Techno-Economic Design of a 100% Renewable House
A Case Study for St. John’s

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List of Abbreviations

FIT: Feed in Tariff
BIPV: Building Integrated Photovoltaics
PV: Photo Voltaic
AM: Air Mass
CanSIA: Canadian Solar Industry Association
CER: Canada Energy Regulator
NEB: National Energy Board
HOMER: Hybrid Optimization Model for Electric Renewables
GHG: Green House Gases
OMAFRA: Ontario Ministry of Agriculture, Food and Rural Affairs
ESPC: The Economics of Solar Power in Canada
SAM: System Advisor Model
NREL: National Renewable Energy Laboratory
PVsyst: Photovoltaic Systems
LCOE: levelized cost of energy
WT: Wind turbine
PMG: permanent magnet generator
CF: Capacity Factor
MPPT: maximum power point tracking
SWCC: Small Wind Certification Council
NL: Newfoundland
Horizontal-axis wind turbines (HAWT)
Vertical-axis wind turbines (VAWT)
CAD: Canadian dollars
USD: U.S. dollars
CWEA: Canada's Wind Energy Atlas
SS3.7: Skystream 3.7
CDD: Cooling Degree Day
ZEB: Zero Energy Building

Techno-Economic Design of a 100% Renewable House
A Case Study for St. John's

Hashem Elsaraf (201992214) and Sharan Manjunath Rudresh (201990212)

Research Highlights

- Simulation of the electric and thermal loads for a house in St. john's using BEOPT.
- PV module selection from a comprehensive list of 25,000 Modules through novel methodology.
- PV system design and cross verification using a combination of HOMER, PVsyst and Helioscope.
- PV shading analysis study for a house in St. John's using Helioscope and Excel.
- Wind system design and verification using HOMER, Mathcad and MATLAB.
- Three electric load and one thermal load generation scenarios were generated, evaluated, and compared.
- Solar PV is competitive with wind in Newfoundland where it is only 1.59% worse than the best wind utilizing scenario.
- Electric heating using wind-solar hybrid is not competitive with heating oil in the province.

Abstract

Nalcor energy, the developer of the Muskrat Falls hydroelectric project, needs to raise 725.9 million CAD annually in order to stabilize the electricity price in Newfoundland at 13.5 cents/kWh, otherwise, the price is forecasted to increase to 22.9 cents/kWh as consequence of the hydroelectric facility's financial burdens. This project assumes the worst-case future scenario (22.9 cents/kWh) and carries out the load profiling and techno-economic design of multiple renewable energy sources for a household in St. John's. The electric and thermal loads for the design house have been simulated using BEOPT. A PV module was selected from a list of 25,000 modules through novel comprehensive methodology. Then a PV system was designed and verified using a combination of Helioscope, PVsyst and HOMER. A shading study was conducted using Helioscope and excel to find the optimum number of modules and their best configuration. Upper and lower boundaries were identified and then the optimum system was selected. The Wind energy system was designed and verified using HOMER, Mathcad and MATLAB after 10 turbines met the inclusion criteria of this study by being certified by Intertek and Small Wind Certification Council. Four Scenarios were created for wind and solar systems in the design house. The results show the feasibility of the three electric load scenarios (A, B and D) and slight unfeasibility of the thermal load scenario (Scenario C).

Keywords: Wind energy in Newfoundland, Solar energy Newfoundland, Zero net energy building, PV shading, Rooftop PV, Residential renewable energy, Net metering, LCOE of energy systems, Residential load simulation.

I. Introduction

This project will carry out the load profiling and design of multiple renewable energy sources for a household in St. John's. The objective of the design is to provide an analysis of what a house that utilizes renewable energy would look like in 2020 given the looming possibility of electricity rate increase due to Muskrat Falls hydroelectric project and depletion of fossil fuels' supply and fluctuation in their prices. This study seeks to simulate and address the feasibility of various residential renewable systems at various penetration levels and give recommendations. The study will span two projects (Projects 990A and 990B). The design will include both electrical and thermal renewable energy generation and storage. The Software that will be used is HOMER, PVSYST, Helioscope, Microsoft Excel, Mathcad, Polysun, MATLAB, Google Earth and BEOPT. The generation sources include pico-hydro, wind, and solar for electrical generation and solar thermal and/or geothermal for thermal generation coupled with thermal storage systems. For the most part, project 990A will address the electrical aspects of the design while project 990B will tackle the thermal aspect.

II. Problem Statement

As a consequence of the Muskrat Falls project, Nalcor energy needs to raise 725.9 million CAD annually in order to stabilize the electricity price in Newfoundland (NL) at 13.5 cents/kWh, otherwise, the price is forecasted to increase to 22.9 cents/kWh which is almost double the current rate of 12.3 cents/kWh [1,2]. Therefore, this project's motivation is in case the government's price stabilization plan fails and the price rises, some St. John's residents might want to go off-grid or at least to produce a portion of their energy from residential renewable sources. Therefore, this project will examine the design of such a system. Multiple scenarios will be created, one of them being the highest energy diversity scenario which offers greater energy security than simply relying on a single source and another being the least-cost scenario which is compared against the worst-case scenario electricity rate (22.9 cents/kWh) and a conclusion can be made whether going off-grid at that time or generating a portion of energy from household renewable sources is feasible or not.

Newfoundlanders are switching back to oil-based heating since the island's residents are worried about the price of electricity due to Muskrat Falls [3]. According to the government of Newfoundland, The consumption of heating oil in the province in 2015 was 98 GJ/household which is an approximately 10 GJ increase from the 2013 figure while household electricity consumption decreased from 65.5 GJ/household in 2013 to 64.3 GJ/household in 2015 highlighting the popularity of heating oil for water and space heating [4]. Heating oil is a petroleum product and thus is environmentally damaging and will eventually be depleted (fossil fuel's bell curve). 20% of all environmentally damaging oil spills in Newfoundland are from domestic heating oil which contaminates the soil and is hazardous to humans [5]. Therefore, this project will study the replacement of oil-based house heating system with geothermal and/or solar thermal system(s) (project 990-B).

III. Literature Review

A previous study stated that hybrid systems are more attractive for standalone systems. The study used HOMER to evaluate a hybrid energy system coupled with hydrogen storage for a stand-alone load in Newfoundland Canada. It was found that wind-diesel-battery system was the most feasible in 2005, however the study predicts that if fuel cell cost drops to 15% of its 2005 value, wind-fuel cell system will also become the best choice. Battery self-discharge is a big problem in cold environments such as Canada's, also battery cost and disposal are constraining factors for stand-alone applications [4].

A recent study (2019) evaluated and compared between the usage of PV and Solar thermal for thermal energy generation for a single-family detached house in St. John’s and the result showed that PV generation was superior to solar thermal in terms of cost, power and flexibility [5].

The price of PV technology has dropped significantly over the past few decades while PV panel efficiency has increased with some PV manufacturers (Sunpower) reporting 22.8% efficiency [8].

In 2016, A study presented the sizing of a solar thermal energy storage system for domestic water heating in a detached house in St. John’s. the proposed model used a combination of BEOPT and Simulink to determine the temperature of a tank and the heat loss of the system. System design depends on temperature, time and flow rate. The proposed model was used to determine storage water and house temperatures. The maximum temperature of the storage tank was 82.4 °C and the house space temperature was found to be 18 to 25.11 °C. Space heating for the studied house required 12,268 kWh/yr [6].

Thermal energy storage is used to store thermal energy for space and water heating through the use of different systems which can be categorized under latent heat, sensible heat and thermochemical energy storage. It is used in conjunction with solar thermal sources to reduce supply and demand mismatch [5].

A recent study verified that solar fraction and output increases proportionally with increases in solar collector area and that hybrid residential system is important in achieving an efficient detached house [9]. The authors of [10] found that thermal energy system from multisource heat pump and solar collectors is efficient and the cheapest way to achieve space heating.

In a 2020 study [87], the authors studied the feasibility and optimal sizing of wind-hydrogen hybrid system for a house in Istanbul, turkey. 10-minute average wind data of the site and the house’s consumption were used to carry out sizing. It was found that for uninterrupted power supply the wind turbine’s rated power should be at least ten times the average load.

In a recent publication (2020), HOMER pro was used to conduct a techno-economic evaluation and optimization of a hybrid renewable energy system for a residential load. The paper states that a hybrid system is composed of 2 or more renewable sources. It provides greater balance in energy supply as well as increased efficiency. A properly planned hybrid system with demand side management also reduces overall system cost. Four cases were proposed the most optimum of which had an LCOE of 0.0895 USD/kWh [88].

A. Zero Energy Building (ZEB)

A zero-energy building is one where the total annual energy consumption is equal to the energy production by renewable sources. Wind energy is readily available in Newfoundland and is a far superior resource to solar irradiance. In this study [7] a typical R-2000 house in St. John’s was studied using HOMER (National Renewable Energy Laboratory (NREL) software) to design the optimum energy system with a wind-based system found to be most feasible to achieve Zero net energy building status.

Energy for space and water heating, cooking, lighting and appliances is provided by a 10-kW wind turbine which is able to convert the dwelling to a zero-energy building provided that grid connection and exchange of power is possible. The study concludes by saying that wind based zero energy building is feasible in Newfoundland especially due to the wide scattering of the province's population [7].

B. Distributed Generation

A 2017 study [17] defined distributed or decentralized electrical power system as a system in which distributed generators (DG) and distributed storages (DS) are installed near to consumer at low voltage side.

Distributed power system is not a new concept. A number of utility consumers have been using distributed power generators for decades. The distributed generation market has been expanding rapidly since the last 10 years. In the late 1990s, new policies, such as net metering, renewable portfolio requirements, and the development of new distributed generation and control technologies, have ignited broader interests in distributed generation plants.

As distributed generation is power generation built near to consumers, distributed energy sources include small-scale, environment friendly technologies (e.g., solar photovoltaic and wind), installed on and designed primarily to serve a single end user's site. But when trustworthiness and power quality issues are critical, distributed generators most often includes conventional fossil fuel fired engines or gas turbines.

Renewable energy source in decentralized power systems can be biomass, geothermal, micro hydroelectric units, tidal, wind, solar thermal and solar photovoltaic. One of the best sources to be used at micro level is solar photovoltaic because it is easy to install, has flexibility of designing and extension, has abundant availability and is cheaper than other sources.

C. Net Metering

Net metering is a policy that allows consumers to generate their own electricity from renewable sources and to sell the excess energy to the grid using a bidirectional meter to measure generation and anticipate energy deficit and surplus.

Net metering has been expected in Newfoundland (particularly St. John's) since 2013 and some studies have carried out their research assuming its existence [12]. According to Newfoundland power, NL has a net metering option for consumers who install up to 100 kW of small-scale renewable sources [18,19].

The mechanism by which net metering works is that once the consumer is connected to the distribution system, NL power monitors his meter and subtracts the amount of electricity supplied to the grid from the amount that is taken from the grid. NL power then bills the "net" difference between these two amounts. The consumer is only billed for his positive "net consumption", which is defined as the total electricity consumption minus the total generation provided to the grid in a given billing cycle, as shown by a positive meter reading. If more energy is generated than consumed the consumer will receive the difference as credit which can be subtracted from future electricity bills. the selling rate is the same as the purchase rate and credits are non-tradable [18,19].

A disadvantage of net metering in Newfoundland is that a 5 MW cap is placed on provincial projects since the program was started in 2017, however, there is no information suggesting the cap has been reached.

D. Feed in Tariff (FIT) Programs

A feed-in tariff is a policy mechanism designed to accelerate investment in renewable energy technologies by offering long-term contracts to renewable energy producers. FIT programs around the world have proved successful for the increased penetration of PV for example, Italy, Germany, and Australia [22].

Ontario, Canada has a generous microFIT program (0.29 to 0.97 CAD/kWh) which was introduced in 2010. This resulted in very favorable economics for residential solar in the province with payback periods as low as 5 years [22]. FIT triggered a growth of PV installations in Italy reaching 11 GW in 2011 [20].

Australia while being the largest per capita emitter of GHG in OECD countries has very high irradiance levels. The FIT program they implemented included lucrative rebate rates and an incentive of 5000$ towards the capital cost of solar PV which triggered heavy PV adoption of approximately 2 million residential PV systems (highest worldwide) [21]. Solar PV capacity in Australia went up from 10 MW in 2007 to 1000 MW in 2010 [22].

Despite the advantages of FIT, there are no such economically lucrative programs in Newfoundland [22].

E. Building Integrated Photovoltaics (BIPV)

Natural Resources Canada (NRCAN) [46] defines BIPV as solar PV systems that are seamlessly integrated into the building's envelope and part of the building's components such as facades or roofs providing a dual function. BIPV can be installed during construction or retrofitted to an existing building.

There are 3 main ways for integrating PV modules to a building:

- As roof materials (shingles or tiles).
- As facades (curtain walls or windows).
- As externally integrated systems (balcony railings or shading systems).

BIPV can impact energy consumption by daylight utilization and reduction in cooling loads thereby contributing to the development of net-zero energy buildings. BIPV is the only building material that can have a return on investment. It can also have aesthetic value thereby improving the visual appearance of the building. A 2006 study by NRCAN estimates that BIPV potential in Canada is about 71.34 TWh for residential and commercial building installations.

BIPVT is a subset of BIPV that involves thermal energy recovery that can be used for low temperature heating purposes or in combination with a heat pump for higher temperatures. BIPVT offers more energy per surface area than BIPV and helps cool the PV panels hence increasing their efficiency.

F. Spertino et al stated that certain phenomena such as shading from nearby obstacles, thermal gradients from lower parts to upper parts of the roof, dirt and non optimal exposure to the sun (wrong tilt) negatively impact the performance of BIPV [20].

In this project, mounting structures will be used as the exact tilt of the roof is unknown, this might violate the definition of BIPV as the panels will not be used as roof tiles, however, proceeding this way will ensure maximum economic feasibility of the project as well as minimal shading and the ability (access) to clean the modules routinely.

F. Heating and Cooling Strategies in the Clean Energy Transition

This analysis is a collaboration between the International Energy Agency (IEA) and Canada's Energy Regulator (CER) formerly known as the National Energy Board (NEB) produced in May 2019.Building sector accounts for 25% of total final energy consumption in Canada. Heating and cooling represent 65% of the building sectors energy consumption [14].

Due to the implementation of Canada's national building code, energy efficient technology has kept the residential energy consumption in Canada relatively stable since 2007. Strategies for heating and cooling demand are significant contributors to sustainability goals in Canada and will depend on factors such as local climate, energy prices, building type and technology used.

In the forecasted scenario known as the Clean Technology Scenario (CTS) energy demand in the building sector of Canada falls more than 35% by 2050 compared to 2018 without reducing the level of energy services in buildings. 85% of that reduction comes from reductions in heating and cooling.

CTS is implemented using known technologies (such as heat pumps) and concepts such as near zero energy buildings for new constructions and deep energy renovations for old buildings. CTS projects that CO_2 footprint of the building sector in 2050 will be 80% lower than that of 2018 due to energy intensity improvements and reduction in fossil fuel usage as can be seen from figure 1. The energy intensity of space heating in Canada for residential buildings ranges from 75 kWh/m^2 for new high energy efficient buildings to 220 kWh/m^2 for old buildings which according to CTS must undergo deep renovations to achieve around 100 kWh/m^2 energy intensity.

Residential sector accounts for 60% of building related heating and cooling energy consumption. Energy prices in provinces plays an important aspect in the implementation of deep energy renovations as owners will find renovations more economically attractive if energy prices are high. Policy level programs might be needed.

Atlantic Canada consumes a higher share of refined petroleum products than the rest of the country due to infrastructure and cost limitations. Liquid fuels are relied on primarily for heating. Under CTS electric resistance heating is replaced by the more efficient heat pump, also oil boilers and gas furnaces are significantly reduced.

Biomass, which is abundant in Canada, represents a higher share under CTS as a heating resource in Quebec and Atlantic provinces. Electric heat pumps are expected to grow heavily for single family dwellings.

Solar thermal is expected to increase in high performance near ZEB or ZEB. 45% of Canada's heating equipment stock in 2050 under CTS is from high performance electric heat pumps which are expected to undergo efficiency increase from 2.5-3.0 today to 3.5 to 5.0 by 2030 while gas boilers have 0.92 to 0.95 efficiency. Fossil fuels usage for building heating drops to 30% by 2050 with oil fired boilers disappear completely by 2050.

As can be seen from figure 2, in 2018 60% of residential heating in Atlantic Canada came from oil which is expected to drop to less than 25% by 2050 under CTS.

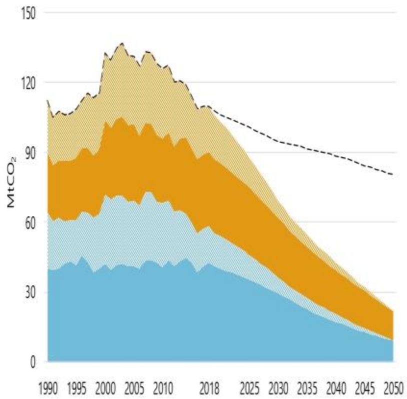


Fig. 1. CO_2 emissions by buildings projections [14].

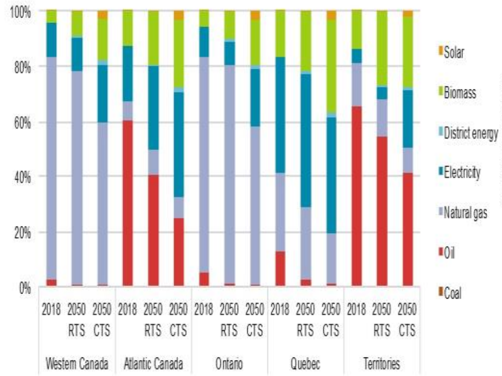


Fig. 2. Heating Energy Consumption in Canada [14].

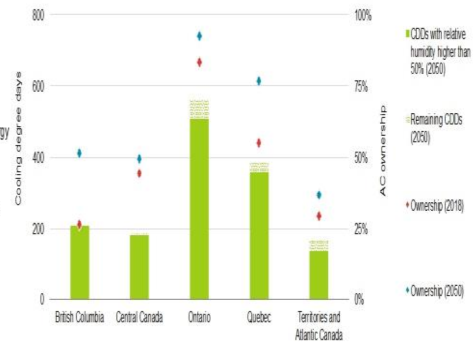


Fig. 3. AC ownership relative to CDDs [14].

One limitation of heat pumps is a drop-in performance at temperatures below 0-5 °C, even cold climate heat pumps struggle in temperatures below -10 °C leading to pump oversizing to ensure heat delivery on cold days or combination with auxiliary heating units such as electric resistance heaters. This signals that continued R&D in efficient technology is required. Solutions include hybrid natural gas and electric units as well as dual compressor units which meet heating demand on extremely cold days (at full load) while maximising energy performance at low partial loads during warmer winter days.

Increased humidity contributes to cooling degree days (CDDs) in Canada making AC use for cooling popular in some parts of the country where felt temperature can exceed 35 °C. Atlantic Canada has one of the lowest AC ownerships of slightly more than 25% and the lowest amount of CDDs around 150-175 CDDs as can be seen from figure 3.

IV. Load Simulation using BEOPT

In a relevant study [15], two houses in St. John's were simulated using BEOPT and the result showed that the annual energy consumption using the software was almost the same as the actual energy consumption logged with a 2-minute sample time. The paper notes that using BEOPT is important for the design of a renewable energy system and to start on the path of zero net energy.

Houses in NL are heated for more than 6 months due to long winters. The utility company logs electricity consumption once per month, but a much faster rate of logging is required for energy analysis of the house. This is why software like BEOPT is recommended.

There is a mismatch between measured consumption from the data logger and data collected by the utility company because the utility company does not measure energy consumption for 3 to 4 winter months in a year as meter access is limited due to snow.

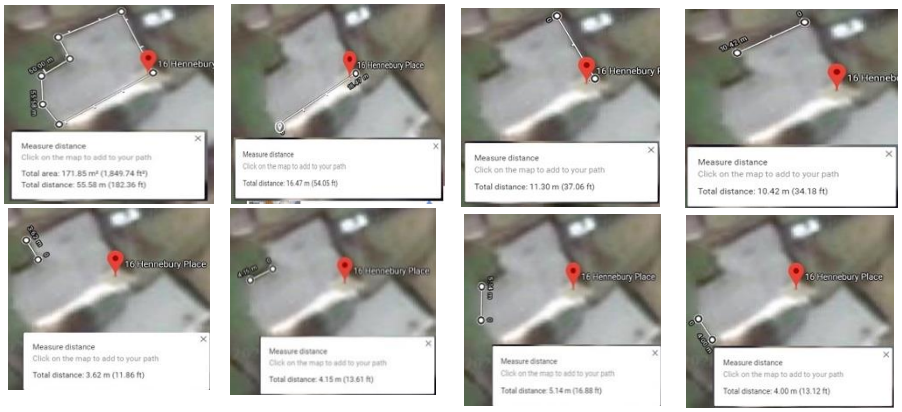


Fig. 4. House dimensions from Google maps

The studied house (for load modelling) is 16 Hennebury Place A1C 2V3 in St. John's Newfoundland. The house is owned by the landlord who lives in the above floor with his wife and baby daughter. The basement apartment is shared amongst three tenants. The following is a study about the energy requirement to meet the energy demand of the house. This section shows the step by step process of simulating the house. First the dimensions of the house were obtained from google maps (figure 4). Then each side measurement was simulated one at a time (figure 5). Then the full area of the house was simulated. The final simulation displays an above ground level of the house, a finished basement level and an unfinished attic. The total area of the house from google maps is 1849.74 ft^2 and from simulation 1852 ft^2.

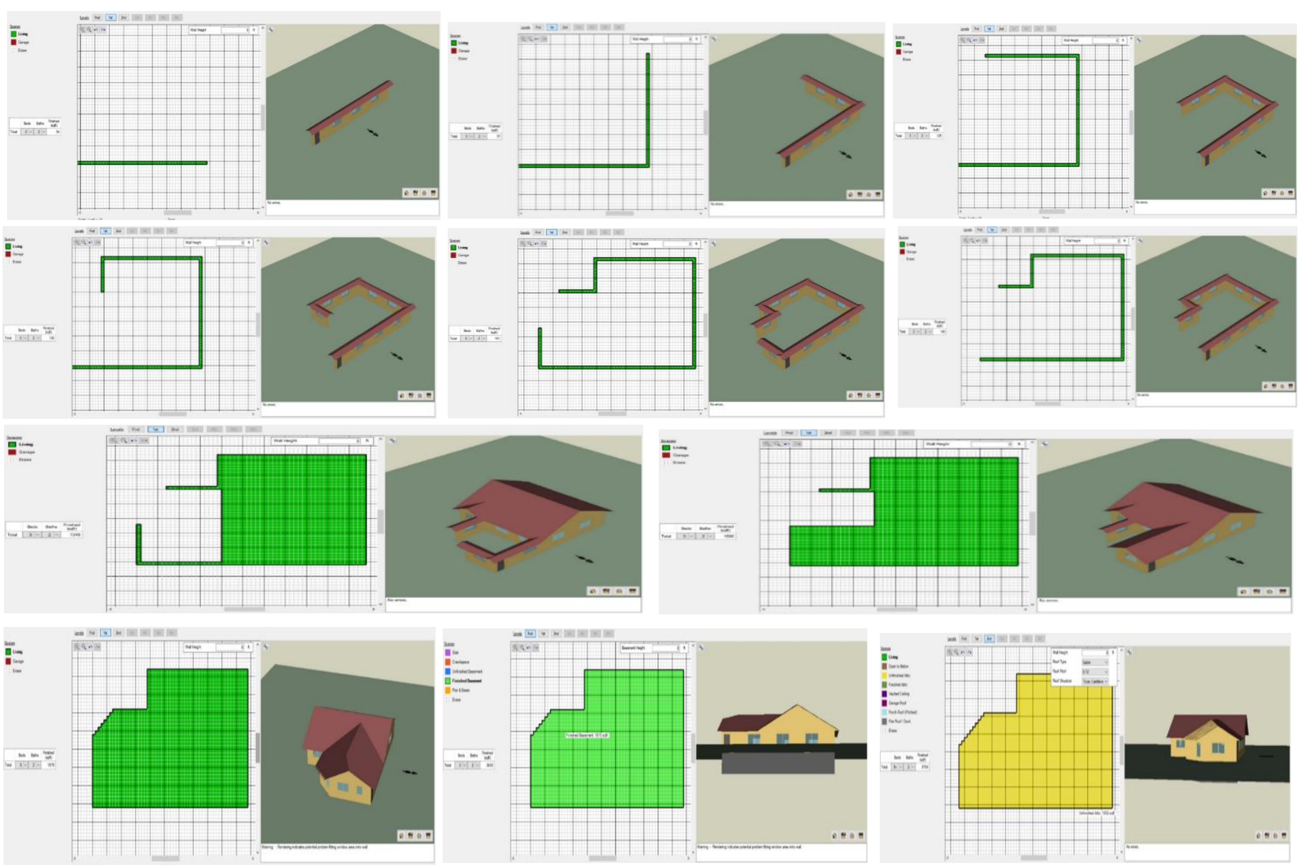


Fig. 5. Step by Step house simulation in BEOPT

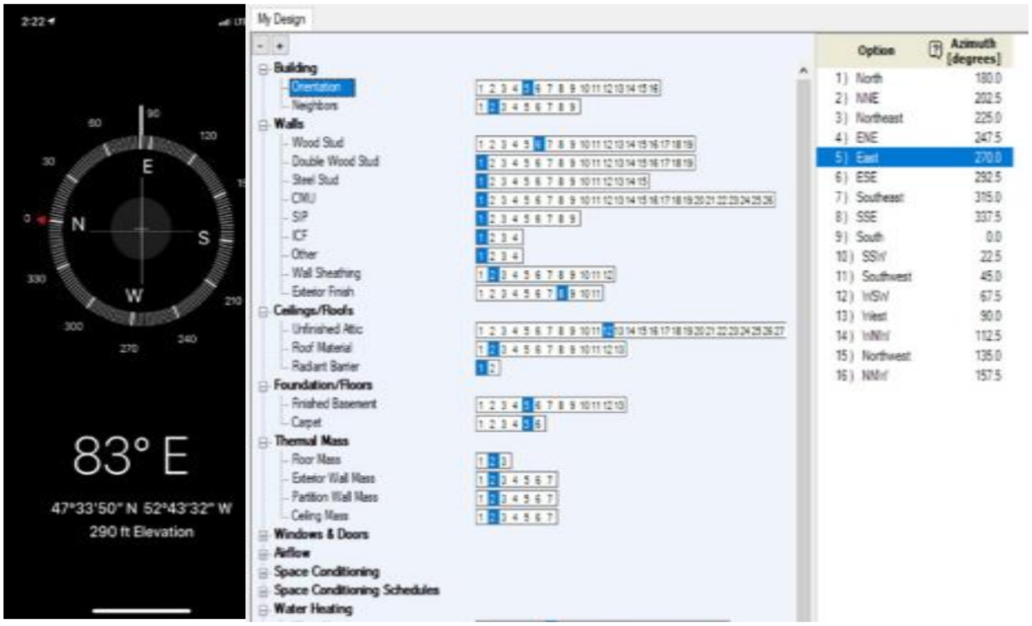


Fig. 6. Compass App and Options Menu in BEOPT

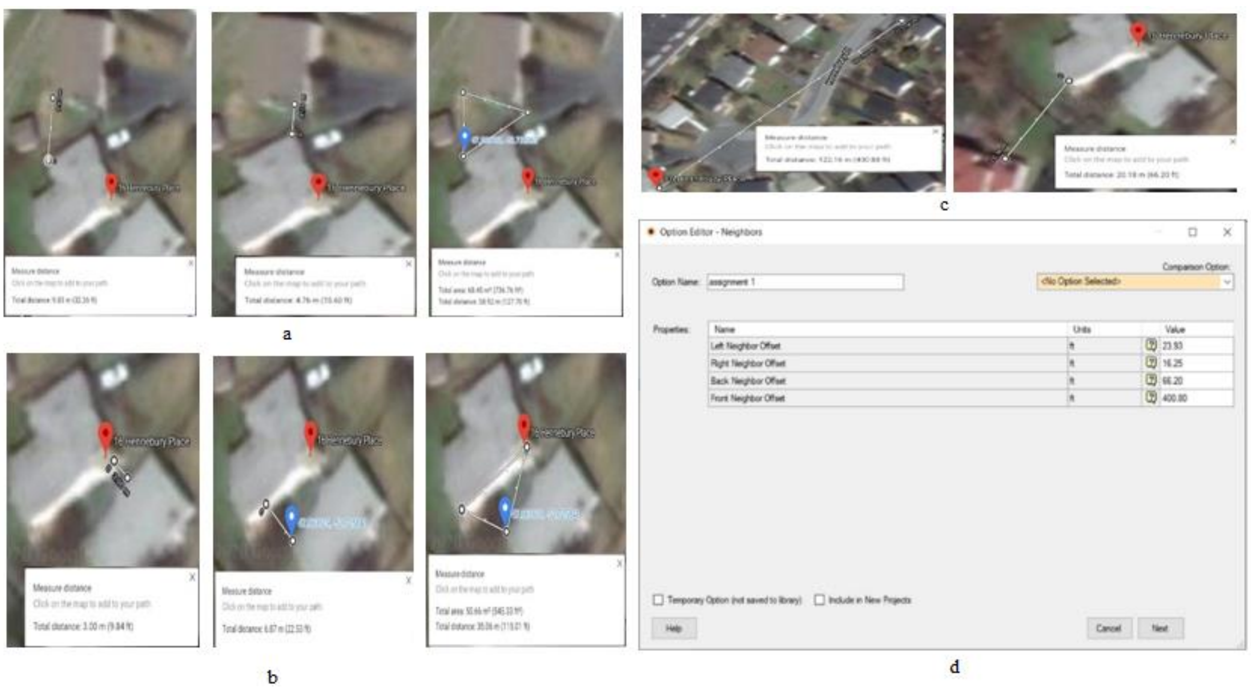


Fig. 7. Neighbours offset. a: left offset, b: right offset, c: front and back offset, d: Offset Options editor in BEOPT

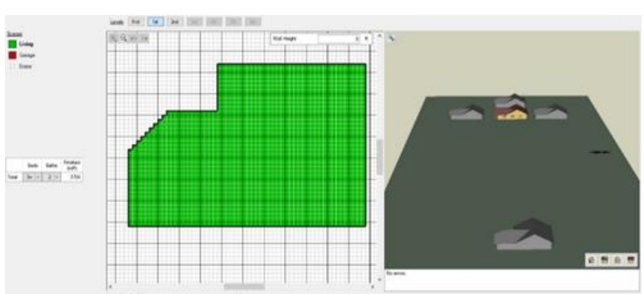


Fig. 8. Final system simulation showing neighbors

By stepping outside of the house with one's back turned to the house, the compass app on an iPhone can be activated. The result shown in figure 6 illustrates that the house is mostly facing east at an 83° angle with pure east being at a 90° angle. Therefore, in the "options screen" under "building" option, orientation was selected as east as can be seen from figure 6.

The house studied is in a cul-de-sac. The separation distance between the house and its neighbors to the left is not the same as the separation distance to the right. The separation distance is not uniform as it forms a triangular area. At the front end of each house, the separation distance is minimum at 15.6 ft while at the back it is maximum at 32.26 ft. as can be seen from figure 7.b. By adding these two numbers and dividing by 2 the average of this distance is 23.93 ft., a similar procedure was applied to get the right, front and back offsets.

The maximum separation distance allowed in BEOPT is 20 ft. to the left and to the right. So, a new customized value is inserted which more accurately reflects the geometry of the surroundings of the studied house (figure 7.d.). the final system is shown in figure 8 which includes all the neighbors.

A. Options Menu Values

The Values for the parameters in the options menu were directly obtained from the landlord and owner of 16 Hennebury place and are shown in table I.

Table I. BEOPT OPTIONS MENU VALUES.

