| 89 | 5 | 3 | 109 | 22 | 80 | 50 | LF | 415,161 | 0.071 | 0.98 | 0.03 | 3,837 | 788 |
| 90 | 0 | 2 | 109 | 26 | 80 | 60 | CC | 415,207 | 0.071 | 0.97 | 0.03 | 4,849 | 801 |
| 91 | 0 | 0 | 109 | 35 | 80 | 50 | CC | 415,227 | 0.071 | 0.96 | 0.03 | 6,810 | 868 |
| 92 | 0 | 3 | 109 | 26 | 60 | 60 | LF | 415,242 | 0.071 | 0.97 | 0.04 | 6,063 | 1,073 |
| 93 | 5 | 1 | 109 | 22 | 80 | 40 | LF | 415,435 | 0.071 | 0.97 | 0.03 | 5,623 | 1,219 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 94 | 0 | 3 | 109 | 26 | 80 | 60 | LF | 415,538 | 0.071 | 0.98 | 0.03 | 4,376 | 748 |
| 95 | 5 | 2 | 109 | 22 | 80 | 60 | LF | 415,597 | 0.071 | 0.98 | 0.04 | 3,656 | 732 |
| 96 | 10 | 0 | 109 | 26 | 60 | 50 | LF | 415,623 | 0.071 | 0.97 | 0.03 | 5,970 | 1,068 |
| 97 | 10 | 2 | 109 | 22 | 60 | 40 | LF | 415,682 | 0.071 | 0.97 | 0.04 | 5,791 | 1,255 |
| 98 | 5 | 1 | 109 | 26 | 80 | 50 | CC | 415,689 | 0.071 | 0.97 | 0.03 | 4,992 | 844 |
| 99 | 0 | 1 | 109 | 35 | 60 | 50 | LF | 415,762 | 0.071 | 0.96 | 0.03 | 8,094 | 1,090 |
| 100 | 0 | 0 | 109 | 35 | 80 | 60 | LF | 415,891 | 0.071 | 0.97 | 0.03 | 6,027 | 781 |
| 101 | 10 | 0 | 109 | 26 | 60 | 40 | LF | 415,892 | 0.071 | 0.96 | 0.03 | 6,976 | 1,287 |
| 102 | 0 | 1 | 109 | 33 | 80 | 50 | CC | 416,030 | 0.071 | 0.97 | 0.03 | 6,320 | 850 |
| 103 | 0 | 2 | 109 | 33 | 60 | 50 | LF | 416,085 | 0.071 | 0.96 | 0.03 | 7,545 | 1,073 |
| 104 | 0 | 0 | 109 | 33 | 60 | 60 | LF | 416,127 | 0.071 | 0.96 | 0.03 | 7,853 | 1,109 |
| 105 | 10 | 2 | 109 | 22 | 60 | 50 | LF | 416,213 | 0.072 | 0.97 | 0.04 | 4,902 | 1,026 |
| 106 | 0 | 0 | 109 | 33 | 60 | 40 | CC | 416,225 | 0.071 | 0.95 | 0.03 | 9,713 | 1,359 |
| 107 | 10 | 1 | 109 | 22 | 80 | 50 | LF | 416,552 | 0.071 | 0.98 | 0.03 | 3,804 | 783 |
| 108 | 0 | 1 | 109 | 22 | 100 | 60 | LF | 416,562 | 0.072 | 0.98 | 0.04 | 3,425 | 683 |
| 109 | 0 | 0 | 109 | 33 | 40 | 40 | LF | 416,569 | 0.071 | 0.94 | 0.03 | 11,614 | 1,718 |
| 110 | 0 | 2 | 109 | 26 | 60 | 60 | CC | 416,617 | 0.072 | 0.96 | 0.04 | 6,700 | 1,130 |
| 111 | 0 | 0 | 109 | 26 | 100 | 50 | CC | 416,849 | 0.071 | 0.97 | 0.03 | 4,757 | 801 |
| 112 | 5 | 2 | 109 | 26 | 80 | 50 | LF | 416,892 | 0.071 | 0.98 | 0.03 | 4,541 | 798 |
| 113 | 0 | 2 | 109 | 33 | 80 | 50 | LF | 416,928 | 0.071 | 0.97 | 0.03 | 5,835 | 818 |
| 114 | 5 | 0 | 109 | 26 | 80 | 60 | CC | 417,083 | 0.071 | 0.97 | 0.03 | 4,802 | 795 |
| 115 | 5 | 1 | 109 | 26 | 60 | 60 | LF | 417,310 | 0.072 | 0.97 | 0.04 | 6,048 | 1,073 |
| 116 | 0 | 1 | 109 | 33 | 80 | 60 | LF | 417,337 | 0.071 | 0.97 | 0.03 | 5,612 | 769 |
| 117 | 5 | 1 | 109 | 26 | 80 | 60 | LF | 417,363 | 0.071 | 0.98 | 0.03 | 4,327 | 742 |
| 118 | 10 | 0 | 109 | 22 | 80 | 60 | LF | 417,399 | 0.072 | 0.98 | 0.04 | 3,605 | 724 |
| 119 | 5 | 3 | 109 | 26 | 60 | 40 | LF | 417,472 | 0.071 | 0.97 | 0.03 | 6,760 | 1,246 |
| 120 | 0 | 0 | 109 | 26 | 100 | 60 | LF | 417,498 | 0.071 | 0.98 | 0.03 | 4,060 | 692 |
| 121 | 5 | 3 | 109 | 26 | 60 | 50 | LF | 417,569 | 0.071 | 0.97 | 0.03 | 5,782 | 1,031 |
| 122 | 0 | 2 | 109 | 22 | 100 | 50 | LF | 417,927 | 0.072 | 0.98 | 0.03 | 3,731 | 769 |
| 123 | 0 | 2 | 109 | 33 | 60 | 40 | LF | 418,079 | 0.071 | 0.95 | 0.03 | 8,774 | 1,282 |
| 124 | 0 | 3 | 109 | 22 | 80 | 40 | CC | 418,139 | 0.072 | 0.97 | 0.03 | 6,007 | 1,241 |
| 125 | 5 | 0 | 109 | 33 | 60 | 50 | LF | 418,190 | 0.071 | 0.96 | 0.03 | 7,543 | 1,077 |

## Table A-4 Overall optimization for Suha

| Rank | PV (kW) | HY-5 kW | Hydro (kW) | Gen (kW) | S6CS25P | Converter (kW) | Dispatch strategy | Total NPC ($) | COE ($/kWh) | Renewable fraction | Unmet load fraction | Diesel (L/yr) | Gen (hrs/yr) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 6 | 81.2 | 35 | 100 | 60 | LF | 558,597 | 0.106 | 0.95 | 0.04 | 10,684 | 1,038 |
| 2 | 5 | 4 | 81.2 | 35 | 100 | 60 | LF | 559,534 | 0.106 | 0.95 | 0.04 | 10,538 | 1,025 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 0 | 5 | 81.2 | 35 | 100 | 60 | CC | 559,718 | 0.106 | 0.94 | 0.04 | 11,314 | 1,057 |
| 4 | 5 | 3 | 81.2 | 35 | 100 | 60 | CC | 560,108 | 0.106 | 0.94 | 0.04 | 11,128 | 1,043 |
| 5 | 10 | 2 | 81.2 | 35 | 100 | 60 | LF | 560,423 | 0.107 | 0.95 | 0.04 | 10,390 | 1,013 |
| 6 | 10 | 1 | 81.2 | 35 | 100 | 60 | CC | 561,647 | 0.107 | 0.94 | 0.04 | 11,044 | 1,036 |
| 7 | 10 | 4 | 81.2 | 33 | 100 | 60 | LF | 561,884 | 0.107 | 0.95 | 0.04 | 9,364 | 962 |
| 8 | 15 | 0 | 81.2 | 35 | 100 | 60 | LF | 562,189 | 0.107 | 0.95 | 0.04 | 10,336 | 1,008 |
| 9 | 5 | 2 | 81.2 | 35 | 120 | 60 | LF | 562,334 | 0.107 | 0.95 | 0.04 | 9,772 | 941 |
| 10 | 5 | 5 | 81.2 | 35 | 100 | 60 | LF | 562,584 | 0.107 | 0.95 | 0.03 | 10,231 | 996 |
| 11 | 0 | 7 | 81.2 | 35 | 100 | 60 | LF | 562,682 | 0.107 | 0.95 | 0.03 | 10,476 | 1,019 |
| 12 | 0 | 6 | 81.2 | 35 | 100 | 60 | CC | 562,920 | 0.107 | 0.94 | 0.03 | 11,037 | 1,032 |
| 13 | 10 | 3 | 81.2 | 35 | 100 | 60 | LF | 563,284 | 0.107 | 0.95 | 0.04 | 10,077 | 982 |
| 14 | 15 | 2 | 81.2 | 33 | 100 | 60 | LF | 563,434 | 0.107 | 0.95 | 0.04 | 9,279 | 957 |
| 15 | 10 | 0 | 81.2 | 35 | 120 | 60 | LF | 563,687 | 0.107 | 0.95 | 0.04 | 9,732 | 940 |
