ENERGY MANAGEMENT COMPARISONS WITH MICROGRIDS

ENERGY MANAGEMENT COMPARISONS WITH MICROGRIDS: AN OVERVIEW OF TRADITIONAL AND HYDROGEN HYBRID MICROGRIDS

By

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Abstract

Energy management in a microgrid is a timely topic because of the Canadian Government's Sustainable Development Strategy (2020 to 2023) to help Canada reach net-zero emissions.

Defining a green and cost-effective microgrid involves solving a complex optimization problem. The design will involve a multi-disciplinary team of sustainable and renewable energy engineers, electrical and electronic engineers, and computing and software engineers. Integrating such a team is not easy.

The HOMER Software (Hybrid Optimization Model for Multiple Energy Resources) is widely used to communicate the ideas of microgrid energy designs into a final production proposal. The HOMER software facilitates the integration of multi-disciplinary teams for designing microgrids.

We used HOMER to design and simulate a hydrogen hybrid microgrid to meet the power needs of a hypothetical data centre. The proposed system is the first of its kind to specifically target the Sarnia, Ontario where the largest photovoltaic plant in Canada with installed capacity of 97 megawatt peak (MWP) is located. The non-conventional energy sources in Sarnia include over 45 wind turbines, access roads, meteorological towers, electrical collector lines, substations, and a 115 kilovolt (KV) transmission line. Cost comparisons and sensitivity analysis are done considering the hydrogen production and storage technologies (i.e. hydrogen tank attachment). Assuming appropriate government rebate programs, the hydrogen hybrid microgrid is proven to be financially beneficial in the long run.

Acknowledgements

I would like to express my sincere gratitude to my advisors, Prof. William Farmer and Prof. Spencer Smith, for their invaluable guidance and patient support throughout my master's program. Their expertise and encouragement helped me to complete this research and write this project report.

I am grateful to my work place for providing me with the opportunity to conduct my research at McMaster University, and for all of the resources and support they provided.

Finally, I would also like to thank my family for their love and support during this process. Without them, this journey would not have been possible.

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Glossary

capacity The maximum electrical load for the system at any given time. 13

centralised generation The centralized generation is the classic standard power management model for the very big power plants connected to the power system.. 4

conventional energy sources Conventional sources of energy are the ones that are commonly used, and generally non-renewable sources of energy, which are being used since a long time. Examples of conventional sources of energy include oil, natural gas, coal, biomass, and electricity. 3

deferrable load An electrical load that requires a certain amount of energy within a given time period, but the exact timing is not important. 26

excess electricity Surplus electrical energy that must be dumped (or curtailed) because it cannot be used to serve as a load or charge batteries. 47, 57

feed-in tariff a policy tool designed to promote investment in renewable energy sources. 12

fuel cell An electrochemical cell that converts the chemical energy of a fuel (often hydrogen) and an oxidizing agent (often oxygen) into electricity through a pair of redox reactions. 55, 58, 59

hybrid power plant Hybrid power systems are those that generate electricity from two or more sources, usually renewable, sharing a single connection point. 4

kilovolt A unit of electric potential. 13

load Energy consumed from the grid. 6

megawatt peak a unit of measurement for the maximum output of power from a source such as solar or wind where the output may vary according to the strength of sunlight or wind speed. MW_p is a measure of the maximum potential output of power. 13

microgrid A microgrid is a local energy grid with control capability, which means it can disconnect from the traditional grid and operate autonomously. 4

net present cost the present value of all the costs of installing and operating a component over the components lifetime, minus the present value of all the revenues that it earns over the components lifetime. 23, 24, 37

non-conventional energy sources Non-conventional sources are also known as renewable sources of energy. Examples of non-conventional sources of energy include solar energy, bioenergy, hydrogen energy and wind energy.. 3

operating reserve Operating reserves refer to the generating capacity available to meet demand in case the scheduled or forecast supply of power is disrupted. 30, 36

present value The current equivalent value of a set of future cash flows, taking into account the time value of money. 33, 37

primary load The electrical load that the system must meet immediately to avoid unmet load. 6, 26, 27

replacement cost The cost of replacing a component at the end of its lifetime. 34, 50–52, 57, 58

salvage value The value remaining in a component of the power system at the end of the component's lifetime. 34

scaled annual average The scaled annual average allows you to scale the entire set of hourly data up or down. For instance, if the baseline data you enter has an average of 200 kWh/day and you wish to simulate a situation in which the load increases by 30% from that baseline, you would enter a scaled annual average of 260 kWh/day. 47

smart grid A smart grid is an electricity network based on digital technology that is used to supply electricity to consumers via two-way digital communication. (eg. smart meter). 4

string size The number of batteries connected in series in each string. 55

the search space The environment where HOMER's user define values, such as capacity or quantity, for various components. HOMER uses these values to simulate all of the feasible configurations in the system and determine the most efficient configuration. 24, 55

unmet load The electrical load that the power system is unable to supply. xiii

Acronyms

AC alternating current. 27, 40, 42, 48

BESS battery energy storage systems. 19

CHP combined heat and power. 21

COE cost of energy. 37, 62

DC directcurrent. 27, 40, 42, 46, 48, 49, 51, 52, 59

Dis12V Discover 12VRE-3000TF. 54

GHI global horizontal irradiance. 15

HOMER hybrid optimization of multiple energy resources. v, vii–x, xiii, 3, 7–9, 11, 12, 23, 24, 26–30, 36, 37, 39, 41, 42, 44, 49–65, 68, 71

HTank hydrogen tank. 42

IRR internal rate of return. 36, 37

KV kilovolt. 13

LaRC Langley Research Center. 14

LCOE levelized cost of energy. 36

MGs microgrids. 4, 8

MWP megawatt peak. 13

NASA National Aeronautics and Space Administration. 14, 15

NPC net present cost. 33, 37, 62, 63, 68, 71

NREL National Renewable Energy Laboratory. 14

OHN Ontario Hydro Network. 53

POWER prediction of worldwide energy resource. 14, 15

PV solar photovoltaic. 11, 19, 26, 39, 40, 51, 55

ROI return on investment. 36, 38

TNPC Total Net Present Cost. 29

Chapter 1

Introduction

The overall goal of the project is to design an abstract model of the power and computing for a hydrogen hybrid microgrid that will establish relationships between energy transmission and computation, given power flow limits and peak consumption times. This model will then be used to simulate and compare strategies for reducing the environmental impact of data centres, while still making a profit.

1.1. The Project Outline

In this Chapter, we present the rationale for the study (Section 1.2), the problem statement (Section 1.3), and the literature review (Section 1.4). Chapter 2 of this report begins by building the foundation that is needed (Section 2.1), such as the software selection (Section 2.1.1), the location choice (Section 2.1.2), available resources (Section 2.1.3), and viable data centre prototypes (Section 2.1.4), as well as providing conceptual background for hybrid microgrid (Section 2.1.5) and the hydrogen production and storage technologies (Section 2.1.6). The hyperlinks are embedded and highlighted in blue throughout the report.

For example, the definitions of technical terms to aid the reader in navigating the terminology (the link to the Glossary) the context (links to sections and references).

We chose to use the Hybrid Optimization Model for Electric Renewables (HOMER) professional software after relevant comparison with the alternative software (Section 1.4). Hence, in Section 2.2 we present the necessary technical information needed to model a microgrid with HOMER.

In Chapter 3 an analysis is undertaken to compare the potential cost benefits of generating electricity from a hydrogen hybrid microgrid (i.e. using non-conventional energy sources including hydrogen production and storage) versus a traditional microgrid (i.e. using conventional energy sources). The fundamental data is gathered from the Sarnia, Ontario area in Canada. All feasible solutions are calculated based on available resources and are displayed using the HOMER software. The study concludes with the report's findings in Chapter 4.

1.2. Rationale for the Study

The Canadian government has announced its sustainable development strategies in the context of climate change for the years 2020 to 2023 [1]. Among the thirteen goals that the report presents, the most rigorous is the Federal Sustainable Development Strategy (FSDS) Goal 2: "Greening government: The Government of Canada will transition to low-carbon, climate-resilient, and green operations". On December 16, 2020, Canada's federal government released its much-anticipated Hydrogen Strategy for Canada [54]. The Strategy sets an ambitious framework to position hydrogen as a key enabler to help Canada reach net-zero emissions with an annual reduction of greenhouse gases of up to 190-megatonnes of

CO2 as a key part of Canada's path to net-zero carbon emissions by 2050 and make Canada a global leader in hydrogen technologies. In 2022, the Government of Canada announced up to $182.7 million to partner organizations to help farmers lower emissions and improve resiliency to climate change [55].

There has never been a more critical time for renewable energy development, particularly in rural areas where diesel or other fossil fuels are still used for heat and power. An additional $300 million is available until 2027 for projects to support clean energy initiatives in Indigenous, rural and remote communities across Canada. These projects can help advance Indigenous-led climate action, support local economic development and create skilled jobs while reducing pollution and improving air quality [56].

The smart grid technologies, distributed generation by small-scale producers, and locally and regionally regulated microgrids (MGs) are all changing how grids are managed [2]. The smart grid clearly allows for the shift from a grid with centralised generation to one with peer-to-peer interactions, distributed generation, and control centres. It is vital that a peer-to-peer match system architecture [75] is developed for local loads. One challenge that remains unanswered is how the energy management of a microgrid can efficiently deal with energy spikes. Data centres and power plants have extra capacity, and must be prepared for unexpected demand increases.

The world's first hydrogen hybrid power plant built in Germany (October 2011) by Enertrag AG [27] pioneered the technological field of intermediate storage of wind energy as hydrogen. Given recent advancements in green energy technologies, the inspiration of this project is to investigate hydrogen hybrid microgrid prospects in Ontario, Canada.

1.3. Problem Statement

In recent years, there has been significant progress in the development of hybrid microgrid models, and the non-conventional energy sources have become increasingly cost and efficiency competitive with the traditional sources of energy (eg. fossil fuels [30]). Solar energy continues to be one of the most rapid growing forms of non-conventional energy, with solar photovoltaic (PV) installations growing by over 20% annually in recent years [36]. Advances in solar technology, including more efficient and lower-cost PV panels, are driving this growth. Wind energy is also a rapidly growing form of non-conventional energy, with wind turbine installations increasing by more than 10% annually in recent years [10]. Advances in wind turbine technology, including larger and more efficient turbines, are making wind energy more cost-effective and reliable.

Adoption of hydrogen energy could be a major driver towards a clean, secure and affordable energy future by 2050 [90]. Hence, hydrogen is emerging as a promising non-conventional energy source, with the potential to be used in fuel cells to produce electricity or as a clean-burning fuel for transportation [84]. Advances in hydrogen production technology, including electrolysis and hydrogen production from biomass, are making hydrogen more viable as a non-conventional energy source.

One of the biggest challenges facing renewable energy is the intermittent nature of solar and wind power, which can fluctuate depending on weather conditions [89]. However, advances in energy storage technology, including batteries, pumped hydro storage and hydrogen tank storage, are helping to address this issue by allowing non-conventional sources of energy to be stored and used when needed.

Overall, the current state of hybrid microgrids is promising, with rapid advances in technology driving growth and making non-conventional energy sources more cost-effective and reliable. However, there are still challenges to be addressed, such as the need for better energy storage solutions and more robust infrastructure to support hybrid microgrid deployment at scale.

The data centre's load (i.e. energy used) must be measured at the facility's utility meter to determine whether or not they can be met. In other words, the load needs to measured and compare to available energy.

Another major issue is the growing demand for digital services, which will necessitate the construction of new data centres and the use of new non-conventional energy sources to power them. One potential solution is to combine the data centre, renewable energy sources, grid energy and storage as components of a "metagrid" – a unified, software-controlled, self-aware power and computing ecosystem. This solution will provide significant benefits by efficiently powering data centres and improving a region's energy profile.