Option	Value	Option	Value
Wood Stud	2x4 fiberglass r-13	Central Air Conditioner	None
Wall Sheathing	r-10 XPS	Furnace	Oil 85%
Exterior Finish	Vinyl, light	Ducts	15% Leakage Uninsulated
Unfinished Attic	R-30 fiberglass vented	Ceiling Fan	None
Roof Material	Asphalt dark	Dehumidifier	Standalone
Radiant Barrier	None	Cooling Set Point	None
Finished Basement	Whole Wall R-10 XPS	Humidity Set Point	45%
Carpet	0%	Heating Set Point	71 F setback 65 F
Floor Mass	Wood Surface	Cooling Set Point	None
Exterior Wall Mass	5/8 Drywall	Water Heater	Oil Standard
Partition Wall	None	Solar Water heating	None
Ceiling Mass	5/8-inch Drywall	Refrigerator	Top freezer
Windows	Double non-metal	Clothes Washer	EnergyStar
Door Area	20 ft^2	Clothes Dryer	Electric
Doors	Wood	Extra Refrigerator	Top Freezer
Eaves	3 ft	Freezer	Chest EF=24
Overhangs	None	PV system	None
Mechanical Ventilation	None	Natural ventilation	3 days/week

B. Output Figures

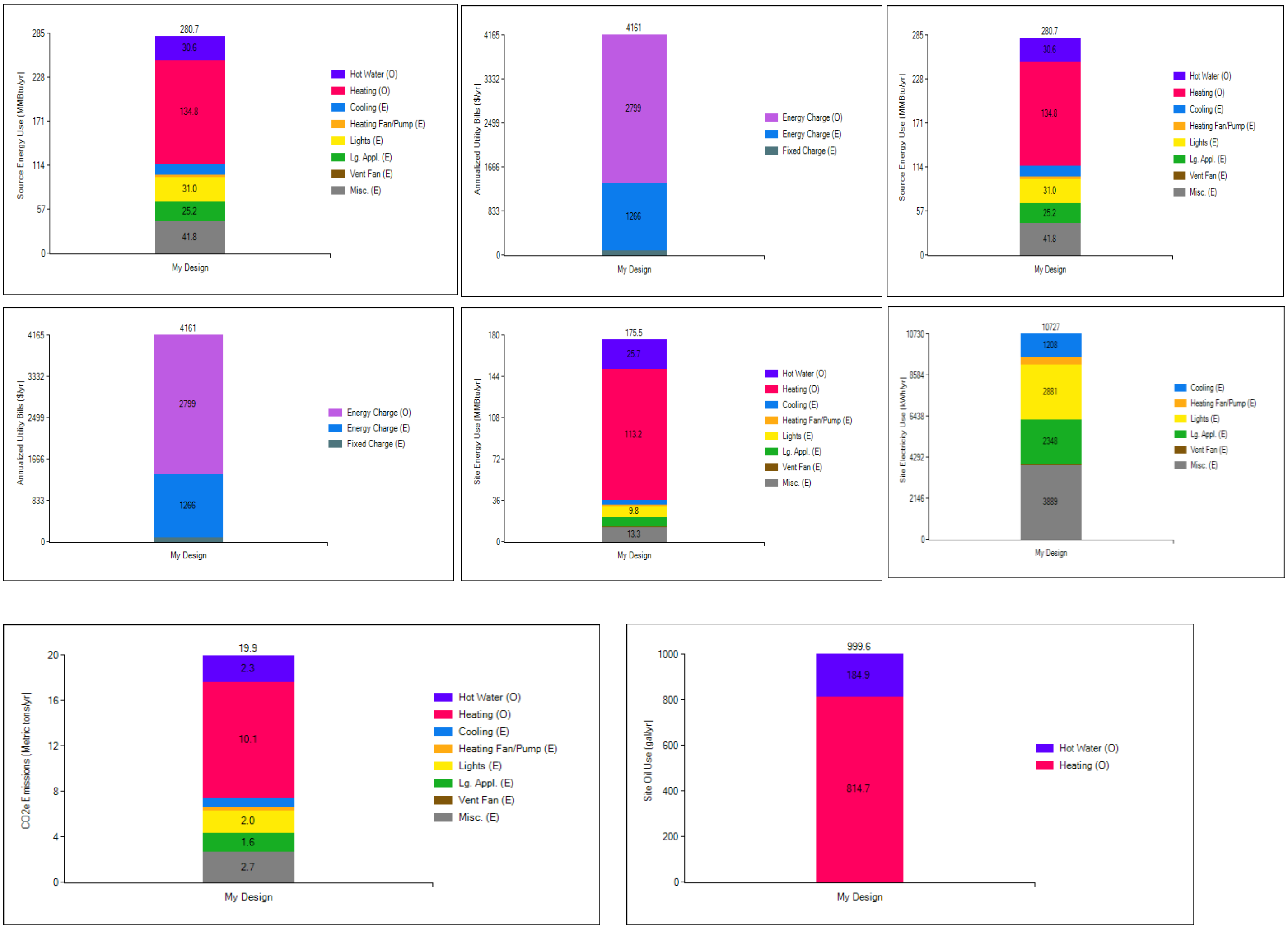


Fig. 9. Output figures.

The Output figures of BEOPT are shown in figure 9. A distinction should be made, however, between source and site energy. Source energy is a measure that accounts for the energy consumed on site in addition to the energy consumed during generation and transmission in supplying the energy to the site. Source energy is much more important than site energy if the concern is environmental performance. Site energy is useful because it can be unambiguously measured. Monthly and daily heating and electricity consumption is shown in figures 10 and 11.

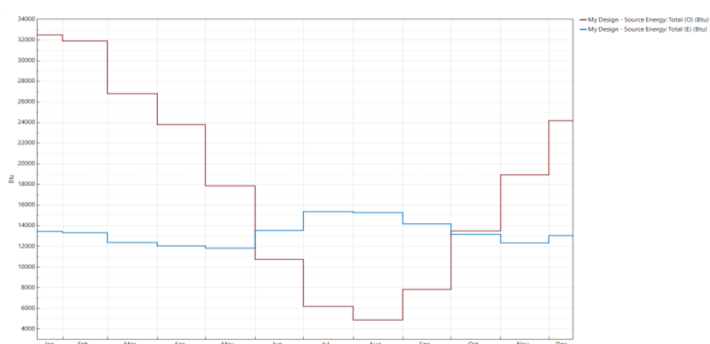


Fig. 10. Monthly heating and electricity consumption

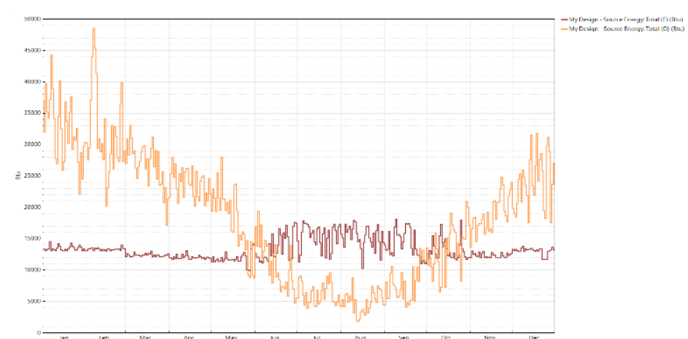


Fig. 11. Daily heating and electricity consumption

C. Energy Intensity

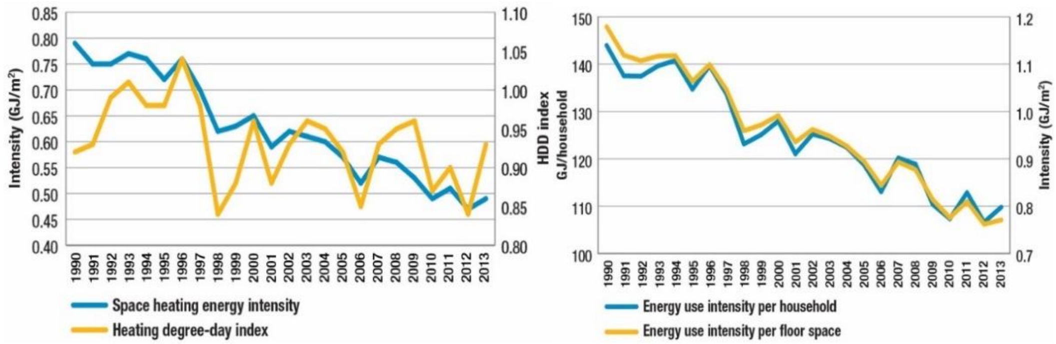


Fig. 12. Energy intensity history [16]

Energy intensity is defined as the energy required, for space heating or in toto, relative to the floor size of the house. The above figures (figure 12) are obtained from reference [16], they show the values of energy intensity between 1990 and 2013. As can be seen there is a steady decline as houses become more energy efficient. Energy intensity for space heating was around 0.5 GJ/m^2 and overall energy intensity per household was 110 GJ and per floor space 0.8 GJ/m^2 in 2013. In another source, energy intensity of space heating in Canada for residential buildings ranges from 75 KWh/m^2 for new high energy efficient buildings to 220 kWh/m^2 for old buildings which according to CTS must undergo deep renovations to achieve around 100 kWh/m^2 energy intensity [14]. According to table II the energy intensity of the design house (for space heating) is 114.8 kWh/m^2 or 0.413 GJ/m^2 and overall energy intensity is 0.86 GJ/m^2 which means energy renovations are possible but not a priority.

Table II. PERFORMANCE PARAMETERS FOR THE STUDIED HOUSE

Parameter	Value
Electricity consumption	10727 kWh/year
Source energy use (total)	280.7 MMBtu/year = 82,265.05 kWh/year
Source energy use (heating)	165.4 MMBtu/year = 48,473.96 kWh/year
Source energy use (space heating)	134.8 MMBtu/year = 39,505.98 kWh/year
Site energy use	175.5 MMBtu/year = 51,433.97 kWh/year
Utility bills	4161 CAD/year
Oil use	999.6 gal/year
Delivered energy	117.1 MMBTU/year = 34,318.62 kWh/year
Heating capacity	41.6 kBtu/hr
Area	1852 ft^2/level = 172 sqm/level = 344.12 m^2
Energy intensity (Source energy use)	239.059 kWh/m^2 year = 0.86 GJ/m^2 year
Energy intensity (Site energy use)	149.46 kWh/m^2 year = 0.538 GJ/m^2 year
Energy intensity (Heating energy)	140.86 kWh/m^2 year = 0.5071 GJ/m^2 year
Energy intensity (Space heating energy)	114.8 kWh/m^2 year = 0.41328 GJ/m^2 year
Energy intensity (Delivered energy)	99.728 h/sqm year

D. Electrical Load

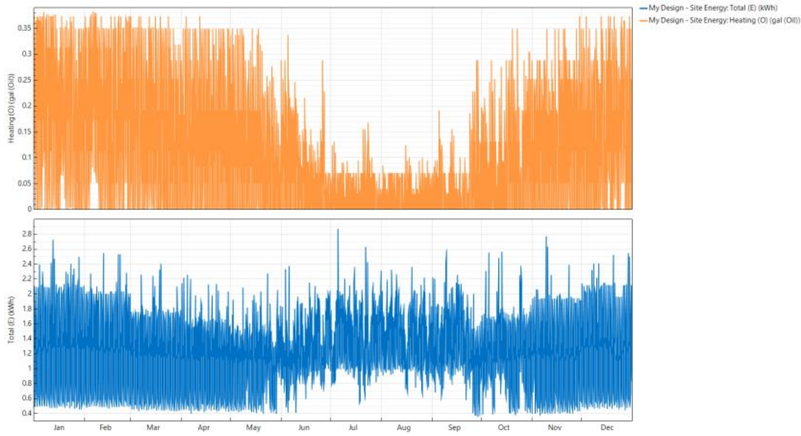


Fig. 13. Hourly load data from D-View; orange for heating and blue for electric

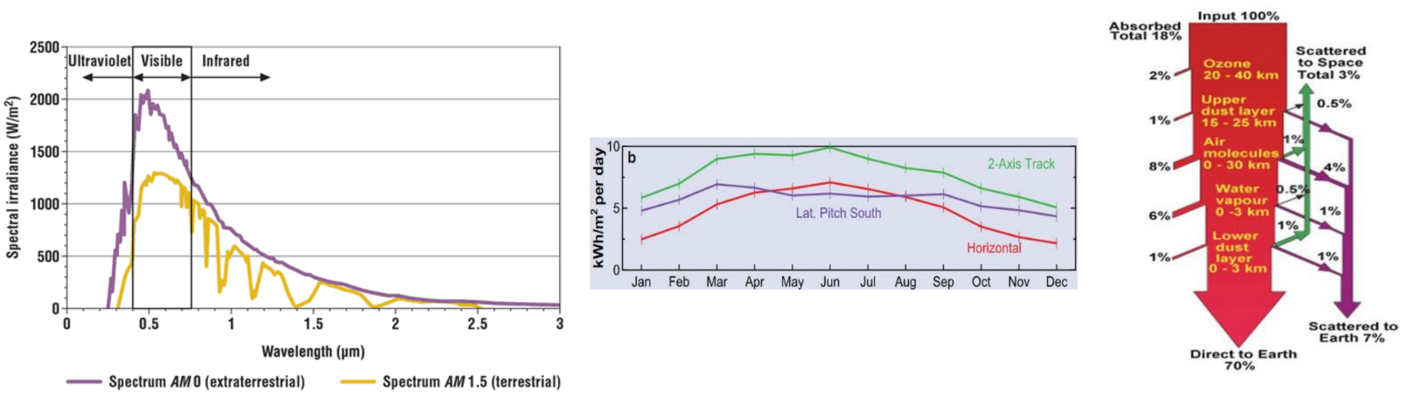
From D-View of BEOPT, the hourly site electric energy consumption can be obtained, as can be seen from figure 13, and exported to excel then to a text file where it can be used as the input to the primary load in HOMER. The total electric load for 1 year is 10.731 MWh while the scaled annual average is 29.4 kWh/day at a peak power of 2.80 kW and average power of 1.22 kW.

E. Thermal Load

From D-View of BEOPT (figure 13), the hourly site and source thermal energy consumption can be obtained. However, while source energy is in BTU and therefore easily convertible to kWh, site energy is in gallons. To convert site energy to kWh, the BTU content of a gallon of heating oil was obtained from the North American Combustion Handbook [61] which shows that heating oil produces 138,500 British thermal units per US gallon. Then, conversion from BTU to kWh is done where 1 BTU is equivalent to 0.000293071 kWh. The annual thermal energy consumption is 40.515 MWh with a scaled annual average of 111 kWh/day, peak power of 27.1 kW and average power of 4.63 kW. The price paid for heating oil per year according to figure 9 is 2799 CAD.

V. Photovoltaic (PV) Design

A. Introduction



a b c

Fig. 14. (a) AM0 radiation Vs AM 1.5 radiation. (b) Horizontal tilt vs latitude tilt vs 2-axis tracking. (c) Losses diagram for radiation as it traverses the atmosphere

The term Photovoltaic refers to the direct generation of electricity from solar irradiation using the photovoltaic effect. The total power from a radiant source falling on a unit area is called Irradiance (W/m^2). The annual mean sun irradiance is known as the solar constant which equals 1367 W/m^2. Only 70% of solar irradiance on the outside of the atmosphere makes it directly to the surface of the earth, 18% is absorbed for example by CO_2 and water vapor in the atmosphere, 3% is scattered back to space and 7% is scattered to the earth through the various elements of the atmosphere.

Irradiance also depends on Air Mass (AM) which is the amount of air the sun's rays pass through to reach earth which depends on the season and time of day. Radiation consists of diffuse and direct radiation, on a sunny day diffuse radiation contributes less than 10% of the total radiation but on a cloudy day it can contribute a lot more. Figure 14 (a) shows a comparison between AM0 (outside the atmosphere) and AM1.5, we can also see the dips in the curves where radiation is absorbed by various gases.

Clearness index is the fraction of solar radiation transmitted through the atmosphere that strikes the earth (dimensionless number between 0 and 1) it is high for clear sunny conditions and low during cloudy days.

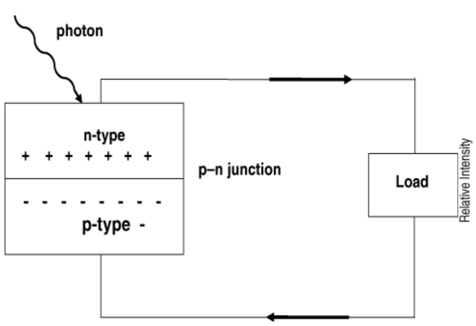
For tilt of PV panel equal latitude of location, energy generated is consistent throughout the year with slight peaks in spring and autumn. For horizontal PV panels, energy is maximum in summer except for locations near the equator (such as Malaysia) where this tilt is optimum as can be seen from figure 14 (b). The best energy yield can be obtained by using 2 axes tracking however, these systems are more expensive.

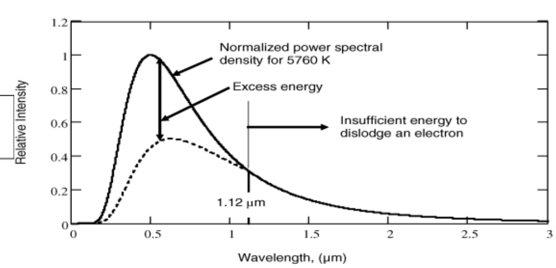
1) PV Cell Fundamentals

According to B. Hodge [45], Silicon which is the most commonly used material for PV cells has an atomic number of 14 with 4 valence band electrons. If valence band electrons are sufficiently energized, they can jump into the conduction band where they can easily move away from the atom thereby conducting heat or electricity. The energy difference between the valence and conduction bands is the band gap energy. Conductors have no band gap, insulators have a band gap of over 3 eV while semiconductors (like silicon) have a bandgap of less than 3 eV.

An N-type semiconductor is the result of the dopant having more electrons than the base material while for P-type holes are more. By combining an N-type silicon layer with a P-type silicon layer a junction, known as p-n junction, is formed in the middle which enhances electron and hole flow.

2) PV Mechanism





(a) (b)

Fig. 15. (a) PV cell simple diagram (b) Photon energy vs Wavelength Curve

In figure 15 (a), a PV cell is represented by a p-n junction with an incident photon and a connected load. If the incident photon has enough energy to “knock” or “dislodge” the valence electron to the conduction band, current will flow. The energy of the photon must be equal to or greater than the bandgap energy.

$$\mathrm{E} = \mathrm{hv} = \frac{h * c}{\lambda} \quad (1)$$

Where E is the energy of the photon, h is planck’s constant, v is the frequency, c is the speed of light and λ is the photon wavelength.

For silicon, photons with a wavelength less than or equal to 1.12 μm have sufficient energy to initiate current flow. A single photon can dislodge only a single electron and excess photon energy is dissipated as heat thus lowering PV cell efficiency.

3) Shading

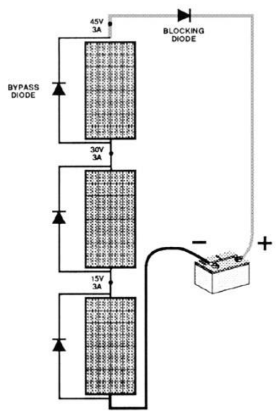


Fig. 16. Bypass and blocking diodes for PV panels

When a PV panel operates in partial shading condition its power efficiency is lowered but more importantly its series electrical resistance increases leading to more losses across the PV module/cell. When the current from unshaded cells flows through it, it leads to a hot spot or higher temperature in the shaded region which eventually leads to cracks in the cell cover through which moisture can penetrate thereby destroying the cell. Therefore, a bypass diode needs to be used as shown in figure 16.

There are different types of bypass diodes configuration such as series parallel, cross tied and honeycomb configurations. They all have their advantages but, as the study [23] explains, most configurations can not isolate the shaded cell. The study compares CMOS embedded PV panel with other bypass diode topologies and commends its ability to deal with shading compared with the established fixed bypass diode setups and concludes that it is more efficient.

In a study [24], self-shading effects of flat rooftops with ground mounted panels were considered. The results showed that for optimum energy yield the distance between PV rows should be 2.88 m with a spacing factor of 1.8. However, for optimum net present value, the distance should be 4.14m with a spacing factor of 2.07.

Ning et al. have integrated existing building information model (BIM) techniques to facilitate precise PV system simulation and optimization. Based on the existing BIM model, shading and radiation are analyzed in detail. Based on these design parameters, the model proposes an optimized PV design oriented by the objective of minimal cost-to-power ratio. Their results reveal that this tool has the potential to improve up to 265% in design efficiency, increase 36.1% power output and reduce around 4.5% capital investment per unit power output compared to a human-based design [25].

4) Solar Power in Canada

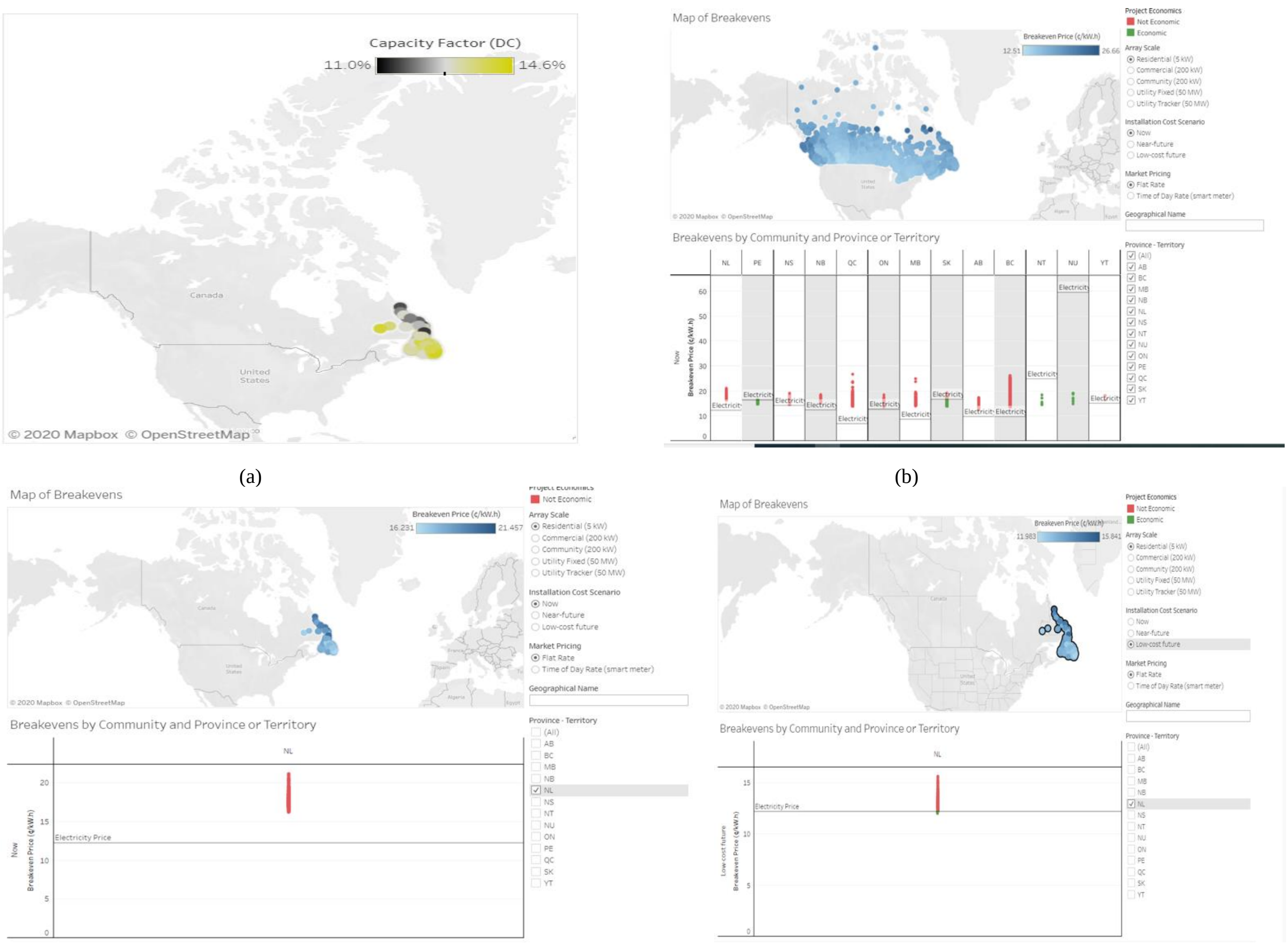
In its vision statement [13], the Canadian Solar Industry Association (CanSIA) laid forward the following ambitious goals "By 2025, solar industry is widely deployed throughout Canada, having already achieved market competitiveness that removes the need for government incentives, and is recognized as an established component of Canada's energy mix. The Solar industry will be supporting more than 35,000 jobs in the economy and displacing 15–31 million tonnes of greenhouse gas emissions per year, providing a safer cleaner environment for generations to come."

The following information was obtained from Canada Energy Regulator (CER) formerly known as the National Energy Board (NEB) [11]. It shows that Canada's west coast and Newfoundland and Labrador have less solar energy potential due to cloudiness and lower solar resources.

Capacity factor (CF) compares actual output of solar panels to their ideal performance if they were producing rated power throughout the day. Since solar energy technology only works during the day and is idle at night, it exhibits low capacity factors (around 18% or below for non-tracking systems and 20% or above for tracking systems). In Newfoundland, the capacity factor for residential solar PV (5 kW) is 11.0% to 14.6% according to figure 17 (a). According to figure 17 (b), the current price of solar power in Newfoundland is not economical relative to the grid price while it is economical in other provinces such as Saskatchewan and Nunavut.

According to figure 17 (c), the current per kWh price of solar energy in Newfoundland is between 16.231 and 21.457 cents/kWh which is higher than the grid price of 12 cents/kWh. The low-cost future scenario will see the price range for solar drop to 11.983 to 15.841 cents/kWh making some projects barely feasible under current electricity prices as can be seen from figure 17 (d). This however does not account for the potential price increase in electricity in the province due to the financial burdens of muskrat falls.

Electricity prices vary widely across Canada from 6.8 cents/kWh in Quebec to 17.6 cents/kWh in Saskatchewan, making solar more easily competitive with higher rates than lower rates. Northwest Territory's and Nunavut's solar breakeven prices are more competitive as these locations can be considered remote and rely on diesel which is expensive.



(a) (b)

(c) (d)

Fig. 17. (a) NL residential capacity factors. (b) Canada residential solar prices. (c) Newfoundland current solar prices (d) Low cost future prices in NL [11].

Time of day or dynamic electricity pricing increases the economics of solar energy as it means that households can consume their self-generated power during the day (when electricity demand is high and price most expensive). This however requires the installation of a smart meter and was not considered in the study.

Furthermore, rebate programs introduce some uncertainty in future solar prices as they can be expanded or reduced at any point in time. Future electricity prices across Canada exhibit large amounts of uncertainty due to the fact that electricity prices are rising faster than the rate of inflation. It was assumed by the ESPC that the value of electricity generated would increase 1.91% above inflation per year or become 19.1% higher in 10 years or 47.75% higher than current prices in 25 years. This improves the present value of solar projects which have a service life of 25 years and makes current investment in solar attractive.

According to the study [12], the optimum PV tilt angle for St. John's is 33 degrees and payback period for solar PV projects is 18 years. St. John's has the least amount of solar resources of Canada's major cities but still has more potential than Berlin, London and Tokyo despite the latter 3 cities deploying more PV installations. China has the most cumulative installed PV capacity (43.5 GW) in 2016 followed by Germany (39.7 GW) and Japan (24.4 GW).

B. Methodology

In this section the methodology related to the PV system design is presented. First the different design software is reported on and examined and then the system components are selected.

1) Design Software Selection

In a recent study [26], different PV simulation software were compared against data from a real 1 MW grid connected PV power plant. The tested simulation software were SAM, PVsyst, HOMER, PV*SOL, RETScreen, Solarius PV, HelioScope, Solar Pro, SOLARGIS, and PV F-Chart. Results of the simulation were compared against actual performance data to identify the most accurate software. The study found that HOMER, SAM, RETScreen and PVSYST to be the best suited for solar PV performance analysis

i. Helioscope

This is a novel web-based software created by Folsom Lab USA to be used for the design of PV systems [26,27]. It contains features from PVsyst while adding some design features from AutoCAD as well as google maps which allows users to use one package to cover many features of PV system design. The main inputs to this online software are: PV module and inverter specifications, array configuration and the address of the design location.

Losses covered by this software include weather, shading, aging, wiring, component efficiency, panel mismatch and most importantly shading losses. These losses are analyzed to provide recommendations for corrective measures. The output of this software includes annual production, performance ratio and losses.
HelioScope has limitations as follows:

- Financial analysis is not supported.
- Feasibility analysis is not supported.
- Does not support advanced scientific calculations.

ii. HOMER

Homer is a micro-grid optimization software developed by National Renewable Energy Laboratory (NREL), USA. It contains Optimization, sensitivity analysis and simulation features. It has become the global standard for microgrid/hybrid energy system design. [26,28]

Inputs to HOMER include location, resources, generation components specification and cost, loads, energy storage specifications as well as grid values and policies. This software application is used to design and evaluate technically and financially the options for off-grid and on-grid power systems for remote, stand-alone and distributed generation applications. It allows the user to consider a large number of technology options to account for energy resource availability and other variables.

HOMER simulation operates via energy balance calculations for each interval (time step) of the year (usually per hour) and compares the energy generated in that interval with the electric and thermal demand of that interval. Thereby calculating the energy flow to and from each system component. HOMER also decides whether or not batteries need to be charged/discharged or fuel generators need to be turned on.

By performing energy balance calculations for all possible system configurations. HOMER optimizer enumerates the most feasible design. The economic analysis of this software also estimates the cost of purchasing, installing and running the different system components throughout the project's lifetime.

Simulation results are displayed using a wide range of graphs and tables which help the user compare different configurations and judge them based on their technical and economic merits. These results can be exported for presentations and reports.

The limitations of HOMER are as follows:

- Inability to guess missing values or sizes
- Can be too time-consuming and sophisticated
- Detailed input data is not always available

iii. System Advisor Model (SAM)

System Advisor Model (SAM) is a financial and performance evaluation model designed by NREL, USA in collaboration with Sandia National Laboratories, USA [26,29] to facilitate decision making for renewable energy engineers. It was first released publicly in august 2007 and later new versions have been released adding new features, technologies, and financial models.

SAM uses weather data from NREL's National Solar Radiation Database (NSRDB) The inputs of SAM include PV module type, inverter type, losses, component lifetime and system design which are used to simulate the system and make performance predictions and energy cost estimates for grid tied power projects factoring in installation and operation costs. The output of SAM includes graphs and tables which can be exported to excel or as text files.

The main limitations of SAM are as follows:

- 3D shade modeling for PV systems is not supported.
- Weather data is not available for all the locations of the world (only U.S).

iv. Photovoltaic Systems (PVsyst)

PVsyst is a software package developed by Swiss physicist Andre Mermoud and electrical engineer Michel Villoz. It is used for the study, sizing and data analysis of PV systems. It can simulate grid connected, stand alone, solar pumping and DC grid connected photovoltaic systems. This software also includes extensive solar engineering tools as well as system components and meteorological databases [26,30]. PVsyst is considered by many practitioners as a standard for PV design and simulation.

Using PVsyst, irradiation data can be imported from PVGIS and NASA databases. This software has 4 main aspects which are: Extensive databases, Simulation tools, Preliminary Design and Project Design.

Inputs to PVsyst include plane orientation (with the option of choosing tracking systems or BIPV), system components (PV and inverter), number of PV modules in series or parallel connection in the array, etc. The output results are numerous and include monthly, daily, and hourly parameter values.

The results can be printed as a report which includes all simulation parameters and results. A detailed economic analysis can be performed using the real prices of the components and any additional costs.

PVsyst has some limitation as follows:

- Inaccurate Module Temperature calculation.
- Inability to handle detailed shadow analysis.
- No single line diagrams.

v. Comparison between PV Design Software

The following table presents a comparison between PVsyst, HOMER, Helioscope and SAM. Information in this table was extracted from reference [26] and updated with 2020 information.