| 16 | 5 | 1 | 81.2 | 35 | 120 | 60 | CC | 564,073 | 0.107 | 0.95 | 0.04 | 10,526 | 982 |
| 17 | 10 | 2 | 81.2 | 35 | 100 | 60 | CC | 564,088 | 0.107 | 0.95 | 0.04 | 10,688 | 1,005 |
| 18 | 5 | 4 | 81.2 | 35 | 100 | 60 | CC | 564,191 | 0.107 | 0.95 | 0.03 | 10,918 | 1,026 |
| 19 | 5 | 2 | 81.2 | 35 | 120 | 70 | LF | 564,545 | 0.107 | 0.95 | 0.04 | 9,163 | 865 |
| 20 | 5 | 7 | 81.2 | 33 | 100 | 60 | LF | 564,581 | 0.107 | 0.95 | 0.04 | 9,260 | 952 |
| 21 | 0 | 8 | 81.2 | 33 | 100 | 60 | CC | 564,617 | 0.107 | 0.95 | 0.04 | 10,026 | 992 |
| 22 | 0 | 6 | 81.2 | 35 | 100 | 70 | LF | 564,879 | 0.107 | 0.95 | 0.04 | 10,378 | 1,000 |
| 23 | 10 | 0 | 81.2 | 35 | 120 | 70 | LF | 565,140 | 0.108 | 0.95 | 0.04 | 9,056 | 857 |
| 24 | 15 | 1 | 81.2 | 35 | 100 | 60 | LF | 565,264 | 0.107 | 0.95 | 0.04 | 10,032 | 981 |
| 25 | 5 | 4 | 81.2 | 35 | 100 | 70 | LF | 565,397 | 0.107 | 0.95 | 0.04 | 10,193 | 981 |
| 26 | 10 | 5 | 81.2 | 33 | 100 | 60 | LF | 565,469 | 0.107 | 0.96 | 0.04 | 9,110 | 938 |
| 27 | 5 | 6 | 81.2 | 33 | 100 | 60 | CC | 565,731 | 0.107 | 0.95 | 0.04 | 9,894 | 982 |
| 28 | 0 | 8 | 81.2 | 35 | 100 | 60 | LF | 565,847 | 0.107 | 0.95 | 0.03 | 10,172 | 990 |
| 29 | 10 | 2 | 81.2 | 35 | 100 | 70 | LF | 565,968 | 0.108 | 0.95 | 0.04 | 10,018 | 964 |
| 30 | 0 | 5 | 81.2 | 35 | 100 | 70 | CC | 566,170 | 0.108 | 0.94 | 0.04 | 11,030 | 1,023 |
| 31 | 0 | 5 | 81.2 | 35 | 120 | 60 | LF | 566,223 | 0.108 | 0.95 | 0.04 | 9,689 | 936 |
| 32 | 5 | 3 | 81.2 | 35 | 100 | 70 | CC | 566,230 | 0.108 | 0.95 | 0.04 | 10,807 | 1,004 |
| 33 | 5 | 1 | 81.2 | 35 | 120 | 70 | CC | 566,243 | 0.108 | 0.95 | 0.04 | 9,911 | 911 |
| 34 | 5 | 6 | 81.2 | 35 | 100 | 60 | LF | 566,278 | 0.107 | 0.95 | 0.03 | 10,001 | 975 |
| 35 | 15 | 0 | 81.2 | 35 | 100 | 60 | CC | 566,359 | 0.108 | 0.95 | 0.04 | 10,683 | 1,007 |
| 36 | 5 | 3 | 81.2 | 35 | 120 | 60 | LF | 566,381 | 0.108 | 0.95 | 0.04 | 9,545 | 922 |
| 37 | 10 | 4 | 81.2 | 33 | 100 | 60 | CC | 566,427 | 0.108 | 0.95 | 0.04 | 9,736 | 969 |
| 38 | 0 | 0 | 81.2 | 44 | 100 | 60 | LF | 566,447 | 0.107 | 0.92 | 0.03 | 14,928 | 1,173 |
| 39 | 10 | 4 | 81.2 | 35 | 100 | 60 | LF | 566,778 | 0.108 | 0.95 | 0.03 | 9,822 | 958 |
| 40 | 0 | 4 | 81.2 | 35 | 120 | 60 | CC | 566,979 | 0.108 | 0.95 | 0.04 | 10,357 | 966 |
| 41 | 0 | 7 | 81.2 | 35 | 100 | 60 | CC | 567,047 | 0.108 | 0.95 | 0.03 | 10,839 | 1,017 |
| 42 | 15 | 3 | 81.2 | 33 | 100 | 60 | LF | 567,106 | 0.108 | 0.96 | 0.04 | 9,039 | 935 |
| 43 | 10 | 1 | 81.2 | 35 | 120 | 60 | LF | 567,141 | 0.108 | 0.95 | 0.04 | 9,452 | 916 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 44 | 5 | 5 | 81.2 | 35 | 100 | 60 | CC | 567,221 | 0.108 | 0.95 | 0.03 | 10,611 | 997 |
| 45 | 10 | 4 | 81.2 | 33 | 100 | 70 | LF | 567,367 | 0.108 | 0.96 | 0.04 | 8,990 | 911 |
| 46 | 10 | 3 | 81.2 | 35 | 100 | 60 | CC | 567,414 | 0.108 | 0.95 | 0.03 | 10,415 | 980 |
| 47 | 5 | 2 | 81.2 | 35 | 120 | 60 | CC | 567,463 | 0.108 | 0.95 | 0.04 | 10,240 | 958 |
| 48 | 15 | 2 | 81.2 | 33 | 100 | 60 | CC | 567,466 | 0.108 | 0.95 | 0.04 | 9,607 | 958 |
| 49 | 15 | 0 | 81.2 | 33 | 120 | 60 | LF | 567,552 | 0.108 | 0.96 | 0.04 | 8,726 | 894 |
| 50 | 15 | 0 | 81.2 | 35 | 100 | 70 | LF | 567,594 | 0.108 | 0.95 | 0.04 | 9,953 | 959 |
| 51 | 10 | 1 | 81.2 | 35 | 100 | 70 | CC | 567,663 | 0.108 | 0.95 | 0.04 | 10,718 | 999 |
| 52 | 5 | 8 | 81.2 | 33 | 100 | 60 | LF | 568,117 | 0.108 | 0.96 | 0.03 | 9,012 | 926 |
| 53 | 5 | 7 | 81.2 | 33 | 100 | 60 | CC | 568,333 | 0.108 | 0.95 | 0.03 | 9,565 | 948 |
| 54 | 0 | 7 | 81.2 | 35 | 100 | 70 | LF | 568,379 | 0.108 | 0.95 | 0.03 | 10,132 | 975 |
| 55 | 20 | 1 | 81.2 | 33 | 100 | 60 | LF | 568,391 | 0.108 | 0.96 | 0.04 | 8,948 | 923 |
| 56 | 15 | 2 | 81.2 | 35 | 100 | 60 | LF | 568,511 | 0.108 | 0.95 | 0.03 | 9,753 | 954 |
| 57 | 15 | 2 | 81.2 | 33 | 100 | 70 | LF | 568,567 | 0.108 | 0.96 | 0.04 | 8,874 | 902 |
| 58 | 5 | 3 | 81.2 | 35 | 120 | 70 | LF | 568,589 | 0.108 | 0.95 | 0.04 | 8,935 | 847 |
| 59 | 5 | 5 | 81.2 | 35 | 100 | 70 | LF | 568,720 | 0.108 | 0.95 | 0.04 | 9,920 | 956 |
| 60 | 10 | 1 | 81.2 | 35 | 120 | 70 | LF | 568,794 | 0.108 | 0.96 | 0.04 | 8,794 | 834 |
| 61 | 10 | 3 | 81.2 | 35 | 100 | 70 | LF | 568,807 | 0.108 | 0.95 | 0.04 | 9,703 | 935 |
| 62 | 15 | 0 | 81.2 | 33 | 120 | 70 | LF | 568,823 | 0.108 | 0.96 | 0.04 | 8,036 | 805 |
| 63 | 20 | 0 | 81.2 | 33 | 100 | 60 | CC | 568,834 | 0.108 | 0.95 | 0.04 | 9,536 | 951 |
| 64 | 10 | 0 | 81.2 | 35 | 120 | 60 | CC | 568,836 | 0.108 | 0.95 | 0.04 | 10,202 | 957 |
| 65 | 0 | 1 | 81.2 | 44 | 100 | 60 | LF | 568,937 | 0.107 | 0.93 | 0.03 | 14,571 | 1,149 |
| 66 | 15 | 1 | 81.2 | 35 | 100 | 60 | CC | 568,963 | 0.108 | 0.95 | 0.03 | 10,332 | 976 |
| 67 | 0 | 5 | 81.2 | 35 | 120 | 70 | LF | 568,993 | 0.108 | 0.95 | 0.04 | 9,129 | 866 |
| 68 | 0 | 8 | 81.2 | 35 | 100 | 60 | CC | 569,011 | 0.108 | 0.95 | 0.03 | 10,449 | 978 |
| 69 | 0 | 6 | 81.2 | 35 | 100 | 70 | CC | 569,298 | 0.108 | 0.95 | 0.04 | 10,737 | 997 |