The purpose of this project is to design a hydrogen hybrid microgrid schema that takes into account the primary load, the grid, non-conventional energy sources with the potential addition of hydrogen production technologies and a hydrogen tank attachment. The objective is to minimize the energy consumption cost using an optimal energy management strategy subject to system constraints and operating reserve.

1.4. Literature Review

Two aspects of the literature review are presented in this section: (1) review of available software support, and (2) review of hydrogen hybrid microgrid systems in Canada.

To start with, in Section 1.4.1, the literature is briefly scanned for the available microgrid management software in the market and the comparative studies to provide insight into the popular software in the field and its implementation for hybrid microgrid. Then, in Section 1.4.2, an independent literature review is conducted to capture the gap of the hybrid microgrid management in Canada and the opportunities for a hydrogen hybrid microgrid.

1.4.1. Software Selection

A brief literature review is done to determine the software that has been developed and is available to model a microgrid. Based on studies that compare the pros and cons of the software (see Table 1.1), we selected HOMER. "HOMER simulation" means that the software can simulate a wide range of microgrid system setups. This is the most extensively utilised aspect of HOMER because it provides for the greatest number of combinations of conventional and non-conventional energy sources. Furthermore, it does optimisation and sensitivity analysis, making it easier and faster to evaluate the different possible system configurations. [66, 76]. Additionally in Table 1.1, we checked whether the hydrogen generation and storage module is available in these softwares. We determined that software systems such as HYSYS, HYBRID2, TRNSYS and INSEL are used only for process simulation and cannot be used as an optimisation program [69]. iHOGA (available in Spanish) is similar to HOMER and its major difference from HOMER lies in the optimization algorithm [74]. While HYBRID2 is a close competitor to HOMER, it lacks economic analysis functionality.

Table 1.1. *Comparison of analytical capabilities of microgrid management systems [76]: Economical Analysis (Eco), Technical Analysis (Tech), Wind System (Wind), Generator Set (Gen), Storage Device (Storage), Biomass Energy (Bio), Hydro Energy (Hydro), Photovoltaic System (PV); and Hydrogen Production and Storage (Hydrogen).*

Tools	Eco	Tech	PV	Wind	Gen	Storage	Bio	Hydro	Hydrogen
HOMER	x	x	x	x	x	x	x	x	x[22]
HYBRID2	-	x	x	x	x	x	-	-	x[50]
iHOGA	x	x	x	x	x	x	-	x	x[44]
iGRHYSO	x	x	x	x	-	x	-	x	x[67]
RETScreen	x	x	x	x	-	x	-	-	-[64]
RAPSIM	-	x	x	x	x	x	-	-	-[65]
SOLSIM	x	x	x	x	x	x	x	-	-[35]
ARES-I-II	-	x	x	x	x	x	-	-	-[51]
HYSYS	-	x	x	x	x	x	-	-	x[73]
INSEL	-	x	x	x	x	x	-	-	x[69]
HybSim	x	x	x	-	x	x	-	-	-[80]
Dymola/Modelica	x	-	x	x	-	x	-	-	x[52]
SOLSTOR	x	x	x	x	x	-	-	-	-[11]
HySim	x	x	x	-	x	x	-	-	-[80]
IPSYS	-	x	x	x	x	x	-	x	-[13]
Hybrid Designer	x	-	x	x	x	x	-	-	-[71]
TRNSYS	x	x	x	x	x	x	-	-	x[38]

1.4.2. The Gap in the Use of HOMER in Canada

Many studies have used HOMER to optimise the value of hybrid power systems, ranging from utility-scale and distributed generation to standalone microgrids (MGs). In this study, the Web of Science is used to give an overview of usage of the software known as "Hybrid Optimization of Multiple Energy Resources" ("HOMER") for application in energy fuels, green sustainable science technology, engineering environment, or construction building technology. This literature review yields studies mostly in Asia and Africa. Selected publications relevant to this study are given in Table 1.2. There is only one publication that implements HOMER in a remote community (Newfoundland, Canada [19]). Our current work uses this opportunity to fill in the gap and investigate the feasibility and potential implementation in Ontario, Canada. The model for this study then can be used to build an enhanced hydrogen hybrid microgrid, offering a beneficial addition to existing research in the field.

Table 1.2. *Summary of studies that uses HOMER for energy modeling; Photovoltic (PV), Diesel Generator (DG), Battery (B), Fuel Cell (FC), Hydrogen (H), Wind (W), Generator (Gen), Electrolyzer (E), Heater (Heat), Hydroelectricity (Hyd), Biomass (bio).*

Author	Year	Country	Area	Configuration
Elsaraf et. al. [19]	2021	Newfoundland	Canada	PV/W/H FC/E/Heat
Margaret et.al. [9]	2016	Southern India	South Asia	PV/DG/B W/DG/B PV/Hyd/DG/ B W/Hyd/DG/B PV/W/Hyd/B PV/W/DG PV/W/B
Shahzad et.al. [72]	2017	Pakistan	South Asia	PV/Bio
Khan et.al. [39]	2015	Bangladesh	South Asia	PV/Bio
Al Garni et.al. [6]	2018	Saudi Arabia	Southwestern Asia	PV/Grid
Han et.al. [29]	2019	Ganzi (China)	East Asia	PV/Bat/H
Lau et.al. [43]	2016	Malaysia	Southeast Asia	PV/Grid
Adentuji et.al. [5]	2018	Tafelkop	South Africa	PV/Grid PV/B/Grid B/Grid
Venkatachary et.al. [87]	2017	Botswana	South Africa	PV/Gen Grid

Chapter 2

Methodology

The methodology is presented in two sub-sections. The first section (Section 2.1) introduces the building blocks of energy management of a microgrid such as the load profile of the hypothetical data centre, location candidate, hybrid microgrid design and hydrogen technologies. The second section (Section 2.2) gives the reader information about the strategic information on building the hybrid microgrid subject to constraints in the cost optimization and navigation between different schemes to compare key performance indicators in economics.

2.1. Foundation

We start by presenting the software tool and the functionality that we configure to fit our microgrids energy management goals in Section 2.1.1. The selection of a geographic location is given in Section 2.1.2. The available national resources are summarized in Section 2.1.3. The load demand in a hypothetical data center is presented in Section 2.1.4. Then, the theoretical hybrid system design is given in Section 2.1.5, and the developments of the hydrogen production and storage technologies are addressed in Section 2.1.6.

2.1.1. HOMER Pro Software

HOMER Energy's HOMER Pro® microgrid software is the global standard for optimising microgrid design, which was originally developed at the National Renewable Energy Laboratory (NREL) [57], a national laboratory of the U.S. Department of Energy. HOMER Pro combines three powerful tools in a single software product, allowing engineering and economics to find common ground: (1) simulation, (2) optimization, and (3) sensitivity analysis.

This software offers flexibility in designing various schematics of power configurations both using traditional and non-conventional sources of energy. The designed schema is then simulated in different combinations of energy components to find the most cost-effective feasible design.

The optimization outputs provide the simulation results in graphical and tabulated form. Additional information about the system can be pulled from the summary of categorized optimization results, such as the number of kilograms of carbon dioxide produced by the system during the year.

2.1.2. Nature of the Selected Area

Within Canada, Sarnia-Lambton is an ideal location for a hybrid microgrid because of the availability of energy. Sarnia has the advantage of non-conventional energy (e.g., hydro, solar photovoltaic (PV) and wind). Canada has a long history of producing energy in Sarnia as well as the supporting sectors that are necessary to keep the energy sector running [70].

Sarnia-Lambton is within a one day drive to 65% of the U.S. market as well as major

Ontario and Quebec markets. In 2009, Ontario introduced a feed-in tariff [61] renewable energy payments program paying up to CDN 44.3 cents per kWh for large ground arrays such as the Sarnia plant [88]. This places Ontario among the top feed-in tariff programmes in the world [62].

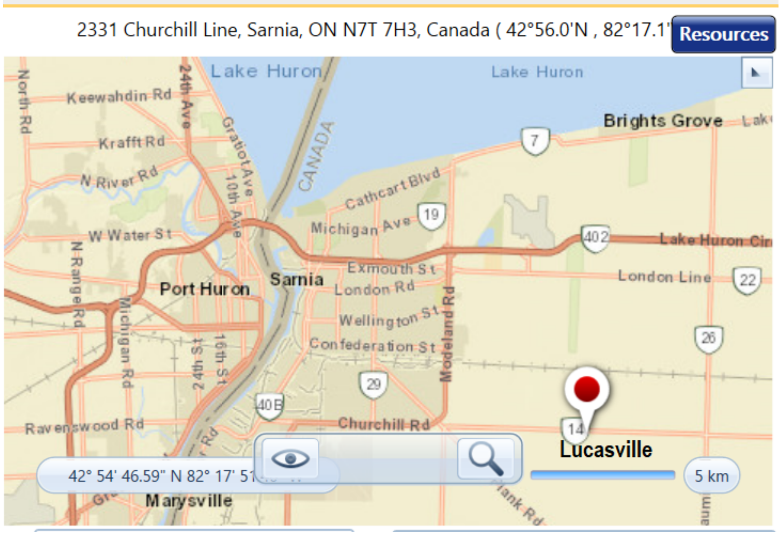


Figure 2.1. *Location Map in HOMER (Lucasville, Sarnia, Ontario, Canada)*

In this project, Lucasville, a rural area in Sarnia, is considered for the design of the proposed hydrogen hybrid microgrid. The latitude and longitude of Lucasville geographic location are $42°56.0'N$ and $82°17.1'W$. The selected area is very close to the Suncor Energy Cedar Point Wind Power Project within the Town of Plympton-Wyoming, the Municipality of Lambton Shores, and Warwick Township, all within Lambton County, Ontario (Fig. 2.2). The Sarnia Solar Farm is a 80MW solar PV power project. The project generates 120,000MWh electricity and supplies enough clean energy to power 12,800 households, offsetting 39,000 tons of carbon dioxide emissions (CO2) a year [83].

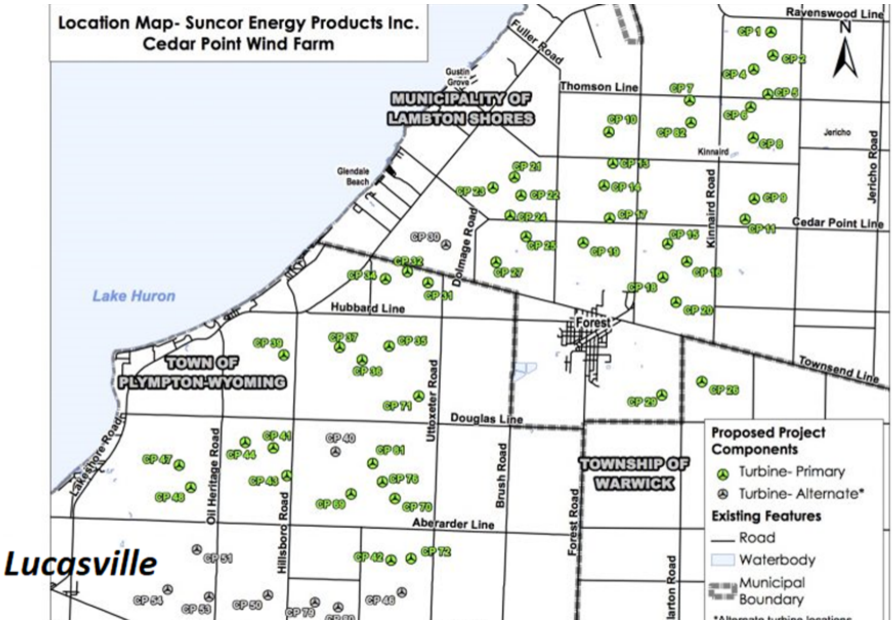


Figure 2.2. *Image: Suncor Energy [49]*

The non-conventional energy sources include over 45 wind turbines (Fig. 2.1), access roads, meteorological towers, electrical collector lines, substations, and a 115 kilovolt (KV) transmission line [45]. The largest photovoltaic plant in Canada with an installed capacity of 97 megawatt peak (MWP) is located near Sarnia, Ontario (Fig. 2.3).