Table III. COMPARISON BETWEEN PV DESIGN SOFTWARE

Software	Developed by	Types of Analysis	Advantages	Disadvantages*	Latest version	Availability
SAM	National Renewable Energy Laboratory (NREL), USA.	• Performance analysis. • Economic analysis.	• User friendly. • Easy to understand. • Graphical representation of results. • Manually add custom modules and inverters.	• 3D shade modeling is not supported. • No available weather data for other locations of the world.	SAM version 6.9 updated on October 2019	Free at https://sam.nrel.gov/
PVsyst	Institute of Environmental Sciences (ISE), University of Geneva, Switzerland	• Performance analysis. • Financial estimation used for both grid-connected, stand-alone, pumping and DC-grid PV systems.	• Extensive meteorological and PV systems components databases. • Has ability to identify the weaknesses of the system design through Loss Diagram. • Results include several dozens of simulation variables.	• Inability to handle shadow analysis. • No single line diagrams. • Inaccurate Module Temperature calculation	PVsyst version 7.0 released on 25th May, 2020	Priced, 30-day trial version is free at http://www.PVsyst.com/en/
HOMER	National Renewable Energy Laboratory (NREL), USA	•Optimization and Sensitivity analysis. •Technical analysis. •Financial analysis.	•Determines the possible combinations of a list of different technologies and its size •Very detailed results for analysis and evaluation •Has optimization algorithms used for feasibility and economic analysis	•Inability to guess missing values or size. •Sophisticated and time consuming. •Detailed input data is needed.	Version 3.14.0 released on June 17 2020	Priced, 21-day free trial available at https://www.homerenergy.com
HelioScope	Folsom Lab, San Francisco, USA	•Technical analysis. •Shading analysis.	•User-friendly. •It is a web-based tool. (no download required) •Provides a detailed wiring diagram. •Has 3D model design. •Robust Shading analysis	•Does not support financial analysis. •Does not support feasibility analysis. •Does not support advance scientific calculation.	Updated in Jan 2020	30-day trial version is available at https://www.helioscope.com/

2) System Component Selection

i. PV Module Selection

In order for optimum PV module selection, different selection parameters were introduced and are covered in this section which include:

- Fill factor.
- Efficiency.
- Degradation rate.
- Power density.
- Module price.

By studying these parameters, an informed decision can be made on which PV module is optimum for this design.

a) Fill Factor (FF)

The fill factor (FF) is a measure of the squareness of the I-V characteristics of the solar cell as can be deduced from figure 18 [31]. The factors affecting the fill factor are:

- The series resistance of the solar cell.
- The parallel resistance of the solar cell.
- The recombination current in the space charge region of the cell.
- The reverse saturation current of the junction.

Fill factor is given by the following equation:

$$FF = \frac{Pm}{(Voc\ Isc)} \qquad (2)$$

Where: Pm is the maximum output power. Voc is the open circuit voltage. Isc is the short circuit current.

Ideally, FF = 1. Fill factor decreases as the cell temperature increases. Decreases in fill factor may indicate problems with the cell. A good fill factor based on [31] starts at 0.7 therefore the PV module list is filtered for fill factors starting at 0.7.

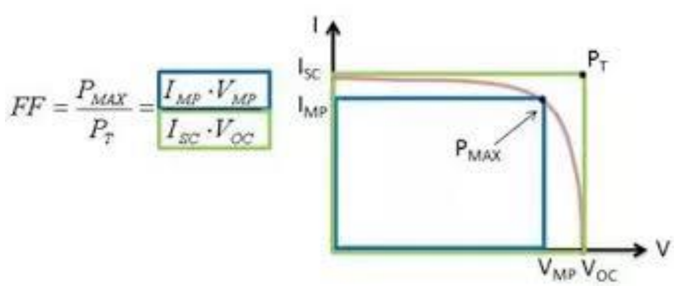


Fig. 18. Fill Factor

b) Efficiency

Efficiency is another measure of PV cell that is sometimes reported. Efficiency is defined as the maximum electrical power output divided by the incident light power. Efficiency is commonly reported for a PV cell temperature of 25 °C and incident light at an irradiance of 1000 W/m^2 with a spectrum close to that of sunlight at solar noon. An improvement in cell efficiency is directly connected to cost reduction in photovoltaic systems [31]. Maximum efficiency is the ratio between the maximum power and the incident light power, given by:

$$\mu_{max} = \frac{P_{max}}{P_{in}} = \frac{I_{max}V_{max}}{AG_T} \quad (3)$$

Where: A = PV cell area (m^2). GT =solar insolation over the cell (W/m^2)

c) Degradation Rate

The degradation rate of solar PV is the loss of efficiency every year. Degradation is strongly correlated with weather conditions i.e. panels in harsh (either too hot or too cold) climates suffer higher degradation than panels in moderate climates [32] which is why it is important to choose a module that is best suited for cold harsh climates.

According to the National Renewable Energy Laboratory [33], which examined the long-term degradation of multiple PV panels, panels made prior to the year 2000 often achieved less than 1% degradation while modern panels achieve even lower. Old monocrystalline silicon panels achieve less than 0.5% per year degradation rate while modern ones achieve less than 0.4%. This means that panels made after the year 2000 should produce 92% of its original power after 20 years.

In [34], the authors examined 11000 degradation rates from 200 studies and analysed them. They found that the median degradation rate for crystalline silicon PV was 0.5-0.6% per year with a mean of 0.8-0.9% per year. Micro silicon and hetero interface PV exhibited a 1%/year degradation.

d) Power Density

Power density is an important factor to consider since at higher power densities more energy is produced using less area. Power density is the ratio of maximum power (P_{max}) to the area and is given by:

$$Power_{density} = \frac{P_{max}}{Area} \left(\frac{Watt}{m^2}\right) \quad (4)$$

e) Selection Process

To select the most optimum PV module and manufacturer, a list of all available PV modules was obtained from the California energy commission [35]. The excel file contained approximately 25000 PV modules updated as of June 22, 2020 and categorized under different performance parameters. Building integrated modules and modules that produce AC power (micro inverter) were omitted.

Initially BVoc (%/°C) was looked at as it is the temperature coefficient. The module, which performs best under hot climate, was found to be REC260TP, which is made by REC Solar with a temperature coefficient of -0.03%/°C.

However, since the temperature in the selected site is very cold for at least half of the year this parameter was disregarded in favor of fill factor and efficiency.

Fill factor was not provided in the file produced by California energy commission and had to be manually inputted. The fill factor equation was (S*R)/(Q*P). Where S is Vpmax, R is Ipmax, Q is Voc and P is Isc.

The best module with the highest fill factor was China Sunergy (Nanjing) CSUN275-60P with a fill factor of 0.974 however; this specific module is not manufactured by a Canadian company. The module with the best fill factor that is manufactured locally is CS6K-290M-FG from Canadian Solar with a fill factor of 0.79, however this module's power density is 176.32 W/m^2 which is not the highest on the list.

The next parameter in consideration was efficiency, which also had to be manually added, the equation for which was E/[(1000*AG*AF)*100] where E is the P_{max}, AG is the long side and AF is the short side. The best performing module in terms of efficiency was LG370Q1C-A5, which is manufactured by LG electronics with an efficiency of 22.134% however; this module is not from a local company or specifically designed for cold climates. From Canadian solar, the module with highest efficiency is CS6K-305M with an efficiency of 18.815%.

The following conditions were set on the performance parameters:

- Efficiency: PV modules with efficiencies above 18% are considered and sorted from highest to lowest.
- Fill Factor: PV modules ranging between 0.72 – 0.79 FF are considered and sorted from highest to lowest after efficiency sorting.
- Power Density (W/m^2): Modules with Power density of 180 W/m^2 or higher were considered.
- Degradation rate :The latest commercial SunPower solar PV panels such as (SPR-X22-360-COM) has a degraded output of 92% and greater after 25 years, LG's latest solar PV panel variants called 'Neon R' gives out 88.4% of the output after 25 years based on the data sheets provided by SunPower and LG [36][37]. However, the best performing local module CS6K-305M degrades to 80% of its original output by 25 years.

The top 7 choices from Canadian solar after filtering and sorting were:

- CS6K-305M, CS6K-305MS.
- CS6K-300M, CS6K-300MS.
- CS6P-285M, CS6P-285MX.
- CS6K-295M, CS6K-295MS.
- CS6U-350M.
- CS6U-340P-AG.
- CS6P-280M, CS6P-280MX.

Prices for the modules were hard to obtain which turned consideration from 7 to 2 options. CS6K-305MS was available at 178 USD/module [38] or 241.83 CAD/module which is 0.58 USD/W. CS6K-300MS was available at 190 USD/module which is 0.63 USD/W.

Canadian solar (CS) was chosen as the manufacturer since:

1. CS is a local company thus minimizing transportation costs
2. CS modules are made for cold climates with advantages over other modules such as:
   - High performance in low irradiance environments.
   - Improved energy production in low temperatures.
   - High tolerance of heavy snow loads up to 6000 Pascal and wind loads up to 4000 Pascal.

The final selected module is CS6K-305MS, which is a monocrystalline panel with 60 cells per module, has a nominal max power of 305 Watts and a module efficiency of 18.63% according to the datasheet and 18.815% according to California energy commission's excel file. It can operate at temperatures as low as -40 °C and comes with a 25-year warranty [39,40]. The Area occupied by the module is 1.621 m^2, the power density is the highest among all CS modules at 188.16 W/m^2 and a decent fill factor of 0.784.

ii. Supporting Structure

The exact tilt of the roof of the studied house is not directly obtainable, a rack/mounting structure will be used to adjust the tilt of the PV modules so that tilt = latitude = 47.5 ° and azimuth = 180 ° or south facing.

For this project, supporting structures are provided by Soeasy (Xiamen) Photovoltaic Technology Co., Ltd [41]. The reason this company's product was chosen is because it is reasonably priced, and the company has high reputation on alibaba.com. The cost of the structure is 0.09 USD/W.

iii. Inverter Selection

Grid-tied solar inverter is always selected as per the capacity of solar panels and voltage specifications of local utility grid. SMA Sunny Tripower CORE1 62-US Inverter [42] was initially selected, but after producing oversizing errors in PVSYST it was replaced by Sunny Boy 11 which is an 11-kW inverter [43].

Both inverters provide 208VAC, 60Hz so they are compatible with local utility grid. Both inverters are 98% efficient with UL 1741, UL 1699B, UL 1998, IEEE 1547 and CAN/CSA-C22.2 No. 62109 certificates and approvals. Sunny Tripower costs 6875.00 USD [47] while Sunny Boy 11 costs 3421.90 USD or 4649.00 CAD [43].

A total of 93.7 kW of solar panels can be connected to Sunny Tripower as the maximum output power from solar panels can never exceed 100KW (NL net metering cap). The net metering law and no feed in tariff policy means that the designed system shouldn't produce annually more electricity than it can consume which means a small inverter like Sunny Boy 11 should be sufficient to output the 10.7 MWh required by the electric load annually. This inverter has 6 MPPT trackers with maximum current input capacity of 20A each tracker has 2 DC input strings. The voltage range of MPPT tracker is 550VDC-800VDC [42]. Calculations of wire size, PV combining box size and steady state model of the system is carried out in HelioScope software.

(a) (b) (c)

Fig. 19. (a) Sunny Tri-power 62 kW (b) Sunny Boy 11 kW (c) Sunny Boy 10 kW [42,43,50]

iv. Balance of System (BOS)

Balance of system (BOS) components include:

- AC and DC cables.
- Fuses or over current protection units.
- AC and DC switches.
- Array junction box or combiner box.
- Connectors.
- AC and DC surge protection devices.
- Earthing system.
- Lightning protection system (LPS).
- Special connectors for PV modules, string cables and inverters.
- Labour cost.
- Inverter cost.
- Support structure cost.

In 2012, IRENA [44] stated that the lowest cost of BOS for residential rooftop systems is 55% of the total cost or 1.85 USD/W while for utility scale systems it is only 20% of the total cost.

In a more recent study (2017) by Canada Energy Regulator (CER) [48], a table was presented which showed that BOS (structural and electrical), installation and development costs for residential projects in Canada will be 0.272, 0.306 and 1.603 CAD/W for the near future (now). Making the total cost without the inverter and PV module equal 2.181 CAD/W or 1.61 USD/W

If this figure is added to the price of the PV module in HOMER, the price increases from 241.83 CAD/module to 907.04 CAD/module. However, if the price of development is neglected the price per module becomes 418.12 CAD/module

The price of the inverter plus module is 1.2155 CAD/W (which is higher than 0.414 CAD/W figure from [48]). While the price of BOS without development is 0.578 and with development is 2.181 CAD/W representing 32% and 64% of the total price, respectively.

The total cost for residential PV is 2.595 CAD/W from [48]. Therefore, if we subtract the cost of module and inverter obtained before, we have the total auxiliary costs as 1.3795 CAD/W or 53% of the total cost. This figure is reasonable and closer to the percentage provided by IRENA and therefore will be used in this project. Operations and maintenance (O&M) costs were taken as 100 CAD/year based on [49]

Table IV. CER RESIDENTIAL PV SYSTEMS COSTS [48]

Initial Costs (CAD/W)	Current	Near future	Low cost future
Module	0.385	0.267	0.203
Inverter	0.213	0.147	0.112
Balance of system (structural and electrical)	0.394	0.272	0.207
Installation	0.353	0.306	0.277
Development	1.852	1.603	1.453
Total	3.197	2.595	2.252

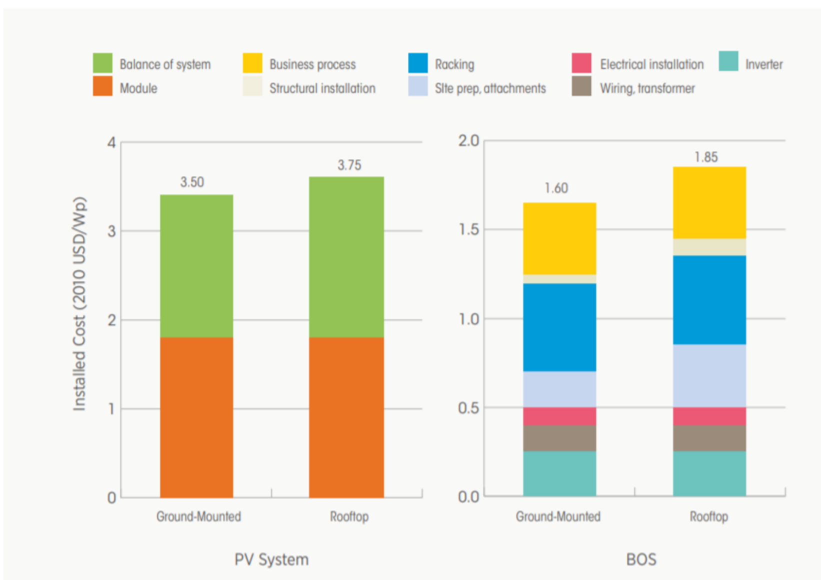


Fig. 20. IRENA balance of system's breakdown [44]

C. Results and discussion (Scenario A)

In this section, the PV system is first designed using helioscope (as it includes robust shading analysis and graphical sizing using google maps), then later using PVsyst (to find out if there are any errors) then finally using HOMER. HOMER results are seen as the final results as it will be used to combine PV with wind and Pico hydro systems later on. Similarities and differences between the results of each software will be reported on. The results reported in this section describe Scenario A which involves covering the electric load of the house using PV technology.

1) Helioscope

First, helioscope is used. In this online software the location of the house is inputted, and the physical characteristics are obtained from google maps as can be seen from figure 21. Canadian Solar CSK-305MS PV module and SMA Sunny Boy 11 KW were initially selected.

The house's roof is shown as flat even though in reality the roof is made up of different segments with different tilts, however, physically obtaining these angles is difficult therefore a flat roof is assumed for this study.

The tilt of the PV modules is designed as fixed at tilt = latitude = 47.5 ° which was obtained from the compass of an I-phone as can be seen from figure 6 while the azimuth is designed at 180 degrees (south facing), which is the ideal angle that can be accomplished while setting up the racking system.

i. Parametric shading study

Shading analysis was conducted by sweeping 3 variables: Orientation, alignment and row spacing. The resulting parametric study includes 64 systems and is shown in appendix A. The 9 evaluation parameters were: Power (kW), Energy (MWh), Shading losses (%), number of modules, PV cost (CAD), Energy price (CAD/kWh), kWh/kW, Relative price, and Capacity factor. The 1st four parameters were obtained directly from helioscope while the remaining five parameters were personally computed using excel. One thing of note is that the Energy price (CAD/kWh) is obtained by dividing PV cost by annual average electricity production and not considering the 25 years PV lifetime like HOMER, therefore this value is not an actual economic marker but more of an evaluation tool for the shading analysis. Another observation that became apparent halfway through the study is that left-hand side, right-hand side and centered alignments displayed the same system performance and therefore were grouped together. A few observations were extracted from the results of the study and will discussed shortly.

Zero meter (0 m) spacing represents the system with maximum energy yield (due to maximum number of modules being installed in the given roof area) but also maximum shading losses. In this system there are 119 modules but losses due to shading are over 52% (figure 22), making it the least economically viable system.

As the spacing between the rows increases, the number of modules that can fit into the area as well as the energy yield decreases while the cost of each kWh of production decreases. In figure 23, the results of the parametric study are summarized in graph format. The bar chart is showing energy prices while the curve is showing energy yield. The different systems are delineated by different colours as can be seen in the legend.

An observation that can be made is that the per kWh price of energy decreases steeply until 3.5 m spacing after which the decrease is much less prominent. This can be seen from figure 24 a, b and c which show the data for left hand side (LHS) alignment and portrait orientation plotted as a scatter plot. Figure 24-a shows the energy price vs row separation for all data points (except 0m). Here the change is not linear and fitting a linear curve to the data is not accurate. The slope of the linear curve is -0.0071. By separating this figure into two regions, 1st region below 3.5m and 2nd region above 3.5m, 2 more figures can be generated and a difference in slope can be observed. In figure 24-b we can see the slope for separations between 1.5 and 3.5m having a steep slope of -0.022 while for the 2nd region (figure 24 c) the slope is much shallower at -0.0014. This shows that the sharp decrease in the differential of energy price with respect to row spacing past 3.5m diminishes. This phenomenon enables us to create a lower boundary where separations above 3.5m are less attractive than ones below 3.5m.

From the parametric study we can also see that some systems are generating more than 10.7 MWh energy per year which means that the system will generate energy that the house will not consume. In net metering, excess energy is converted to credits that only the generator can use in future times. Meaning that these credits are non tradable and can’t be exchanged for money. Therefore in this project credits will be used intra-annually to balance the difference in generation between summer months and winter months, however, excess credits at the end of the year are seen as economic deficit, therefore, the system will seek to not generate more than 10.7 MWh per year. This creates an upper boundary for the parametric study**.**

The other parameters also displayed a similar pattern with the lowest performance for the 0m Landscape LHS system (corresponding to the 52% shading losses) and best for the 10m systems (which correspond to 0% shading losses). Capacity factor ranged from 6.42% for the 0m system to 13.47% for the 10m system. kWh/kW ranged from 562 to 1180 kWh/kW while energy price was 1.04 CAD/kWh for 0m system and 0.494 CAD/kWh for 10m system.

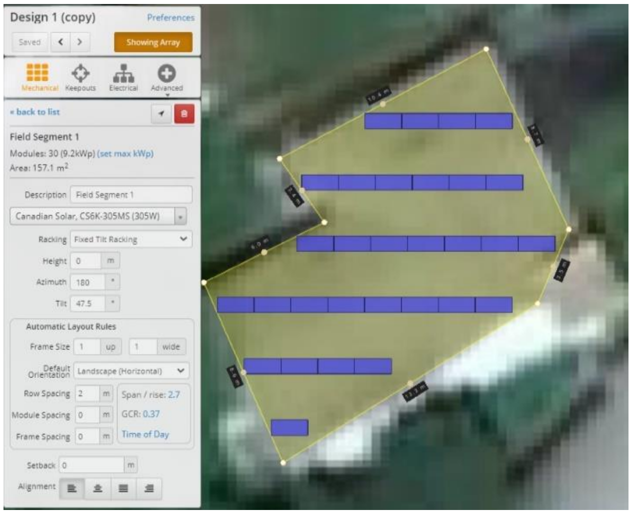
By applying the upper and lower boundaries the 64-system parametric study can be reduced to 16 systems. Systems below 1.5m row spacing were omitted by the upper boundary as they generated more than 10.7 MWh of energy according to helioscope. Systems with row spacing higher than 3.5m were omitted by the lower boundary as the energy yield sacrificed for less shading was less economically attractive in that region. All systems follow the same patterns except for the system with Landscape orientation, Left hand side alignment and 2 meter row spacing which shows 0.1 MWh more energy generated than its predecessor (1.9m) with 1% less shading and the same number of modules (31 modules) as can be seen from table V.

For the 2m system the power was 9.46 kW, the energy yield 10.8 MWh, the shading percentage 3.3%, the system used 31 PV modules which cost 5518 USD, the energy price was 0.511 USD/kWh and the kWh/kW was 1141.65 at a capacity factor of 13.03% (which is within the range of CF for Newfoundland reported earlier).

ii. Helioscope results

By simulating the system, more results can be obtained from helioscope which are shown in figure 25. From the wiring and single line diagrams it should be noted that 3 (two 10-module and one 11-module) strings are needed to connect all PV modules to the inverter otherwise not all modules will be connected. The connection is achieved via 49 meters of 500 mm^2 of copper wire. This results in a maximum power point voltage of 32.7 V and a maximum power point current of 9.33 A. However, there are some losses, most notably a 3.7% clipping loss using Sunny Boy 11kW as can be seen from figure 25 a. The energy generated for each month is also shown which shows that the energy is higher during summer than winter. While the total shading was 5.6% with the individual modules operating at 93% or higher (figure 25 d).

Through the use of PVSYST some fatal errors were found that led to a switch being made from Sunny Boy 11kW to Sunny-Boy 10 kW. The result of the switch is 3.6% less clipping losses, 0.9% less inverter losses, cheaper inverter cost and 468 kWh more energy generated as can be seen from figure 26 and 27.



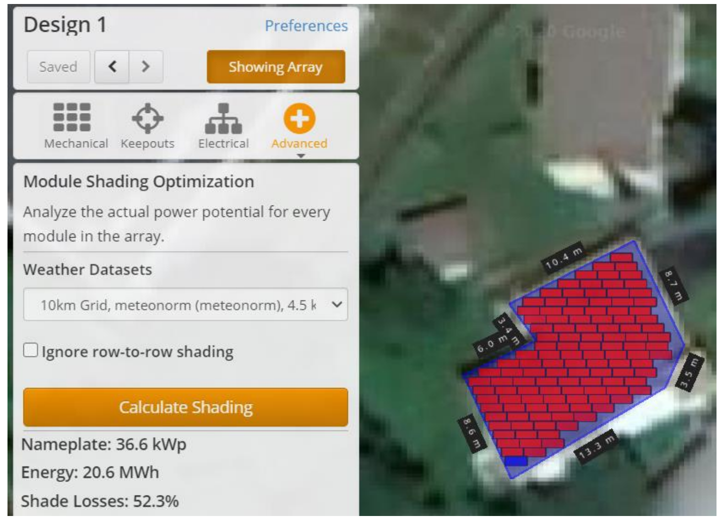


Fig. 21. Helioscope PV system design

Fig. 22. 0m spacing PV system

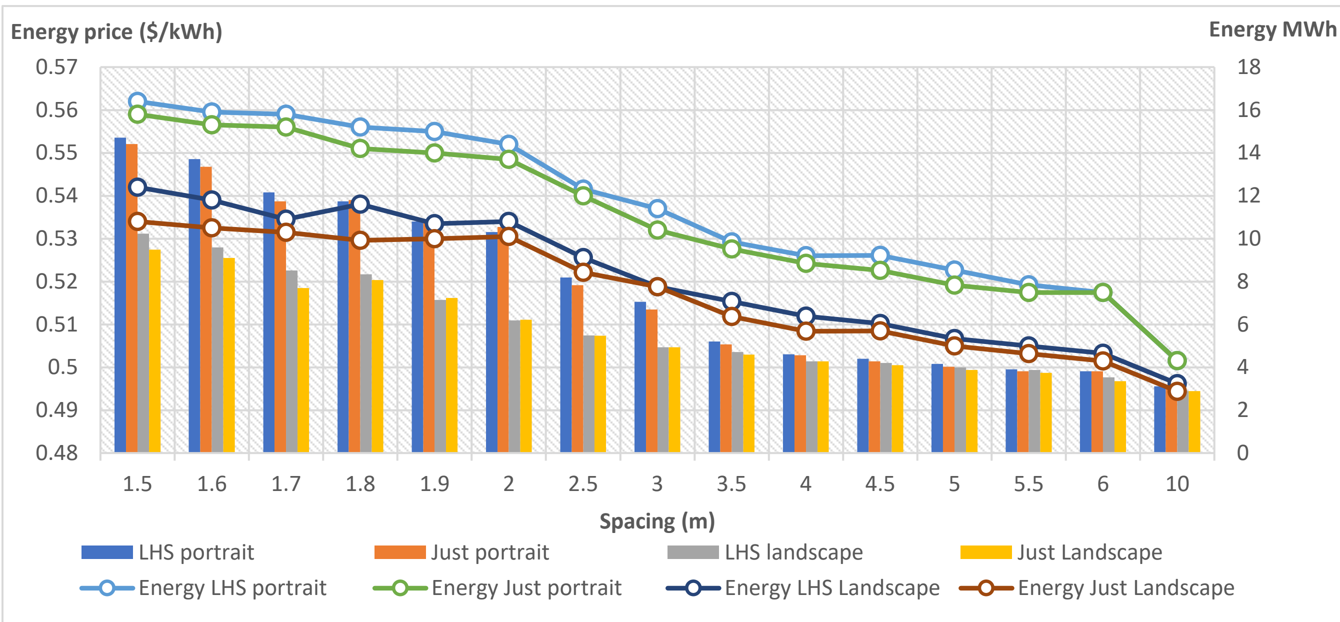


Fig. 23. Parametric study results graph

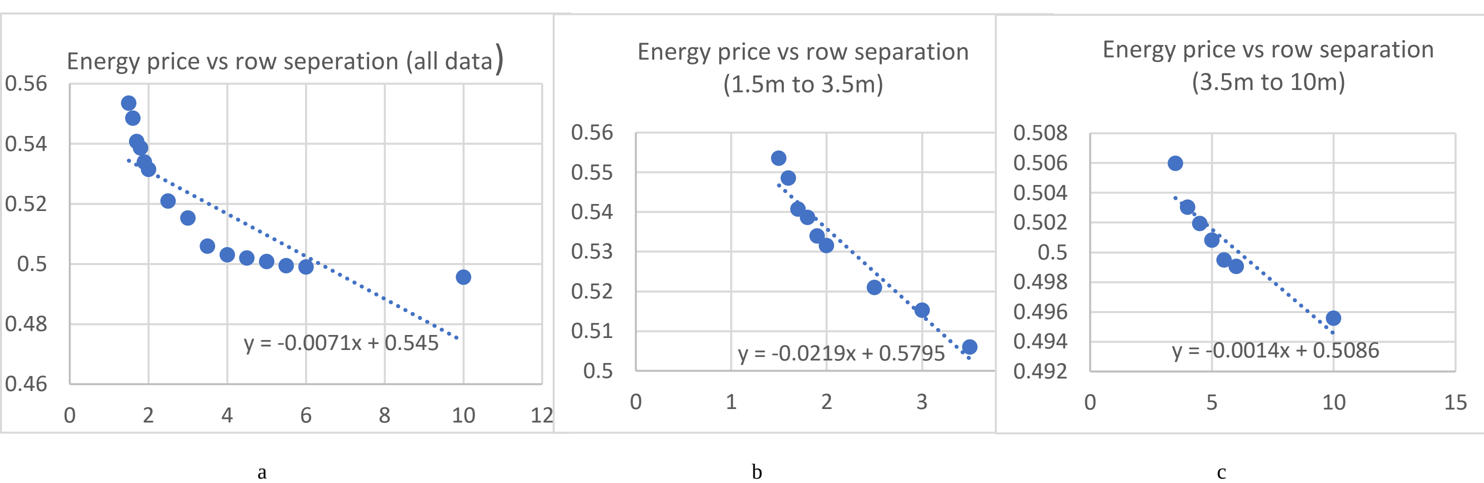


Fig. 24. LHS-portrait scatter plot with trendline: a) all data, b) spacing below 3.5m, c) spacing above 3.5m.

Fig. 25. Helioscope results: a) Losses pie chart, b) Wiring diagram, c) Shading graph, d) Monthly energy yield, e) Single line diagram

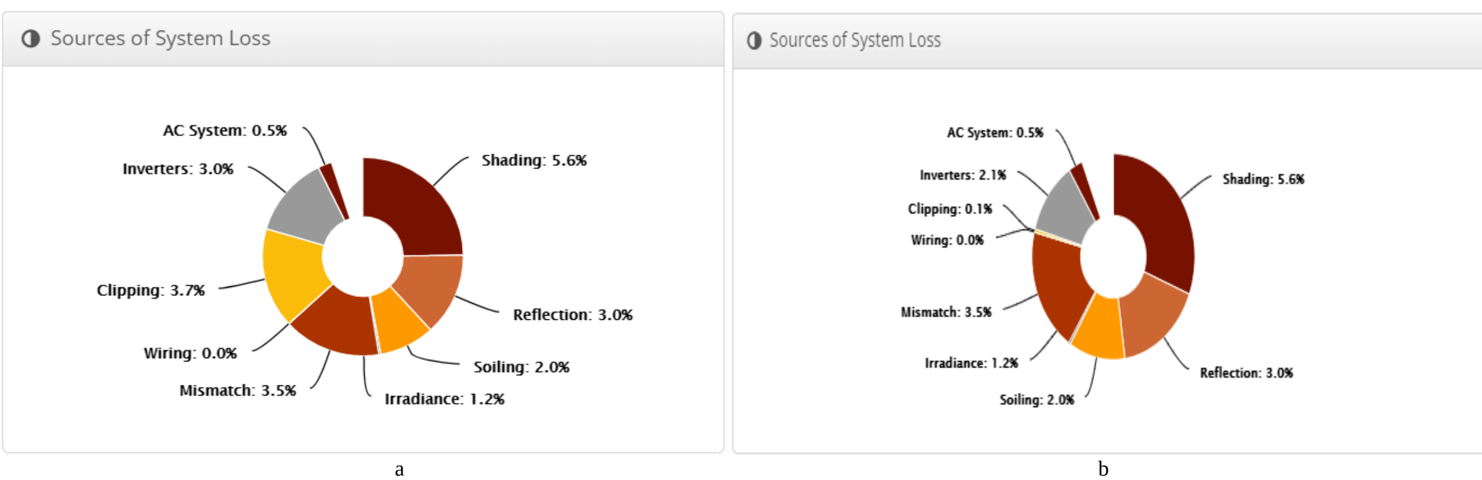


Fig. 26. Helioscope losses diagram: a) using Sunny Boy 11 kW b) using Sunny Boy 10 kW

Annual Production

	Description	Output	% Delta
Irradiance (kWh/m²)	Annual Global Horizontal Irradiance	1,128.5	
	POA Irradiance	1,318.7	16.9%
	Shaded Irradiance	1,245.4	-5.6%
	Irradiance after Reflection	1,207.8	-3.0%
	Irradiance after Soiling	1,183.7	-2.0%
	Total Collector Irradiance	**1,184.0**	**0.0%**
Energy (kWh)	Nameplate	11,199.4	
	Output at Irradiance Levels	11,064.9	-1.2%
	Output at Cell Temperature Derate	11,190.4	1.1%
	Output After Mismatch	10,796.1	-3.5%
	Optimal DC Output	10,795.8	0.0%
	Constrained DC Output	10,399.9	-3.7%
	Inverter Output	10,092.3	-3.0%
	Energy to Grid	**10,041.8**	**-0.5%**
Temperature Metrics			
	Avg. Operating Ambient Temp		8.2 °C
	Avg. Operating Cell Temp		13.9 °C
Simulation Metrics			
		Operating Hours	4602
		Solved Hours	4602

a

Annual Production

	Description	Output	% Delta
Irradiance (kWh/m²)	Annual Global Horizontal Irradiance	1,128.5	
	POA Irradiance	1,318.7	16.9%
	Shaded Irradiance	1,245.4	-5.6%
	Irradiance after Reflection	1,207.8	-3.0%
	Irradiance after Soiling	1,183.7	-2.0%
	Total Collector Irradiance	**1,184.0**	**0.0%**
Energy (kWh)	Nameplate	11,199.4	
	Output at Irradiance Levels	11,064.9	-1.2%
	Output at Cell Temperature Derate	11,190.4	1.1%
	Output After Mismatch	10,796.1	-3.5%
	Optimal DC Output	10,795.8	0.0%
	Constrained DC Output	10,786.4	-0.1%
	Inverter Output	10,562.7	-2.1%
	Energy to Grid	**10,509.9**	**-0.5%**
Temperature Metrics			
	Avg. Operating Ambient Temp		8.2 °C
	Avg. Operating Cell Temp		13.9 °C
Simulation Metrics			
		Operating Hours	4602
		Solved Hours	4602

b

Fig. 27. Helioscope energy yield: a) using Sunny Boy 11 kW b) using Sunny Boy 10 kW

Table V. 16 SYSTEM PARAMETRIC STUDY

Row Spacing	Orientation	Alignment	Power (kW)	Energy (MWh)	Shading Losses (%)	Number of Modules	PV cost (CAD)	Energy price (CAD/kWh)	kWh/kW	Capacity Factor (%)
1.6m	Landscape horizontal	justified	9.46	10.5	6	31	5518	0.526	1109.94	12.67
1.7m	Landscape horizontal	justified	9.15	10.3	5	30	5340	0.518	1125.68	12.85
1.8m	Landscape horizontal	justified	8.85	9.92	4.9	29	5162	0.52	1120.9	12.8
1.9m	Landscape horizontal	Left hand side/ Center/ Right hand side	9.46	10.7	4.3	31	5518	0.516	1131.08	12.91
		justified	8.85	10	4.1	29	5162	0.516	1129.94	12.9
2.0m	Landscape horizontal	Left hand side/ Center/ Right hand side	9.46	10.8	3.3	31	5518	0.511	1141.65	13.03
		justified	8.85	10.1	3.2	29	5162	0.511	1141.24	13.03
2.5m	Landscape horizontal	Left hand side/ Center/ Right hand side	7.93	9.12	2.5	26	4628	0.507	1150.06	13.13
		justified	7.23	8.42	2.5	24	4272	0.507	1164.59	13.29
3m	Portrait vertical	justified	9.15	10.4	3.6	30	5340	0.513	1136.61	12.98
	Landscape horizontal	Left hand side/ Center/ Right hand side	6.71	7.76	2	22	3916	0.505	1156.48	13.2
		justified	6.71	7.76	2	22	3916	0.505	1156.48	13.2
3.5m	Portrait vertical	Left hand side/ Center/ Right hand side	8.54	9.85	2.2	28	4984	0.506	1153.4	13.17
		justified	8.24	9.51	2.1	27	4806	0.505	1154.13	13.17
	Landscape horizontal	Left hand side/ Center/ Right hand side	6.1	7.07	1.7	20	3560	0.504	1159.02	13.23
		justified	5.49	6.37	1.7	18	3204	0.503	1160.29	13.25

2) PVsyst

By using SMA Sunny Tripower CORE1 62-US, PVSYST shows a fatal error saying that the inverter is oversized therefore a switch was made to Sunny Boy 11. With Sunny Boy 11 kW however another fatal error shows that the array’s maximum power point voltage at 60 ℃ is lower than the inverter’s minimum operating voltage. This problem can be fixed by switching to Sunny Boy 10 kW where no fatal errors occurred. For the final system, there was still an undervoltage error for the array at 60 ℃ temperature. However, this was not a fatal error (not red) and 60 ℃ temperatures do not happen in Canada often, so the simulation was conducted anyway. Another thing to note is that PVsyst does not allow for an odd number of modules so 30 modules were used instead of 31. The results of the simulation are shown in figure 28.