| 70 | 0 | 7 | 81.2 | 33 | 120 | 60 | LF | 569,335 | 0.108 | 0.96 | 0.04 | 8,776 | 897 |
| 71 | 10 | 6 | 81.2 | 33 | 100 | 60 | LF | 569,351 | 0.108 | 0.96 | 0.03 | 8,891 | 917 |
| 72 | 5 | 7 | 81.2 | 35 | 100 | 60 | LF | 569,398 | 0.108 | 0.95 | 0.03 | 9,711 | 946 |
| 73 | 10 | 0 | 81.2 | 35 | 120 | 70 | CC | 569,543 | 0.108 | 0.95 | 0.04 | 9,458 | 871 |
| 74 | 10 | 5 | 81.2 | 33 | 100 | 60 | CC | 569,548 | 0.108 | 0.95 | 0.03 | 9,444 | 941 |
| 75 | 0 | 4 | 81.2 | 35 | 120 | 70 | CC | 569,566 | 0.108 | 0.95 | 0.04 | 9,779 | 898 |
| 76 | 5 | 2 | 81.2 | 35 | 120 | 70 | CC | 569,640 | 0.108 | 0.95 | 0.04 | 9,625 | 886 |
| 77 | 5 | 4 | 81.2 | 33 | 120 | 60 | CC | 569,663 | 0.108 | 0.95 | 0.04 | 9,244 | 914 |
| 78 | 0 | 6 | 81.2 | 35 | 120 | 60 | LF | 569,731 | 0.108 | 0.95 | 0.03 | 9,414 | 911 |
| 79 | 0 | 6 | 81.2 | 33 | 120 | 60 | CC | 569,771 | 0.108 | 0.95 | 0.04 | 9,413 | 930 |
| 80 | 5 | 4 | 81.2 | 35 | 100 | 70 | CC | 569,866 | 0.108 | 0.95 | 0.04 | 10,556 | 982 |
| 81 | 20 | 0 | 81.2 | 35 | 100 | 60 | LF | 569,966 | 0.108 | 0.95 | 0.04 | 9,693 | 945 |
| 82 | 5 | 5 | 81.2 | 33 | 120 | 60 | LF | 570,041 | 0.108 | 0.96 | 0.04 | 8,679 | 890 |
| 83 | 10 | 2 | 81.2 | 35 | 100 | 70 | CC | 570,073 | 0.108 | 0.95 | 0.04 | 10,355 | 963 |
| 84 | 10 | 5 | 81.2 | 35 | 100 | 60 | LF | 570,134 | 0.108 | 0.95 | 0.03 | 9,551 | 932 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 85 | 10 | 3 | 81.2 | 33 | 120 | 60 | LF | 570,294 | 0.108 | 0.96 | 0.04 | 8,543 | 876 |
| 86 | 5 | 6 | 81.2 | 35 | 100 | 60 | CC | 570,332 | 0.108 | 0.95 | 0.03 | 10,331 | 971 |
| 87 | 5 | 7 | 81.2 | 33 | 100 | 70 | LF | 570,370 | 0.108 | 0.96 | 0.04 | 8,911 | 905 |
| 88 | 15 | 4 | 81.2 | 33 | 100 | 60 | LF | 570,372 | 0.108 | 0.96 | 0.03 | 8,763 | 906 |
| 89 | 5 | 4 | 81.2 | 35 | 120 | 60 | LF | 570,386 | 0.108 | 0.95 | 0.03 | 9,313 | 903 |
| 90 | 15 | 1 | 81.2 | 35 | 100 | 70 | LF | 570,496 | 0.108 | 0.95 | 0.04 | 9,634 | 929 |
| 91 | 10 | 5 | 81.2 | 33 | 100 | 70 | LF | 570,795 | 0.108 | 0.96 | 0.04 | 8,721 | 885 |
| 92 | 0 | 2 | 81.2 | 44 | 100 | 60 | LF | 570,850 | 0.108 | 0.93 | 0.03 | 14,158 | 1,116 |
| 93 | 0 | 5 | 81.2 | 35 | 120 | 60 | CC | 570,864 | 0.108 | 0.95 | 0.03 | 10,116 | 943 |
| 94 | 10 | 2 | 81.2 | 35 | 120 | 60 | LF | 570,878 | 0.108 | 0.95 | 0.03 | 9,198 | 892 |
| 95 | 0 | 8 | 81.2 | 33 | 100 | 70 | CC | 570,924 | 0.108 | 0.95 | 0.04 | 9,729 | 955 |
| 96 | 5 | 6 | 81.2 | 33 | 100 | 70 | CC | 570,963 | 0.109 | 0.95 | 0.04 | 9,496 | 933 |
| 97 | 10 | 2 | 81.2 | 33 | 120 | 60 | CC | 571,049 | 0.109 | 0.95 | 0.04 | 9,207 | 914 |
| 98 | 10 | 4 | 81.2 | 35 | 100 | 60 | CC | 571,087 | 0.108 | 0.95 | 0.03 | 10,175 | 959 |
| 99 | 15 | 3 | 81.2 | 33 | 100 | 60 | CC | 571,163 | 0.108 | 0.95 | 0.04 | 9,374 | 937 |
| 100 | 15 | 0 | 81.2 | 35 | 100 | 70 | CC | 571,227 | 0.109 | 0.95 | 0.04 | 10,253 | 955 |
| 101 | 5 | 0 | 81.2 | 44 | 100 | 60 | LF | 571,293 | 0.108 | 0.93 | 0.03 | 13,987 | 1,100 |
| 102 | 5 | 3 | 81.2 | 35 | 120 | 60 | CC | 571,355 | 0.108 | 0.95 | 0.03 | 9,998 | 938 |
| 103 | 15 | 1 | 81.2 | 33 | 120 | 60 | LF | 571,548 | 0.109 | 0.96 | 0.04 | 8,495 | 873 |
| 104 | 0 | 7 | 81.2 | 33 | 120 | 70 | LF | 571,626 | 0.109 | 0.96 | 0.04 | 8,174 | 820 |
| 105 | 5 | 6 | 81.2 | 35 | 100 | 70 | LF | 571,729 | 0.108 | 0.95 | 0.03 | 9,613 | 926 |
| 106 | 10 | 4 | 81.2 | 33 | 100 | 70 | CC | 571,786 | 0.109 | 0.95 | 0.04 | 9,353 | 919 |
| 107 | 0 | 8 | 81.2 | 35 | 100 | 70 | LF | 571,864 | 0.108 | 0.95 | 0.03 | 9,868 | 952 |
| 108 | 15 | 3 | 81.2 | 35 | 100 | 60 | LF | 571,928 | 0.108 | 0.95 | 0.03 | 9,499 | 930 |
| 109 | 5 | 5 | 81.2 | 33 | 120 | 70 | LF | 571,957 | 0.109 | 0.96 | 0.04 | 8,045 | 808 |
| 110 | 0 | 6 | 81.2 | 33 | 120 | 70 | CC | 571,991 | 0.109 | 0.95 | 0.04 | 8,803 | 856 |
| 111 | 20 | 2 | 81.2 | 33 | 100 | 60 | LF | 572,012 | 0.109 | 0.96 | 0.04 | 8,695 | 899 |
| 112 | 15 | 0 | 81.2 | 33 | 120 | 60 | CC | 572,032 | 0.109 | 0.95 | 0.04 | 9,134 | 910 |
| 113 | 10 | 4 | 81.2 | 35 | 100 | 70 | LF | 572,130 | 0.109 | 0.95 | 0.03 | 9,431 | 908 |
| 114 | 10 | 3 | 81.2 | 33 | 120 | 70 | LF | 572,160 | 0.109 | 0.96 | 0.04 | 7,905 | 793 |
| 115 | 0 | 6 | 81.2 | 35 | 120 | 70 | LF | 572,220 | 0.109 | 0.96 | 0.04 | 8,829 | 839 |
| 116 | 0 | 0 | 81.2 | 44 | 100 | 60 | CC | 572,301 | 0.108 | 0.92 | 0.03 | 15,389 | 1,160 |
| 117 | 15 | 0 | 81.2 | 35 | 120 | 60 | LF | 572,302 | 0.109 | 0.95 | 0.03 | 9,165 | 890 |
| 118 | 5 | 4 | 81.2 | 33 | 120 | 70 | CC | 572,304 | 0.109 | 0.96 | 0.04 | 8,672 | 844 |
| 119 | 15 | 3 | 81.2 | 33 | 100 | 70 | LF | 572,340 | 0.109 | 0.96 | 0.04 | 8,644 | 881 |
| 120 | 0 | 0 | 81.2 | 44 | 120 | 60 | LF | 572,354 | 0.108 | 0.93 | 0.03 | 13,222 | 1,030 |
| 121 | 20 | 1 | 81.2 | 33 | 100 | 60 | CC | 572,362 | 0.109 | 0.95 | 0.04 | 9,271 | 925 |
| 122 | 15 | 2 | 81.2 | 33 | 100 | 70 | CC | 572,391 | 0.109 | 0.95 | 0.04 | 9,185 | 903 |
| 123 | 10 | 2 | 81.2 | 35 | 120 | 70 | LF | 572,447 | 0.109 | 0.96 | 0.04 | 8,532 | 810 |
| 124 | 15 | 2 | 81.2 | 35 | 100 | 60 | CC | 572,463 | 0.109 | 0.95 | 0.03 | 10,072 | 952 |