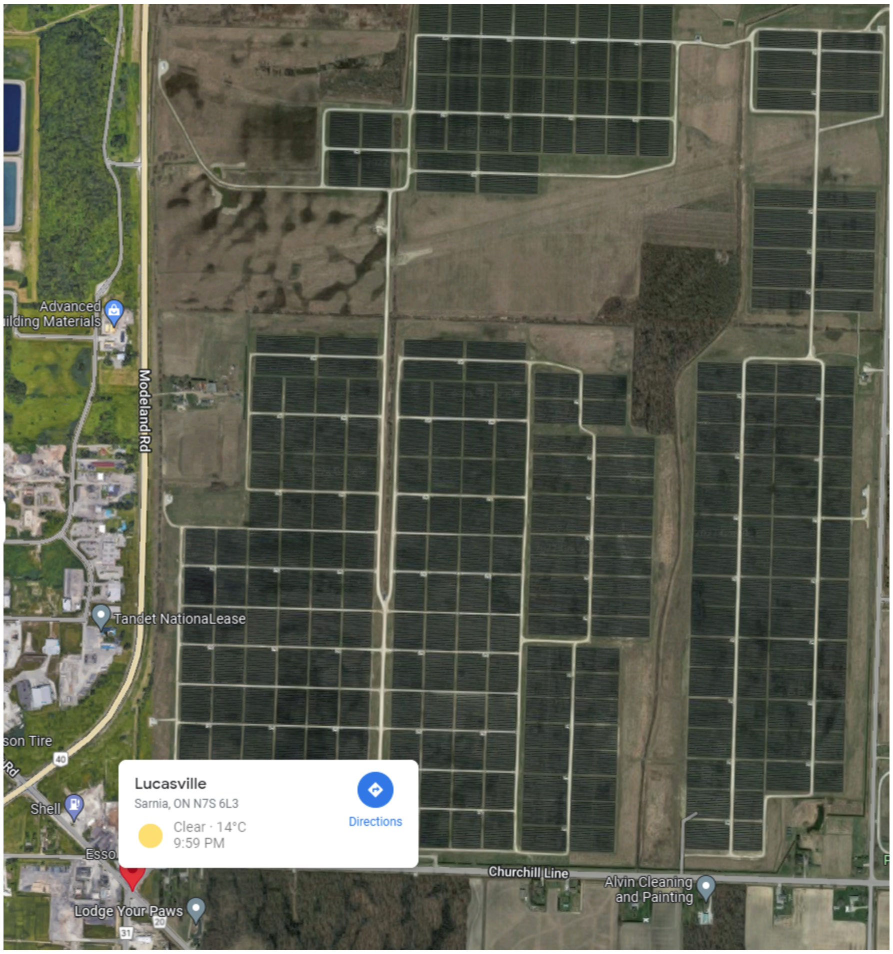
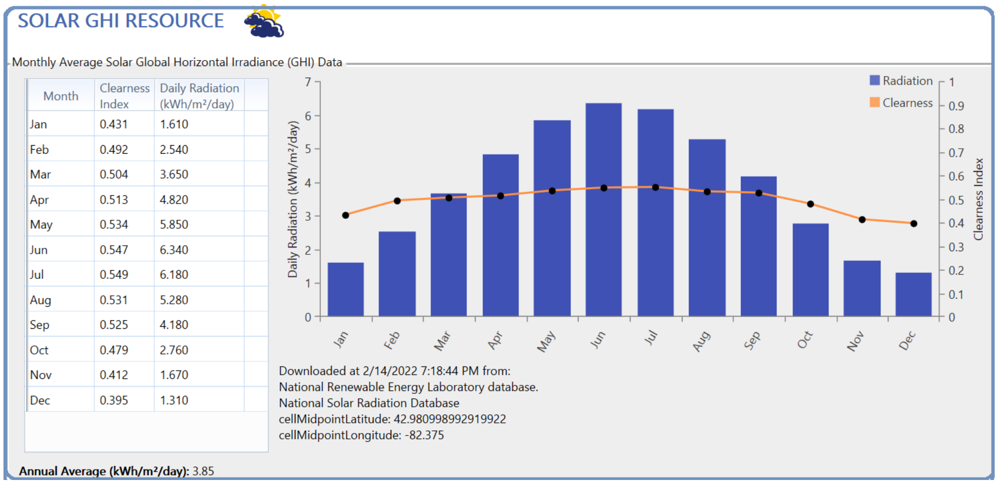


Figure 2.3. *Photovoltaic plant land image in Lucasville, Sarnia, Ontario [image capture from Google Earth on 9-June-2022].*

2.1.3. Resources

Weather data for wind and temperature at the chosen location are obtained from the National Aeronautics and Space Administration (NASA) Langley Research Center (LaRC) Prediction of Worldwide Energy Resource (POWER) Project funded through the NASA Earth Science/Applied Science Program [3]. The solar data was pulled from National Renewable Energy Laboratory (NREL) resources [4]. The information received from these resources are shown in Fig. 2.4 – Fig. 2.6. The annual average of daily radiation produced from solar global horizontal irradiance (GHI) resource in this selected location is 3.85 ($kWh/m^2/day$) the annual average wind speed is 7.08 (m/s) and the annual average temperature is 8.74°C .

Biomass and solar resource assessments are imported externally from the databases by National Renewable Energy Laboratory, the National Solar Radiation (Fig. 2.4), and the NASA Prediction of Worldwide Energy Resource (POWER) - Fig. 2.5 and 2.6.



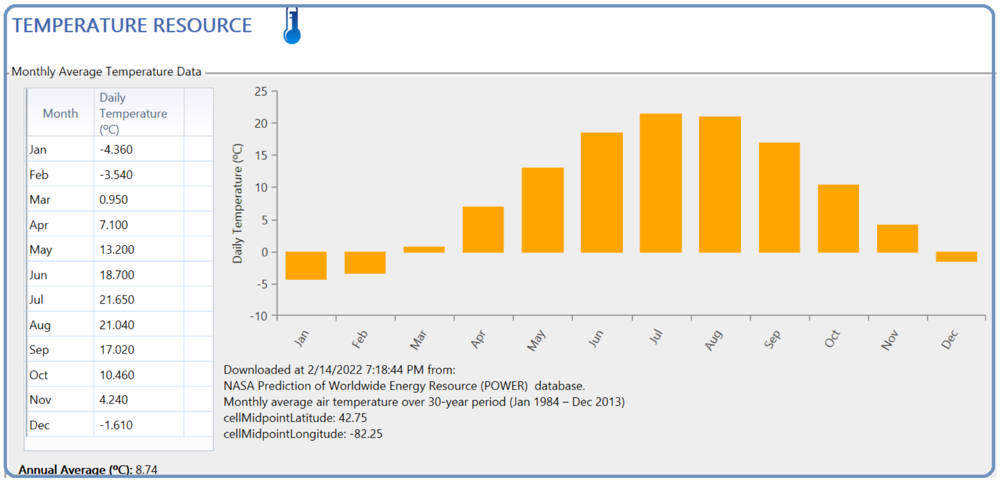
Monthly Average Solar Global Horizontal Irradiance (GHI) Data

Month	Clearness Index	Daily Radiation (kWh/m²/day)
Jan	0.431	1.610
Feb	0.492	2.540
Mar	0.504	3.650
Apr	0.513	4.820
May	0.534	5.850
Jun	0.547	6.340
Jul	0.549	6.180
Aug	0.531	5.280
Sep	0.525	4.180
Oct	0.479	2.760
Nov	0.412	1.670
Dec	0.395	1.310

Downloaded at 2/14/2022 7:18:44 PM from:
National Renewable Energy Laboratory database.
National Solar Radiation Database
cellMidpointLatitude: 42.980998992919922
cellMidpointLongitude: -82.375

Annual Average (kWh/m²/day): 3.85

Figure 2.4. *Monthly distribution of solar global horizontal irradiance* ($kWh/m^2/day$)



TEMPERATURE RESOURCE

Monthly Average Temperature Data

Month	Daily Temperature (°C)
Jan	-4.360
Feb	-3.540
Mar	0.950
Apr	7.100
May	13.200
Jun	18.700
Jul	21.650
Aug	21.040
Sep	17.020
Oct	10.460
Nov	4.240
Dec	-1.610

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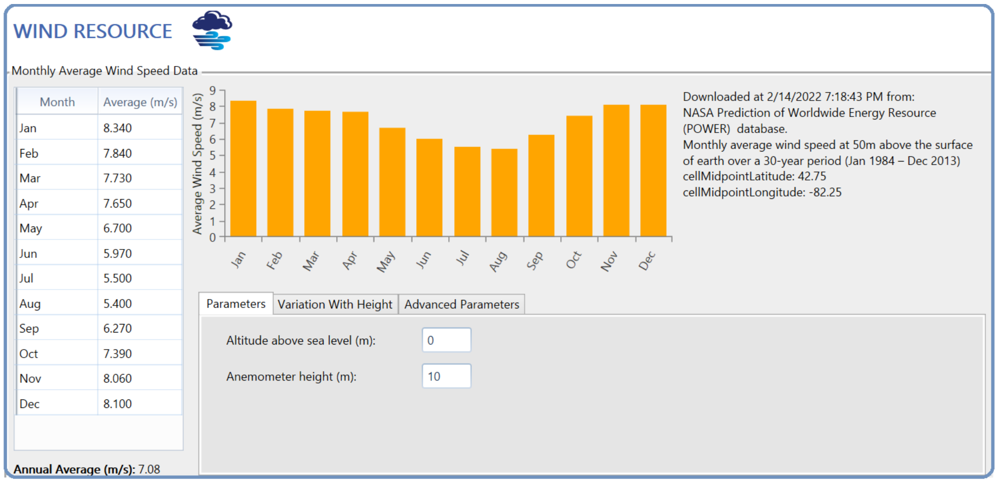
NASA Prediction of Worldwide Energy Resource (POWER) database.
Monthly average air temperature over 30-year period (Jan 1984 – Dec 2013)
cellMidpointLatitude: 42.75
cellMidpointLongitude: -82.25

Annual Average (°C): 8.74

Figure 2.5. *Monthly distribution of average daily temperature (°C)*



WIND RESOURCE

Monthly Average Wind Speed Data

Month	Average (m/s)
Jan	8.340
Feb	7.840
Mar	7.730
Apr	7.650
May	6.700
Jun	5.970
Jul	5.500
Aug	5.400
Sep	6.270
Oct	7.390
Nov	8.060
Dec	8.100

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NASA Prediction of Worldwide Energy Resource (POWER) database.
Monthly average wind speed at 50m above the surface of earth over a 30-year period (Jan 1984 – Dec 2013)
cellMidpointLatitude: 42.75
cellMidpointLongitude: -82.25

Altitude above sea level (m): 0
Anemometer height (m): 10

Annual Average (m/s): 7.08

Figure 2.6. *Monthly distribution of average wind speed (m/s)*

HOMER provides the default parameter settings based on the geographical location of the resources.