Energy losses from PVsyst were less than helioscope due to less losses (no shading losses) being taken into consideration. Global horizontal irradiation for both helioscope and PVSYST was around 1130 kWh/m2. Both had soiling losses of 2%. They had reflection losses of 3% and 3.1% respectively. However, they had mismatch losses of 3.5% and 2.1% respectively. Inverter losses were 2.1% for helioscope and 2.7% for PVsyst. PVsyst had less energy due to a smaller number of PV modules (PVsyst does not allow for odd number of modules) but more energy due to shading not being calculated. Overall, the energy from PVsyst was 0.228 MWh higher than Helioscope. Some economic parameters from PVsyst are reported in table VI which show a 10-year payback period and 125% return on investment.

From figure 28, it can also be seen that by undergoing this project the house owner will be able to save 26 tons of CO_2 emissions if the source of the original electricity was polluting.

Table VI. PVSYST ECONOMIC RESULTS

Parameter	**Value**
Total installation cost	23582.62 CAD
Net present Value (NPV)	29472.32 CAD
Payback period	10 years
Return on investment (ROI)	125%

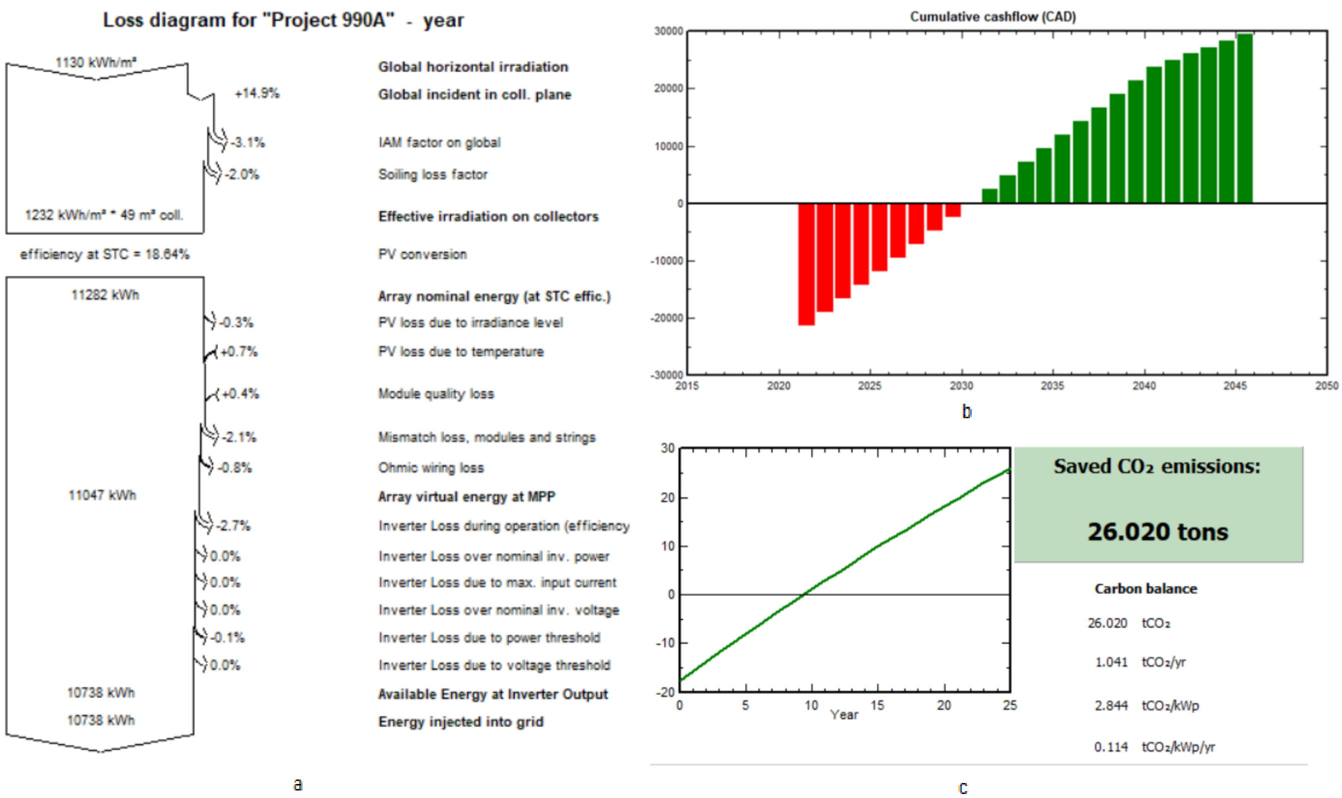


Fig. 28. PVsyst results: a) PVsyst losses diagram, b) Cash flow, c) CO_2 balance

3) HOMER

In this section, the system was designed using HOMER. Figure 29 shows a PV, Converter, load, solar irradiance, temperature, and grid inputs. The output shows a total net present cost of 26,103 CAD for a 9.46 kW system with an associated LCOE of 19 cents/kWh.

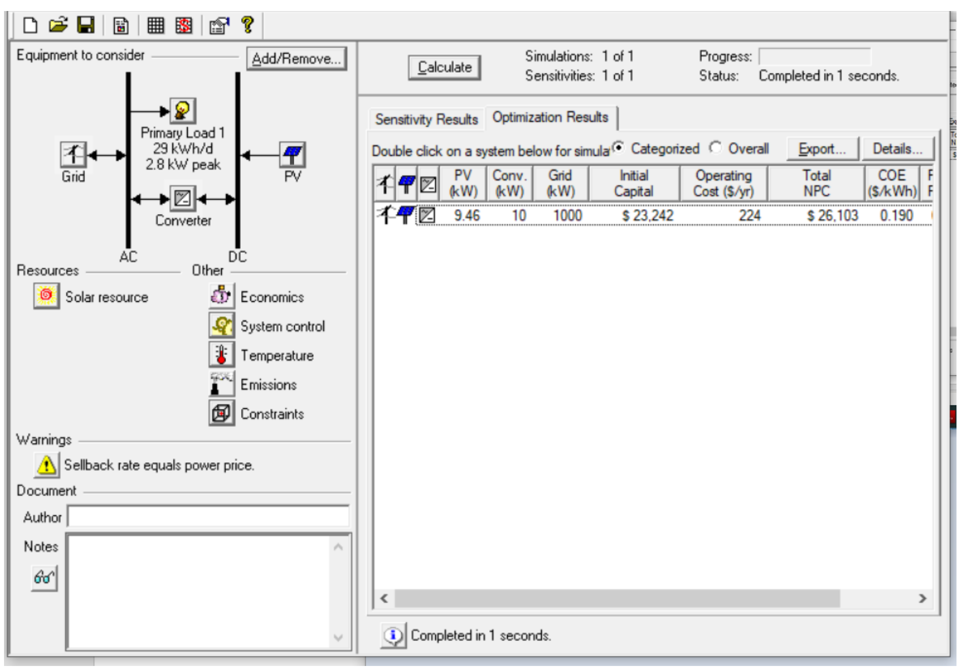


Fig. 29. HOMER screen showing inputs and results

i. HOMER inputs

Inputs to HOMER are reported in this section. All figures from the software are in appendix B.1

- **Solar resource**

  Solar resource is obtained via the internet for the latitude and longitude of the design location. The average annual irradiance is 3.18 kWh/m^2/day with peaks in May to August and the lowest performance in January and December.

- **Temperature**

  Hourly Temperature data was obtained from [51] for each month in 2019 for St. John's and then compiled in a text file and then imported into HOMER. The highest temperatures were in July and August and lowest in February. The scaled annual average temperature in St. John's is shown as 4.86℃.

- **Load Input**

  Hourly Load data was obtained from BEOPT and then imported into HOMER where the scaled annual average load is 29.4 kWh/day. The electric load was mostly uniform throughout the year with slight dips in May and November. This is mostly due to no heating or cooling electric devices being used.

- **PV input**

  In the PV input, the cost of BOS was included in the cost of PV module making the total cost of the module 663 CAD while its replacement only costs 242 CAD. However, replacement is unlikely to occur since the PV module lifetime is the same as the project lifetime. The O&M cost for the system is 100 CAD per year or 3 CAD/module/year. The size of the system is the same as the size used in Helioscope which is 9.46 kW. The derating factor is 80% of the original capacity after 25 years. The slope = latitude = 47.5 degrees. Azimuth and ground reflectance were left at their default values (south facing and 20%). Temperature effect was considered where the temperature coefficient of power of the module was obtained from the data sheet as -0.39% and the nominal operating cell temperature as 42℃. While the data sheet efficiency was inputted as 18.63%.

- **Converter**

  The converter size was chosen as 10kW costing 2678 CAD with 15-year lifetime and 98.7% efficiency (from Sunny Boy 10kW data sheet).

- **Grid**

  In the grid input, 0.23 CAD/kWh was selected as the electricity price and net metering was enabled.

ii. HOMER Results

Results from HOMER are reported on and discussed in this section. figures from HOMER are in appendix B.2

- **Cost Summary**

  The annualized cost of the system is 2042 CAD per year with the BOS cost being the predominant contributor to the price while the LCOE of the system is 0.19 CAD/kWh which is less than the 0.23

CAD/kWh electricity rate, making the system profitable. The total system cost is 26,103 CAD. On the other hand, O&M costs and replacement costs are negligible. Since the system is generating 10,614 kWh valued at 23 cents/kWh then annually the system is generating 2441.2 CAD worth of electricity. This makes the payback period 10.7 years (close to the 10-year figure from PVSYST) and the total profit by the end of year 25, 34177 CAD which means the project is profitable with 133% ROI.

- **Cash flow**

  The cash flow diagram shows that replacement of the inverter occurs around the 15th year of the project, the new inverter operates for the remaining 10 years and is then salvaged for some money at the end of the project lifetime.

- **Electrical output**

  In this tab (shown in appendix B.2) we can see that the PV array generated 10,614 kWh with the load consuming 10,731 kWh, therefore grid sales are slightly less than grid purchases since 117 kWh of energy, which are not generated, need to be imported from the grid which is equivalent to 1.09% of the load making this system not fully zero net energy but near zero net energy. Excess electricity and unmet load are both at 0%.

- **PV result**

  In the PV results tab, the capacity factor of the system was reported as 12.8% while the one calculated in excel was 13% (11%-14.6% was the range of PV capacity factors in NL reported earlier). The system operated for 4382 hours per year which is almost half the number of hours in a year. The levelized cost of the PV panels plus BOS costs are 0.160 CAD/kWh and the penetration of the PV system is 99%.

- **Converter**

  The converter exhibited 12% capacity factor while the losses in this component were minimal at 138 kWh/year. The component worked purely as an inverter and never as a rectifier.

Earlier in this report, figure 14-b illustrated that pitch angle should be equal to latitude for optimum year-round energy yield. This is further confirmed by [52] where the authors stated that a PV panel facing south can achieve at least 98% of its maximum energy yield by setting its latitude as the tilt angle. However, the optimum tilt angle suggestion box from PVsyst displays that the optimum angle should be 40°. By conducting a sensitivity analysis for tilt angle using HOMER, this is further confirmed. Energy yield increases to 10,698 kWh for 40° tilt which represents an 84-kWh increase (0.79% increase) over the 47.5° tilt system. This reduces LCOE from 0.19 to 0.189 CAD/kWh which is not at all significant and barely changes any of the results presented earlier. This LCOE figure falls in the range of PV LCOEs in NL of 16.231-21.457 cents/kWh according to CER and NEB [11].

4) Uncertainty Analysis

The price of the auxiliary costs (BOS, installation, and development) taken for the PV system was 1.379 CAD/W which was supported by IRENA [44] and the overall figure from CER [48]. However, this figure could be as much as 0.8 CAD/W higher if the whole price of development was considered producing some uncertainty in the economics of the PV system despite the justification of the chosen figure and the fact that the 18.9 cents/kWh LCOE figure reported in this study falls within the range of LCOEs for NL (16.231-21.457 cents/kWh) [11].

The energy output from HOMER was also slightly less than that of PVsyst but slightly more than helioscope's at around $\pm$ 1% difference. Overall, the results in this section are fairly accurate.

VI. Wind Energy System Design

A. Introduction

Wind turbines (WT) mounted in locations with favorable wind patterns, convert kinetic energy from moving air into electricity. Wind turbines maybe employed individually or as a part of a wind farm with the electricity generated being either used locally or injected into the grid to power loads farther away. This electricity is free from greenhouse gases and requires no fuel. Wind energy can also be used in remote locations that run on diesel as it provides a cheaper and pollution free alternative.

Natural Resources Canada [54] stated that electricity from wind is the fastest growing method for electrical generation in the world. The Canadian Wind Energy Association (Canwea) [53] has also highlighted the fact that more wind energy has been developed in Canada between 2009 and 2019 than any other form of electricity generation.

In Canada, wind is currently generating enough power for 3 million homes. There are 301 wind farms in operation from coast to coast throughout Canada with a total installed capacity of around 13 GW in 2019. However, Newfoundland is trailing behind other provinces with only 27 wind turbine installations spanning 4 projects producing 55 MW of power despite Atlantic Canada having the strongest wind regimes in the country which correlate with periods of peak demand making wind energy the cheapest option for electricity generation in the region [56].

Canada has especially significant wind resources for example the installation of six 65 kW wind turbines in Newfoundland is expected to produce 1 million kWh of electricity in a year and reduce CO_2 emissions by 750 tonnes [54]. However, some issues associated with wind energy such as turbine efficiency, operation in harsh climates and lifetime and interconnection grid problems require continued innovation.

Small scale wind energy also known as microgeneration (which can operate in either stand alone or grid tied mode) enables homes to offset some or all of their onsite electricity consumption by generating their own electricity at reduced costs and emissions. Every kWh of electricity generated but not used is converted to credits under net metering in some provinces [55].

In a recent study regarding the barriers to wind energy development in Newfoundland, the authors found out that despite Newfoundland having the highest energy resources of any province in Canada, barriers to the development of wind energy included political and economic obstacles as well as lack of knowledge and agreement as determined by interviewing experts from academia, community groups and government representatives [59].

In a study, regarding the feasibility of a zero-energy home in Newfoundland using a wind energy system to provide energy for space and water heating, cooking, lightning and electrical appliances using a 10 kW wind turbine, the authors stated that such a system is feasible [7].

B. Fundamentals

To begin with the design of a wind system, first some fundamentals are briefly mentioned.

The basic components of a wind turbine are:

- A rotor comprised of aerodynamic blades which capture the kinetic energy of the wind via the pressure difference between the lower side of the blade and the upper side and start rotating. This rotation leads the generator in the turbine (which is connected to the rotor via the shaft) to rotate and produce electricity.
- A gearbox which converts the rotation of the rotor to a higher rotation rate for the generator in order to produce electricity at the predetermined grid frequency. Turbines smaller than 10 kW usually do not require a gearbox.
- A nacelle which is a housing that protects the generator, gearbox, and other parts of the turbine from damage.
- A yaw system which aligns the turbine towards the direction of the wind as the rotor of a Horizontal-axis wind turbines (HAWT) should always be perpendicular to the wind direction.
- For larger turbines, pitch or stall mechanism is also used to control the rotation speed of the rotor at high wind speeds. For small turbines, furling mechanism is used.

There are two basic types of wind turbines:

- Vertical-axis wind turbines (VAWT) are omnidirectional i.e. they can operate regardless of wind direction by rotating in the vertical plane but require a lot more ground space to support their guy wires. Most common configurations include Savonius (a drag device) and Darrieus (a lift device).
- Horizontal-axis wind turbines (HAWT) are the most frequently used type of wind turbine. They rotate in the horizontal plane and must be aimed directly at the wind and therefore require a yaw system. Most common configurations include 2 and 3 bladed, windmill and sail wing. The total capacity of HAWTs exceeds that of VAWTs HAWTs can be facing upwind or downwind direction but mostly upwind.

There are several types of towers available:

- Guyed lattice tower is a type of tower which is anchored down and supported by guy wires. This type of tower costs the least but tends to occupy more space.
- Guyed tilt-up tower is a type of tower that can be lowered down and raised up for ease of maintenance or to protect against exceptionally high wind speeds such as tornadoes or hurricanes.
- A Self-supporting tower which does not require guy wires; however, it tends be more expensive and heavier than the other types. On the other hand, it tends to take up less yard space.

According to the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) [56], a small wind turbine is a turbine which produces no more than 50 kW of electricity with some jurisdictions defining it as 100 kW or less. The blades rotate at 175 to 500 rpm on average with some going as high as 1,150 rpm. Micro wind turbines are defined as having less than 1 kW power and are often used to recharge batteries in recreational vehicles, electric fencing and irrigation systems. Most of these systems have a lifespan of 10-15 years. OMAFRA also recommends turbine heights greater than 18.2m for optimum operation. Average annual wind speeds for a location with residential WT installation should be higher than 4 m/s according to [55] or 15 km/h according to [60].

For accurate wind resource evaluation, it is usually recommended to record wind speeds at the location at hub height for 1 year. It is important that the anemometer is set high enough to avoid turbulence from nearby trees and obstacles. Data from nearby small wind systems can alternatively be requested and used. OMAFRA states that the average cost for a small-scale wind turbine installation is 8000-11000 CAD/kW however the cost can be up to 50% higher under special circumstances. [56]

The power of the wind is proportional to the cube of wind speed which increases with tower height. if wind speed is doubled, power increases 8 folds. Power is also affected by tower height. A 200% increase in height can result in 10% increase in wind speed and so 35% increase in power. The ideal tower height is usually between 24 and 37 meters. The general rule is that at a minimum the tips of the rotor blades should be 9 m above any nearby obstacles within a 90m radius and according to [60] it should be placed such that its hub height is 10 m above any obstacle in a 100m radius.

OMAFRA recommends that wind turbines should be certified by Small Wind Certification Council or Intertek or the Wind Energy Institute of Canada. [56]

1) Power Coefficient (Cp)

The power coefficient (Cp) is defined as the power extracted by the turbine divided by the power available in the wind. While operating at maximum Cp for all wind speeds would maximize energy extracted, it has negative impact on factors such as generator capacity, structural requirements and safety. Maximum speeds occur for a few hours per year only which means that sizing the generator to extract maximum power from these speeds would lead to needless oversizing. To maintain maximum Cp, tip speed ratio λ would also have to be maintained for higher wind speeds by increasing the rotation speed ω, this would lead to radial stresses in the rotor which would lead to safety and structural integrity issues (see equation 11).

There are 4 regions of operation of the conventional wind turbine

- Not started (till cut-in wind speed).
- Constant Cp region *(cut -in wind speed to rated wind speed)*: In this region, the turbine extracts maximum power from the wind, but power extracted is less than the rated power. Here, rotor speed is varied to maintain constant λ in order to maintain Cp_{max}.
- Constant power region *(rated wind speed to cut-out wind speed)*: In this region, the generator is made to produce the same output by operating the system at a Cp lower than $Cp_{max.}$
- Stopped *(Cut-out wind speed and above)*: when cut-out speed is reached furling or pitch mechanism is used to reduce rotor speed and brakes are applied.

American multiblade and Dutch windmills have the lowest Cp. The performance of a WT is described using its power curve. A power curve is the power output of the WT versus wind speed. Using the power curve, power output estimate can be calculated which elaborates on the size of turbine required and the economics of the project such as its payback period. Power output of a WT is also a function of its diameter or swept area.

2) Sizing the Wind Turbine

It is recommended by OMAFRA [56] to attempt energy conservation measures before deciding to install a wind turbine as it will reduce its size (and cost). A preliminary estimate of the performance of a particular WT can be calculated using the following formula

$$AOE = 1.64 * D^2 * V^3 \quad (5)$$

Where AOE = Annual rated energy output (kWh), D = Diameter & V = Annual average wind speed. AOE can be compared against the annual energy consumption of the house (kWh) to find out if the WT can supply the amount of energy needed.

3) Maintenance Requirements

Periodic maintenance is required such as oiling, greasing and safety inspections. An annual inspection should comprise:

- Examining the guy wires supporting the tower for proper tension.
- Examining and tightening bolts and electrical connections.
- Examining the wind turbine for corrosion.

After 10 years blades and bearings should be completely replaced. With proper maintenance the WT can last 20-30 years and operate at minimal noise. Ice buildup on the blades is a major problem during winters in Canada. To decrease damage due to ice the following steps should be observed:

- Keeping the rotor turning which limits ice growth on the blade
- Minimization of the downtime period of the wind turbine, which also maximizes the power output from the stronger winter winds.
- De-icing when necessary.

4) Other Requirements

Other technical requirements involve the following:

- Turbine should be placed so as to minimize discomfort to neighbours (for this project neighbor consent is assumed).
- Tower should be approved by the wind turbine manufacturer or else the warranty might become invalid (manufacturer approval will also be assumed).
- Tower should be grounded to protect against lightening strikes.
- A disconnect switch is required to isolate the WT from the rest of the system for safety and ease of maintenance

- If batteries are used, inverter will need to be used (not required in this project)
- Small wind turbines usually use furling mechanism for speed control (to protect against high speeds) however this leads to reduced power output and increased noise.
- If turbine blades are made from wood they should be painted (coated) to protect against the elements.

5) Small Wind Certification Council (SWCC)

SWCC provides an evaluation of specific wind turbines an example of which can be seen in figure 30. The rated annual energy for the wind turbine is calculated for an average annual wind speed of 5m/s, Rayleigh distribution of wind speeds, sea level air density and 100% availability (assumptions). SWCC provides sound level for 95% of the time of the WT's operation (given the previous assumptions) for an observer within 60m of the rotor center.

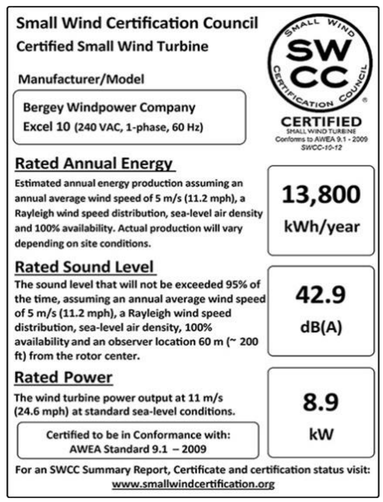

Small Wind Certification Council
Certified Small Wind Turbine
Manufacturer/Model
Bergey Windpower Company
Excel 10 (240 VAC, 1-phase, 60 Hz)
SW CC
CERTIFIED
Rated Annual Energy
Estimated annual energy production assuming an annual average wind speed of 5 m/s (11.2 mph), a Rayleigh wind speed distribution, sea-level air density and 100% availability. Actual production will vary depending on site conditions.
13,800
kWh/year
Rated Sound Level
The sound level that will not be exceeded 95% of the time, assuming an annual average wind speed of 5 m/s (11.2 mph), a Rayleigh wind speed distribution, sea-level air density, 100% availability and an observer location 60 m (~ 200 ft) from the rotor center.
42.9
dB(A)
Rated Power
The wind turbine power output at 11 m/s (24.6 mph) at standard sea-level conditions.
8.9
kW
Certified to be in Conformance with:
AWEA Standard 9.1 – 2009
For an SWCC Summary Report, Certificate and certification status visit:
www.smallwindcertification.org

Fig. 30. SWCC certificate [71]

6) Wind Turbine Noise

In this section, wind turbine noise will be discussed which is a notorious issue associated with this form of energy. Types of WT noise include:

- Aerodynamic noises: are noises made by the movement of air over the blades of the rotor. This type of noise increases at high rotor speeds. When the flow of air is turbulent a whooshing sound can be produced by the turbine.
- Mechanical noises: are noises produced by parts of the wind turbine due to wear and tear, poor design or lack of maintenance.

Therefore, proper selection and maintenance of WT can effectively reduce noise levels.

Table VIII shows the noise levels of various turbines measured by SWCC at 60m away observation point while table VII shows decibel levels of various devices and activities. By comparing the 2 tables one can note that the noise of a WT 60 m away from the rotor center is quitter than the hum of a refrigerator.

Table VII. NOISE LEVELS OF EVERYDAY DEVICES AND ACTIVITIES

Decibels (dB)	Activity
0	Threshold of hearing for humans
15	Normal threshold of hearing for humans
20	Calm human breathing or very soft whisper
30	Calm room or library
45	Rural ambient background
50	Inside of average house, Refrigerator hum
55	Low volume of TV or radio
60	Normal Conversation
65	Sleep disturbance
70	Busy office
80	Curb side of a busy road
90	Barn full of pigs, lawnmower
1000	Chainsaw, circular saw, ATV
110	Grain dryer fan
120	Threshold of discomfort, rock and roll concert
130	Threshold of pain, jet engine

Table VIII. NOISE LEVELS OF TURBINE INCLUDED IN THE STUDY

Small turbine	SWCC rated noise level (dB)
SD6	43.1
SS3.7	41.2
DS3000	42.3
E10	42.9
E15	49.3

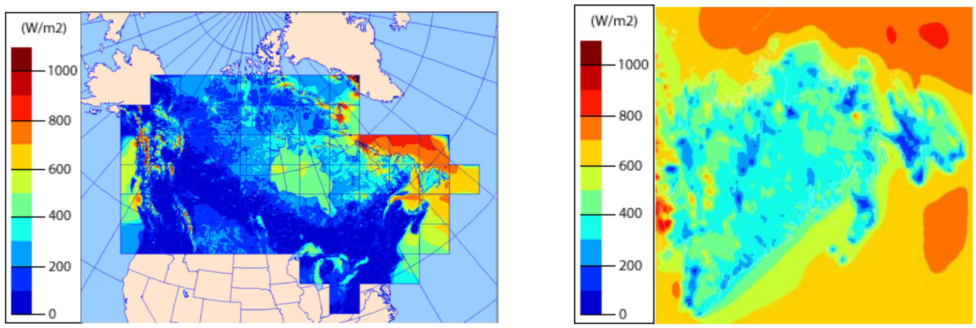
In a 2019 review paper regarding WT noise, studies focusing on the health effects of WT on humans in residential settings were assessed. Eighty four papers met the inclusion criteria of this review article and were evaluated. Multiple studies reported that wind turbine noise is associated with noise annoyance which is dependant on noise sensitivity, attitude towards WTs and economic benefit. However, WT noise was not associated with stress effects or biophysiological variables of sleep [79]. For this project acceptable noise levels will be assumed.

C. Methodology

1) Wind Atlas

Canada’s Wind Energy Atlas (CWEA) provides users with the facility to create and examine custom maps of wind speed and wind power density. By zooming in on different locations users can also look at wind speeds at different heights. The atlas is an interactive wind map that produces wind speed data for sites with a 200 m resolution. Data includes seasonal and annual averages, wind roses and wind speed histograms.

According to CWEA, wind energy in Newfoundland can reach 600-800 W/m^2 at 30m height [57]. However, once you zoom in to St. John's wind energy declines to 200 to 500 W/m^2 due to built environment (figure 31)

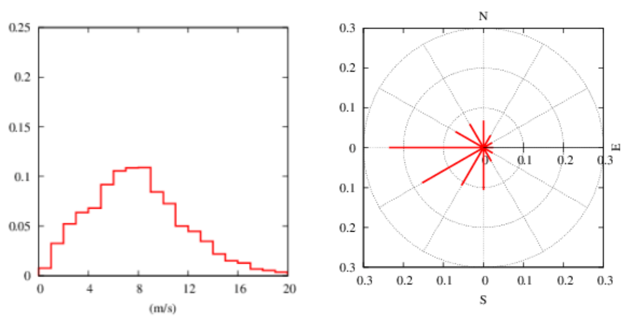


a b

Fig. 31. Wind energy density; a) of Canada b) of Newfoundland

By inputting the longitude and latitude of the design house location [58] (Latitude = 47.551, longitude = -52.712) or its postal code (A1C 2V3) into the wind atlas of Canada, average wind speeds, histogram and wind rose results were obtained and are shown in figure 32 and table IX

The wind rose figure (figure 33 c) shows the wind direction computed in degrees starting from the east then rotating counterclockwise (0 degree = east, 90 degrees = north). Windspeeds for the design location are mostly facing west and south west.



a b

Fig. 32. Wind Atlas results: a) Histogram b) Wind rose

Table IX: NOISE LEVELS OF TURBINE INCLUDED IN THE STUDY

Period	Mean Wind Speed	Mean Wind Energy	Weibull Shape Parameter (k)	Weibull Scale Parameter (c)
Annual	7.44	348.75 W/m^2	2.28	8.4 m/s
Winter	9.59	509.25 W/m^2	2.44	9.69 m/s
Spring	7046	351.62 W/m^2	2.28	8.42 m/s
Summer	6.45	215.44 W/m^2	2.44	7.27 m/s
Fall	7.39	337.38 W/m^2	2.32	8.34 m/s

2) Wind Resource Selection

By visiting the Canadian government website [51] to obtain the wind speeds in St. John's, there are 2 metrological stations in the city. One titled St. John's west and one titled St. John's international airport. Data for both these stations was downloaded, compiled and inserted into HOMER after being converted from 10m hub height to 30m hub height for ease of comparison. The equation used for this conversion is:

$$V_2 = V_1 * \left(\frac{h_2}{h_1}\right)^{\alpha} \quad (7)$$

Where: V_2 is the unknown velocity at height 2, V_1 is the known velocity at height 1 and α is the sheer factor which is equal to 1/7 in most cases depending on the local topography (α=1/7 will be assumed for this project). To convert from km/h to m/s the following relationship is used:

$$1\ \frac{km}{h} = 0.277778\ \frac{m}{s} \quad (8)$$

Note: results from the Wind Atlas can not be used in HOMER as they are not in hourly format however they will be used to guide the selection of the metrological station as these speeds were obtained using the postal code of the design house.