| 125 | 5 | 8 | 81.2 | 33 | 100 | 60 | CC | 572,486 | 0.109 | 0.95 | 0.03 | 9,369 | 931 |

## Table A-5 Overall optimization for Muga I

| Rank | PV (kW) | HY-5 kW | Hydro (kW) | Gen (kW) | S6CS25P | Converter (kW) | Dispatch strategy | Total NPC ($) | COE ($/kWh) | Renewable fraction | Unmet load fraction | Diesel (L) | Gen (hrs) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 20 | 2 | 193 | 132 | 320 | 190 | LF | 1,681,425 | 0.11 | 0.88 | 0.03 | 46,459 | 1,668 |
| 2 | 20 | 2 | 193 | 132 | 320 | 180 | LF | 1,682,372 | 0.11 | 0.88 | 0.03 | 47,482 | 1,728 |
| 3 | 30 | 0 | 193 | 132 | 320 | 190 | LF | 1,683,941 | 0.11 | 0.88 | 0.03 | 45,136 | 1,624 |
| 4 | 20 | 2 | 193 | 132 | 360 | 200 | LF | 1,684,171 | 0.11 | 0.89 | 0.03 | 41,478 | 1,463 |
| 5 | 20 | 4 | 193 | 132 | 320 | 190 | LF | 1,685,163 | 0.11 | 0.88 | 0.03 | 45,632 | 1,643 |
| 6 | 20 | 4 | 193 | 132 | 320 | 180 | LF | 1,685,477 | 0.11 | 0.88 | 0.03 | 46,615 | 1,701 |
| 7 | 20 | 4 | 193 | 132 | 360 | 200 | LF | 1,685,866 | 0.11 | 0.89 | 0.03 | 40,488 | 1,427 |
| 8 | 30 | 0 | 193 | 132 | 360 | 200 | LF | 1,685,969 | 0.11 | 0.89 | 0.03 | 40,186 | 1,421 |
| 9 | 10 | 8 | 193 | 132 | 320 | 190 | LF | 1,685,976 | 0.11 | 0.88 | 0.03 | 46,052 | 1,657 |
| 10 | 30 | 0 | 193 | 132 | 320 | 180 | LF | 1,686,535 | 0.11 | 0.88 | 0.03 | 46,398 | 1,695 |
| 11 | 20 | 2 | 193 | 132 | 360 | 190 | LF | 1,686,688 | 0.11 | 0.89 | 0.03 | 42,578 | 1,522 |
| 12 | 10 | 6 | 193 | 132 | 360 | 190 | LF | 1,686,862 | 0.11 | 0.89 | 0.03 | 42,902 | 1,531 |
| 13 | 40 | 16 | 193 | 114 | 360 | 200 | LF | 1,687,001 | 0.111 | 0.93 | 0.03 | 28,731 | 1,165 |
| 14 | 10 | 8 | 193 | 132 | 320 | 180 | LF | 1,687,056 | 0.11 | 0.88 | 0.03 | 47,057 | 1,716 |
| 15 | 20 | 2 | 193 | 132 | 320 | 200 | LF | 1,687,351 | 0.11 | 0.88 | 0.03 | 45,970 | 1,640 |
| 16 | 0 | 10 | 193 | 132 | 320 | 180 | LF | 1,687,587 | 0.11 | 0.87 | 0.03 | 48,539 | 1,768 |
| 17 | 50 | 12 | 193 | 114 | 360 | 200 | LF | 1,687,901 | 0.111 | 0.93 | 0.03 | 28,422 | 1,156 |
| 18 | 30 | 0 | 193 | 132 | 320 | 200 | LF | 1,688,312 | 0.111 | 0.88 | 0.03 | 44,477 | 1,588 |
| 19 | 10 | 6 | 193 | 132 | 360 | 200 | LF | 1,688,347 | 0.11 | 0.89 | 0.03 | 42,145 | 1,487 |
| 20 | 30 | 2 | 193 | 132 | 320 | 190 | LF | 1,688,579 | 0.11 | 0.88 | 0.03 | 44,370 | 1,604 |
| 21 | 10 | 10 | 193 | 132 | 320 | 190 | LF | 1,688,954 | 0.11 | 0.88 | 0.03 | 45,147 | 1,623 |
| 22 | 0 | 10 | 193 | 132 | 320 | 190 | LF | 1,689,069 | 0.11 | 0.87 | 0.03 | 47,790 | 1,723 |
| 23 | 20 | 6 | 193 | 132 | 360 | 200 | LF | 1,689,245 | 0.11 | 0.9 | 0.03 | 39,641 | 1,399 |
| 24 | 20 | 6 | 193 | 132 | 320 | 190 | LF | 1,689,333 | 0.11 | 0.88 | 0.03 | 44,831 | 1,619 |
| 25 | 30 | 2 | 193 | 132 | 360 | 200 | LF | 1,689,366 | 0.11 | 0.9 | 0.03 | 39,340 | 1,394 |
| 26 | 30 | 0 | 193 | 132 | 360 | 190 | LF | 1,689,427 | 0.11 | 0.89 | 0.03 | 41,364 | 1,487 |
| 27 | 30 | 2 | 193 | 132 | 320 | 180 | LF | 1,689,458 | 0.11 | 0.88 | 0.03 | 45,517 | 1,665 |
| 28 | 20 | 4 | 193 | 132 | 280 | 180 | LF | 1,689,610 | 0.111 | 0.87 | 0.03 | 50,823 | 1,861 |
| 29 | 60 | 8 | 193 | 114 | 360 | 200 | LF | 1,689,670 | 0.111 | 0.93 | 0.03 | 28,146 | 1,148 |
| 30 | 20 | 4 | 193 | 132 | 360 | 190 | LF | 1,689,677 | 0.11 | 0.89 | 0.03 | 41,697 | 1,493 |
| 31 | 20 | 4 | 193 | 132 | 320 | 200 | LF | 1,689,856 | 0.111 | 0.88 | 0.03 | 45,004 | 1,608 |
| 32 | 0 | 12 | 193 | 132 | 320 | 190 | LF | 1,690,096 | 0.11 | 0.88 | 0.03 | 46,750 | 1,683 |
| 33 | 10 | 10 | 193 | 132 | 320 | 180 | LF | 1,690,242 | 0.11 | 0.88 | 0.03 | 46,201 | 1,683 |
| 34 | 20 | 2 | 193 | 132 | 360 | 210 | LF | 1,690,385 | 0.111 | 0.89 | 0.03 | 41,126 | 1,438 |
| 35 | 10 | 8 | 193 | 132 | 360 | 200 | LF | 1,690,468 | 0.111 | 0.89 | 0.03 | 41,190 | 1,456 |
| 36 | 0 | 12 | 193 | 132 | 320 | 180 | LF | 1,690,528 | 0.11 | 0.88 | 0.03 | 47,662 | 1,735 |
| 37 | 30 | 0 | 193 | 132 | 360 | 210 | LF | 1,690,871 | 0.111 | 0.89 | 0.03 | 39,721 | 1,392 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 38 | 10 | 8 | 193 | 132 | 280 | 180 | LF | 1,690,950 | 0.111 | 0.87 | 0.03 | 51,296 | 1,877 |
| 39 | 20 | 6 | 193 | 132 | 320 | 180 | LF | 1,691,158 | 0.11 | 0.88 | 0.03 | 45,967 | 1,683 |
| 40 | 30 | 4 | 193 | 132 | 320 | 190 | LF | 1,691,335 | 0.111 | 0.89 | 0.03 | 43,452 | 1,569 |
| 41 | 40 | 0 | 193 | 132 | 320 | 190 | LF | 1,691,404 | 0.111 | 0.89 | 0.03 | 43,045 | 1,552 |
| 42 | 20 | 0 | 193 | 132 | 400 | 200 | LF | 1,691,495 | 0.111 | 0.9 | 0.03 | 38,827 | 1,366 |
| 43 | 10 | 8 | 193 | 132 | 360 | 190 | LF | 1,691,554 | 0.111 | 0.89 | 0.03 | 42,166 | 1,512 |
| 44 | 10 | 8 | 193 | 132 | 320 | 200 | LF | 1,691,699 | 0.111 | 0.88 | 0.03 | 45,545 | 1,627 |
| 45 | 40 | 0 | 193 | 132 | 360 | 200 | LF | 1,691,701 | 0.111 | 0.9 | 0.03 | 38,096 | 1,350 |
| 46 | 30 | 2 | 193 | 132 | 320 | 200 | LF | 1,691,967 | 0.111 | 0.89 | 0.03 | 43,613 | 1,559 |
| 47 | 30 | 4 | 193 | 132 | 360 | 200 | LF | 1,692,136 | 0.111 | 0.9 | 0.03 | 38,442 | 1,362 |
| 48 | 20 | 4 | 193 | 132 | 360 | 210 | LF | 1,692,642 | 0.111 | 0.89 | 0.03 | 40,182 | 1,407 |