2.1.4. Data Centre Prototype

In North America, the “Kevin Smith Studebaker campus” [8] demonstrates a replicable approach to design and operate locally integrated energy systems that have a high and stable level of social acceptability. The Studebaker campus is being redeveloped into the largest mixed-use technology campus in the Midwest region of the USA, the Renaissance District [17], a 80 block area just south of downtown South Bend, Indiana. The Studebaker campus incorporates mixed-use spaces, including a data center, work space, residential, discourse (i.e. a free and open-source internet forum system) and commerce as is shown in Fig. 2.7.

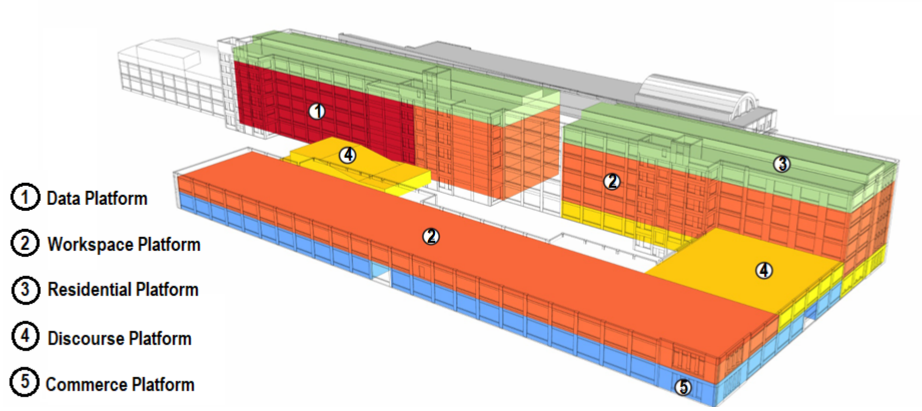


Figure 2.7. *Studebaker buildings [85]*

Kevin Smith is the local entrepreneur who owns Union Station Technology Center and had the vision to see new possibilities in the Studebaker buildings. He is also our project’s industry consultant.

2.1.5. Hybrid System Design

Using non-conventional energy sources such as the sun, biomass, wind, ocean, geothermal, and other sources, we can reduce our reliance on fossil fuels while also protecting the environment. A hybrid microgrid combines several power stations [15], each of which includes photovoltaic and wind power generators, along with a diesel power generator as backup when non-conventional energy is insufficient (i.e. doesn't include power from the grid). Because of the unavailability of sustainable sources throughout the entire year, researchers have turned their attention to the field of hybrid microgrid. A hybrid microgrids has the advantage of improved reliability and gives better energy service when compared to a traditional microgrid [79].

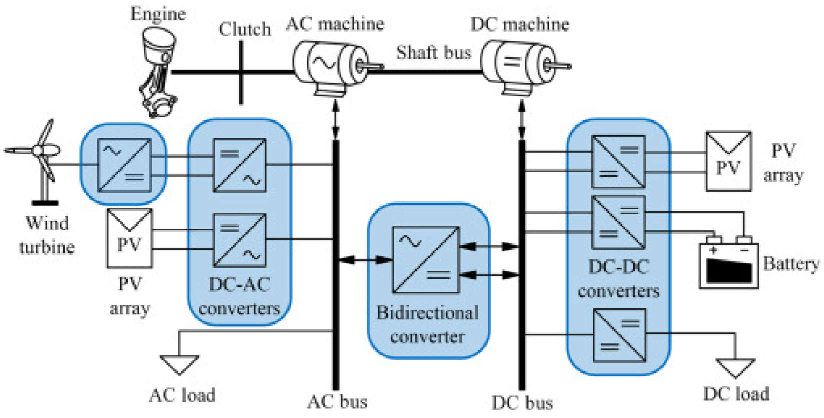


Figure 2.8. *An example hybrid microgrid (off-grid) and the multiple roles of power electronics in it [41].*

Hybrid microgrids integrate multiple generating, storage, and consumption technologies into a single system, providing greater overall benefits than a single-source system. Originally defined as a combination of traditional (e.g., diesel generators) with battery energy storage system (BESS), its definition has been expanded to include systems that are entirely powered by non-conventional energy (e.g., hydro, solar photovoltaic (PV) and wind) or that combine multiple energy storage systems (e.g., hydrogen storage). Konstantinou and Hredzak [41] illustrated the state of a hybrid microgrid (off-grid) as of 2020 in Fig. 2.8.

2.1.6. Hydrogen Production and Storage Technologies

Hydrogen is a clean, renewable fuel that could help address Canada's energy and environment problems. It also has the ability to replace the present energy infrastructure that is based on fossil fuel. Hydrogen can dramatically reduce the dependence on oil and significantly reduce tailpipe emissions [12].

The seven key hydrogen production technologies fall into two broad categories: electrolytic and photolytic processes [60].

- *Electrolytic Processes*: Water (H_2O) can be split into hydrogen (H_2) and oxygen (O_2) using electricity.
    - For example, microbial electrolysis cells use bacteria to efficiently extract energy from organic matter (see Fig. 2.9).

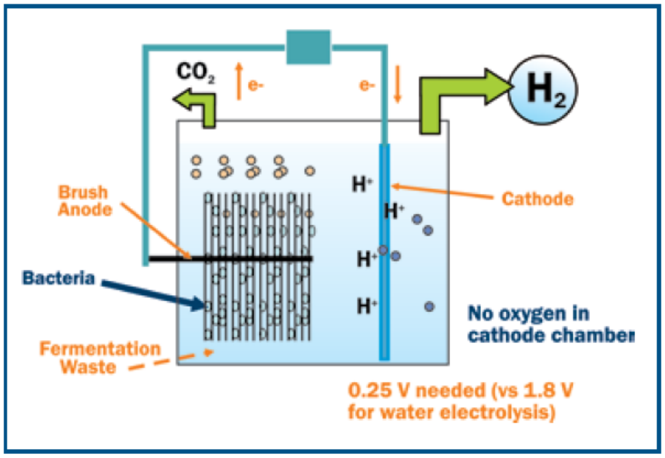


Figure 2.9. *Microbial electrolysis cells use bacteria to break up acetic acid from plant waste and produce hydrogen gas using a bit of added electricity. The process produces more than 250% more energy than the electricity required to extract it [59].*

- For example, an integrated systems approach may use the byproducts of some production pathways as inputs to others in a nearly closed-loop system that produces hydrogen at each stage (see Fig. 2.10).

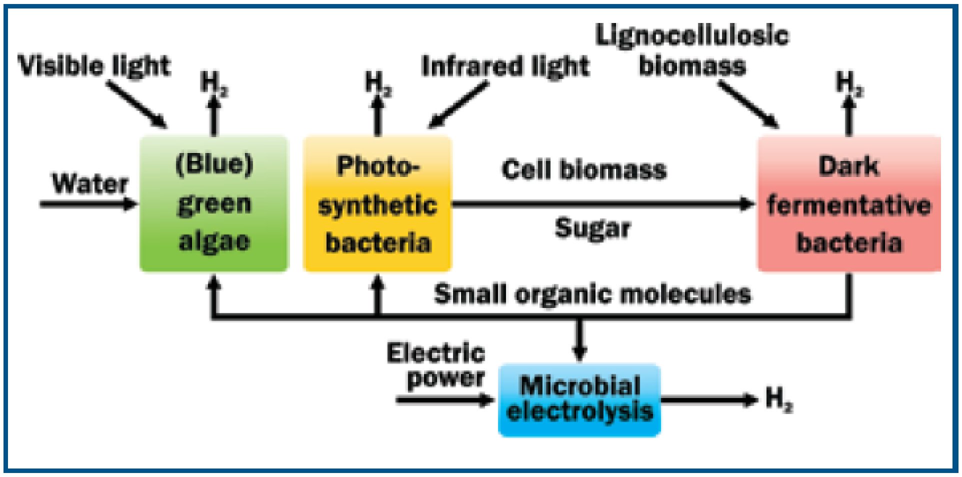


Figure 2.10. *A system using multiple biological processes can provide internally generated feedstock and produce hydrogen at each step [59].*

- *Photolytic Processes*: Hydrogen and oxygen are separated from water using light energy in photolytic reactions (direct solar water splitting). Hydrogen production with low environmental effect can be achieved using these processes, which are currently in the early phases of development.
  - For example, one closed chemical cycle of this type of hydrogen production is illustrated in Fig. 2.11.

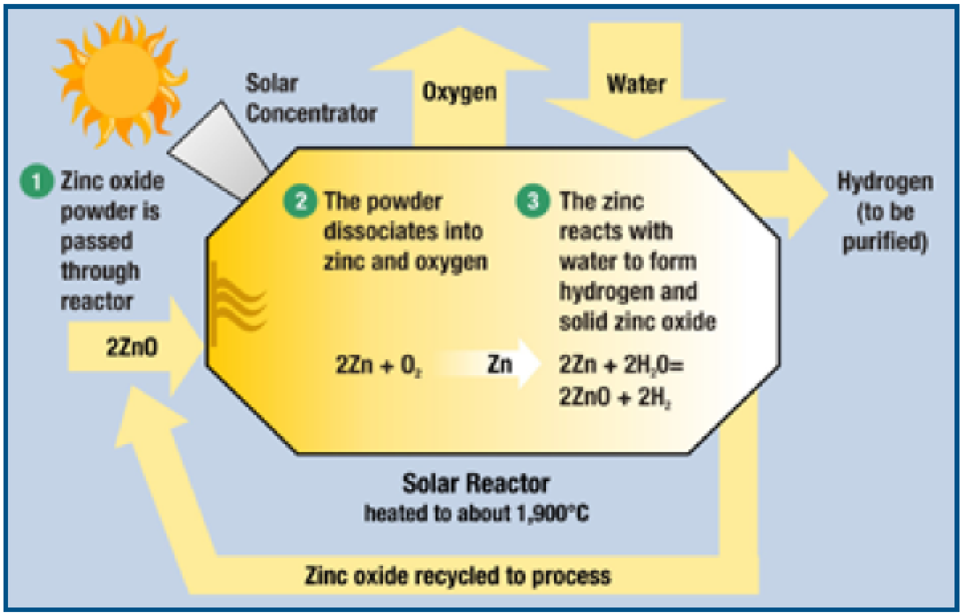


Figure 2.11. *One closed chemical cycle produces hydrogen using zinc oxide and solar energy [59].*

- *Hydrogen Storage*

The most recent publication of Grunow in 2022 [28] focuses on hydrogen as a storage technology called "Storage CHP" uses a small fuel cell with additional electrolysis in thermal coupling as a component. CHP technology to convert power to hydrogen and back to power has a round-trip of 12% - 39% of efficiency. In other words, as shown in Figure 2.12, lost (missing) heat due to temporary mismatches between local heat demand and excess power at the grid is around 12%, implying that hydrogen to power conversion contributes only 12% to the end use. The ratio of the energy recovered from the energy storage to the energy put into the device (1259TWh) is only 39% (i.e. round-trip efficiency) instead of the calculated 42% (= electrolysis 70% × Fuel Cell 60%). The loss is provided by a heating rod powered by excess electricity or, in the event of a power outage, by power from hydrogen via the Storage CHP.