As can be seen from the below table, wind speeds from St. John's west station are barely feasible at 4.79 m/s at 30m hub height while wind speeds from St. John's international airport station are much higher as the station is further away from built environment. Windspeeds from BEOPT are closer to the values obtained from the Wind Atlas for the design location (in terms of c, k and average annual speed values) and therefore will be used in this project. Mathcad was used to calculate the energy density in the wind for each source and to plot a comparison curve between the 4 resources as can be seen from table VII and figure 34. BEOPT wind distribution is closest to that of the wind atlas.

Table X. WIND RESOURCE COMPARISON

Resource	Hub height	Average annual wind speed (m/s)	C value (m/s)	K value	Max wind speed	Energy density of the wind (Wh/m^2)
Wind Atlas	30 m	7.44	8.40	2.28	-	3.627*10^6
St. John's International Airport		8.08	9.12	1.98	27.62	3.659*10^6
St. John's West		4.79	5.37	1.77	15.6	1.243*10^6
BEOPT		7.82	8.82	2.21	24.59	3.6*10^6

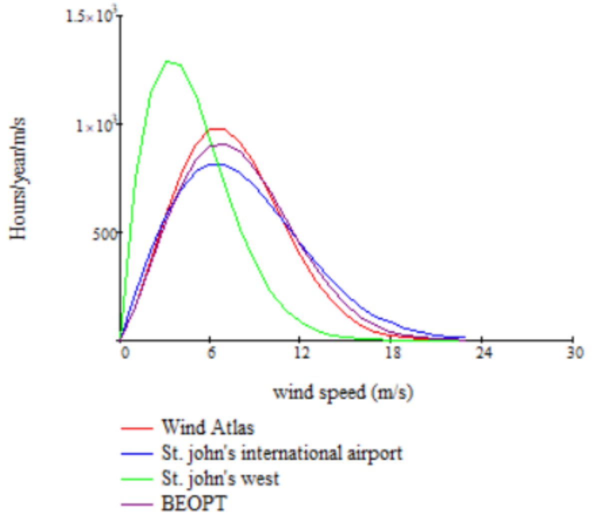


Fig. 33. Weibull distribution curves for the 4 different wind resource at 30m hub height.

3) Wind Turbine Selection

In order to select the optimum wind turbine for this design, specifications of wind turbines from SWCC and Intertek were acquired and inputted into HOMER. There is a total of 5 turbines certified by SWCC and 5 turbines certified by Intertek whose datasheets and certifications are obtainable via their respective websites [68-77]. According to the U.S department of energy, turbines certified by SWCC produced 30% more energy than uncertified small turbines [90]. The power curves for the 10 turbines are shown in appendix C.1 and C.2. The energy of each turbine was calculated for the design location at 17 m hub height using HOMER. 17 m was used since the height of tallest point of the house (the chimney) was measured at around 24 feet or 7 meters, by adding an additional 10 m, as recommended by the buyers guide from Natural Resources Canada [60], the result yields 17m minimum hub height. A comparison graph was produced using excel and is shown in figure 35.

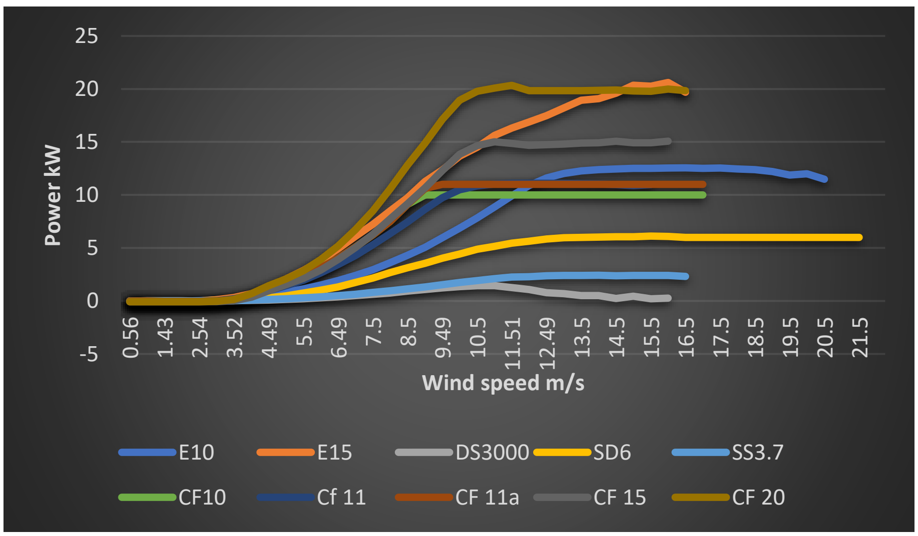


Fig. 34. Comparison between the power curves of the 10 wind turbines included in this study

4) Mathematical Relationships

Some important relationships relating to wind turbine operation are provided by B.Hodge [45] which will be used to guide Mathcad calculations.

Power available from the wind of wind speed V for swept Area A and air density ρ is derived from the wind's kinetic energy by:

$$E_{kinetic} = \frac{1}{2}mv^2 \rightarrow P_{kinetic} = \frac{1}{2}\dot{m}v^2 \rightarrow P_{kinetic} = \frac{1}{2}(\rho A v)v^2 \rightarrow \mathrm{P_{wind}} = \frac{1}{2}\rho * \mathrm{A} * \mathrm{V}^3 \text{ (6)}$$

Air density can be calculated manually if the pressure (P) and temperature (T) of the air at the location are known by:

$$\rho = \frac{\mathrm{P}}{\mathrm{RT}}, \text{ where R (gas constant) = 287 } \frac{\mathrm{J}}{\mathrm{kg*K}} \text{ (9)}$$

Betz analysis uses actuator disk theory to determine the power coefficient Cp which is defined as the power extracted by the turbine divided by the power available in the wind (τ is torque and rotor rotation rate is ω)

$$\mathrm{C_p} = \frac{\mathrm{P_{extracted}}}{\frac{1}{2}\rho * \mathrm{A} * \mathrm{V}^3} = \frac{\tau * \omega}{\frac{1}{2}\rho * \mathrm{A} * \mathrm{V}^3} \quad (10)$$

The maximum power that can be extracted by a wind turbine from the wind is defined as the Betz limit where

$$\mathrm{C_{p-max}} = 0.5926 \quad (11)$$

Rewriting the previous equation extracted power can be given as

$$\mathrm{P_{extracted}} = \frac{1}{2} * \mathrm{C_p} * \rho * \mathrm{A} * \mathrm{V}^3 \quad (12)$$

Practical values of C_p for different wind turbine types can reach 0.45 for 2-bladed HAWT and Darrieus VAWT.

Another important equation is the relationship between tip speed ratio λ, rotor radius (r), rotor rotation rate (ω) and wind speed (V):

$$\lambda = \frac{r * \omega}{V} \quad (13)$$

Wind varies in terms of speed, direction and altitude. Therefore, average annual wind speed can be used to provide rough estimates but for more accurate results hourly wind speeds should be used for calculation using software such as HOMER or Mathcad.

The probability of occurrence of wind speed v is expressed by the Weibull distribution

$$\mathrm{h(v,k,c)} = \frac{\mathrm{k}}{\mathrm{c}}\left(\frac{\mathrm{v}}{\mathrm{c}}\right)^{\mathrm{k}-1} \exp\left[-\left(\frac{\mathrm{v}}{\mathrm{c}}\right)^{\mathrm{k}}\right] \quad (14)$$

Where c is the scale parameter and k is the shape parameter. k controls the shape of the distribution and is dimensionless. Larger k leads to a gaussian distribution and lower values of k result in exponential distribution, however, for wind speed distribution, k is usually near 2. c controls the value of the mode (most probable speed which corresponds to the peak of the Weibull curve) and has the same units as wind speed. Larger c means larger mode speed and lower probability of wind speeds less than the mode. The value of the mean wind speed is given by:

$$V_{mean} = \int_0^\infty h(v,k,c)v\,dv \quad (15)$$

The average value of available power density at the mean wind speed is

$$P_{mean} = \int_0^\infty \frac{1}{2}\rho h(v,k,c)v^3\,dv \quad (16)$$

The root mean cube speed is given by

$$V_{rmc} = \sqrt[3]{\int_0^\infty h(v,k,c)v^3\,dv} \quad (17)$$

The average value of available power density for collection over a year per unit area is

$$P_{rmc} = \frac{1}{2}\rho {V_{rmc}}^3 \quad (18)$$

The extracted power then becomes

$$P_{extracted} = \frac{1}{2}C_p\,\rho\,{V_{rmc}}^3 \quad (19)$$

The total energy extracted per year is the integral of the previous equation

$$Energy_{rmc} = \frac{1}{2}C_p\,\rho\int_0^\infty h(v,k,c) * 8760 * v^3\,dv \quad (20)$$

Wind turbines capacity factor (CF) is defined as the ratio of energy generated per year to the maximum possible energy generated if the turbine was operating at rated power for every hour of the year

$$CF = \frac{Energy\ generated/year}{P_{rated} * 8760} \quad (21)$$

D. Results and Discussion

1) Scenario B

From the tables in appendix C.1 and C.2, none of the turbines provided by SWCC or Intertek are optimal for covering the electric load i.e. none of the turbines produced around 10.7 MWh in a year. However, Skystream 3.7 (SS3.7) from Xzeres Wind Corporation produced 7,431 kWh when installed at 17 m hub height which is the closest figure to the load.

This turbine is available with a 70 feet (21.3 m) monopole tower [62]. At this height, the turbine will produce 7,854 kWh/year. This turbine can be combined with 8 CS6K-305MS PV modules to produce 10613 kWh of electricity which is 98.9% of the electric load. The remaining 1.1% will have to be imported from the grid.

Xzeres Skystream 3.7 is a 2.4 kW turbine with a rotor diameter of 3.7 m making its swept area 10.9 m^2. The turbine produces 240 single phase Volts AC at 60 Hz frequency which is compatible with the local grid and satisfies NL Hydro net metering interconnection requirements [78]. The noise level of the WT is 41.2 dB [69] and the lifetime of the turbine is 20 years [66], which are reasonable figures.

Xzeres SS3.7 costs 7000-10000 USD depending on tower height and cost of installation [63]. The upper value of this range will be considered since the tallest tower was selected. This value is equivalent to 13413 CAD which is cheaper than the cost of the average turbine [56]. According to reference [64], O&M costs for a wind turbine are 10 to 35% of the total LCOE cost while in [65] the cost was between 11 and 30%. For this project, O&M cost of 20% will be assumed which is equivalent to 268 CAD/year.

In the following sections, two ways for calculating annual wind energy generation of a turbine at the design location are presented and compared. One is using equations provided by [45] implemented in Mathcad and the other is using HOMER simulation software.

i. HOMER Results

The results of the simulation (shown in appendix C4 and summarized in tale XI) show that for Scenario B, the total cost of the system is 25,487 CAD with the main contributor to the cost being the wind turbine itself. A replacement of the WT takes place in year 20 but is quickly salvaged 5 years later (HOMER assumes the system can be salvaged and so will this project). The PV array produced 2759 kWh and the wind turbine produced 7854 kWh. The PV array had a rated capacity of 2.44 kW and a capacity factor of 12.9% and operated for 4382 hours per year. The WT had a rated power of 2.4 kW and capacity factor of 37.4% and operated for 7991 hours per year.

For Scenario B, initially, 3.63% or 521 kWh were categorized as excess electricity which should not happen given the net metering interconnection. A solution attempted to remedy this was to increase the purchase capacity of the grid indefinitely, however, this did not work. It appears that the problem was with the 1 kW inverter used being undersized leading to a portion of energy generated by the PV array to not be converted. By increasing the inverter size to 2 kW, excess energy decreased to 9.2 kWh/year and LCOE reduced from 0.194 to 0.186 CAD/kWh making the system marginally better than the one in Scenario A by 1.59%. The payback period for this scenario is 10.44 years and the return on investment is 139%

It is somewhat counterintuitive that under the assumptions set out for this project, solar PV is competitive with wind energy in Newfoundland. A solar and wind systems trading company in Ottawa has stated that solar is superior to wind due to PV panels having no moving parts, warranties of 25 years, lifetime of 30 years or more and no maintenance requirement, while wind systems are often overpriced with high maintenance costs. Also, most locations in North America have less wind resources than what is needed for economic feasibility of the system. [80]

In a 2018 master's thesis, the author found that the lowest LCOE results for an off-grid solar/wind/fuel cell residential system is 0.3418 USD/kWh or 0.46 CAD/kWh [82]. Therefore, by omitting energy storage and instead opting for net metering the LCOE of this system can achieve 59.6% reduction in levelized cost.

Table XI: SCENARIO B HOMER RESULTS

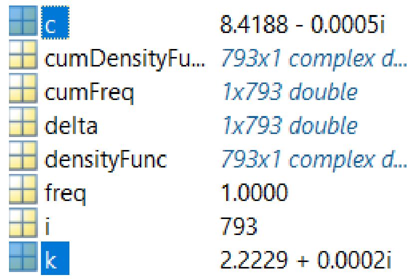
Parameter	Value	Parameter	Value
Total cost (NPV)	25487 CAD	PV capacity factor	12.9 %
Annualized Cost	1994 CAD	PV hours of operation	4382
PV array output	2759 kWh/year	PV levelized cost	0.159 CAD/kWh
Wind turbine output	7854 kWh/year	WT rated capacity	2.4 kW
Grid purchases	3674 kWh/year	WT capacity factor	37.4 %
Grid sales	3511 kWh/year	WT hours of operation	7991 hours
PV rated Capacity	2.44 kW	WT levelized cost	0.186 CAD/kWh
Excess energy	0.06 %	Unmet load	0%

ii . Mathcad Results

Using the equations provided in the "Mathematical Relationships" section of the methodology, a Mathcad worksheet (shown in appendix C.5) was created in order to confirm the results from HOMER and to enumerate variables not considered by HOMER. Three notes should be mentioned first regarding the usage of Mathcad:

1. The standard air density at sea level is $\rho_{standard} = 1.225\ \frac{kg}{m^3}$, however, the elevation of the design location stands well above sea level at 140.5m and the tower height adds an additional 21.3m (at a 4.85 ℃ average temperature, 29 in.Hg altimeter setting and 2 ℃ dew point). Therefore, air density was corrected for height using [67] where the new air density was found to be $\rho_{actual} = 1.202\frac{kg}{m^3}$.
2. Cp as shown in the table in [69] does not assume a maximum value in the cut in to rated region but slowly builds up 0.29 and then degrades. Since the rated wind speed is 11 m/s and cut in 3 m/s, values of cp from cut in to rated were added and the divided by the number of data points to obtain the average cp for that region which was 0.26.
3. Wind speeds from BEOPT used in HOMER were inputted at 30m hub height and HOMER converts them to the actual tower hub height of 21.3 m. However this option is not present in Mathcad and so the wind speeds were converted manually in excel to 21.3m hub height (using equation 7) then inputted into HOMER to obtain the value of the c and k which were c = 8.4 m/s, k = 2.22 and V_{mean} = 7.45 m/s.

Before using Mathcad, the values of c and k obtained from HOMER are verified with MATLAB (the code and results of which can be seen in appendix C.8). The result shows c = 8.41 and k = 2.22, as can be seen from figure 36, which verifies the earlier obtained values.



c	8.4188 - 0.0005i
cumDensityFu...	793x1 complex d...
cumFreq	1x793 double
delta	1x793 double
densityFunc	793x1 complex d...
freq	1.0000
i	793
k	2.2229 + 0.0002i

Fig. 35. MATLAB Result (c & k values)

By examining the Mathcad worksheet, the following table is obtained which summarizes the key variables from the calculations.

Table XII. MATHCAD INPUTS AND OUTPUT

Designation	Variable	Value	Variable	Value
input	c	$8.4\ \frac{m}{s}$	D	3.7 m
	k	2.22	vcutin	$3\ \frac{m}{s}$
	vmax	$23.4\ \frac{m}{s}$	vcutout	$16.5\ \frac{m}{s}$
	P	2400 W	cp	0.26
output	Vmode	$6.42\ \frac{m}{s}$	Pden(Vmode)	$161.7\ \frac{W}{m^2}$
	Vmean	$7.44\ \frac{m}{s}$	Pden(Vmean)	$252.2\ \frac{W}{m^2}$
	Vrmc	$8.936\ \frac{m}{s}$	Pden(Vrmc)	$437.1\ \frac{W}{m^2}$
	Ewind	$3.8\text{x}10^6\ \frac{W.hr}{m^2}$	Emax	$9\text{x}10^5\ \frac{W.hr}{m^2}$
	Eideal	$1.9\text{x}10^6\ \frac{W.hr}{m^2}$	Energyout	$7.85\text{x}10^6$ Whr $= 2.82\text{x}10^{10}$J
	Econ	$7.3\text{x}10^5\ \frac{W.hr}{m^2}$	ratio	19.1%
	Capacity factor	37.3%	Capture ratio	80.95%

Vmax is the maximum wind speed at the given location at 21.3m hub height which was obtained using a max function in excel on the data from BEOPT after height conversion. P is the rated power of the turbine while D is its diameter. Pden(Vmode), Pden(Vmean) and Pden(Vrmc) are Power densities at mode velocity, mean velocity and rmc velocity. Ewind is the energy density available in the wind. Eideal is the energy extracted by an ideal turbine with cp = 0.5. Econ is the Energy density (per year per m^2) captured by the turbine while accounting for changes in Cp in different regions where as Emax is the energy captured (per year per m^2) with no control. Energyout is the output energy. Ratio is the percentage of wind energy captured by the turbine, it is the ratio between Econ and

Ewind. Capacity factor is the ratio between the actual energy (Econ) and the theoretical output if the turbine was producing rated power for every hour in the year. Capture ratio is the percentage of maximum energy (with no control) that can be captured with control (Econ/Emax).

As can be seen the results of HOMER and Mathcad are very similar. The mean wind speed from HOMER is 7.45 m/s while from Mathcad it is 7.44 m/s. The energy output from HOMER was 7854 kWh while from Mathcad it was 7845 kWh, a mere 0.1% difference. The capacity factor for the wind turbine from HOMER was 37.4% while for Mathcad it was 37.312%, a 0.088% difference. This verifies both methods.

2) Scenario C

In the third scenario, a wind-solar hybrid system will be used to provide the thermal load. As enumerated earlier the thermal load is 40.515 MWh worth 2799 CAD/year. Bergery excel 10 is the chosen turbine which costs 60024 CAD and comes with an 80-foot (24.384 m) tower [83]. The WT is deigned to operate for a minimum of 30 years [84]. By combining it with 14 CS6K-305MS PV modules, the turbine produces 35856 kWh while the PV array produces 4828 kWh making the total energy produced equal 40684 kWh which satisfies 100% of the thermal load with 0.4% extra energy that can be saved as credits.

The system's LCOE is the lowest yet at 0.162 CAD/kWh. The system uses 1 WT, 14 PV panels and a 4-kW inverter which in total cost 83969 CAD which is equivalent to 6569 CAD/year. This annualized figure is more than double the amount the household currently spends on heating (using heating oil) proving that the switch to renewable electric heating is not an economically sound move despite the relatively low LCOE. However, opting for this system will save the residence 12.4 metric tons of CO_2 equivalent emissions per year.

Canada currently has one of the most ambitious carbon pricing programs in the world. Under Prime Minister Justin Trudeau, the Liberal government has enacted a nationwide tax on oil, coal and gas that starts at 15 CAD per ton of carbon dioxide in 2019 and will rise to 38 CAD per ton by 2022 [85]. Despite these taxes being mostly aimed at industry, a holistic approach must factor it in as heating oil is a very polluting fossil fuel that produces 161.3 lb of CO_2/Btu (same as diesel) [86].

By factoring in pollution cost, the house will be saving an additional 471.2 CAD per year which slightly improves the economics of the project, however, it still remains more expensive than maintaining the status quo as far as the thermal load is concerned. Another disadvantage of this system is that it can not be easily combined with scenario A as it would lead to an oversized PV system with high shading losses. The payback period after including carbon externalities is 25.8 years with no positive ROI making this system marginally unfeasible however the existence of government rebate programs to switch off of oil would make this scenario more viable. HOMER results pertaining to this scenario are provided in appendix C.7 and the results are summarized in table XIII.

Table XIII. SCENARIO C HOMER RESULTS

Parameter	Value	Parameter	Value
Total cost (NPV)	83969 CAD	PV capacity factor	12.9 %
Annualized Cost	6569 CAD	PV hours of operation	4382
PV array output	4828 kWh/year	PV levelized cost	0.159 CAD/kWh
Wind turbine output	35856 kWh/year	WT rated capacity	12 kW
Grid purchases	17700 kWh/year	WT capacity factor	34.1 %
Grid sales	17806 kWh/year	WT hours of operation	8316 hours
PV rated Capacity	4.27 kW	WT levelized cost	0.159 CAD/kWh
Excess energy	0 %	Unmet load	0%

This scenario serves as the premise for the 990-B research project where the following research questions will be addressed: Can ground sourced heat pump and solar thermal replace heating oil at a competitive price? Is it more economical than using electric heating?

3) Scenario D

Most of the turbines collected for this study do not have a published price. To use DS3000 3kW WT from Hi VAWT Technology, the price of another 3kW WT with the same lifetime (20 years) was assumed. The price of the turbine which was obtained from Alibaba.com is 7381.34 CAD [89]. O&M costs are taken as 20% of the LCOE (same as before) at 147.48 CAD.

DS3000 is a 3 bladed vertical access turbine. It has a rated power of 3kW at 12 m/s speed; however, SWCC testing proved its realistic rated power is 1.4kW. Its cut in speed is 3 m/s and cut-out 15 m/s. It can survive speeds up to 60 m/s. It has a 4 m rotor diameter and 4.16 m rotor height. it can operate as either a battery charger or grid tied WT. The DS part of the name stands for Darries and Savonius as the manufacturer claims the WT integrates the functionality of both VAWT types and outperforms both. The turbine includes a direct drive 3 phase permanent magnet generator (PMG) and a maximum power point tracking (MPPT) controller. It can produce 48 VDC or 220 VAC depending on the application. The main features of this turbine are that it can be installed on rooftops at a weight of 680 kg without a tower and that it does not require a yaw or pitch system as it omnidirectional. This turbine was the first VAWT to be tested for safety, function, performance, and durability by SWCC and meet the American Wind Energy Association (AWEA) standards. The sound level of the turbine will not exceed 42.3 dB 95% of the time according to SWCC. The turbine can operate at temperatures as low as -20℃. [91-94].

VAWT have the following advantages over HAWT: 1-lesser stress on mounting structure, 2- can obtained energy from any wind direction without use of a yaw system, 3-higher efficiency in built environment, 4- can operate in environments with high turbulence intensity. The disadvantage is unstable aerodynamic behaviour [95].

For this project, DS3000 will be roof mounted i.e. its hub height will be equal to the height of the roof which is 7.3m. In the roof mounted Scenario D, to satisfy the electric load, 2 DS3000 WT, 8 CS6K-305MS PV modules and a 2 kW converter will be used. The system produces a total of 10853 kWh/year which satisfies 100% of the electric load with 1.14% extra energy that can be saved as credits.

The results show an LCOE of 0.194 CAD/kWh which is the worst LCOE yet despite a larger portion of the cost coming from the WTs. The reason for this is the lowered hub height (below the minimum recommended 17 m) for the roof mount wind turbine scenario which has resulted in lower energy yield and higher wind turbine cost at an LCOE of 0.199 CAD/kWh. In fact the LCOE of the PV modules (without the inverter) is much lower at 0.159 CAD/kWh proving again that solar can compete with wind power in Newfoundland given the correct design. HOMER inputs and outputs for this scenario are shown in the appendix C.9 and C.10 and the results are summarized in Table XIV

Another potential problem of this scenario is the weight of the wind turbines which totals 1360 kg being too much of a load for the rooftop. This amount of weight is equal to 15 adult males divided into 2 groups standing in two 4m radius circles. This might be acceptable for high rise concrete buildings but is likely to cause structural problems for a residential 2 story wooden house especially since roof mounting of the turbines means they are exposed to high turbulence from nearby trees and houses.

Table XIV: SCENARIO D HOMER RESULTS

Parameter	Value	Parameter	Value
Total cost (NPV)	26661 CAD	PV capacity factor	12.9 %
Annualized Cost	1066.44 CAD	PV hours of operation	4382
PV array output	2759 kWh/year	PV levelized cost	0.159 CAD/kWh
Wind turbine output	8094 kWh/year	WT rated capacity	2.8 kW
Grid purchases	3745 kWh/year	WT capacity factor	33 %
Grid sales	3822 kWh/year	WT hours of operation	7982 hours
PV rated Capacity	2.44 kW	WT levelized cost	0.199 CAD/kWh
Excess energy	0 %	Unmet load	0%

4) Uncertainty Analysis

All turbines certified by SWCC use furling mechanism and therefore do not have a cut out speed only a survival speed (of around 60 m/s). The power curves inputted into HOMER are the power curves provided by SWCC during their testing. However, there is a chance that the turbines produce power at speeds higher than those that were tested. Similarly, for turbines tested by Intertek the cut-out speed that is listed in the data sheet is higher than the highest wind speeds the turbines were tested at. This could be because testing occurred for durations that were too short (ex: 1 month) so the full range of wind speeds did not manifest or that the test locations (ex: certain parts of Ireland) do not have robust wind profiles. By extending the power curve of the turbine used in Scenario B to the cut-out speed such as the curve provided by [81], around 3% more energy is produced which is a small figure due to a smaller portion of wind speeds occurring at the higher end of the spectrum (lower probability of occurrence). Therefore, 3% is the error margin for the wind systems. Power curves from SWCC and Intertek were preferred since they were recommended by the government of Ontario and its better to err on the side of the lower guaranteed estimate.

Despite the robust wind resource selection process, there is a chance that wind speeds from St. John's international airport are more accurate than BEOPT wind speeds, however, this would only lower the energy generated by the wind turbine in scenario B from 7,854 kWh to 7,796 kWh which is a 0.74% decrease. Overall, the uncertainty in this section is slightly higher than the one in the PV section but it is still very low (below 3%).

Conclusions

This project carried out the design of solar and wind energy systems to satisfy the electric and thermal loads of a house in St. John's Newfoundland. Component selection was carried out and justified. Four renewable energy generation scenarios were generated, verified and compared. Scenario A used 31 CS6K-305MS PV modules and generated 10614 kWh (98.9% of the load) at an LCOE of 0.189. Scenario B used a combination of a horizontal axis wind turbine (SS3.7) and 8 PV modules to generate 98.9% of the load at an LCOE of 0.186 CAD/kWh which was the best system. Scenario D used 2 roof-mounted vertical axis wind turbines (DS300) and 8 PV modules to generate 101.14% of the electric load; however, it had the worst LCOE of 0.194 CAD/kWh due to lower WT height. Although varying in levelized cost, payback period and return on investment, the three aforementioned electric load scenarios are all feasible under the premise of the project. Scenario A underperformed Scenario B by an LCOE margin of only 1.59% making Solar PV competitive with Wind energy in the province. Unlike the other 3 scenarios which covered the electric load, Scenario C addressed the thermal load. The installation of Bergery E10 wind turbine and 14 PV panels was able to cover the thermal load of 40.515 MWh. However, the system was slightly over the feasibility line with a payback period of 25.8 years after including emission externalities of Heating oil.

Future Work

In Project 990B, pico-hydro will be included to finalize the electrical system and compared against the four scenarios proposed in project 990A. Scenario C serves as the premise for the 990-B research project where the following research questions will be addressed: Can ground sourced heat pump and solar thermal replace heating oil at a competitive price? Is it more economical than using electric heating? Thermal energy storage will also be studied as renewable sources suffer from intermittency since there is no mechanism similar to net metering for thermal energy. Polysun will be the primary software to be used for the thermal system simulation. If time permits, demand side management (DSM) and energy conservation measures might also be addressed.