| 49 | 10 | 12 | 193 | 132 | 320 | 190 | LF | 1,692,813 | 0.111 | 0.88 | 0.03 | 44,328 | 1,595 |
| 50 | 0 | 10 | 193 | 132 | 360 | 190 | LF | 1,692,916 | 0.111 | 0.88 | 0.03 | 43,730 | 1,563 |
| 51 | 20 | 6 | 193 | 132 | 320 | 200 | LF | 1,693,072 | 0.111 | 0.88 | 0.03 | 44,090 | 1,575 |
| 52 | 20 | 8 | 193 | 132 | 320 | 190 | LF | 1,693,116 | 0.111 | 0.89 | 0.03 | 43,960 | 1,590 |
| 53 | 20 | 6 | 193 | 132 | 280 | 180 | LF | 1,693,181 | 0.111 | 0.87 | 0.03 | 49,967 | 1,832 |
| 54 | 10 | 10 | 193 | 132 | 360 | 200 | LF | 1,693,190 | 0.111 | 0.89 | 0.03 | 40,287 | 1,424 |
| 55 | 70 | 4 | 193 | 114 | 360 | 200 | LF | 1,693,214 | 0.111 | 0.93 | 0.03 | 28,028 | 1,148 |
| 56 | 50 | 12 | 193 | 114 | 360 | 210 | LF | 1,693,282 | 0.111 | 0.93 | 0.03 | 27,877 | 1,123 |
| 57 | 40 | 16 | 193 | 114 | 360 | 210 | LF | 1,693,292 | 0.111 | 0.93 | 0.03 | 28,291 | 1,139 |
| 58 | 30 | 2 | 193 | 132 | 280 | 180 | LF | 1,693,325 | 0.111 | 0.87 | 0.03 | 49,615 | 1,820 |
| 59 | 40 | 18 | 193 | 114 | 360 | 200 | LF | 1,693,398 | 0.111 | 0.93 | 0.03 | 28,145 | 1,144 |
| 60 | 30 | 4 | 193 | 132 | 320 | 180 | LF | 1,693,406 | 0.111 | 0.88 | 0.03 | 44,724 | 1,638 |
| 61 | 20 | 4 | 193 | 132 | 280 | 170 | LF | 1,693,636 | 0.111 | 0.87 | 0.03 | 52,448 | 1,952 |
| 62 | 10 | 8 | 193 | 132 | 280 | 170 | LF | 1,693,791 | 0.111 | 0.86 | 0.03 | 52,791 | 1,959 |
| 63 | 20 | 4 | 193 | 132 | 280 | 190 | LF | 1,693,890 | 0.111 | 0.87 | 0.03 | 50,182 | 1,819 |
| 64 | 10 | 10 | 193 | 132 | 280 | 180 | LF | 1,693,923 | 0.111 | 0.87 | 0.03 | 50,393 | 1,843 |
| 65 | 60 | 0 | 193 | 114 | 400 | 210 | CC | 1,693,934 | 0.111 | 0.93 | 0.04 | 27,978 | 1,070 |
| 66 | 30 | 2 | 193 | 132 | 360 | 210 | LF | 1,693,979 | 0.111 | 0.9 | 0.03 | 38,851 | 1,362 |
| 67 | 20 | 8 | 193 | 132 | 360 | 200 | LF | 1,694,054 | 0.111 | 0.9 | 0.03 | 38,916 | 1,377 |
| 68 | 10 | 10 | 193 | 132 | 320 | 200 | LF | 1,694,062 | 0.111 | 0.88 | 0.03 | 44,559 | 1,589 |
| 69 | 50 | 14 | 193 | 114 | 360 | 200 | LF | 1,694,077 | 0.111 | 0.93 | 0.03 | 27,801 | 1,131 |
| 70 | 30 | 2 | 193 | 132 | 360 | 190 | LF | 1,694,132 | 0.111 | 0.89 | 0.03 | 40,634 | 1,459 |
| 71 | 20 | 6 | 193 | 132 | 360 | 190 | LF | 1,694,153 | 0.111 | 0.89 | 0.03 | 40,945 | 1,468 |
| 72 | 0 | 14 | 193 | 132 | 320 | 190 | LF | 1,694,255 | 0.111 | 0.88 | 0.03 | 45,976 | 1,655 |
| 73 | 10 | 12 | 193 | 132 | 320 | 180 | LF | 1,694,394 | 0.111 | 0.88 | 0.03 | 45,425 | 1,657 |
| 74 | 40 | 2 | 193 | 132 | 360 | 200 | LF | 1,694,520 | 0.111 | 0.9 | 0.03 | 37,203 | 1,317 |
| 75 | 60 | 8 | 193 | 114 | 360 | 210 | LF | 1,694,573 | 0.111 | 0.93 | 0.03 | 27,552 | 1,111 |
| 76 | 20 | 2 | 193 | 132 | 400 | 200 | LF | 1,694,790 | 0.111 | 0.9 | 0.03 | 37,973 | 1,336 |
| 77 | 50 | 8 | 193 | 114 | 400 | 210 | LF | 1,694,828 | 0.111 | 0.93 | 0.04 | 26,069 | 1,042 |
| 78 | 0 | 10 | 193 | 132 | 320 | 200 | LF | 1,694,924 | 0.111 | 0.88 | 0.03 | 47,389 | 1,700 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 79 | 40 | 0 | 193 | 132 | 320 | 180 | LF | 1,694,994 | 0.111 | 0.89 | 0.03 | 44,553 | 1,632 |
| 80 | 40 | 0 | 193 | 132 | 320 | 200 | LF | 1,695,002 | 0.111 | 0.89 | 0.03 | 42,309 | 1,509 |
| 81 | 60 | 10 | 193 | 114 | 360 | 200 | LF | 1,695,003 | 0.111 | 0.93 | 0.03 | 27,464 | 1,120 |
| 82 | 70 | 0 | 193 | 114 | 400 | 210 | LF | 1,695,009 | 0.111 | 0.93 | 0.04 | 25,468 | 1,020 |
| 83 | 10 | 4 | 193 | 132 | 400 | 200 | LF | 1,695,017 | 0.111 | 0.89 | 0.03 | 39,440 | 1,384 |
| 84 | 30 | 4 | 193 | 132 | 320 | 200 | LF | 1,695,081 | 0.111 | 0.89 | 0.03 | 42,690 | 1,527 |
| 85 | 0 | 14 | 193 | 132 | 320 | 180 | LF | 1,695,133 | 0.111 | 0.88 | 0.03 | 46,925 | 1,710 |
| 86 | 60 | 4 | 193 | 114 | 400 | 210 | LF | 1,695,173 | 0.111 | 0.93 | 0.04 | 25,790 | 1,033 |
| 87 | 30 | 6 | 193 | 132 | 320 | 190 | LF | 1,695,224 | 0.111 | 0.89 | 0.03 | 42,606 | 1,541 |
| 88 | 40 | 16 | 193 | 114 | 360 | 190 | LF | 1,695,244 | 0.111 | 0.92 | 0.03 | 30,319 | 1,253 |
| 89 | 50 | 8 | 193 | 114 | 400 | 200 | LF | 1,695,425 | 0.111 | 0.93 | 0.03 | 27,005 | 1,094 |
| 90 | 10 | 10 | 193 | 132 | 360 | 190 | LF | 1,695,425 | 0.111 | 0.89 | 0.03 | 41,364 | 1,480 |
| 91 | 50 | 12 | 193 | 114 | 360 | 190 | LF | 1,695,431 | 0.111 | 0.92 | 0.03 | 30,026 | 1,245 |
| 92 | 20 | 8 | 193 | 132 | 320 | 180 | LF | 1,695,479 | 0.111 | 0.88 | 0.03 | 45,206 | 1,657 |
| 93 | 40 | 2 | 193 | 132 | 320 | 190 | LF | 1,695,535 | 0.111 | 0.89 | 0.03 | 42,244 | 1,527 |
| 94 | 30 | 6 | 193 | 132 | 360 | 200 | LF | 1,695,611 | 0.111 | 0.9 | 0.03 | 37,604 | 1,333 |
| 95 | 20 | 2 | 193 | 132 | 320 | 210 | LF | 1,695,805 | 0.111 | 0.88 | 0.03 | 45,774 | 1,628 |
| 96 | 10 | 6 | 193 | 132 | 360 | 210 | LF | 1,695,877 | 0.111 | 0.89 | 0.03 | 41,905 | 1,469 |
| 97 | 10 | 8 | 193 | 132 | 280 | 190 | LF | 1,695,910 | 0.111 | 0.87 | 0.03 | 50,722 | 1,838 |
| 98 | 20 | 0 | 193 | 132 | 400 | 210 | LF | 1,695,920 | 0.111 | 0.9 | 0.03 | 38,322 | 1,333 |
| 99 | 30 | 4 | 193 | 132 | 280 | 180 | LF | 1,695,946 | 0.111 | 0.88 | 0.03 | 48,668 | 1,786 |
| 100 | 0 | 10 | 193 | 132 | 360 | 200 | LF | 1,695,975 | 0.111 | 0.89 | 0.03 | 43,108 | 1,525 |