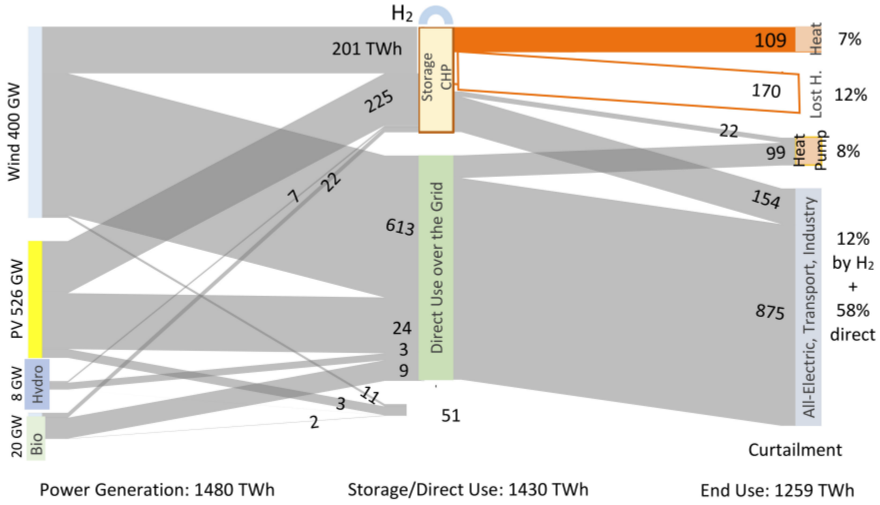


Figure 2.12. *Energy flows for an all-electric renewable [28] .*

In comparison to a diesel reference case, a hydrogen storage microgrid was able to provide a reduction in carbon emissions of between 66 and 99 percent, but at a cost that was increased by between 30 and 100 percent [19].

2.2. Microgrid System Modeling with HOMER

The conceptional relationship of simulation, optimization and sensitivity analysis is presented in Section 2.2.1 and the details on load profile and strategies are given in Section 2.2.2. Economics are fundamental to both HOMER's simulation process, which operates the system in the most cost-effective manner possible, and its optimization process, which seeks out the system configuration with the lowest total net present cost. Section 2.2.3.3 addresses why life-cycle cost is the best metric for comparing the economics of various system configurations, why HOMER utilises total net present cost as the economic figure of merit, and how HOMER calculates total net present cost.

2.2.1. Simulation, Optimization and Sensitivity

The term "simulation" in this project refers to the process of developing various architectures rather than computationally calculating specific equations or utilising random number generation to mimic load fluctuations (or other quantities that are inherently random such as wind). For instance, wind data is retrieved from a national database and used as a real-time data input to the software (see Section 2.1.3).

The link between simulation, optimization, and sensitivity analysis is illustrated in the following diagram in Fig. 2.13. There are several simulations in an optimization and this is represented by an ellipse that encircles it. Similarly, a sensitivity analysis is made up of several optimizations.

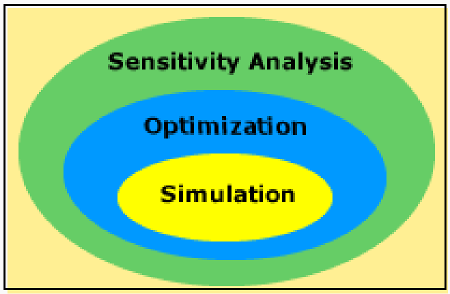


Figure 2.13. *Conceptual relationship between simulation, optimization, and sensitivity analysis. [42], [26]*

HOMER simulates several microgrid architectures with different combinations of distributed resources that are constructed to evaluate (1) the microgrid's feasibility and (2) the life-cycle cost of the microgrid. As long as the microgrid is capable of meeting the user's electrical load requirements, HOMER considers it as feasible. To calculate the energy balance of a microgrid, several combinations of components are used. The interaction between simulation and optimization occurs in the search space [31]. The analyst can choose parameters like capacity and quantity for each component. Using these parameters, HOMER runs a simulation of all possible setups to find the optimal one. The search space values can be updated by the analyst throughout the construction of the system.

HOMER's optimization process uses simulations consisting of many different system configurations, discards the infeasible ones (those that do not satisfy the user specified constraints), and ranks the feasible ones according to total net present cost (TNPC) (see formulation in Section 2.2.3.3). In other words, the winning microgrid design is determined based on the simulation output with the lowest net present cost. The overall optimization process is shown in Fig. 2.14. The components of the microgrid configuration changes in each repeat of the process to refine the analysis until the optimal design subject to system constraints (see Section 2.2.3) is found.

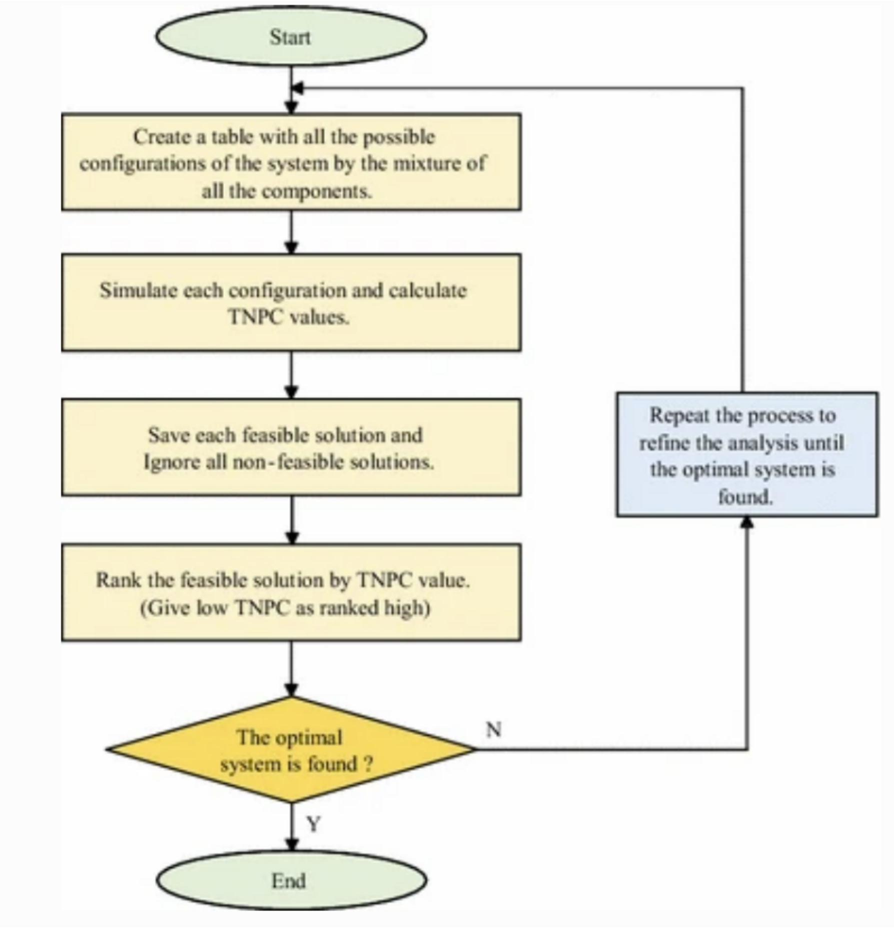


Figure 2.14. *Flow Chart for the Optimization Process [63]*

Finding the optimal microgrid configuration may involve deciding on the mix of components, and the size or quantity of each component. This is known as sensitivity analysis. A sensitivity variable is a variable over which the system designer has control and for which multiple values can be specified (i.e. the size, the quantity, or the life time). During sensitivity analysis, the goal of the optimization process is to determine the optimal value of each sensitivity variable that interests the modeller. A full sensitivity analysis is outside the scope of this work.

2.2.2. Load Profile and Strategies

A load is an energy-consuming component of a system. Electricity must be supplied on a continual basis with a controller in place. HOMER uses a load-following strategy given the system configurations to satisfy the demand. The strategy statement is “a dispatch strategy whereby whenever a generator operates, it produces only enough power to meet the primary load. Lower-priority objectives such as charging the storage bank or serving the deferrable load are left to the renewable power sources. The generator may still ramp up and sell power to the grid if it is economically advantageous.” [21]. The load following strategy is the dominant strategy that leads to the final calculation decisions.

The load following strategy is a way to make sure that, when a generator is running, it only makes enough power to meet the primary load. Non-conventional energy sources are used for things like charging the battery bank or powering the things that cannot be used right away - such as producing hydrogen [58]. As a result, HOMER moves the microgrid’s controllable power sources (generators, grids and batteries) so that they can be used to supply the primary load each time step, while still meeting the system’s operating reserve needs. The deferrable load is second in priority behind the primary load. The assumption of the load priority is made similar to Hybrid2 Software (see Fig. 2.15). The approach in HOMER is known as a dispatch technique in which a generator operates at full output power whenever it needs to supply the primary load. HOMER follows a defined order of generator combinations, and uses the first combination in the list that meets the Operating Capacity. The Generator Order strategy only supports systems with generators, PVs, wind turbines, a converter and/or storage components.

HOMER Pro makes a separate set of decisions about how to allocate the power when determining load priority. The presence of an Alternating Current (AC) and a Direct Current (DC) bus complicates these decisions slightly. HOMER Pro assumes that electricity generated on one bus will first serve primary load on the same bus, then primary load on the opposite bus, then deferrable load on the same bus, then deferrable load on the opposite bus, then charge the battery bank, then grid sales, then serve the electrolyzer (therefore the hydrogen tank) [25]. To summarize, surplus electrical production is directed toward lower-priority goals such as feeding the deferrable load, charging the storage bank, and serving the electrolyzer, in that order.

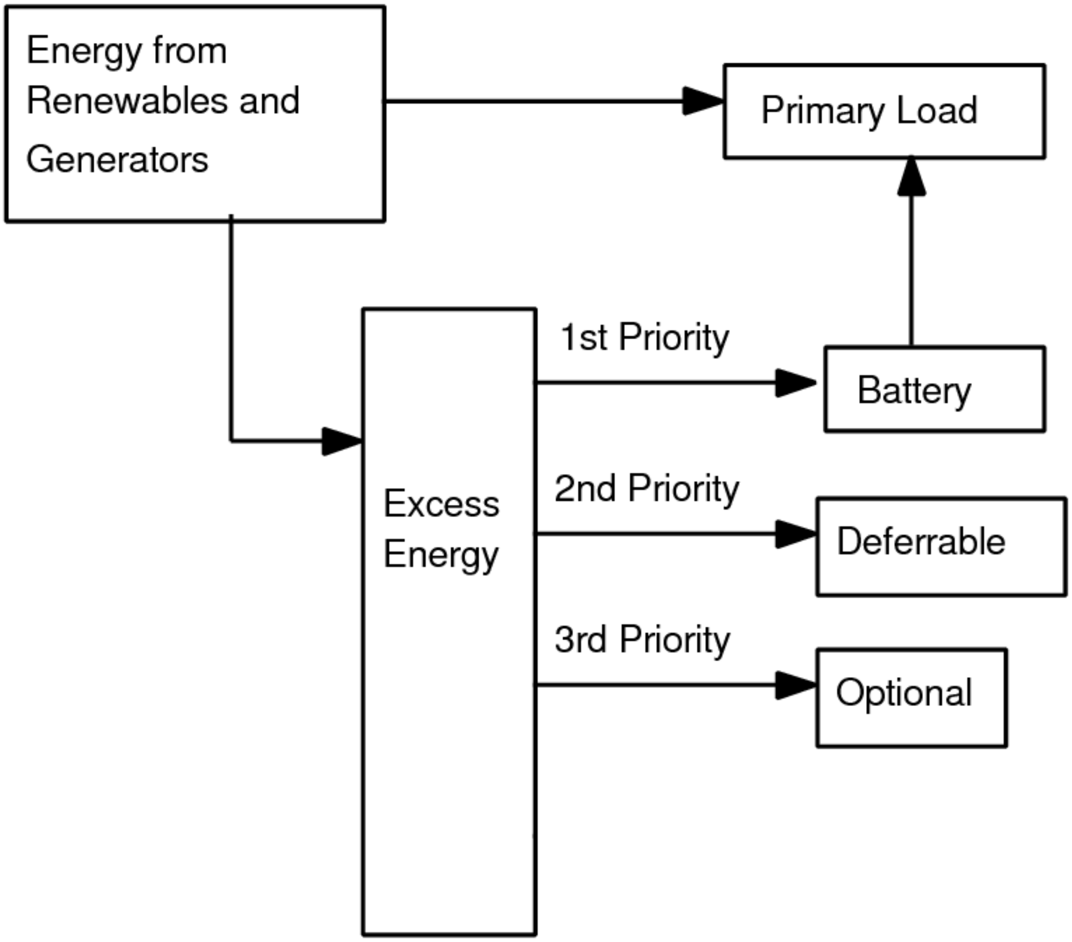
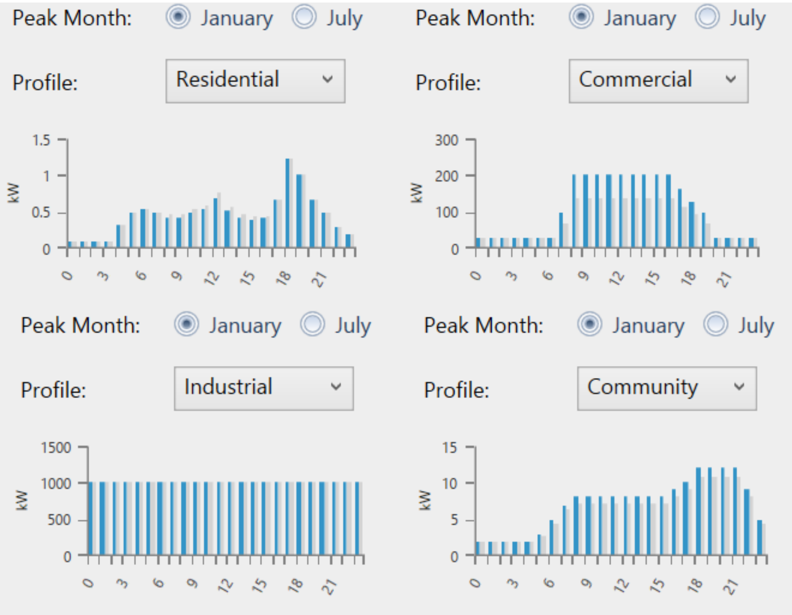