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Appendix

Appendix A- Parametric Shading Study

row spacing	orientation	alignment	Power (kW)	Energy (MWh)	Shading losses (%)	Number of Modules	PV cost (CAD)	Energy Price (CAD/kWh)	kWh/kW	Capacity Factor (%)
0m	Portrait vertical	Left hand side/ Center/ Right hand side	36	21.8	48.7	118	21004	0.963	605.56	6.91
		justified	33.6	20.5	48.3	110	19580	0.955	610.12	6.96
	Landscape horizontal	Left hand side/ Center/ Right hand side	36.3	20.4	52.3	119	21182	1.038	561.98	6.42
		justified	33.6	19.4	50.9	110	19580	1.009	577.38	6.59
1.5m	Portrait vertical	Left hand side/ Center/ Right hand side	15.6	16.4	10.7	51	9078	0.554	1051.28	12
		justified	14.9	15.8	10.4	49	8722	0.552	1060.4	12.11
	Landscape horizontal		11.3	12.4	6.6	37	6586	0.531	1097.35	12.53

		Left hand side/ Center/ Right hand side								
		justified	9.76	10.8	6.4	32	5696	0.527	1106.56	12.63
1.6m	Portrait vertical	Left hand side/ Center/ Right hand side	14.9	15.9	9.6	49	8722	0.549	1067.11	12.18
		justified	14.3	15.3	9.4	47	8366	0.547	1069.93	12.21
	Landscape horizontal	Left hand side/ Center/ Right hand side	10.7	11.8	6.2	35	6230	0.528	1102.8	12.59
		justified	9.46	10.5	6	31	5518	0.526	1109.94	12.67
1.7m	Portrait vertical	Left hand side/ Center/ Right hand side	14.6	15.8	8.4	48	8544	0.541	1082.19	12.35
		justified	14	15.2	8.2	46	8188	0.539	1085.71	12.39
	Landscape horizontal	Left hand side/ Center/ Right hand side	9.76	10.9	5.2	32	5696	0.523	1116.8	12.75
		justified	9.15	10.3	5	30	5340	0.518	1125.68	12.85
1.8m	Portrait vertical	Left hand side/ Center/ Right hand side	14	15.2	8	46	8188	0.539	1085.71	12.39
		justified	13.1	14.2	7.8	43	7654	0.539	1083.97	12.37
	Landscape horizontal	Left hand side/ Center/ Right hand side	10.4	11.6	5.1	34	6052	0.522	1115.38	12.73
		justified	8.85	9.92	4.9	29	5162	0.52	1120.9	12.8
1.9m	Portrait vertical	Left hand side/ Center/ Right hand side	13.7	15	7.4	45	8010	0.534	1094.89	12.5
		justified	12.8	14	7.3	42	7476	0.534	1093.75	12.49
	Landscape horizontal	Left hand side/ Center/ Right hand side	9.46	10.7	4.3	31	5518	0.516	1131.08	12.91
		justified	8.85	10	4.1	29	5162	0.516	1129.94	12.9

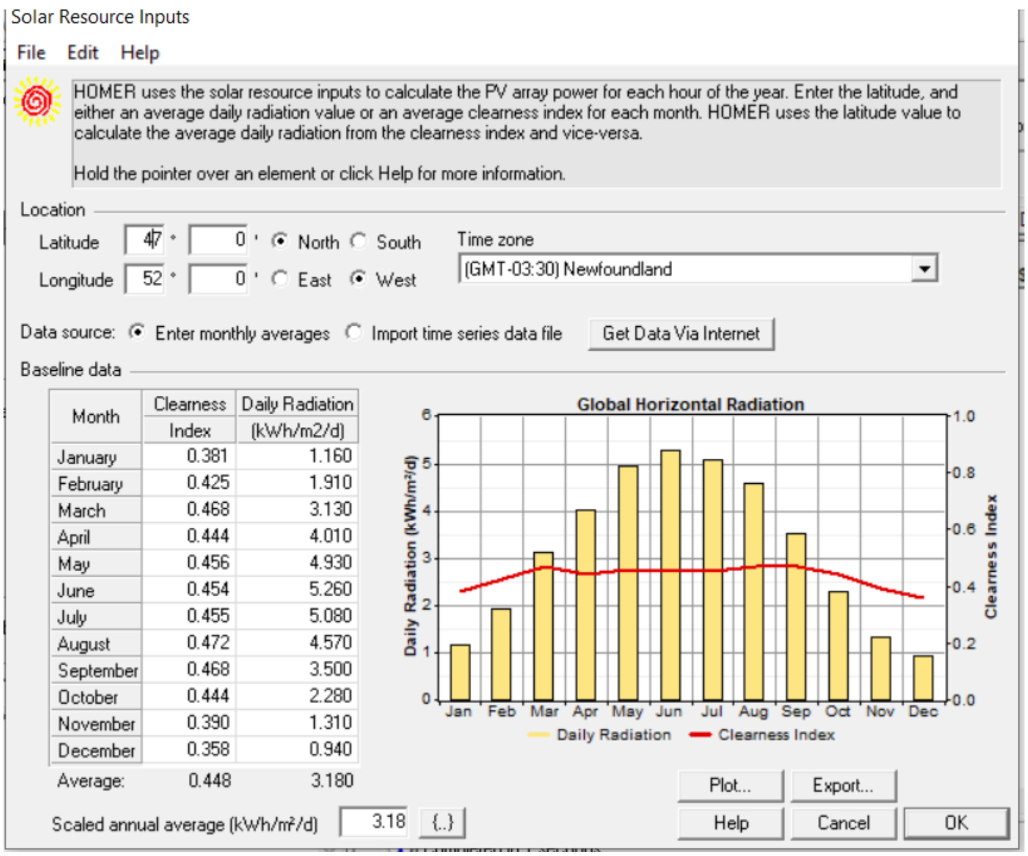
2.0m	Portrait vertical	Left hand side/ Center/ Right hand side	13.1	14.4	6.9	43	7654	0.532	1099.24	12.55
		justified	12.5	13.7	6.8	41	7298	0.533	1096	12.51
	Landscape horizontal	Left hand side/ Center/ Right hand side	9.46	10.8	3.3	31	5518	0.511	1141.65	13.03
		justified	8.85	10.1	3.2	29	5162	0.511	1141.24	13.03
2.5m	Portrait vertical	Left hand side/ Center/ Right hand side	11	12.3	4.9	36	6408	0.521	1118.18	12.76
		justified	10.7	12	4.8	35	6230	0.519	1121.5	12.8
	Landscape horizontal	Left hand side/ Center/ Right hand side	7.93	9.12	2.5	26	4628	0.507	1150.06	13.13
		justified	7.23	8.42	2.5	24	4272	0.507	1164.59	13.29
3m	Portrait vertical	Left hand side/ Center/ Right hand side	10.1	11.4	3.7	33	5874	0.515	1128.71	12.88
		justified	9.15	10.4	3.6	30	5340	0.513	1136.61	12.98
	Landscape horizontal	Left hand side/ Center/ Right hand side	6.71	7.76	2	22	3916	0.505	1156.48	13.2
		justified	6.71	7.76	2	22	3916	0.505	1156.48	13.2
3.5m	Portrait vertical	Left hand side/ Center/ Right hand side	8.54	9.85	2.2	28	4984	0.506	1153.4	13.17
		justified	8.24	9.51	2.1	27	4806	0.505	1154.13	13.17
	Landscape horizontal	Left hand side/ Center/ Right hand side	6.1	7.07	1.7	20	3560	0.504	1159.02	13.23
		justified	5.49	6.37	1.7	18	3204	0.503	1160.29	13.25
4m	Portrait vertical	Left hand side/ Center/ Right hand side	7.93	9.2	1.6	26	4628	0.503	1160.15	13.24

		justified	7.63	8.85	1.6	25	4450	0.503	1159.9	13.24
	Landscape horizontal	**Left hand side/ Center/ Right hand side**	5.49	6.39	1.4	18	3204	0.501	1163.93	13.29
		justified	4.88	5.68	1.3	16	2848	0.501	1163.93	13.29
4.5m	**Portrait vertical**	**Left hand side/ Center/ Right hand side**	7.93	9.22	1.4	26	4628	0.502	1162.67	13.27
		justified	7.32	8.52	1.3	24	4272	0.501	1163.93	13.29
	Landscape horizontal	**Left hand side/ Center/ Right hand side**	5.19	6.04	1.2	17	3026	0.501	1163.78	13.29
		justified	4.88	5.69	1.2	16	2848	0.501	1165.98	13.31
5m	**Portrait vertical**	**Left hand side/ Center/ Right hand side**	7.32	8.53	1.2	24	4272	0.501	1165.3	13.3
		justified	6.71	7.83	1.1	22	3916	0.5	1166.92	13.32
	Landscape horizontal	**Left hand side/ Center/ Right hand side**	4.58	5.34	1	15	2670	0.5	1165.94	13.31
		justified	4.27	4.99	0.9	14	2492	0.499	1168.62	13.34
5.5m	**Portrait vertical**	**Left hand side/ Center/ Right hand side**	6.71	7.84	0.9	22	3916	0.499	1168.41	13.34
		justified	6.41	7.49	0.9	21	3738	0.499	1168.49	13.34
	Landscape horizontal	**Left hand side/ Center/ Right hand side**	4.27	4.99	0.8	14	2492	0.499	1168.62	13.34
		justified	3.97	4.64	0.9	13	2314	0.499	1168.77	13.34
6m	**Portrait vertical**	**Left hand side/ Center/ Right hand side**	6.41	7.49	0.8	21	3738	0.499	1168.49	13.34
		justified	6.41	7.49	0.8	21	3738	0.499	1168.49	13.34

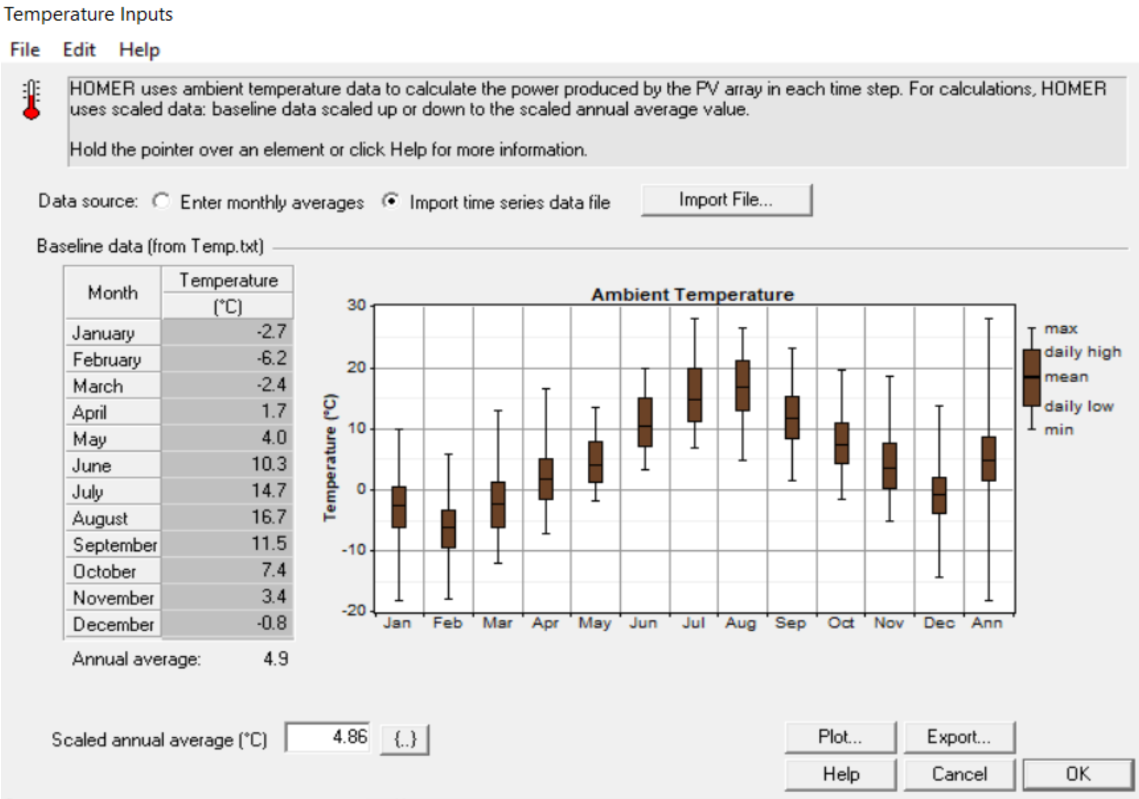
	Landscape horizontal	**Left hand side/ Center/ Right hand side**	3.97	4.65	0.5	13	2314	0.498	1171.28	13.37
		justified	3.66	4.3	0.5	12	2136	0.497	1174.86	13.41
10m	**Portrait vertical**	**Left hand side/ Center/ Right hand side**	3.66	4.31	0.1	12	2136	0.496	1177.6	13.44
		justified	3.66	4.31	0.1	12	2136	0.496	1177.6	13.44
	Landscape horizontal	**Left hand side/ Center/ Right hand side**	2.75	3.24	0	9	1602	0.494	1178.18	13.45
		justified	2.44	2.88	0	8	1424	0.494	1180.33	13.47

Appendix B- PV System Design Using HOMER

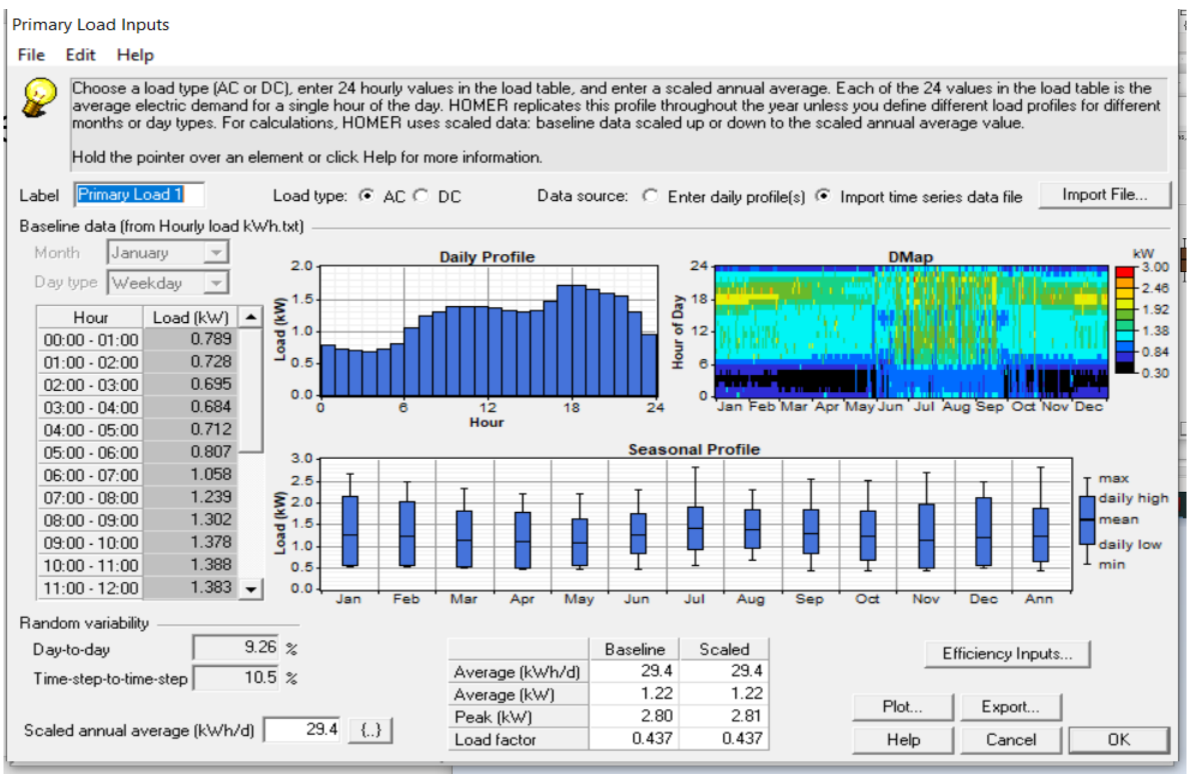
B.1 HOMER Inputs



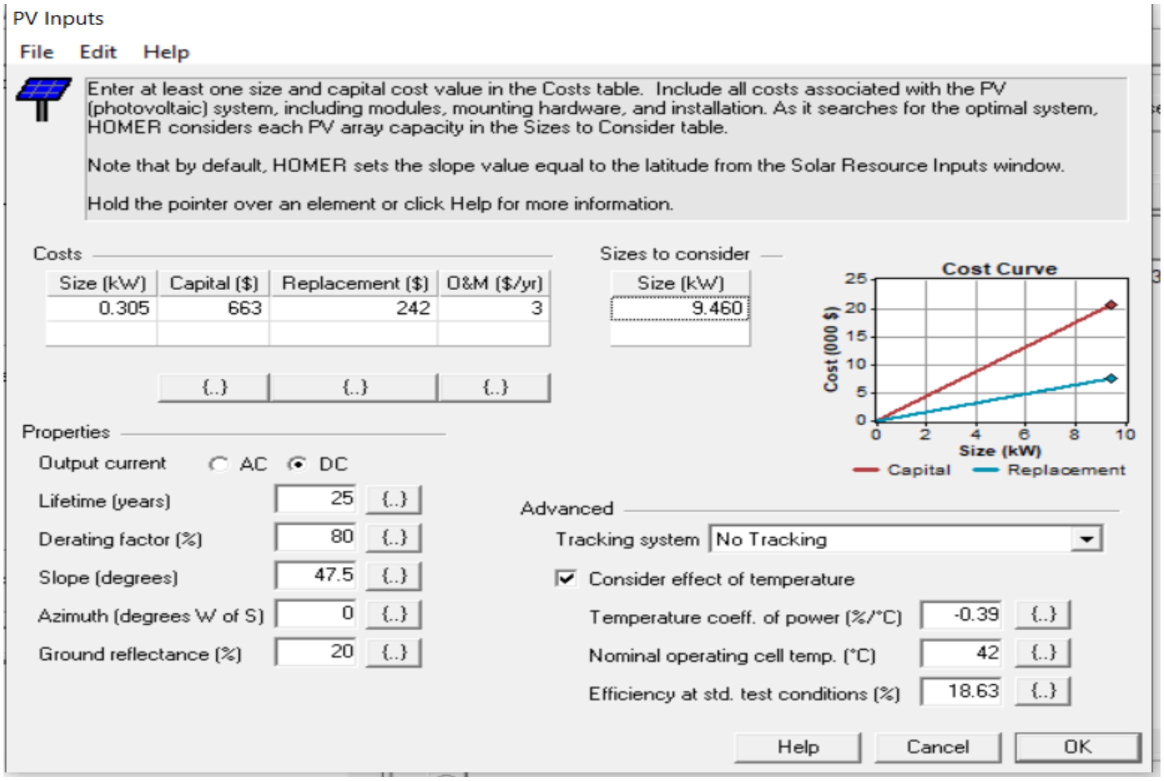
Solar resource



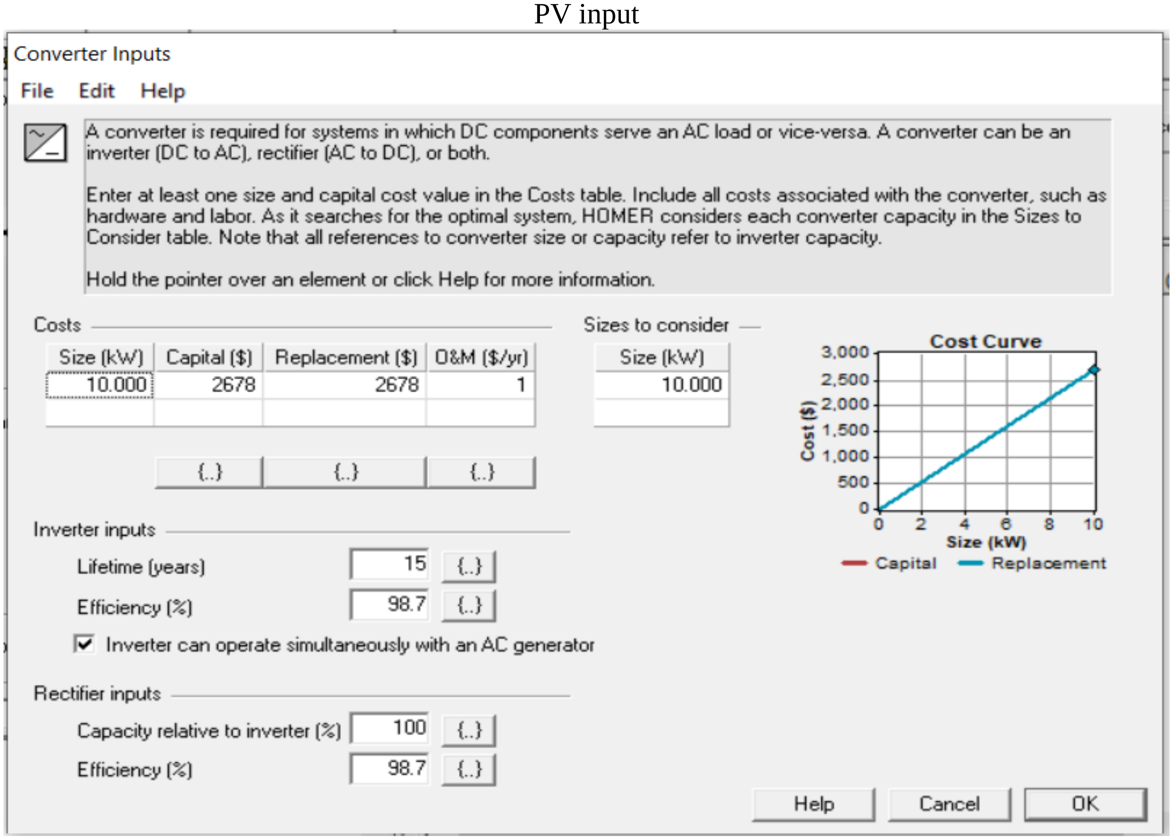
Temperature input



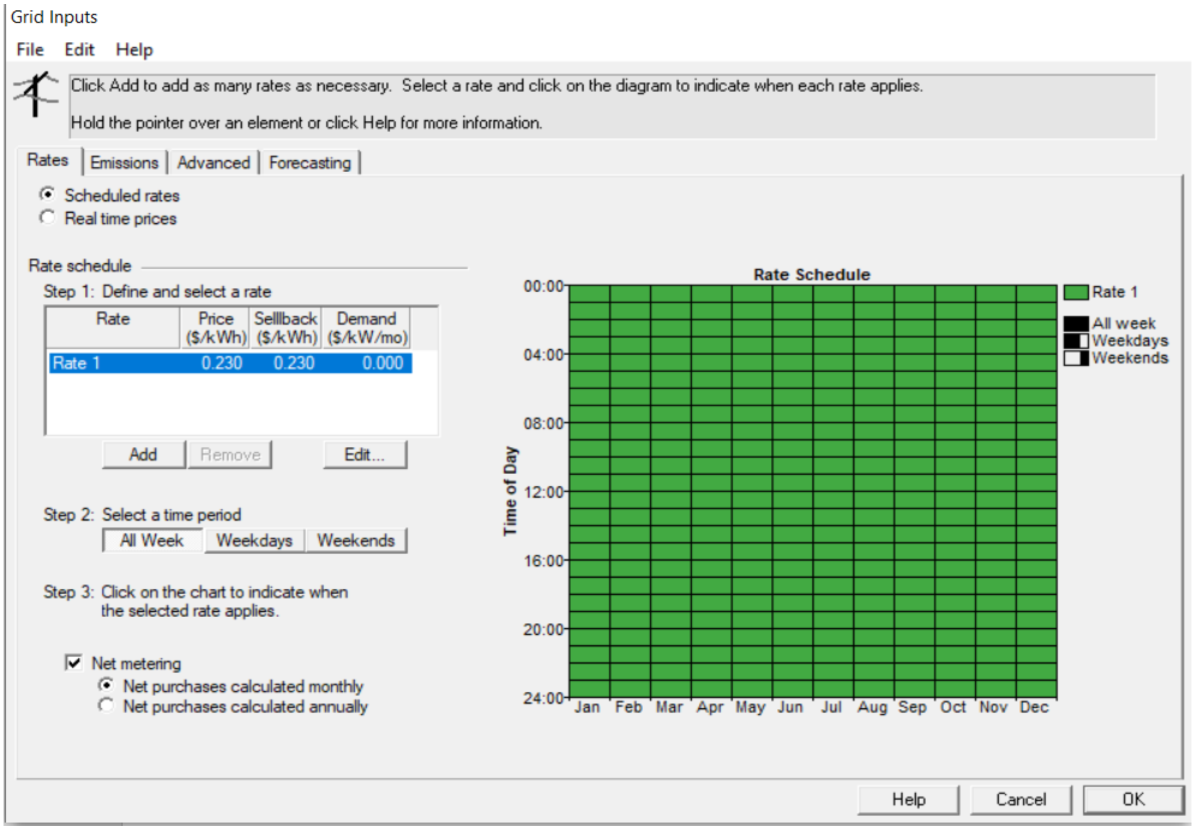
Load input



PV input

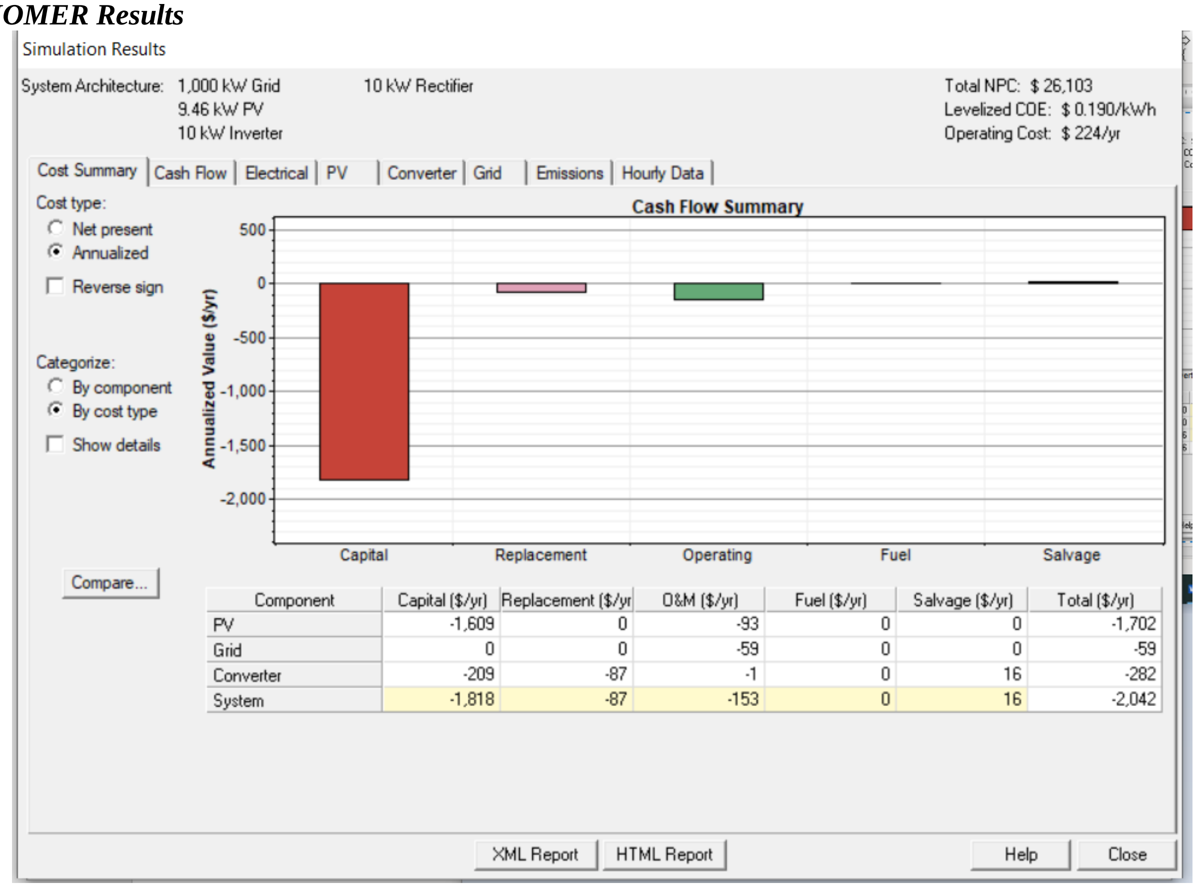


Converter input



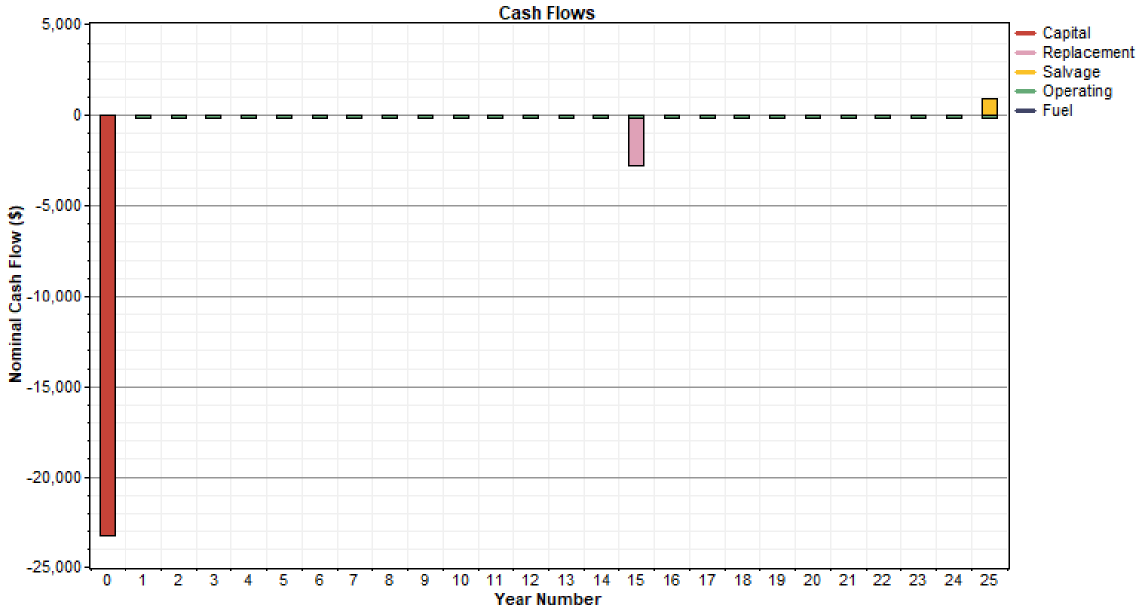
Grid input

B.2 HOMER Results

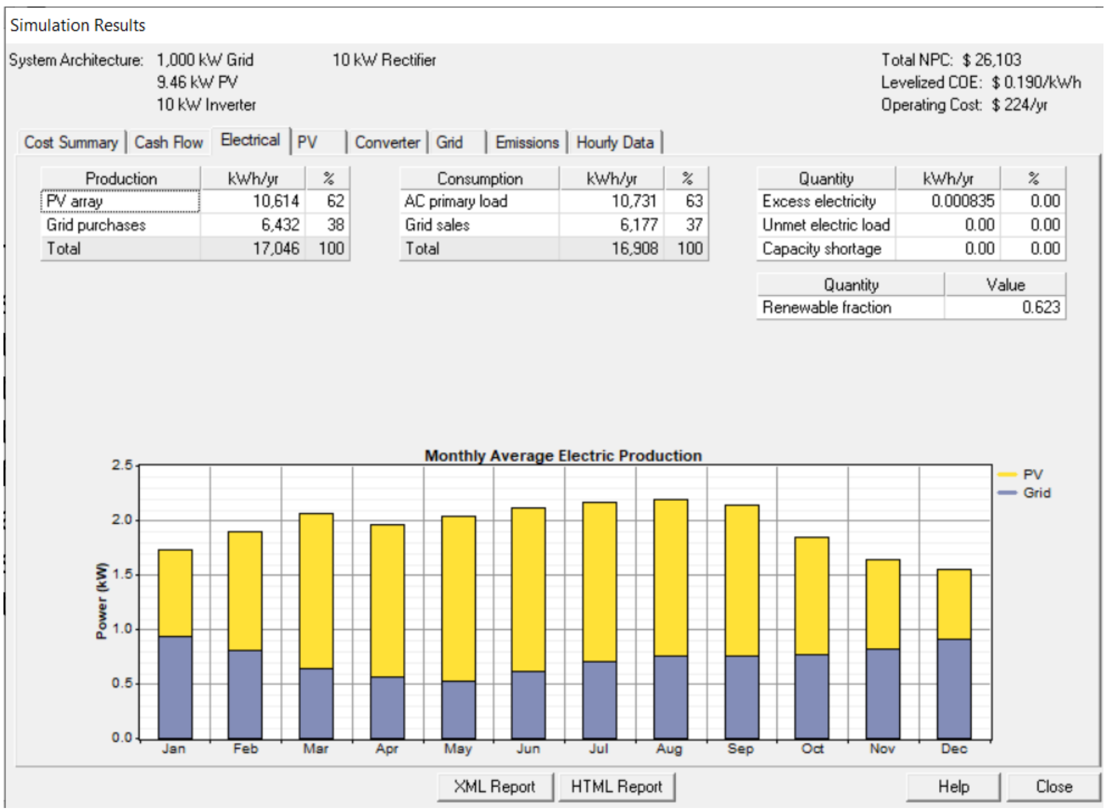


Component	Capital ($/yr)	Replacement ($/yr)	O&M ($/yr)	Fuel ($/yr)	Salvage ($/yr)	Total ($/yr)
PV	-1,609	0	-93	0	0	-1,702
Grid	0	0	-59	0	0	-59
Converter	-209	-87	-1	0	16	-282
System	-1,818	-87	-153	0	16	-2,042