| 101 | 0 | 12 | 193 | 132 | 360 | 190 | LF | 1,696,006 | 0.111 | 0.89 | 0.03 | 42,858 | 1,534 |
| 102 | 10 | 12 | 193 | 132 | 360 | 200 | LF | 1,696,096 | 0.111 | 0.9 | 0.03 | 39,402 | 1,390 |
| 103 | 30 | 0 | 193 | 132 | 400 | 200 | LF | 1,696,200 | 0.111 | 0.9 | 0.03 | 36,648 | 1,293 |
| 104 | 20 | 6 | 193 | 132 | 280 | 190 | LF | 1,696,258 | 0.111 | 0.87 | 0.03 | 49,191 | 1,783 |
| 105 | 60 | 10 | 193 | 114 | 320 | 190 | LF | 1,696,293 | 0.111 | 0.92 | 0.03 | 32,305 | 1,347 |
| 106 | 30 | 0 | 193 | 132 | 320 | 210 | LF | 1,696,356 | 0.111 | 0.88 | 0.03 | 44,247 | 1,571 |
| 107 | 40 | 0 | 193 | 132 | 360 | 210 | LF | 1,696,364 | 0.111 | 0.9 | 0.03 | 37,610 | 1,321 |
| 108 | 20 | 6 | 193 | 132 | 360 | 210 | LF | 1,696,376 | 0.111 | 0.9 | 0.03 | 39,364 | 1,384 |
| 109 | 0 | 12 | 193 | 132 | 320 | 200 | LF | 1,696,495 | 0.111 | 0.88 | 0.03 | 46,348 | 1,658 |
| 110 | 30 | 0 | 193 | 132 | 400 | 210 | LF | 1,696,589 | 0.111 | 0.9 | 0.03 | 35,797 | 1,245 |
| 111 | 20 | 4 | 193 | 132 | 400 | 200 | LF | 1,696,716 | 0.111 | 0.9 | 0.03 | 37,001 | 1,304 |
| 112 | 30 | 4 | 193 | 132 | 360 | 210 | LF | 1,696,759 | 0.111 | 0.9 | 0.03 | 37,952 | 1,334 |
| 113 | 60 | 4 | 193 | 114 | 400 | 200 | LF | 1,696,771 | 0.111 | 0.93 | 0.03 | 26,812 | 1,089 |
| 114 | 20 | 10 | 193 | 132 | 320 | 190 | LF | 1,696,904 | 0.111 | 0.89 | 0.03 | 43,149 | 1,557 |
| 115 | 30 | 22 | 193 | 114 | 360 | 200 | LF | 1,697,010 | 0.111 | 0.93 | 0.03 | 28,762 | 1,171 |
| 116 | 20 | 8 | 193 | 132 | 280 | 180 | LF | 1,697,036 | 0.111 | 0.87 | 0.03 | 49,127 | 1,801 |
| 117 | 70 | 4 | 193 | 114 | 360 | 210 | LF | 1,697,160 | 0.111 | 0.93 | 0.03 | 27,329 | 1,106 |
| 118 | 30 | 2 | 193 | 132 | 280 | 190 | LF | 1,697,169 | 0.111 | 0.87 | 0.03 | 48,909 | 1,777 |
| 119 | 40 | 0 | 193 | 132 | 360 | 190 | LF | 1,697,357 | 0.111 | 0.9 | 0.03 | 39,465 | 1,421 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 120 | 80 | 0 | 193 | 114 | 360 | 200 | LF | 1,697,376 | 0.111 | 0.93 | 0.03 | 27,989 | 1,149 |
| 121 | 10 | 12 | 193 | 132 | 320 | 200 | LF | 1,697,391 | 0.111 | 0.89 | 0.03 | 43,672 | 1,560 |
| 122 | 20 | 8 | 193 | 132 | 320 | 200 | LF | 1,697,448 | 0.111 | 0.89 | 0.03 | 43,282 | 1,551 |
| 123 | 30 | 4 | 193 | 132 | 360 | 190 | LF | 1,697,469 | 0.111 | 0.9 | 0.03 | 39,784 | 1,430 |
| 124 | 60 | 10 | 193 | 114 | 320 | 200 | LF | 1,697,484 | 0.111 | 0.92 | 0.03 | 31,290 | 1,289 |
| 125 | 20 | 4 | 193 | 132 | 320 | 210 | LF | 1,697,598 | 0.111 | 0.88 | 0.03 | 44,742 | 1,590 |

## Table A-6 Overall optimization for Muga II

| Rank | PV (kW) | HY-5 kW | Hydro (kW) | Gen (kW) | S6CS25P | Converter (kW) | Dispatch strategy | Total NPC ($) | COE ($/kWh) | Renewable fraction | Unmet load fraction | Diesel (L/yr) | Gen (hrs/yr) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 831 | 382 | 320 | 280 | LF | 3,529,068 | 0.088 | 0.91 | 0.04 | 120,634 | 1,474 |
| 2 | 0 | 0 | 831 | 382 | 320 | 270 | LF | 3,529,095 | 0.088 | 0.91 | 0.04 | 121,433 | 1,486 |
| 3 | 0 | 1 | 831 | 382 | 320 | 280 | LF | 3,530,627 | 0.088 | 0.91 | 0.04 | 120,195 | 1,468 |
| 4 | 5 | 0 | 831 | 382 | 320 | 280 | LF | 3,530,666 | 0.088 | 0.91 | 0.04 | 119,470 | 1,458 |
| 5 | 0 | 0 | 831 | 382 | 320 | 260 | LF | 3,531,804 | 0.088 | 0.91 | 0.04 | 122,466 | 1,501 |
| 6 | 5 | 0 | 831 | 382 | 320 | 270 | LF | 3,532,878 | 0.088 | 0.91 | 0.04 | 120,459 | 1,473 |
| 7 | 0 | 1 | 831 | 382 | 320 | 270 | LF | 3,532,912 | 0.088 | 0.91 | 0.04 | 121,191 | 1,483 |
| 8 | 0 | 0 | 831 | 382 | 320 | 290 | LF | 3,532,970 | 0.088 | 0.91 | 0.04 | 120,175 | 1,467 |
| 9 | 0 | 1 | 831 | 382 | 320 | 260 | LF | 3,534,826 | 0.088 | 0.91 | 0.04 | 122,155 | 1,497 |
| 10 | 5 | 0 | 831 | 382 | 320 | 290 | LF | 3,534,830 | 0.088 | 0.91 | 0.04 | 119,034 | 1,451 |
| 11 | 0 | 2 | 831 | 382 | 320 | 280 | LF | 3,535,243 | 0.088 | 0.91 | 0.04 | 120,023 | 1,466 |
| 12 | 0 | 1 | 831 | 382 | 320 | 290 | LF | 3,535,273 | 0.088 | 0.91 | 0.04 | 119,802 | 1,462 |
| 13 | 5 | 0 | 831 | 382 | 320 | 260 | LF | 3,535,652 | 0.088 | 0.91 | 0.04 | 121,497 | 1,488 |
| 14 | 0 | 0 | 831 | 382 | 320 | 300 | LF | 3,535,830 | 0.088 | 0.91 | 0.04 | 119,626 | 1,459 |
| 15 | 5 | 0 | 831 | 382 | 320 | 300 | LF | 3,536,089 | 0.088 | 0.91 | 0.04 | 118,346 | 1,441 |
| 16 | 5 | 1 | 831 | 382 | 320 | 280 | LF | 3,536,484 | 0.088 | 0.91 | 0.04 | 119,401 | 1,458 |
| 17 | 0 | 2 | 831 | 382 | 320 | 270 | LF | 3,536,807 | 0.088 | 0.91 | 0.04 | 120,956 | 1,480 |
| 18 | 0 | 1 | 831 | 382 | 320 | 300 | LF | 3,538,130 | 0.088 | 0.91 | 0.04 | 119,252 | 1,454 |
| 19 | 0 | 3 | 831 | 382 | 320 | 280 | LF | 3,538,245 | 0.088 | 0.91 | 0.04 | 119,709 | 1,462 |
| 20 | 0 | 2 | 831 | 382 | 320 | 290 | LF | 3,538,491 | 0.088 | 0.91 | 0.04 | 119,507 | 1,458 |
| 21 | 0 | 3 | 831 | 382 | 320 | 270 | LF | 3,538,542 | 0.088 | 0.91 | 0.04 | 120,533 | 1,474 |
| 22 | 0 | 2 | 831 | 382 | 320 | 260 | LF | 3,538,691 | 0.088 | 0.91 | 0.04 | 121,917 | 1,494 |
| 23 | 5 | 1 | 831 | 382 | 320 | 270 | LF | 3,538,774 | 0.088 | 0.91 | 0.04 | 120,397 | 1,473 |