Figure 2.15. *Diagram of Load Priority [46]*

Load in HOMER Pro contains Electrical, Deferrable, and Hydrogen Load. Once the load is introduced to the model, the load profile describes how the load energy consumption varies depending on the time of day. Depending on the sort of centre that requires energy, four default profiles are offered in HOMER (Figure 2.16).



Peak Month: ● January ○ July
Profile: Residential

Peak Month: ● January ○ July
Profile: Commercial

Peak Month: ● January ○ July
Profile: Industrial

Peak Month: ● January ○ July
Profile: Community

Figure 2.16. *Electric Load Profile Types*

The preset load profiles: Residential, Commercial, Industrial, Community, and Blank. Blank is an empty template. These load templates all have different default overall magnitudes: 11.35, 2620, 24000, and 170 kWh/day, respectively [23]. The user can easily scale the average load of any of them to fit the customized application by changing the value for "Scaled Annual Average (kWh/day)". The load profile used in this study is covered in detail in Section 3.2.2.

2.2.3. Mathematical Formulation of the Problem

This section presents the abstract version of the optimization problem. The details have been omitted and can be uncovered through careful investigation of the HOMER software.

The Total Net Present Cost (TNPC) is HOMER's main economic output, the value by which it ranks all potential microgrid configurations in the optimization results. The basis from which HOMER Pro uses the objective function subject to system constraints given in Section 2.2.3.1 is introduced in Section 2.2.3.2. The economic metrics are presented in Section 2.2.3.3.

2.2.3.1. System Constraints

The Project Constraints page allows the modeler to change the system constraints, which are conditions that the microgrid must meet. HOMER eliminates the combinatorial configurations that do not meet the stated constraints, removing them from the optimization and sensitivity findings. The system constraints are given in the Table 2.1.

Table 2.1. *System Constraints*

Variable	Description
Maximum annual capacity shortage	The maximum allowable value of the capacity shortage fraction, in %
Minimum renewable fraction	The minimum allowable value of the annual renewable fraction, in %

Table 2.2 presents the constraints on the operating reserve which is the capacity to generate more energy than is currently needed. *"Operating reserve is surplus operating capacity that ensures reliable electricity supply even if the load suddenly increases, or renewable power output suddenly decreases. HOMER defines the required amount of operating reserve using four inputs, two related to the variability of the electric load and two related to the variability of the renewable power. The total required operating reserve is the sum of the four values resulting from these four inputs. In its simulation, HOMER operates the power system so as to keep the operating reserve equal to or greater than the*

required operating reserve. It records any shortfall as a capacity shortage" [23].

Table 2.2. *Operating Reserve*

Variable	Description
As a percentage of load: Load in current time step ($\pi_{load}, \%$):	HOMER adds this percentage of the primary load in the current time step (AC and DC separately) to the required operating reserve in each time step.
As a percentage of load: Annual peak load ($\pi_{peak}, \%$):	HOMER adds this percentage of the peak primary load (AC and DC separately) to the required operating reserve in each time step. It, therefore, defines a constant amount of operating reserve.
As a percentage renewable output: Solar power output ($\pi_{pv}, \%$):	HOMER adds this percentage of the PV array power output to the required operating reserve in each time step.
As a percentage renewable output: Wind power output ($\pi_{wt}, \%$):	HOMER adds this percentage of the wind turbine power output to the required operating reserve in each time step.

In the next Section 2.2.3.2, we use these system constraints to formulate the mathematical optimization problem.

2.2.3.2. Objective Function

The constraints in the HOMER optimization model reflect the operational and design limitations of the microgrid. Some common constraints in HOMER models include [21]:

- Energy balance: The energy balance constraint ensures that the energy supplied to the load is equal to the energy generated by the system components.
- Capacity constraints: The capacity constraints specify the maximum and minimum limits of the generator, storage, and battery capacities.

- Energy storage constraints: Constraints on the state of charge and power of the energy storage system ensure that the storage system operates within safe and efficient limits.
- Time-of-use pricing: The time-of-use pricing constraint ensures that the system is operated in a manner that takes advantage of time-varying electricity prices.
- Renewable energy availability: The renewable energy availability constraint ensures that the system is designed to meet the load requirements even when renewable energy sources are not available.
- Emissions constraints: Emissions constraints limit the amount of greenhouse gas emissions generated by the system components, such as diesel generators.
- Reliability constraints: Reliability constraints ensure that the system is designed to meet the load requirements even when some of the system components fail.

These are just some of the many constraints that can be included in the HOMER optimization model. The specific constraints for a given microgrid will depend on the goals and requirements of the microgrid.

HOMER assumes that all costs will increase by the same amount over the course of a project's life. Using the real (inflation-adjusted) interest rate instead of the nominal interest rate when discounting future cash flows to the present eliminates the impact of inflation on the study. This means that the user of HOMER inputs the real interest rate, which is roughly the difference between the nominal interest rate and the inflation rate. Real costs, defined as those that remain the same throughout time, are used for everything in HOMER. All expenses incurred over the course of a microgrid's expected lifetime are factored into the final life-cycle cost. Given that, the NPC of a microgrid is the present value of all the costs that it incurs over its lifetime, minus the present value of all the revenue that it earns over its lifetime. HOMER can only use the total NPC as the objective value of its optimization function.

Net Present Cost depends on the microgrid designed based on various decision variables that interest the modeler. The number of decision variable varies by the number of components (eg. resources, storages etc) taken into account in the potential configuration (eg. combinations of the components).

Let $\mathscr{D}$ denote a decision vector. A decision variable is defined as a variable over which the microgrid designer has control and for which HOMER can consider possible values in its optimization process.

The vector $\underline{\mathscr{D}}$ is decomposed into subvectors $\underline{s}$, $\underline{k}$ and $\underline{n}$ as follows:

$$\underline{\mathscr{D}} = \begin{bmatrix} \underline{s} \\ \underline{k} \\ \underline{n} \end{bmatrix}, \qquad \underline{s} = \begin{bmatrix} s_1 \\ \vdots \\ s_m \end{bmatrix}, \qquad \underline{k} = \begin{bmatrix} k_1 \\ \vdots \\ k_n \end{bmatrix}, \qquad \underline{n} = \begin{bmatrix} n_1 \\ \vdots \\ n_p \end{bmatrix}$$

where $\underline{s}$ represents the decision variables related to sizes (i.e. the size of the hydrogen tank); $\underline{k}$ represents the decision variable related to capacity (i.e. the capacity of a generator); $\underline{\mathrm{n}}$ represents the decision variables related to the count of something (i.e. the number of batteries). The type of the elements of $\underline{s}$ and $\underline{k}$ are real number, while the type of the entries in $\underline{n}$ is natural number. All decision variables are considered to be greater than 0. The natural numbers m, n and p refer to the number of decision variables for $\underline{\mathrm{s}}$, $\underline{\mathrm{k}}$ and $\underline{\mathrm{n}}$, respectively. The specific decision variables and thus the number of variables of each kind depends on the configuration of the problem in HOMER. For instance, if there are no hydrogen tanks then there will be no variable corresponding to the size of the tank. The units for $\underline{s}$ and $\underline{k}$ entries vary depending on the meaning of the entry.

Possible decision variables in HOMER include but are not limited to the following list, where each entry shows the notation, type and unit (where applicable):
– The number of batteries (n_1, natural number, quantity)
– The number of wind turbines (n_2, natural number, quantity)
– The capacity of the PV array (k_1, real number, kW)
– The capacity of the first generator (k_2, real number, kW)
– The capacity of the second generator (k_3, real number, kW)
– The capacity of the AC–DC converter (k_4, real number, kW)
– The capacity of the electrolyzer (k_5, real number, kW)
– The size of the hydrogen storage tank (s_1, real number, kg)

Let us define the objective function for net present cost (i.e. C_{NPC}) using the decision vector $\underline{\mathscr{D}}$. Our HOMER's goal is to minimize NPC. The NPC includes microgrid system costs (capital costs, replacement cost, operation and management costs, fuel costs, emissions penalties, and the costs of buying power from the grid) and depends on revenues, such as salvage value and grid sales. The formula for C_{NPC} is:

$$C_{NPC}(\underline{\mathscr{D}}) = -C_0(\underline{\mathscr{D}}) + \sum_{t=1}^{T} \frac{C_t(\underline{\mathscr{D}})}{(1+r)^t} \tag{2.1}$$

where C_0 = the initial investment, which depends on the choices in $\underline{\mathscr{D}}$; and $C_t(\underline{\mathscr{D}})$ = the net cash flow (i.e., revenues minus costs incurred) with r representing the discount rate (%), t the time of the cash flow (years), and T the time for planning horizon (years).

The optimization problem is formulated as finding the variables for $\underline{\mathscr{D}}$ that minimize $C_{NPC}(\underline{\mathscr{D}})$ subject to power generation from photovoltaics (f_{PV}) and the power generation from wind turbine (f_{WT}):

$$arg\ min\ C_{NPC}(\underline{\mathscr{D}}) \tag{2.2}$$

for each

$$s_i \geq 0 \text{ for all } i \in [1 \dots m] \tag{2.3}$$

$$k_i \geq 0 \text{ for all } i \in [1 \dots n] \tag{2.4}$$

$$n_i \geq 0 \text{ for all } i \in [1 \dots p] \tag{2.5}$$

subject to

$$f_{PV}(\underline{\mathscr{D}}) \geq \pi_{pv}\ E_{gen}(\underline{\mathscr{D}}) \tag{2.6}$$

$$f_{WT}(\underline{\mathscr{D}}) \geq \pi_{wt}\ E_{gen}(\underline{\mathscr{D}}) \tag{2.7}$$

where π_{pv} is the percentage of electricity generation from the solar, π_{wt} is the percentage of electricity generation from the wind, π_{load} is the percentage of load in current time step and π_{peak} is the percentage for the annual peak load (see Table 2.2). Furthermore, $E_{gen}(\underline{\mathscr{D}})$

is the electricity generation $[kWh/year]$ for the given decision variables $\underline{\mathscr{D}}$. In addition to the constraints on power generation (f_{PV} and f_{WT}), the constraints on load are taken into account for inputting the operating reserve such as:

$$r_{load,t} \geq \pi_{load}\, P_{load,t}, \tag{2.8}$$

$$r_{peak\ load} \geq \pi_{peak}\, P_{load}, \tag{2.9}$$

where $P_{load,t}$ is the load in time step $t[kWh]$, P_{load} is annual load $[kWh]$, $r_{load,t}$ is the input operating reserve as a percentage of load in the time step $t[\%]$ and $r_{peak\ load}$ is the input operating reserve as a percentage of annual peak load $[\%]$.