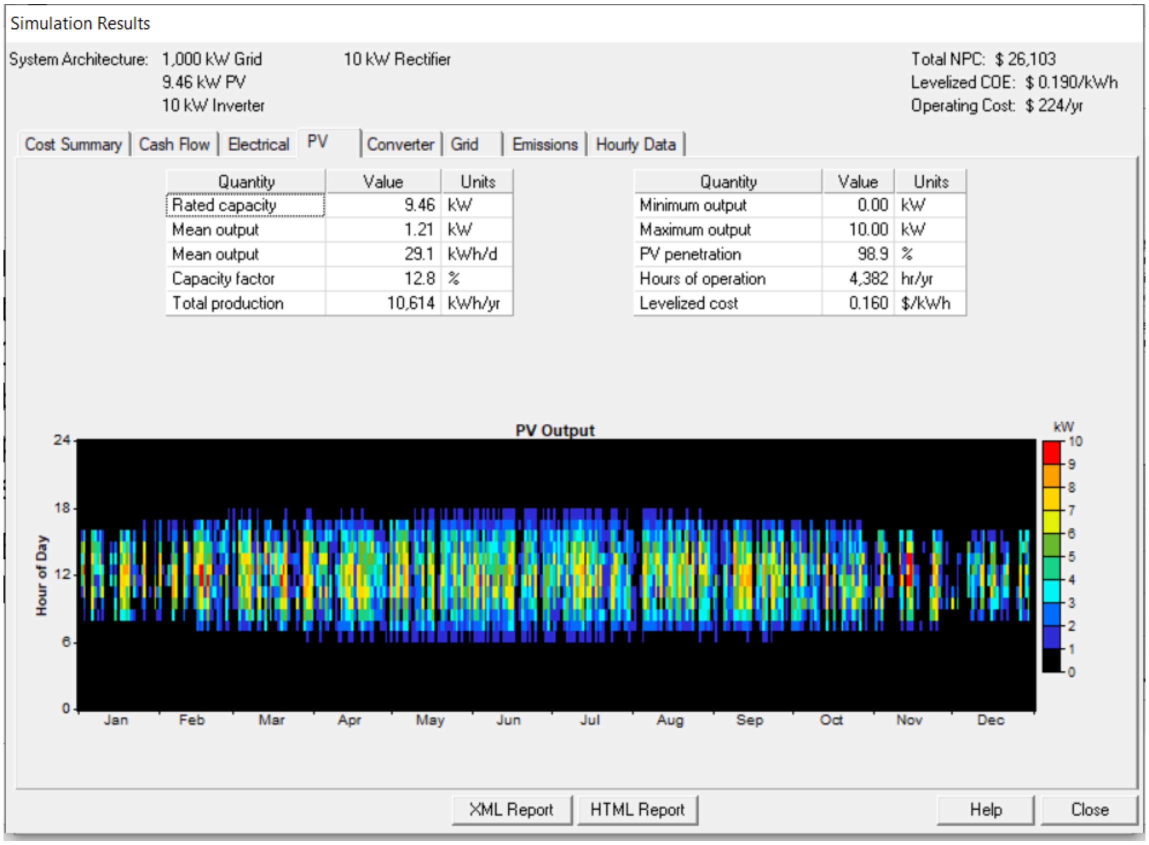
Cost summary



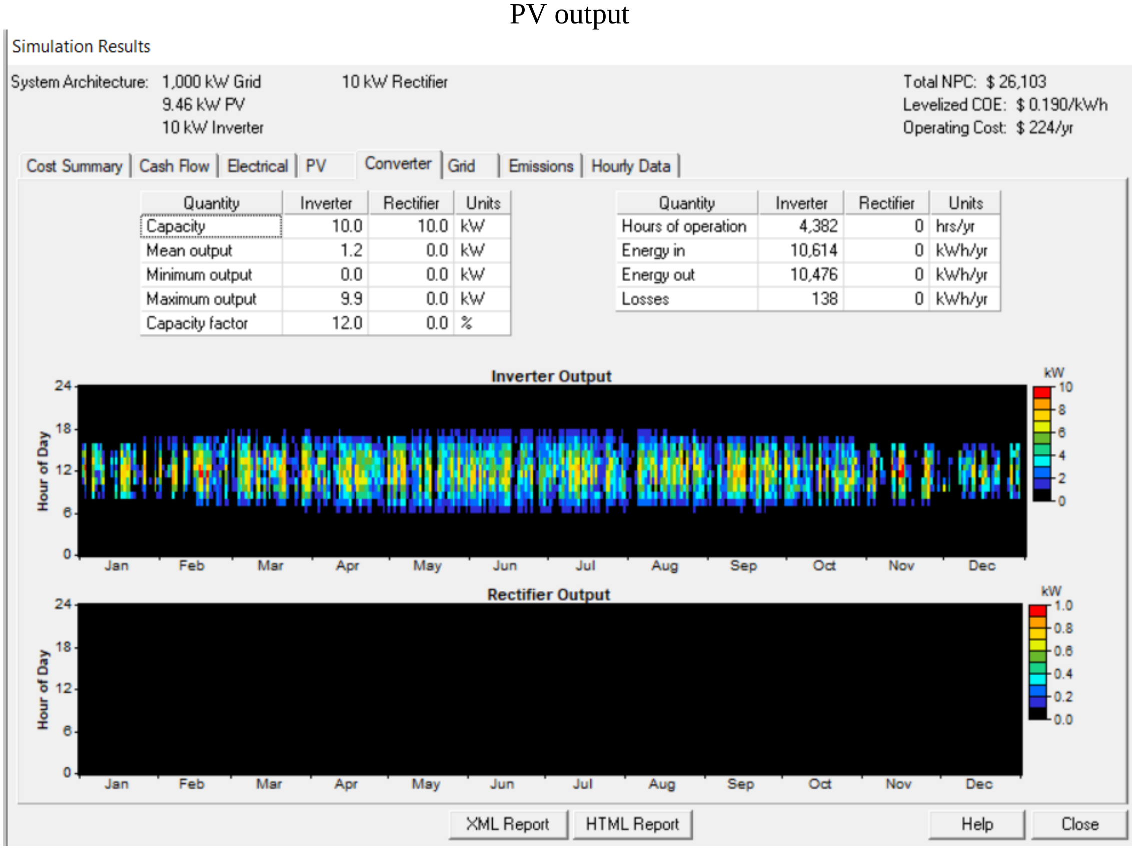
Cash flow



Electrical output



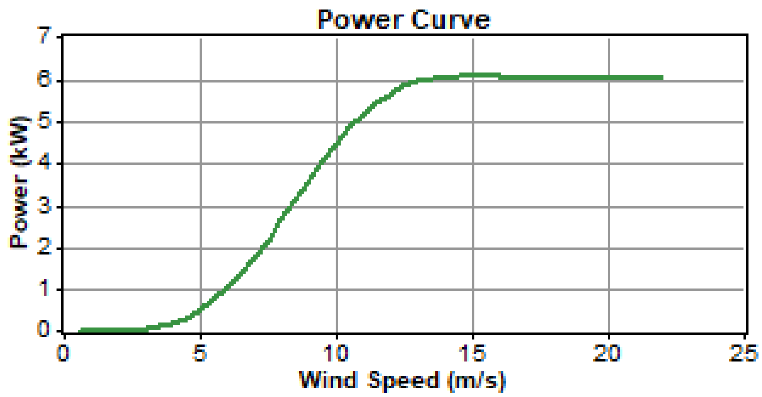
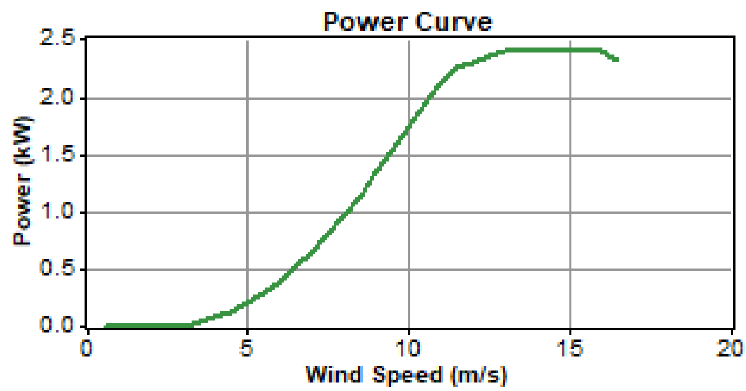
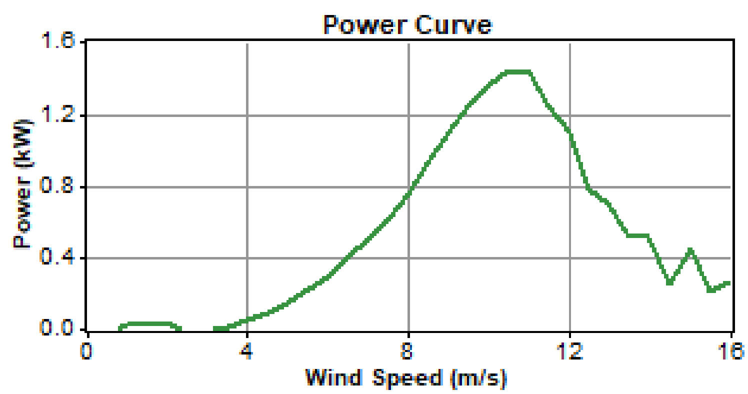
PV output

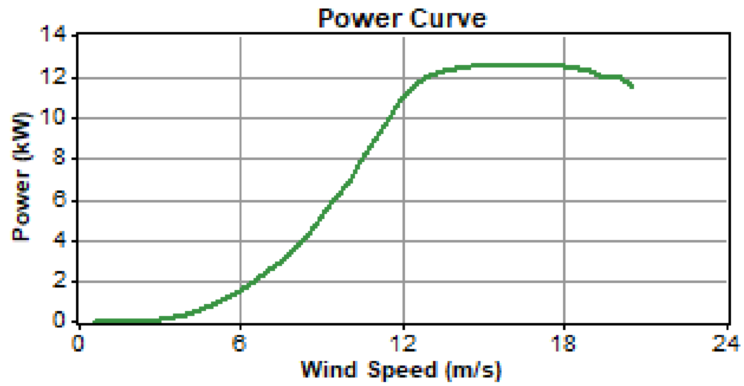
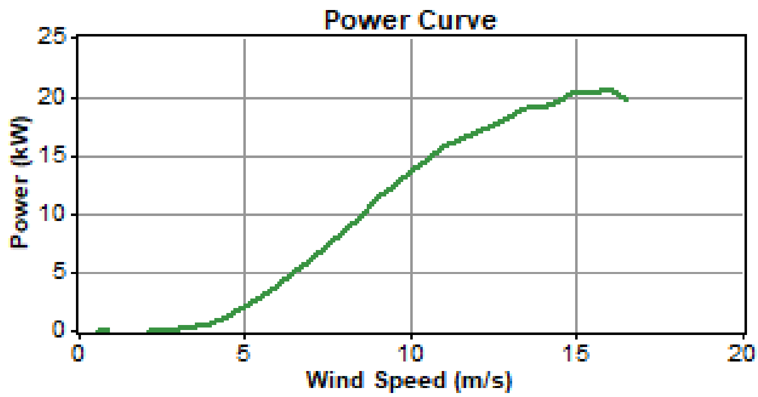


Converter output

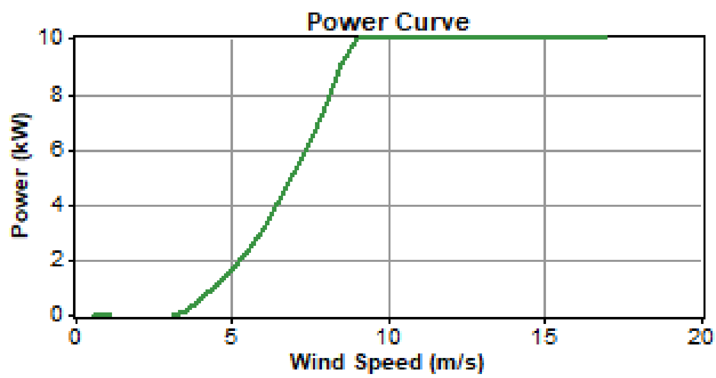
Appendix C- Wind System Design

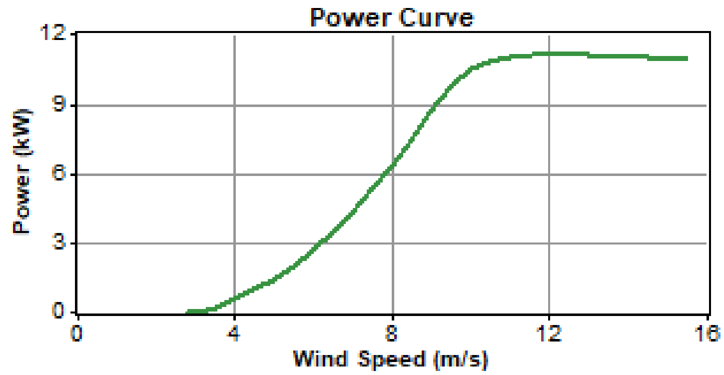
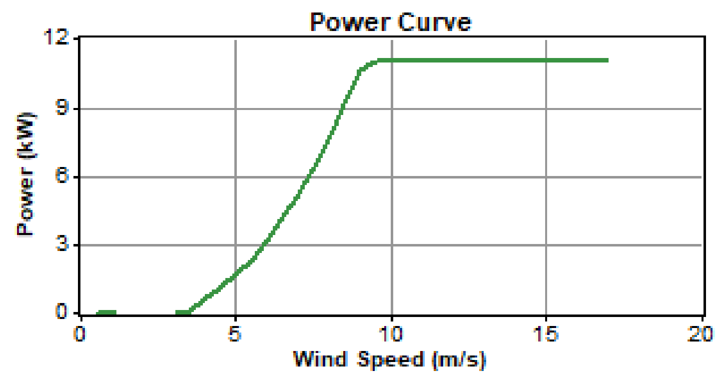
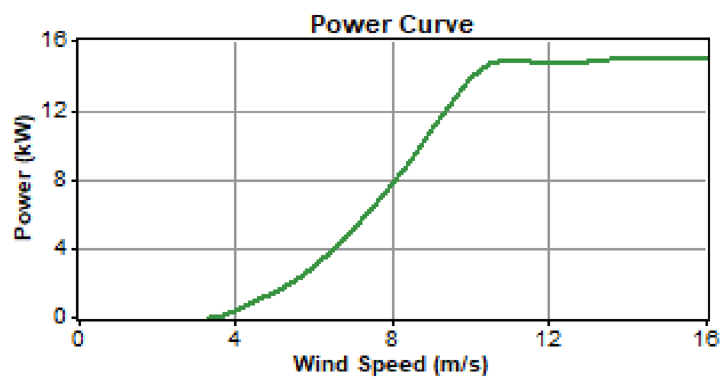
C.1 SWCC Certified Turbines

Turbine name	Manufacturer	Power	Power curve	Energy output (kWh/year)
SD6 [68]	SD Wind Energy Ltd	6 kW		19,723
SS3.7 [69]	Xzeres Wind Corporation	2.4 kW		7,431
DS3000 (VAWT) [70]	Hi VAWT Technology	1.4 kW		4,792

E10 [71]	Bergey Windpower Company	10 kW		32,216
E15 [72]	Bergey Windpower Company	15 kW		61,273

C.2 Intertek Certified Turbines

Turbine name	Manufacturer	Power	Power curve	Energy output (kWh/year)
CF10 [73]	CF Green Energy	10 kW		46,068

<table>
<tr><td>CF 11
[74]</td><td>CF Green Energy</td><td>11 kW</td><td>
</td><td>42,857</td></tr>
<tr><td>CF 11a
[75]</td><td>CF Green Energy</td><td>12 kW</td><td>
</td><td>48,471</td></tr>
<tr><td>CF 15
[76]</td><td>CF Green Energy</td><td>15 kW</td><td>
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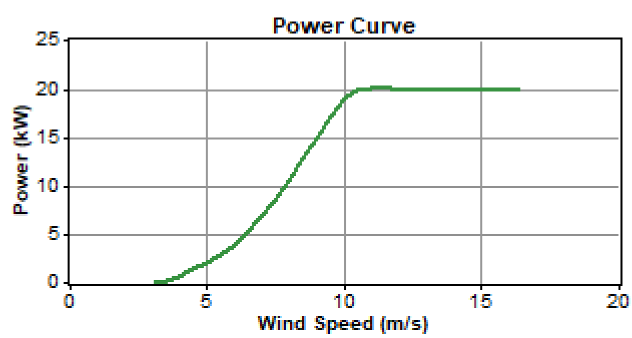
[77]</td><td>CF Green Energy</td><td>20 kW</td><td>
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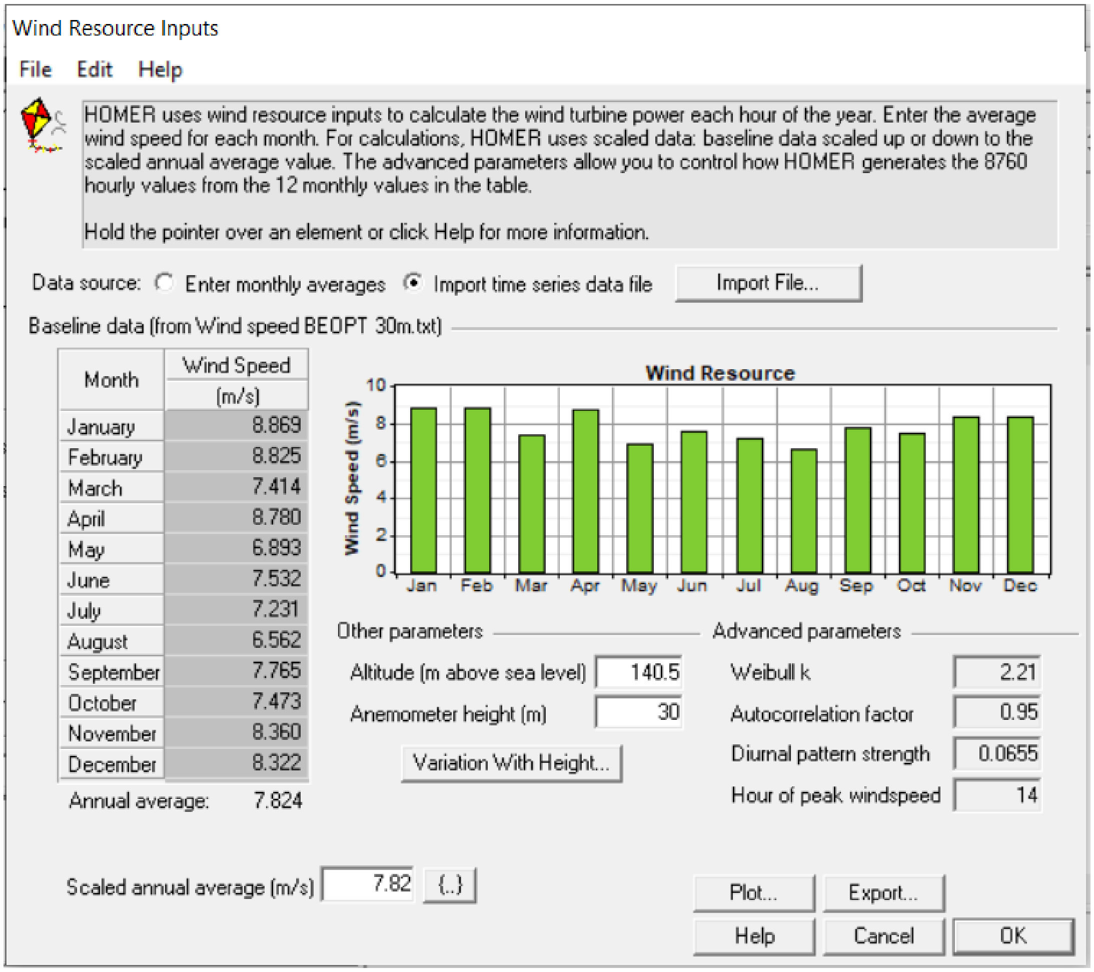
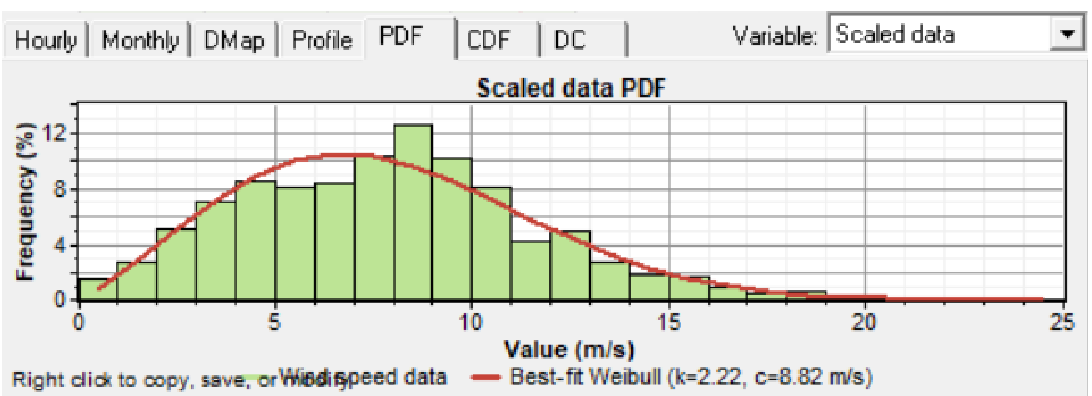
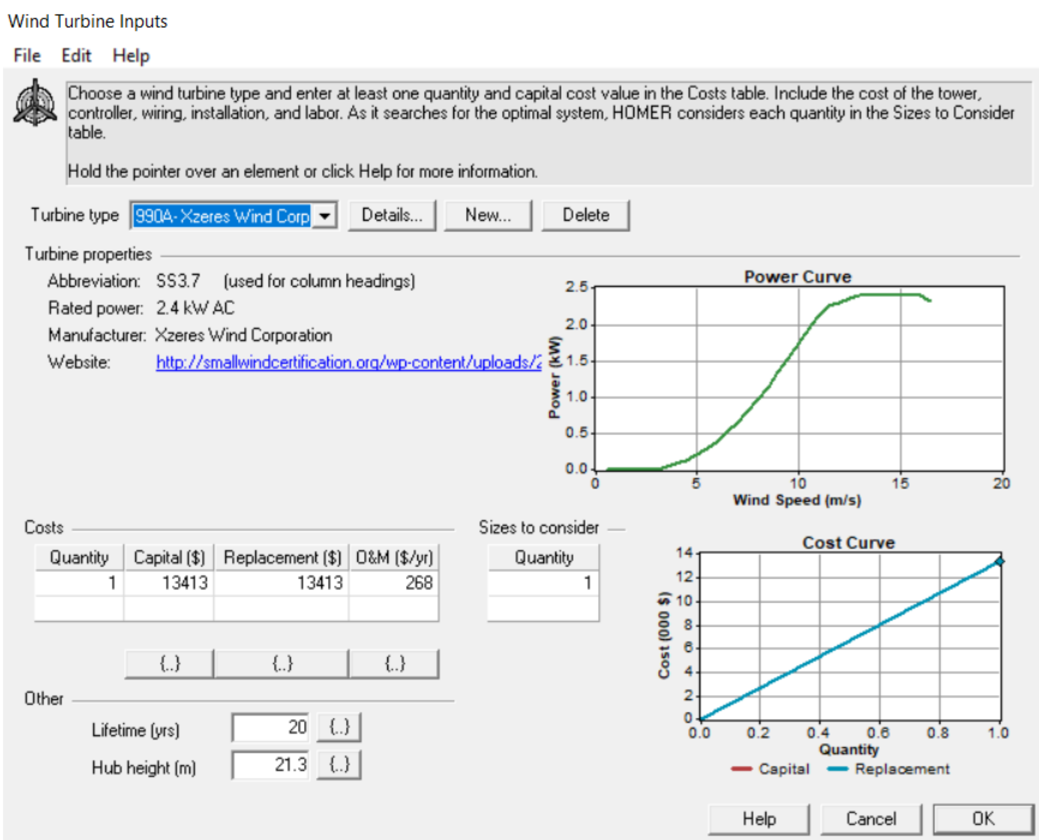
C.3 Scenario B-HOMER Inputs



Wind resource input

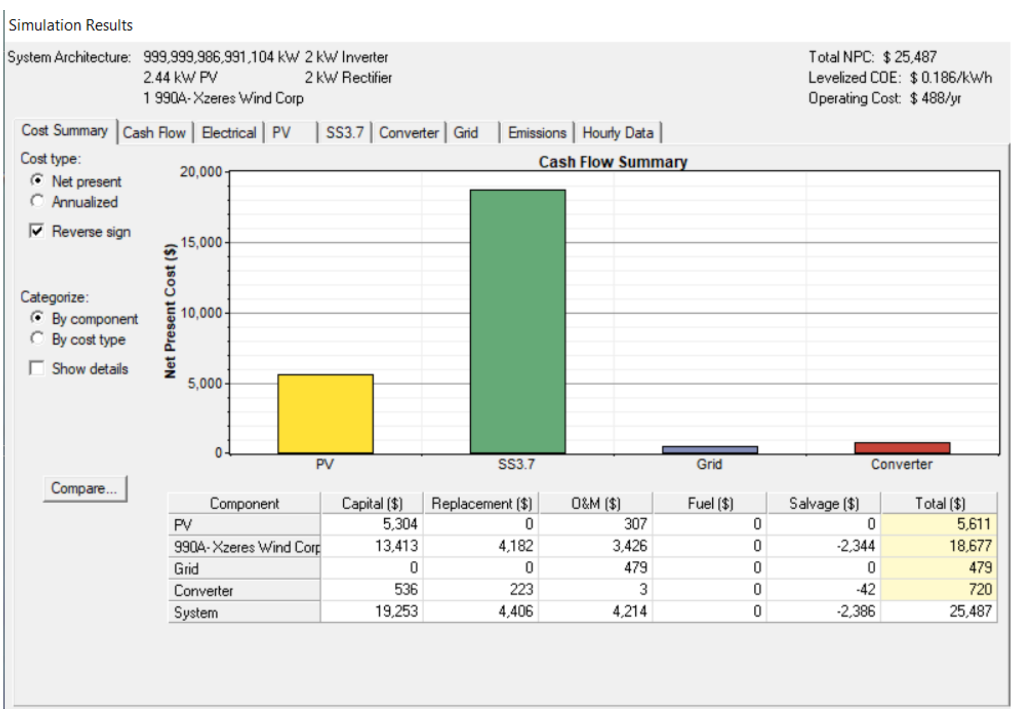


Wind speed distribution and Weibull parameters



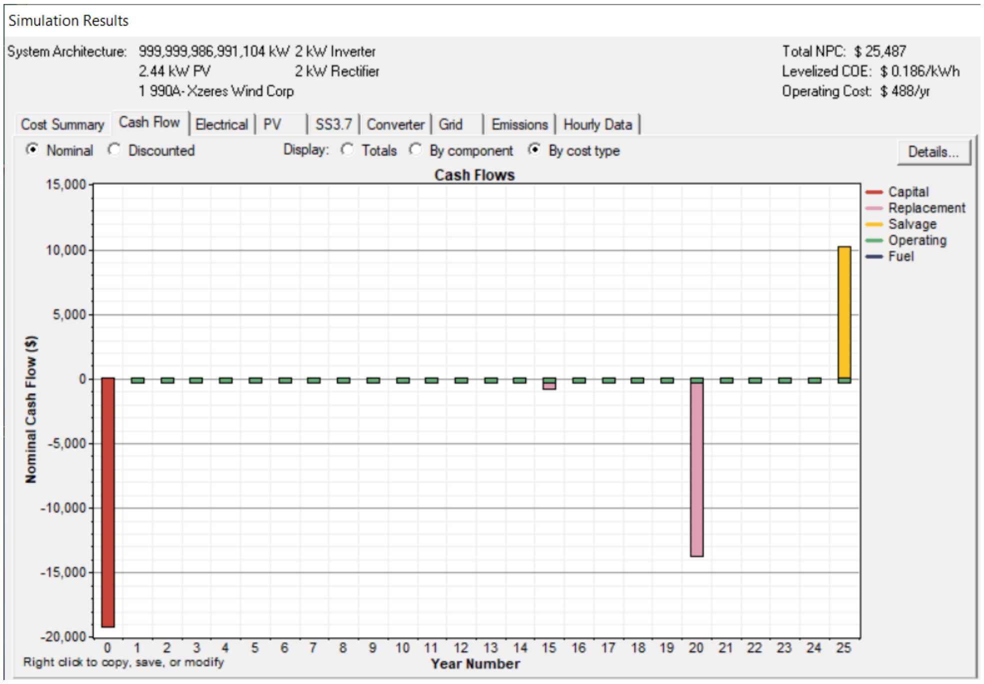
Wind turbine input

C.4 Scenario B-HOMER Results

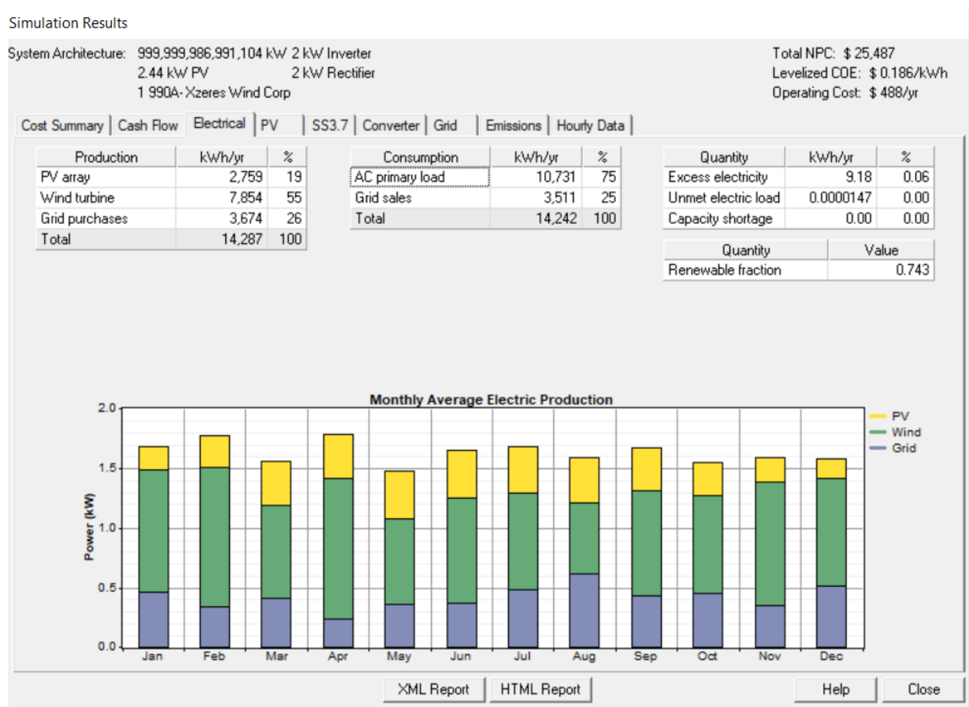


Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	5,304	0	307	0	0	5,611
990A-Xzeres Wind Corp	13,413	4,182	3,426	0	-2,344	18,677
Grid	0	0	479	0	0	479
Converter	536	223	3	0	-42	720
System	19,253	4,406	4,214	0	-2,386	25,487

Cost summary



Simulation results



Electrical results

Quantity	Value	Units
Rated capacity	2.44	kW
Mean output	0.31	kW
Mean output	7.56	kWh/d
Capacity factor	12.9	%
Total production	2,759	kWh/yr

Quantity	Value	Units
Minimum output	0.00	kW
Maximum output	2.45	kW
PV penetration	25.7	%
Hours of operation	4,382	hr/yr
Levelized cost	0.159	$/kWh

PV output

Quantity	Value	Units
Total rated capacity	2.40	kW
Mean output	0.90	kW
Capacity factor	37.4	%
Total production	7,854	kWh/yr

Quantity	Value	Units
Minimum output	0.00	kW
Maximum output	2.39	kW
Wind penetration	73.2	%
Hours of operation	7,991	hr/yr
Levelized cost	0.186	$/kWh

SS3.7 Wind turbine output

C.5 Mathcad worksheet

$vmax := 23.4\cdot\frac{m}{s}$ $cpideal := 0.5$ $D := 3.7\cdot m$ $Area := \pi\cdot\frac{D^2}{4} = 10.752m^2$ $P := 2400\cdot W$

$u := 0\frac{m}{s}, 1\frac{m}{s} .. 23.4\frac{m}{s}$ $v := u$

$vcutout := 16.5\frac{m}{s}$ $vcutin := 3\frac{m}{s}$ $pmax := \frac{P}{Area} = 223.212\cdot\frac{W}{m^2}$ $cp := 0.26$

$c := 8.4\cdot\frac{m}{s}$ $\rho := 1.186\frac{kg}{m^3}$ $k := 2.22$

$h(v,k,c) := \frac{k}{c}\cdot\left(\frac{v}{c}\right)^{k-1}\cdot e^{-\left(\frac{v}{c}\right)^k}$ $Pden(v) := 0.5\cdot\rho\cdot v^3$

Given

$vm := 10\frac{m}{s}$

$\frac{d}{dvm}(h(vm,k,c)) = 0$

$Vmode := Find(vm) = 6.415\frac{m}{s}$ $Pden(Vmode) = 156.513\frac{1}{m^2}\cdot W$

$Vmean := \int_{0\frac{m}{s}}^{\infty\frac{m}{s}} h(v,k,c)\cdot v\,dv = 7.44\frac{m}{s}$ $Pden(Vmean) = 244.168\frac{1}{m^2}\cdot W$

$Vrmc := \sqrt[3]{\int_{0\frac{m}{s}}^{\infty\frac{m}{s}} h(v,k,c)\cdot v^3\,dv} = 8.936\frac{m}{s}$ $Pden(Vrmc) = 423.2\frac{1}{m^2}\cdot W$

$Ewind := \int_{0\cdot\frac{m}{s}}^{vmax} 0.5\cdot\rho\cdot h(v,k,c)\cdot 8760hr\cdot v^3\,dv = 3.703\times10^6\frac{1}{m^2}\cdot W\cdot hr$ **Energy in the wind W hr/yr*m2**

$Eideal := \int_{0\cdot\frac{m}{s}}^{vmax} 0.5\cdot cpideal\cdot\rho\cdot h(v,k,c)\cdot 8760\cdot hr\cdot v^3\,dv = 1.851\times10^6\frac{1}{m^2}\cdot W\cdot hr$ **this assumes that cp will equal 0.5 throughout the entire power curve (not pracitical) kWhr/yr*m2**

$Pden(v) := 0.5\cdot cp\cdot\rho\cdot v^3$

$$Pdencon(v) := \begin{cases} 0 & \text{if } v < vcutin \\ pmax & \text{if } Pden(v) > pmax \\ 0 & \text{if } v > vcutout \\ Pden(v) & \text{otherwise} \end{cases}$$

Pdencon(v) = ($\frac{W}{m^2}$)	Pden(v) = ($\frac{W}{m^2}$)
0	0
0	0.159
0	1.274
4.3	4.3
10.192	10.192
19.906	19.906
34.398	34.398
54.623	54.623
81.536	81.536
116.093	116.093
159.25	159.25
211.962	211.962
223.212	275.184
223.212	349.872
223.212	436.982
...	...