| 24 | 0 | 0 | 831 | 382 | 320 | 310 | LF | 3,540,237 | 0.088 | 0.91 | 0.04 | 119,211 | 1,453 |
| 25 | 0 | 0 | 831 | 382 | 320 | 250 | LF | 3,540,597 | 0.088 | 0.91 | 0.04 | 124,026 | 1,525 |
| 26 | 5 | 1 | 831 | 382 | 320 | 290 | LF | 3,540,608 | 0.088 | 0.91 | 0.04 | 118,962 | 1,451 |
| 27 | 5 | 0 | 831 | 382 | 320 | 310 | LF | 3,540,724 | 0.088 | 0.91 | 0.04 | 117,951 | 1,435 |
| 28 | 5 | 2 | 831 | 382 | 320 | 280 | LF | 3,541,089 | 0.088 | 0.91 | 0.04 | 119,227 | 1,456 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 29 | 0 | 3 | 831 | 382 | 320 | 260 | LF | 3,541,236 | 0.088 | 0.91 | 0.04 | 121,564 | 1,489 |
| 30 | 0 | 2 | 831 | 382 | 320 | 300 | LF | 3,541,346 | 0.088 | 0.91 | 0.04 | 118,958 | 1,450 |
| 31 | 0 | 3 | 831 | 382 | 320 | 290 | LF | 3,541,507 | 0.088 | 0.91 | 0.04 | 119,195 | 1,454 |
| 32 | 5 | 1 | 831 | 382 | 320 | 260 | LF | 3,541,566 | 0.088 | 0.91 | 0.04 | 121,437 | 1,488 |
| 33 | 10 | 0 | 831 | 382 | 320 | 280 | LF | 3,541,770 | 0.088 | 0.91 | 0.04 | 119,131 | 1,454 |
| 34 | 5 | 1 | 831 | 382 | 320 | 300 | LF | 3,541,858 | 0.088 | 0.91 | 0.04 | 118,273 | 1,441 |
| 35 | 0 | 0 | 831 | 382 | 360 | 290 | LF | 3,542,037 | 0.089 | 0.91 | 0.04 | 116,502 | 1,415 |
| 36 | 5 | 2 | 831 | 382 | 320 | 270 | LF | 3,542,141 | 0.088 | 0.91 | 0.04 | 120,116 | 1,469 |
| 37 | 0 | 0 | 831 | 382 | 360 | 300 | LF | 3,542,416 | 0.089 | 0.91 | 0.04 | 115,737 | 1,404 |
| 38 | 0 | 0 | 831 | 382 | 360 | 310 | LF | 3,542,536 | 0.089 | 0.92 | 0.04 | 114,950 | 1,393 |
| 39 | 0 | 1 | 831 | 382 | 320 | 310 | LF | 3,542,538 | 0.089 | 0.91 | 0.04 | 118,837 | 1,448 |
| 40 | 0 | 3 | 831 | 382 | 320 | 300 | LF | 3,543,562 | 0.089 | 0.91 | 0.04 | 118,576 | 1,445 |
| 41 | 5 | 2 | 831 | 382 | 320 | 290 | LF | 3,543,701 | 0.089 | 0.91 | 0.04 | 118,657 | 1,447 |
| 42 | 10 | 0 | 831 | 382 | 320 | 270 | LF | 3,543,973 | 0.089 | 0.91 | 0.04 | 120,119 | 1,469 |
| 43 | 5 | 2 | 831 | 382 | 320 | 260 | LF | 3,544,132 | 0.089 | 0.91 | 0.04 | 121,086 | 1,483 |
| 44 | 0 | 1 | 831 | 382 | 320 | 250 | LF | 3,544,368 | 0.089 | 0.91 | 0.04 | 123,780 | 1,522 |
| 45 | 5 | 0 | 831 | 382 | 360 | 290 | LF | 3,544,730 | 0.089 | 0.92 | 0.04 | 115,434 | 1,399 |
| 46 | 5 | 2 | 831 | 382 | 320 | 300 | LF | 3,544,931 | 0.089 | 0.91 | 0.04 | 117,966 | 1,437 |
| 47 | 0 | 0 | 831 | 382 | 360 | 280 | LF | 3,544,997 | 0.089 | 0.91 | 0.04 | 117,556 | 1,431 |
| 48 | 5 | 0 | 831 | 382 | 360 | 300 | LF | 3,545,192 | 0.089 | 0.92 | 0.04 | 114,677 | 1,388 |
| 49 | 5 | 0 | 831 | 382 | 320 | 250 | LF | 3,545,229 | 0.089 | 0.91 | 0.04 | 123,125 | 1,513 |
| 50 | 5 | 0 | 831 | 382 | 360 | 310 | LF | 3,545,245 | 0.089 | 0.92 | 0.04 | 113,883 | 1,377 |
| 51 | 5 | 3 | 831 | 382 | 320 | 280 | LF | 3,545,683 | 0.089 | 0.91 | 0.04 | 119,052 | 1,454 |
| 52 | 0 | 1 | 831 | 382 | 360 | 290 | LF | 3,545,848 | 0.089 | 0.91 | 0.04 | 116,259 | 1,412 |
| 53 | 5 | 3 | 831 | 382 | 320 | 270 | LF | 3,545,955 | 0.089 | 0.91 | 0.04 | 119,873 | 1,466 |
| 54 | 0 | 1 | 831 | 382 | 360 | 300 | LF | 3,546,272 | 0.089 | 0.91 | 0.04 | 115,499 | 1,401 |
| 55 | 0 | 1 | 831 | 382 | 360 | 310 | LF | 3,546,356 | 0.089 | 0.92 | 0.04 | 114,708 | 1,390 |
| 56 | 10 | 1 | 831 | 382 | 320 | 280 | LF | 3,546,363 | 0.089 | 0.91 | 0.04 | 118,956 | 1,452 |
| 57 | 10 | 0 | 831 | 382 | 320 | 290 | LF | 3,546,457 | 0.089 | 0.91 | 0.04 | 118,741 | 1,448 |
| 58 | 5 | 1 | 831 | 382 | 320 | 310 | LF | 3,546,489 | 0.089 | 0.91 | 0.04 | 117,877 | 1,435 |
| 59 | 0 | 2 | 831 | 382 | 320 | 310 | LF | 3,546,549 | 0.089 | 0.91 | 0.04 | 118,612 | 1,445 |
| 60 | 5 | 0 | 831 | 382 | 360 | 280 | LF | 3,547,494 | 0.089 | 0.91 | 0.04 | 116,471 | 1,415 |
| 61 | 10 | 0 | 831 | 382 | 320 | 300 | LF | 3,547,669 | 0.089 | 0.91 | 0.04 | 118,048 | 1,438 |
| 62 | 10 | 0 | 831 | 382 | 320 | 260 | LF | 3,547,815 | 0.089 | 0.91 | 0.04 | 121,250 | 1,486 |
| 63 | 0 | 2 | 831 | 382 | 320 | 250 | LF | 3,548,200 | 0.089 | 0.91 | 0.04 | 123,539 | 1,519 |
| 64 | 0 | 3 | 831 | 382 | 320 | 310 | LF | 3,548,257 | 0.089 | 0.91 | 0.04 | 118,187 | 1,439 |
| 65 | 5 | 3 | 831 | 382 | 320 | 290 | LF | 3,548,288 | 0.089 | 0.91 | 0.04 | 118,481 | 1,445 |
| 66 | 0 | 0 | 831 | 382 | 360 | 320 | LF | 3,548,574 | 0.089 | 0.92 | 0.04 | 114,677 | 1,389 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 67 | 10 | 1 | 831 | 382 | 320 | 270 | LF | 3,548,616 | 0.089 | 0.91 | 0.04 | 119,949 | 1,467 |
| 68 | 0 | 1 | 831 | 382 | 360 | 280 | LF | 3,548,778 | 0.089 | 0.91 | 0.04 | 117,311 | 1,428 |
| 69 | 0 | 0 | 831 | 382 | 280 | 260 | LF | 3,549,083 | 0.089 | 0.91 | 0.04 | 128,423 | 1,592 |
| 70 | 0 | 1 | 831 | 382 | 280 | 260 | LF | 3,549,200 | 0.089 | 0.91 | 0.04 | 127,860 | 1,583 |
| 71 | 5 | 3 | 831 | 382 | 320 | 260 | LF | 3,549,244 | 0.089 | 0.91 | 0.04 | 120,956 | 1,482 |
| 72 | 5 | 3 | 831 | 382 | 320 | 300 | LF | 3,549,498 | 0.089 | 0.91 | 0.04 | 117,789 | 1,435 |
| 73 | 10 | 1 | 831 | 382 | 320 | 290 | LF | 3,549,588 | 0.089 | 0.91 | 0.04 | 118,439 | 1,444 |
| 74 | 0 | 0 | 831 | 382 | 320 | 320 | LF | 3,549,875 | 0.089 | 0.91 | 0.04 | 119,250 | 1,454 |