2.2.3.3. Comparing Cost Economics

The Economic Metrics such as Internal Rate of Return (IRR), The Return on Investment (ROI) and simple payback are common economic measures representing the value of the difference between the initial state (base case) and after operation through life cycle (current state). These computations are primarily driven by the total net present cost, the levelized cost of energy, and the operational expense. These are the standard metrics that are used for the cost summary and the economics comparison out of HOMER, as is illustrated in Section 3.3.4. The total cost of each component includes the cost of fuel, operation and maintenance, and replacement [21]. The levelized cost of energy (LCOE) focuses on the net present value and employs the discount rate to determine the net present value of the overall cost, the formula given in Eq. 2.10:

$$LCOE = \frac{\text{Total lifetime cost}}{\text{Total lifetime output}} = \frac{\sum_{t=1}^{T} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}} \tag{2.10}$$

where I_t is investment cost, M_t is operation and maintenance cost, F_t is fuel cost, E_t is the energy generated, r is discount rate, T expected life time and t time of the cash flow (years). The result is expressed in terms of money per kilowatt-hour.

Despite the fact that the levelized COE is a simple tool for comparing the costs of different systems, HOMER prefers to use the total NPC value as its primary economic figure of merit. This is due to the fact that the definition of the levelized COE is debatable [7] in a way that the definition of the total net present value of the energy is not. For example, the levelized COE fails to account for certain key terms such as inflation, integration costs, and system costs [77].

Internal rate of return (IRR) is the discount rate at which the base case and current system have the same net present cost. HOMER calculates the IRR by determining the discount rates that makes the present value of the difference of the two cash flow sequences equal to zero. The equation holds:

$$\sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 = 0, \tag{2.11}$$

where C_t is the net cash flow during the period t (i.e. $C_t = I_t + M_t + F_t$ in Eq. 2.10), C_0 is the total initial investment cost, r is the discount rate and t is the number of time periods. IRR tells traders the projected rate of growth that a company is likely to experience following a project. A high IRR means that a project is likely to be good for growth and a low IRR is an indicator of slow or minimal growth.

The Return on Investment (ROI) is the yearly cost savings relative to the initial investment. The ROI is the average yearly difference in nominal cash flows over the project lifetime divided by the difference in capital cost. The formula is given as

$$ROI = \frac{\text{yearly cost savings}}{\text{the initial investment}}, \tag{2.12}$$

Simple payback is the number of years at which the cumulative cash flow of the difference between the current system and base case system switches from negative to positive. The payback is an indication of how long it would take to recover the difference in investment costs between the current system and the base case system.

$$\text{Payback Period} = \frac{\text{Initial Investment} - \text{Opening Cumulative Cash Flow}}{\text{Closing Cumulative Cash Flow} - \text{Opening Cumulative Cash Flow}}, \tag{2.13}$$

Chapter 3

Design and Modeling of the Proposed Hydrogen Hybrid Microgrid

This chapter addresses the schematic design of hydrogen hybrid microgrid in Section 3.1, parameter setting in Section 3.2, simulation results of the candidate microgrids designed in this project, and interpretation of and conclusion about the results in Section 3.3.

3.1. Hydrogen Hybrid Microgrid

Clean, sustainable, and cost-effective hydrogen production processes are critical for hydrogen powered data centres.

In this project, we studied and designed a hydrogen hybrid microgrid (on-grid) in HOMER. The configuration of this hydrogen hybrid microgrid includes a single load that is powered by renewable energy (hydro, photovoltaic (PV), and wind) with additional hydrogen production technologies such as an electrolyzer and a reformer with an H_2 storage tank. We contrast the hydrogen hybrid microgrid with a traditional microgrid with that both is an on-grid system with a storage and a generator with an AC to DC converter.

We selected two generators in the HOMER schema setup to allow the system to simulate combinatorial scenarios with each available options separately. Using a hydrogen-fueled electric generator, a generator can produce clean, emission-free electricity from hydrogen gas [34]. To be clear, the diesel-fueled generator is in place for consideration as a component in the configuration of the traditional microgrid design and the hydrogen-fueled generator is in place for consideration as a component in the configuration of the hydrogen hybrid microgrid design.

An abstract vision of the hydrogen hybrid microgrid design is given in Fig. 3.1. A hydrogen-fueled electric generator and an alternative diesel generator are used to design the microgrid configurations that could work best to compare the traditional microgrid to the hydrogen hybrid microgrid. Hydro, Wind and Solar PV panels are used as non-conventional energy sources. The converter is used to convert DC to AC, the battery and H_2 storage tank is used to store energy.

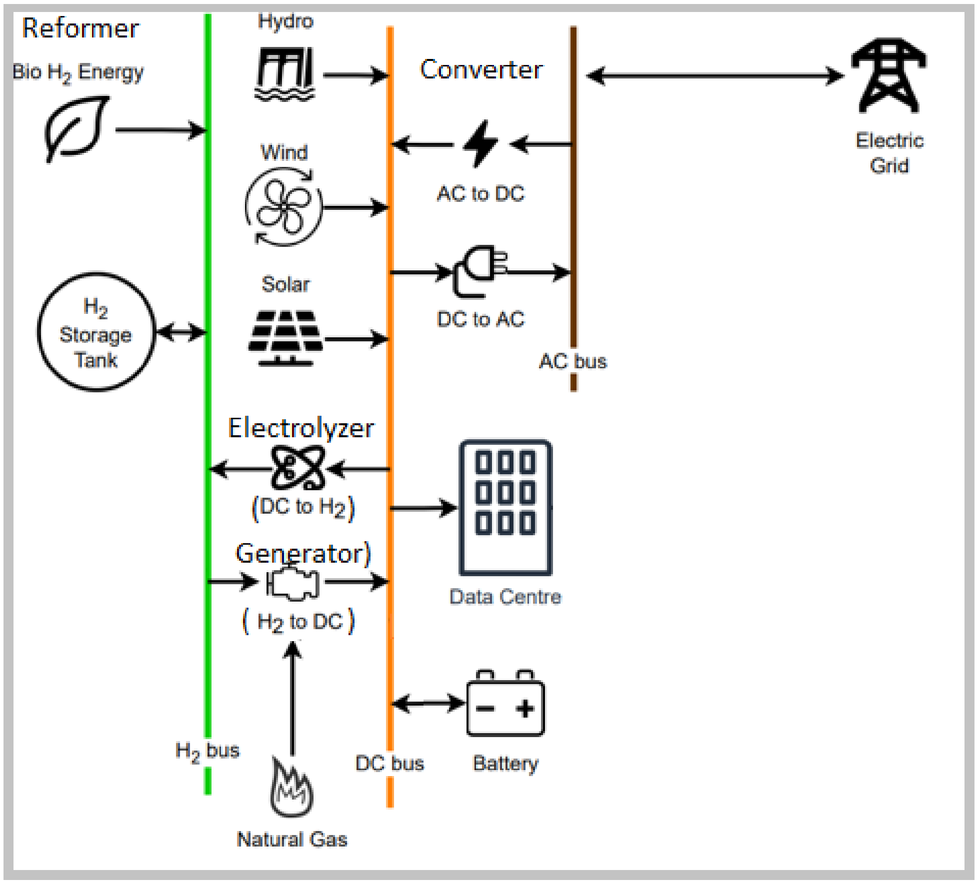


Figure 3.1. *Abstract Hydrogen Hybrid Microgrid Design*

This hydrogen hybrid microgrid presented in Fig. 3.1 can be divided into three specific phases:

(1) Hydrogen production phase: Two key production technologies, a reformer and an electrolyzer, are integrated into the hydrogen hybrid microgrid design, respectively implementing electrolytic processes. More information about hydrogen production technologies is available in Section 2.1.6.

(2) Storage phase: The hydrogen module add-on to HOMER Pro is used to integrate hydrogen storage into the hydrogen hybrid microgrid design. The traditional method of

storing energy using batteries is also taken into consideration. A hydrogen gas storage system has an economic and technical advantage over a battery storage system for long-term storage [18]. The connection between a hydrogen storage tank (HTank) and a hydrogen generator is internal in HOMER Pro. In other words, the hydrogen bus connection in green does not show on the schema design. For example, the hydrogen generator uses hydrogen as fuel internally but it is not depicted externally on the hydrogen bus in HOMER Pro model design as is shown in Fig. 3.2.

(3) Utilization phase: The schema is designed as on-grid, with the only grid connected to AC. All non-conventional energy source components, such as hydro, wind turbines, and solar photovoltaic panels, as well as the battery and generator, are connected to DC.

In this study, the HOMER Pro software is used to convert the abstract hydrogen hybrid microgrid design (Fig. 3.1) into a schematic design (Fig. 3.2), which serves as a platform for computational optimization.

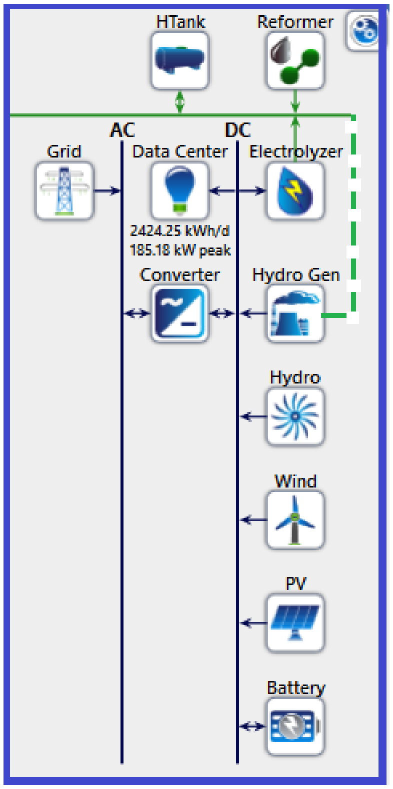


Figure 3.2. *Proposed Hydrogen Hybrid Microgrid Design in HOMER*

Fig. 3.3 shows the traditional microgrid which is used as a competitor later in the study.