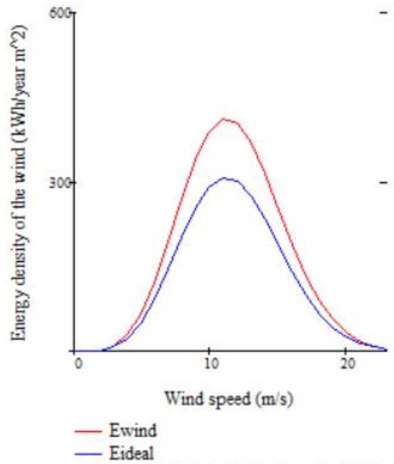
$Econ := \int_{0\cdot\frac{m}{s}}^{vcutout} Pdencon(v)\cdot h(v,k,c)\cdot 8760\cdot hr\,dv = 7.296\times10^5\cdot\frac{W}{m^2}\cdot hr$ **Energy captured by turbine while accounting for changes Cp in different regions (energy density)**

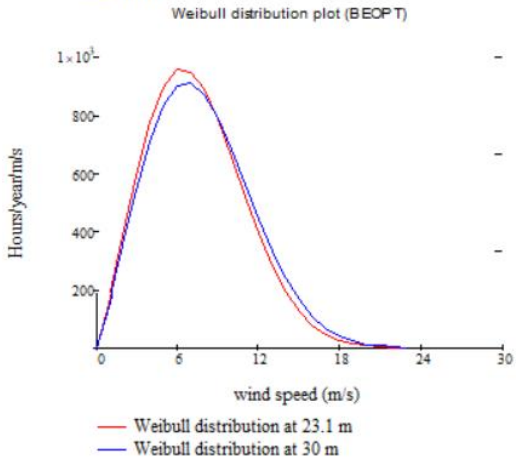
$Energyout := Area\cdot Econ = 7.845\times10^6\cdot W\cdot hr$ Energy output of wind turbine (kWhr/year)

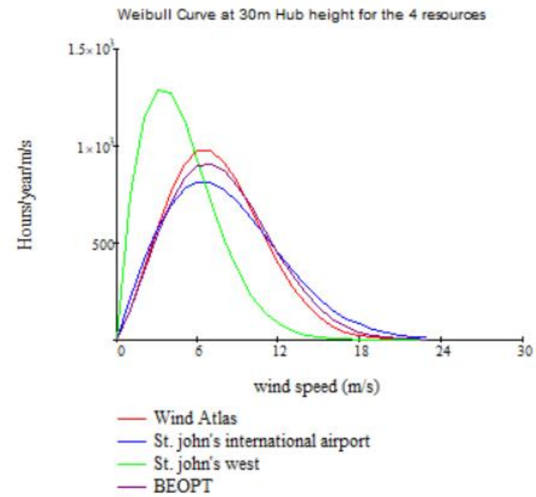
$Energyout = 2.824\times10^{10}J$

$ratio := \frac{Econ}{Ewind} = 19.077\cdot\%$ **% of wind energy captured by turbine accounting for different Cp in different regions**

$Emax := \int_{0\cdot\frac{m}{s}}^{vcutout} Pden(v)\cdot h(v,k,c)\cdot 8760\cdot hr\,dv = 9.013\times10^5\cdot\frac{W}{m^2}\cdot hr$ Energy captured per year per m2 with no control (energy density)

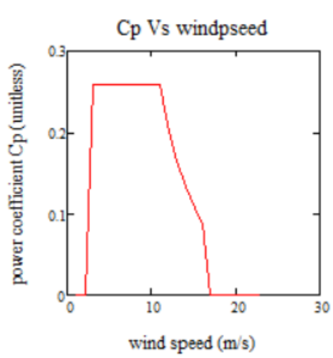


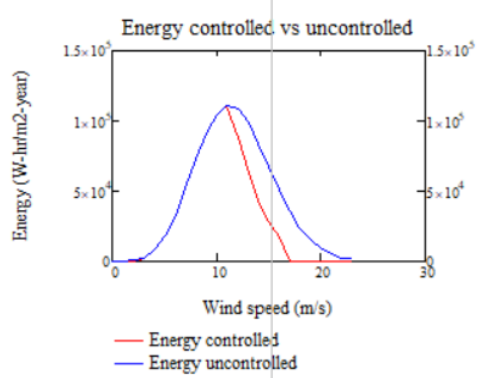


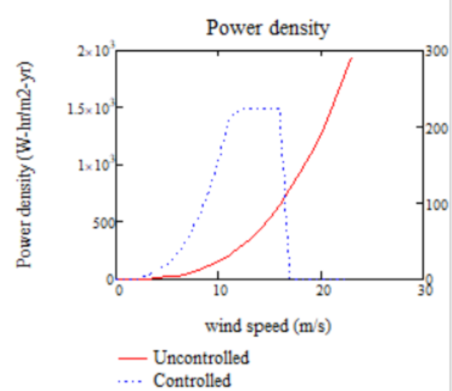


$CaptureRatio := \frac{Econ}{Emax} = 80.951 \cdot \%$ $\qquad$ $CapcityFactor := \frac{Econ}{pmax \cdot 8760 \cdot hr} = 37.312 \cdot \%$

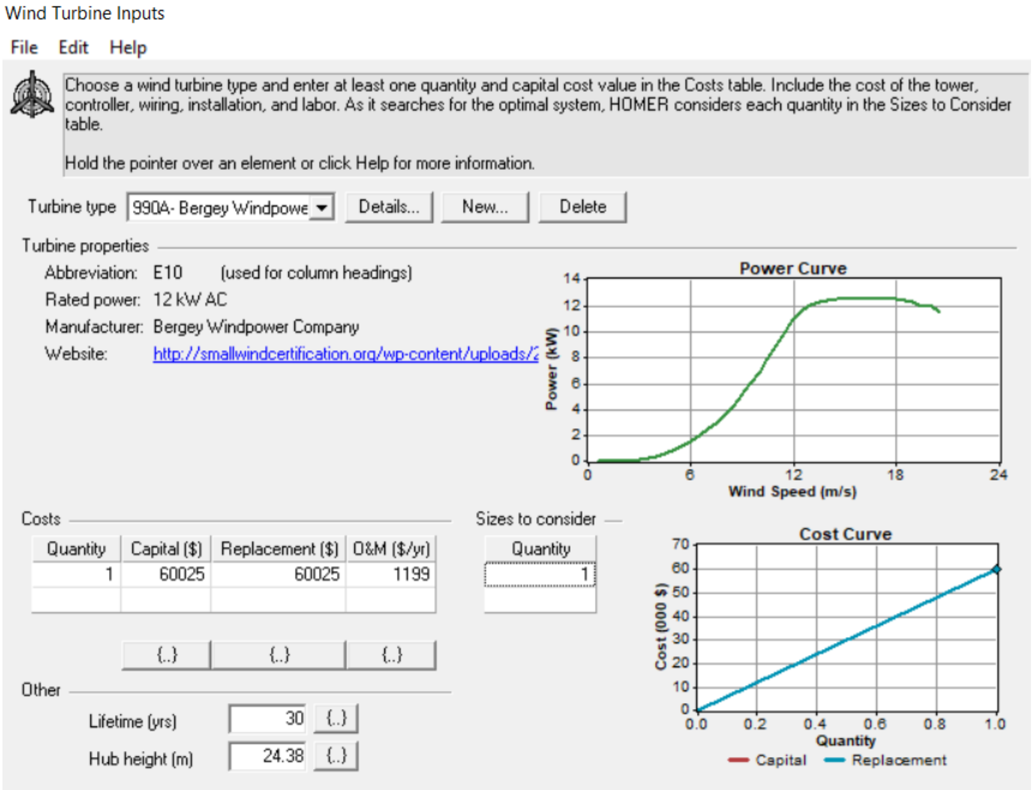
$Cp(v) := \frac{cp \cdot Pdencon(v)}{Pden(v)}$



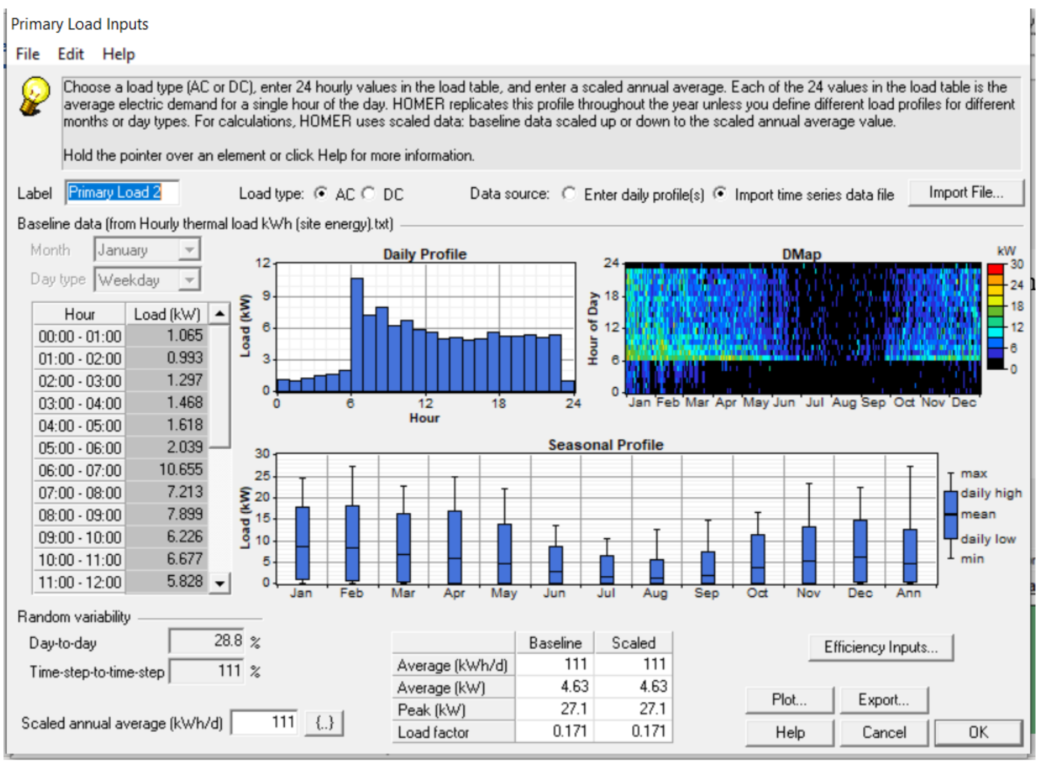




C.6 Scenario C-HOMER Inputs

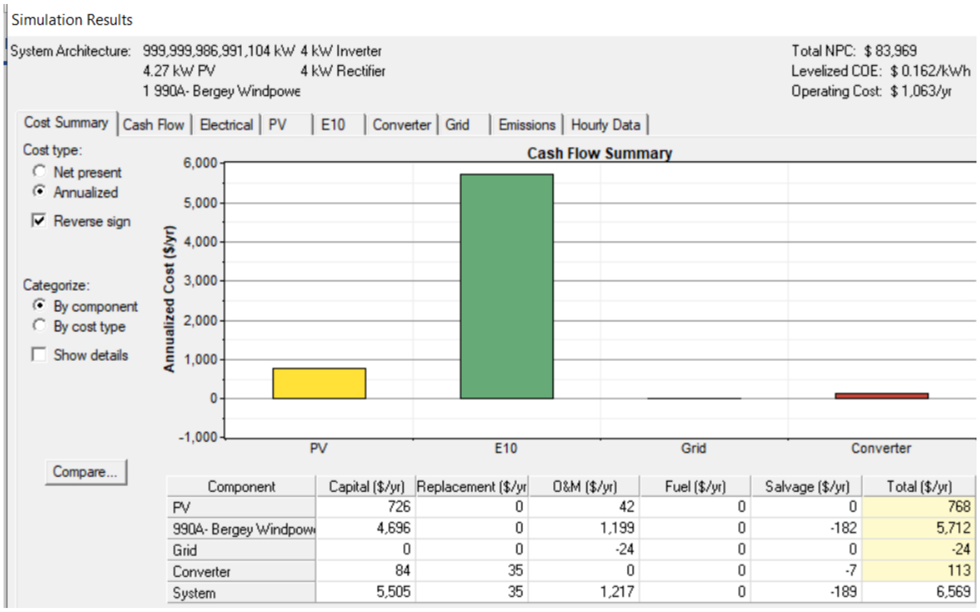


Scenario C, Wind input



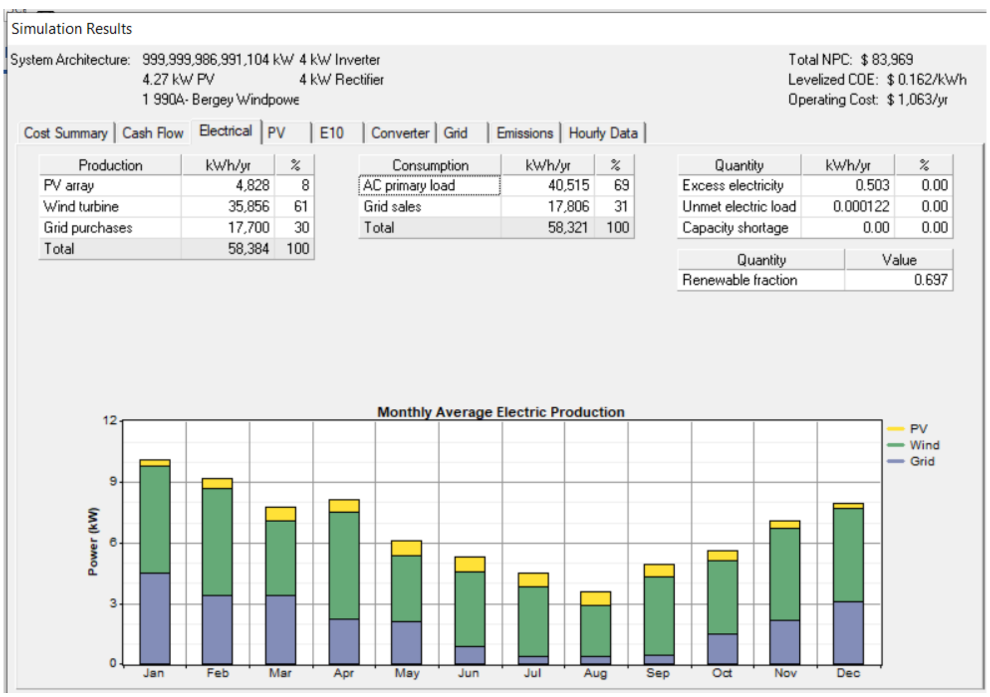
Scenario C, Thermal load

C.7 Scenario C-HOMER Results



Component	Capital ($/yr)	Replacement ($/yr	O&M ($/yr)	Fuel ($/yr)	Salvage ($/yr)	Total ($/yr)
PV	726	0	42	0	0	768
990A- Bergey Windpow	4,696	0	1,199	0	-182	5,712
Grid	0	0	-24	0	0	-24
Converter	84	35	0	0	-7	113
System	5,505	35	1,217	0	-189	6,569

Scenario C, Cost summary



Production	kWh/yr	%
PV array	4,828	8
Wind turbine	35,856	61
Grid purchases	17,700	30
Total	58,384	100

Consumption	kWh/yr	%
AC primary load	40,515	69
Grid sales	17,806	31
Total	58,321	100

Quantity	kWh/yr	%
Excess electricity	0.503	0.00
Unmet electric load	0.000122	0.00
Capacity shortage	0.00	0.00

Quantity	Value
Renewable fraction	0.697

Scenario C, Electrical output tab

Quantity	Value	Units
Rated capacity	4.27	kW
Mean output	0.55	kW
Mean output	13.2	kWh/d
Capacity factor	12.9	%
Total production	4,828	kWh/yr

Quantity	Value	Units
Minimum output	0.00	kW
Maximum output	4.29	kW
PV penetration	11.9	%
Hours of operation	4,382	hr/yr
Levelized cost	0.159	$/kWh

Scenario C, PV output

Quantity	Value	Units
Total rated capacity	12.0	kW
Mean output	4.1	kW
Capacity factor	34.1	%
Total production	35,856	kWh/yr

Quantity	Value	Units
Minimum output	0.0	kW
Maximum output	12.4	kW
Wind penetration	88.5	%
Hours of operation	8,316	hr/yr
Levelized cost	0.159	$/kWh

Scenario C, Wind turbine output

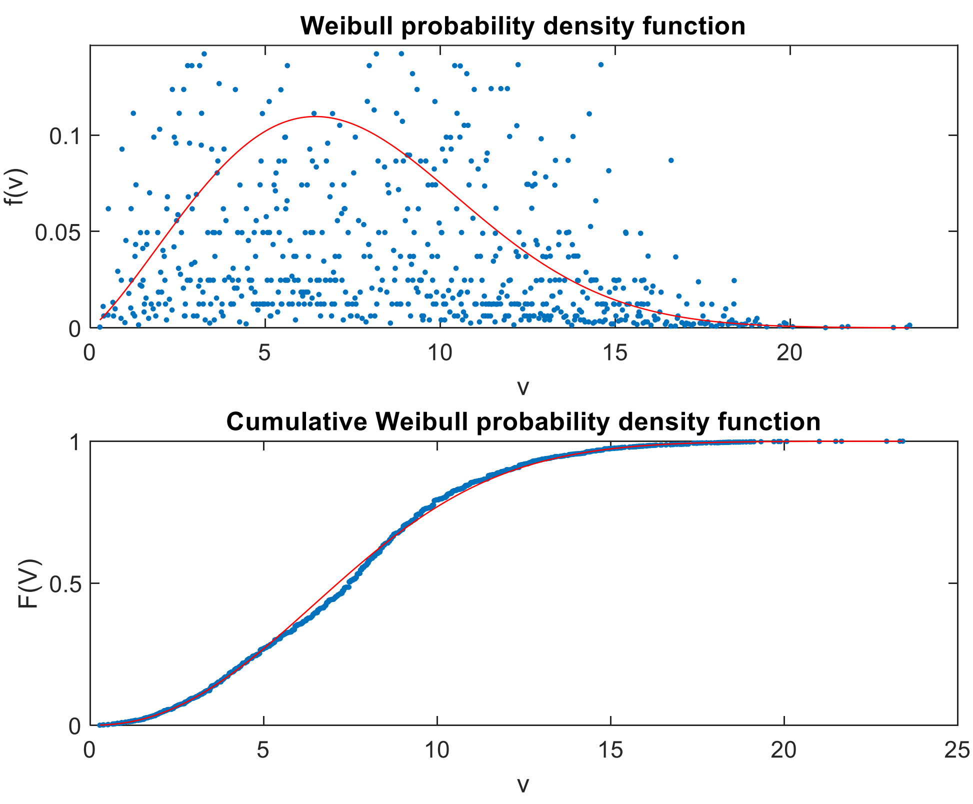
C.8 MATLAB

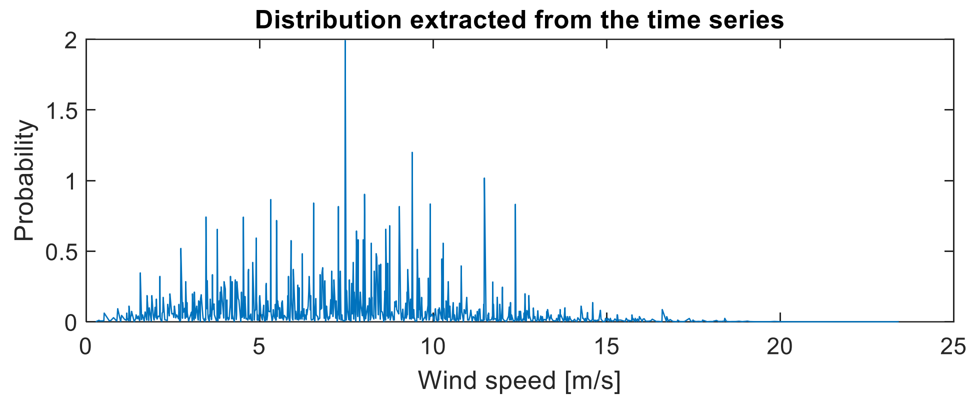
C.8.1 Code

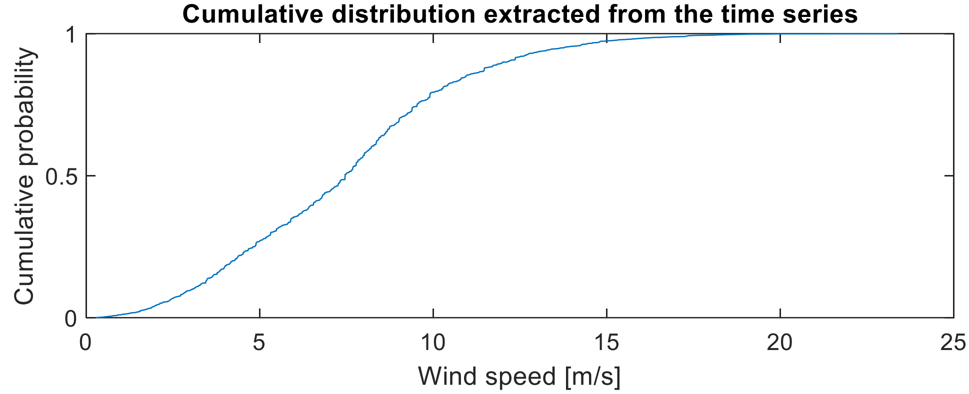
```
clear all
close all
clc
v = xlsread('BEOPT 21.3m wind speeds.xlsx');
figure
plot(v)
title('Wind speed time series');
xlabel('Measurement #');
ylabel('Wind speed [m/s]');
v(find(v==0)) = [];
uniqueVals = unique(v);
nbUniqueVals = length(uniqueVals);
for i=1:nbUniqueVals
    nbOcc = v(find(v==uniqueVals(i)));
    N(i) = length(nbOcc);
end
nbMeas = sum(N);
delta(1) = uniqueVals(1);
for i=2:(nbUniqueVals)
    delta(i) = uniqueVals(i) - uniqueVals(i-1);
end
for i=1:nbUniqueVals
    prob(i) = N(i)/(nbMeas*delta(i));
end
freq = 0;
for i=1:nbUniqueVals
    freq = prob(i)*delta(i) + freq;
    cumFreq(i) = freq;
end
figure
subplot(2,1,1);
plot(uniqueVals,prob)
title('Distribution extracted from the time series');
xlabel('Wind speed [m/s]');
ylabel('Probability');
subplot(2,1,2);
plot(uniqueVals,cumFreq)
title('Cumulative distribution extracted from the time series');
xlabel('Wind speed [m/s]');
ylabel('Cumulative probability');
ln = log(uniqueVals);
lnln = log(-log(1-cumFreq));
test = isinf(lnln);
for i=1:nbUniqueVals
    if (test(i)==1)
        ln(i)= [];
        lnln(i)= [];
    end
end
params = polyfit(ln,lnln',1);
a = params(1);
b = params(2);
y=a*ln+b;
figure
plot(ln,y,'b',ln,lnln,'r')
```

```
title('Linearized curve and fitted line comparison');
xlabel('x = ln(v)');
ylabel('y = ln(-ln(1-cumFreq(v)))');
k = a
c = exp(-b/a)
a1 = uniqueVals/c;
a2 = a1.^k;
cumDensityFunc = 1-exp(-a2);
k1 = k-1;
a3 = a1.^k1;
k2 = k/c;
densityFunc = k2*a3.*exp(-a2);
figure
subplot(2,1,1);
plot(uniqueVals,prob,'.',uniqueVals,densityFunc, 'r')
title('Weibull probability density function');
xlabel('v');
ylabel('f(v)');
subplot(2,1,2);
plot(uniqueVals,cumFreq,'.',uniqueVals,cumDensityFunc, 'r')
title('Cumulative Weibull probability density function');
xlabel('v');
ylabel('F(V)');
```

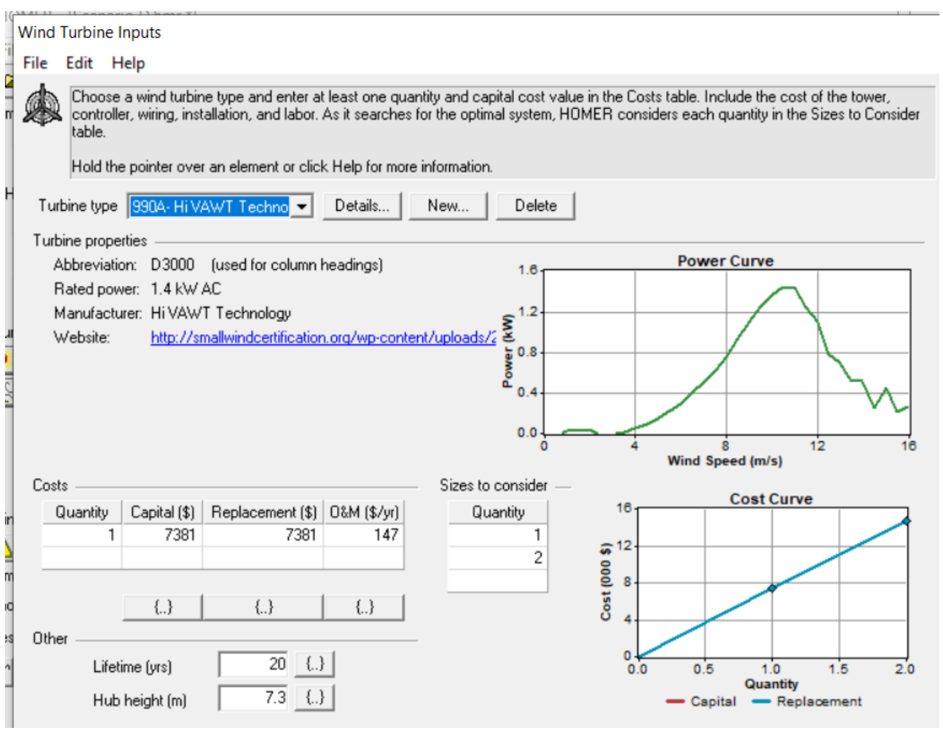
C.8.2 Results





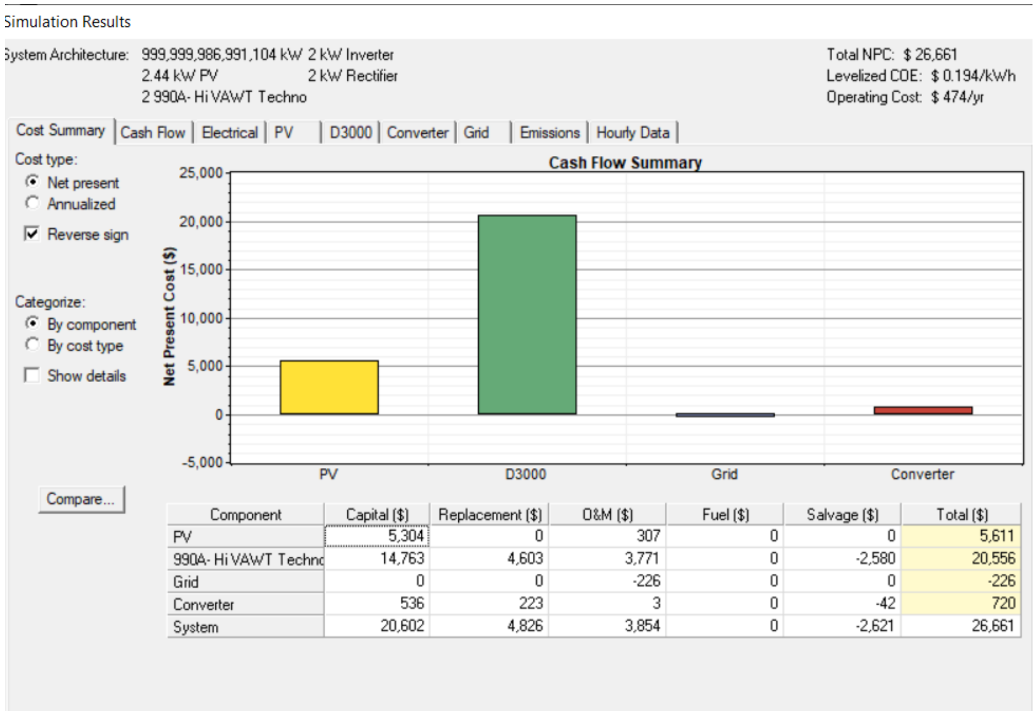


C.9 Scenario D-HOMER Inputs



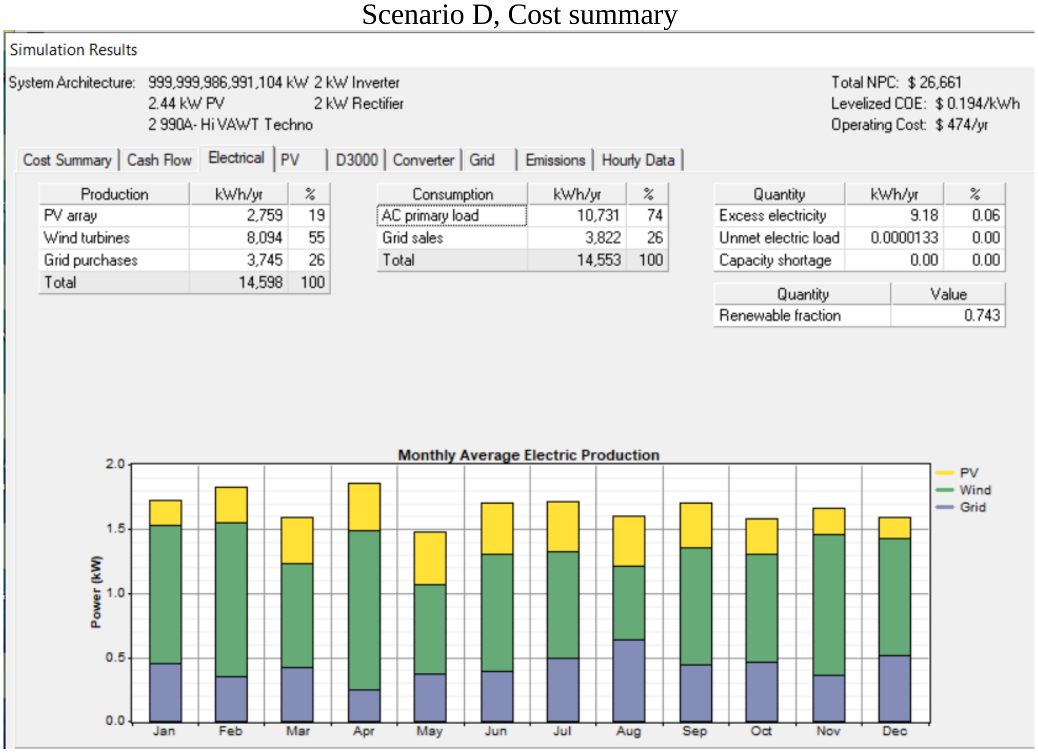
Scenario D, Wind input

C.10 Scenario D-HOMER Results



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	5,304	0	307	0	0	5,611
990A- Hi VAWT Techno	14,763	4,603	3,771	0	-2,580	20,556
Grid	0	0	-226	0	0	-226
Converter	536	223	3	0	-42	720
System	20,602	4,826	3,854	0	-2,621	26,661

Scenario D, Cost summary



Production	kWh/yr	%
PV array	2,759	19
Wind turbines	8,094	55
Grid purchases	3,745	26
Total	14,598	100

Consumption	kWh/yr	%
AC primary load	10,731	74
Grid sales	3,822	26
Total	14,553	100

Quantity	kWh/yr	%
Excess electricity	9.18	0.06
Unmet electric load	0.0000133	0.00
Capacity shortage	0.00	0.00

Quantity	Value
Renewable fraction	0.743

Scenario D, Electrical output

Quantity	Value	Units
Rated capacity	2.44	kW
Mean output	0.31	kW
Mean output	7.56	kWh/d
Capacity factor	12.9	%
Total production	2,759	kWh/yr

Quantity	Value	Units
Minimum output	0.00	kW
Maximum output	2.45	kW
PV penetration	25.7	%
Hours of operation	4,382	hr/yr
Levelized cost	0.159	$/kWh

Scenario D, PV output

Quantity	Value	Units
Total rated capacity	2.80	kW
Mean output	0.92	kW
Capacity factor	33.0	%
Total production	8,094	kWh/yr

Quantity	Value	Units
Minimum output	0.00	kW
Maximum output	2.83	kW
Wind penetration	75.4	%
Hours of operation	7,982	hr/yr
Levelized cost	0.199	$/kWh

Scenario D, WT output

Appendix D- Plagiarism Report