| 75 | 5 | 1 | 831 | 382 | 360 | 290 | LF | 3,550,205 | 0.089 | 0.92 | 0.04 | 115,336 | 1,398 |
| 76 | 5 | 1 | 831 | 382 | 360 | 300 | LF | 3,550,256 | 0.089 | 0.92 | 0.04 | 114,543 | 1,386 |
| 77 | 5 | 0 | 831 | 382 | 320 | 320 | LF | 3,550,304 | 0.089 | 0.91 | 0.04 | 117,985 | 1,436 |
| 78 | 5 | 1 | 831 | 382 | 360 | 310 | LF | 3,550,315 | 0.089 | 0.92 | 0.04 | 113,750 | 1,375 |
| 79 | 5 | 2 | 831 | 382 | 320 | 310 | LF | 3,550,356 | 0.089 | 0.91 | 0.04 | 117,639 | 1,432 |
| 80 | 0 | 3 | 831 | 382 | 320 | 250 | LF | 3,550,443 | 0.089 | 0.91 | 0.04 | 123,160 | 1,514 |
| 81 | 5 | 0 | 831 | 382 | 280 | 260 | LF | 3,550,775 | 0.089 | 0.91 | 0.04 | 127,267 | 1,576 |
| 82 | 10 | 1 | 831 | 382 | 320 | 300 | LF | 3,550,810 | 0.089 | 0.91 | 0.04 | 117,747 | 1,434 |
| 83 | 0 | 2 | 831 | 382 | 360 | 290 | LF | 3,550,840 | 0.089 | 0.91 | 0.04 | 116,119 | 1,410 |
| 84 | 15 | 0 | 831 | 382 | 320 | 280 | LF | 3,550,857 | 0.089 | 0.91 | 0.04 | 118,618 | 1,446 |
| 85 | 0 | 0 | 831 | 382 | 360 | 270 | LF | 3,551,056 | 0.089 | 0.91 | 0.04 | 118,879 | 1,451 |
| 86 | 0 | 0 | 831 | 382 | 280 | 270 | LF | 3,551,075 | 0.089 | 0.91 | 0.04 | 127,798 | 1,583 |
| 87 | 5 | 1 | 831 | 382 | 320 | 250 | LF | 3,551,109 | 0.089 | 0.91 | 0.04 | 123,062 | 1,513 |
| 88 | 0 | 2 | 831 | 382 | 280 | 260 | LF | 3,551,174 | 0.089 | 0.91 | 0.04 | 127,458 | 1,577 |
| 89 | 0 | 2 | 831 | 382 | 360 | 300 | LF | 3,551,280 | 0.089 | 0.92 | 0.04 | 115,360 | 1,399 |
| 90 | 0 | 2 | 831 | 382 | 360 | 310 | LF | 3,551,376 | 0.089 | 0.92 | 0.04 | 114,570 | 1,388 |
| 91 | 5 | 0 | 831 | 382 | 360 | 320 | LF | 3,551,407 | 0.089 | 0.92 | 0.04 | 113,621 | 1,373 |
| 92 | 5 | 1 | 831 | 382 | 280 | 260 | LF | 3,551,579 | 0.089 | 0.91 | 0.04 | 126,764 | 1,568 |
| 93 | 10 | 2 | 831 | 382 | 320 | 280 | LF | 3,551,620 | 0.089 | 0.91 | 0.04 | 118,839 | 1,451 |
| 94 | 0 | 1 | 831 | 382 | 320 | 320 | LF | 3,552,147 | 0.089 | 0.91 | 0.04 | 118,874 | 1,449 |
| 95 | 10 | 1 | 831 | 382 | 320 | 260 | LF | 3,552,410 | 0.089 | 0.91 | 0.04 | 121,075 | 1,484 |
| 96 | 0 | 1 | 831 | 382 | 360 | 320 | LF | 3,552,411 | 0.089 | 0.92 | 0.04 | 114,436 | 1,386 |
| 97 | 0 | 3 | 831 | 382 | 280 | 260 | LF | 3,552,622 | 0.089 | 0.91 | 0.04 | 127,011 | 1,570 |
| 98 | 10 | 2 | 831 | 382 | 320 | 270 | LF | 3,552,646 | 0.089 | 0.91 | 0.04 | 119,725 | 1,464 |
| 99 | 10 | 0 | 831 | 382 | 320 | 310 | LF | 3,552,730 | 0.089 | 0.91 | 0.04 | 117,690 | 1,433 |
| 100 | 0 | 2 | 831 | 382 | 360 | 280 | LF | 3,552,798 | 0.089 | 0.91 | 0.04 | 117,086 | 1,425 |
| 101 | 5 | 1 | 831 | 382 | 360 | 280 | LF | 3,553,009 | 0.089 | 0.91 | 0.04 | 116,376 | 1,414 |
| 102 | 15 | 0 | 831 | 382 | 320 | 270 | LF | 3,553,081 | 0.089 | 0.91 | 0.04 | 119,608 | 1,461 |
| 103 | 0 | 1 | 831 | 382 | 280 | 270 | LF | 3,553,554 | 0.089 | 0.91 | 0.04 | 127,441 | 1,577 |
| 104 | 5 | 0 | 831 | 382 | 360 | 270 | LF | 3,553,560 | 0.089 | 0.91 | 0.04 | 117,795 | 1,435 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 105 | 5 | 3 | 831 | 382 | 320 | 310 | LF | 3,554,123 | 0.089 | 0.91 | 0.04 | 117,393 | 1,429 |
| 106 | 5 | 2 | 831 | 382 | 320 | 250 | LF | 3,554,126 | 0.089 | 0.91 | 0.04 | 122,750 | 1,509 |
| 107 | 10 | 0 | 831 | 382 | 360 | 290 | LF | 3,554,127 | 0.089 | 0.92 | 0.04 | 114,947 | 1,393 |
| 108 | 0 | 3 | 831 | 382 | 360 | 290 | LF | 3,554,180 | 0.089 | 0.91 | 0.04 | 115,836 | 1,406 |
| 109 | 0 | 3 | 831 | 382 | 360 | 310 | LF | 3,554,216 | 0.089 | 0.92 | 0.04 | 114,244 | 1,383 |
| 110 | 0 | 0 | 831 | 382 | 280 | 250 | LF | 3,554,320 | 0.089 | 0.91 | 0.04 | 129,671 | 1,611 |
| 111 | 5 | 0 | 831 | 382 | 280 | 270 | LF | 3,554,342 | 0.089 | 0.91 | 0.04 | 126,779 | 1,569 |
| 112 | 0 | 1 | 831 | 382 | 360 | 270 | LF | 3,554,357 | 0.089 | 0.91 | 0.04 | 118,592 | 1,447 |
| 113 | 0 | 1 | 831 | 382 | 280 | 250 | LF | 3,554,380 | 0.089 | 0.91 | 0.04 | 129,106 | 1,602 |
| 114 | 5 | 2 | 831 | 382 | 360 | 290 | LF | 3,554,510 | 0.089 | 0.92 | 0.04 | 115,136 | 1,395 |
| 115 | 0 | 3 | 831 | 382 | 360 | 300 | LF | 3,554,618 | 0.089 | 0.92 | 0.04 | 115,076 | 1,395 |
| 116 | 0 | 0 | 831 | 382 | 280 | 280 | LF | 3,554,686 | 0.089 | 0.91 | 0.04 | 127,314 | 1,576 |
| 117 | 5 | 2 | 831 | 382 | 280 | 260 | LF | 3,554,734 | 0.089 | 0.91 | 0.04 | 126,464 | 1,564 |
| 118 | 10 | 2 | 831 | 382 | 320 | 290 | LF | 3,554,848 | 0.089 | 0.91 | 0.04 | 118,322 | 1,443 |
| 119 | 10 | 0 | 831 | 382 | 360 | 310 | LF | 3,554,906 | 0.089 | 0.92 | 0.04 | 113,419 | 1,371 |
| 120 | 15 | 0 | 831 | 382 | 320 | 290 | LF | 3,555,051 | 0.089 | 0.91 | 0.04 | 118,185 | 1,439 |
| 121 | 10 | 0 | 831 | 382 | 360 | 300 | LF | 3,555,349 | 0.089 | 0.92 | 0.04 | 114,255 | 1,383 |
| 122 | 15 | 0 | 831 | 382 | 320 | 300 | LF | 3,555,503 | 0.089 | 0.91 | 0.04 | 117,427 | 1,428 |
| 123 | 0 | 2 | 831 | 382 | 280 | 270 | LF | 3,555,504 | 0.089 | 0.91 | 0.04 | 127,037 | 1,571 |
| 124 | 0 | 2 | 831 | 382 | 280 | 250 | LF | 3,555,604 | 0.089 | 0.91 | 0.04 | 128,640 | 1,595 |
| 125 | 10 | 2 | 831 | 382 | 320 | 260 | LF | 3,555,648 | 0.089 | 0.91 | 0.04 | 120,783 | 1,480 |