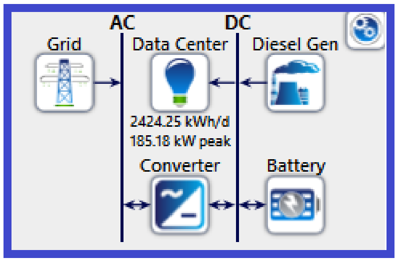


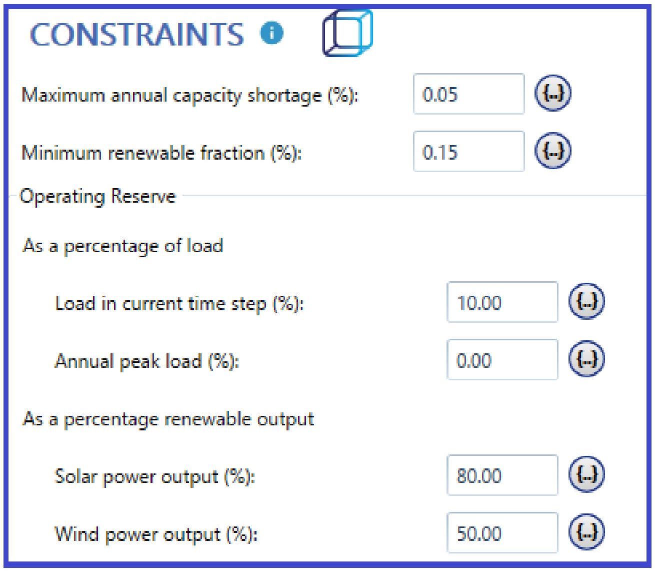
Figure 3.3. *Traditional Microgrid Design in HOMER*

3.2. Modelling Assumptions

Throughout the analysis, many decisions are made regarding the configuration of product parameters and energy distribution proportions within the energy system. HOMER treats those options as modelling assumptions, and the results are based on those assumptions. In this section, the constraints that are important for the objective function are given in Section 3.2.1 and the justification for the modelling assumptions is given in detail in Section 3.2.2 - Section 3.2.4.

3.2.1. Constraints Setup

Operating reserve refers to excess operating capacity that can respond instantly to a sudden increase in electric load or a sudden decrease in renewable power output. Operating reserve provides a safety margin that aids in ensuring a reliable electricity supply despite fluctuations in electric load and renewable energy supply. Note that according to HOMER, under most circumstances you do not need to change the values of these advanced inputs. Their default values are appropriate for most systems. For the technical definition, we refer to Table 2.2.



Maximum annual capacity shortage (%): 0.05

Minimum renewable fraction (%): 0.15

Operating Reserve

As a percentage of load

Load in current time step (%): 10.00

Annual peak load (%): 0.00

As a percentage renewable output

Solar power output (%): 80.00

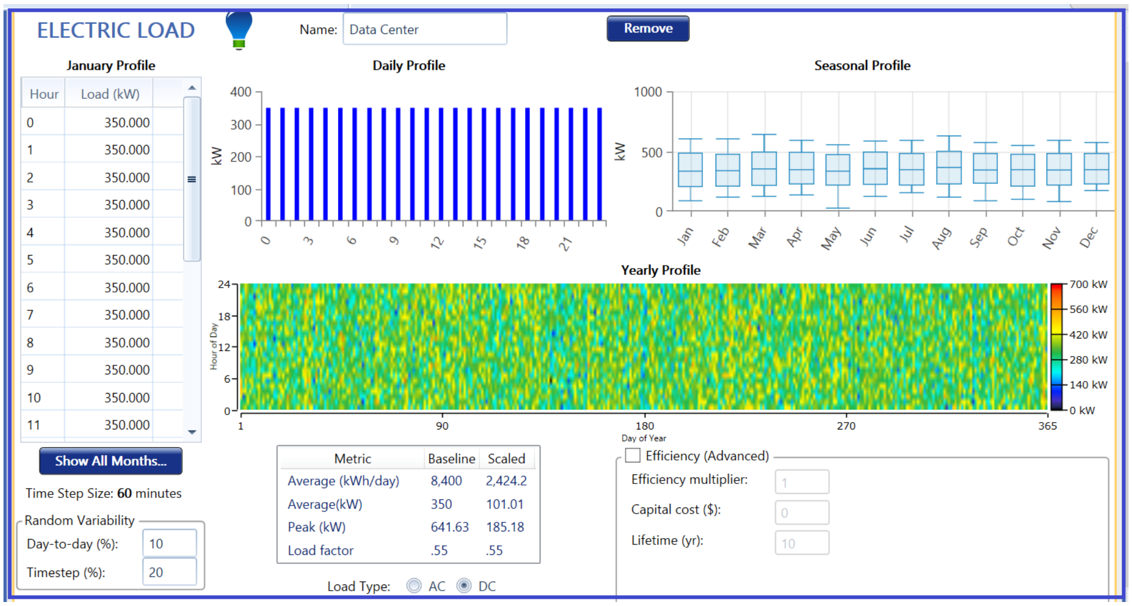
Wind power output (%): 50.00

Figure 3.4. *Constraints setup in HOMER*

According to the Figure 3.4, the maximum annual capacity shortage can not exceed 5% and the minimum renewable fraction is 15%. A value of 10% means that the system must keep enough spare capacity operating to serve a sudden 10% increase in the load. A value of 80% means that the system must keep enough spare capacity operating to serve the load even if the PV array output suddenly decreases 80%.

3.2.2. Load Setup

First of all, the commercial profile of the electric load is selected since the study's objective is only the data center's energy consumption. In this study, we did not select any peak month since the computational needs are assumed independent from the weather conditions. We assumed that the distribution of electric demand is the same for each month as is shown in Fig. 3.5 for the seasonal profile. The January profile is illustrated to show the default features that are shared by every month. According to our industry advisor, Kevin Smith, the demand for computing does not typically fluctuate throughout the year.



Name: Data Center

January Profile

Hour	Load (kW)
0	350.000
1	350.000
2	350.000
3	350.000
4	350.000
5	350.000
6	350.000
7	350.000
8	350.000
9	350.000
10	350.000
11	350.000

Time Step Size: **60** minutes

Random Variability
Day-to-day (%): 10
Timestep (%): 20

Metric	Baseline	Scaled
Average (kWh/day)	8,400	2,424.2
Average(kW)	350	101.01
Peak (kW)	641.63	185.18
Load factor	.55	.55

Load Type: ○ AC ● DC

☐ Efficiency (Advanced)
Efficiency multiplier: 1
Capital cost ($): 0
Lifetime (yr): 10

Figure 3.5. *Data Center Electric Load*

We assumed a data center runs in DC only with 800 hosts using a real CPU workload. Each host has four CPU cores, 8 GB of RAM, and 1 GB/s network bandwidth.

Table 3.1. *The Metrics of an Electrical Load*

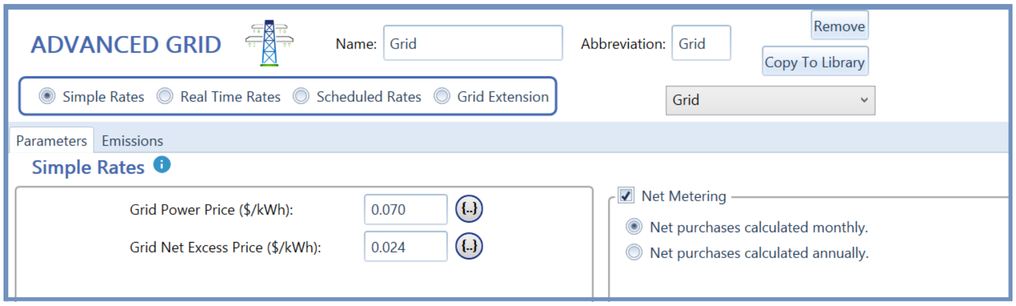
Metric	Baseline	Scaled
Average (kWh/day)	8,400	2,424.2
Average (kW)	350	101.01
Peak (kW)	641.63	185.18
Load Factor	0.55	0.55

As is shown in Fig. 3.5, on average, the hosts within the data center consumed around

8,400 kWh per day according to Kevin Smith [8], who is our sector consultant and entrepreneur for the real-world systems perspective (e.g. Studebaker campus) introduced in Section 2.1.4. Therefore, a vetted value of 350 kW is setup as the hourly load consumption and so the average kWh per day is fixed at 8,400 kWh/day and the scaled annual average is fixed at 2,424.2 kWh/day. In HOMER, ‘scaling’ means changing the magnitude of the data by scale it by a factor of 2 or 0.75 or the choice of the system designer [32]. The metric given in Fig. 3.5 is summarized in Table 3.1.

3.2.3. Advanced Grid Setup

The average cost of electricity in Ontario is $0.07 per kWh [53]. If you have some excess electricity and you want to sell it [24], as of 2021, Ontario homeowners are selling solar power to the grid at a guaranteed rate of $0.024 per kWh [14]. These are the values used in Fig. 3.6.



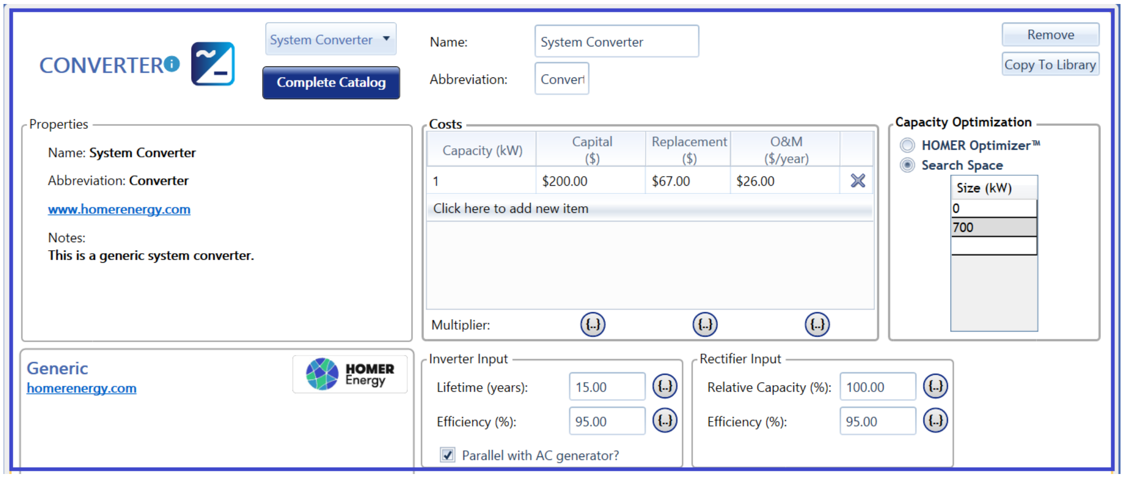
Name: Grid
Abbreviation: Grid
● Simple Rates ○ Real Time Rates ○ Scheduled Rates ○ Grid Extension
Grid
Grid Power Price ($/kWh): 0.070
Grid Net Excess Price ($/kWh): 0.024
☑ Net Metering
● Net purchases calculated monthly.
○ Net purchases calculated annually.

Figure 3.6. *Advanced Grid Parameter Assumption*

3.2.4. Experimental Setup of Components

In this section, the setup of the components and their associated cost parameters are presented. In this report, the retail prices are adjusted according to the inflation rise as of July 2022 and it is fixed for the purpose of this report. The specific model of each selected component may be paid for, replaced, and maintained with funds already invested in the company.

Converter: The converter is utilised to balance the energy supplied by a wind turbine and turn it into power to charge the batteries or power the electrolyzer. It can also change DC energy obtained from solar panels or stored in the batteries into usable AC. Because the peak consumption is 641.63kW (see Table 3.1), as a rule of thumb the converter has a capacity that is 25% greater. This gives an approximation cost of the 700kW converter, followed by the capital and annual operation and maintenance costs. Therefore, if the converter capital per 1KW is \$200 then the total capital cost of the system converter is $\$140,000$. The converter's life-time is set at 20 years, indicating the need for a replacement within the project's lifetime.



Name: System Converter

Abbreviation: Convert

Properties

Name: System Converter

Abbreviation: Converter

www.homerenergy.com

Notes:
This is a generic system converter.

Costs

Capacity (kW)	Capital ($)	Replacement ($)	O&M ($/year)
1	$200.00	$67.00	$26.00

Size (kW)
0
700

Inverter Input

Lifetime (years): 15.00

Efficiency (%): 95.00

☑ Parallel with AC generator?

Rectifier Input

Relative Capacity (%): 100.00

Efficiency (%): 95.00

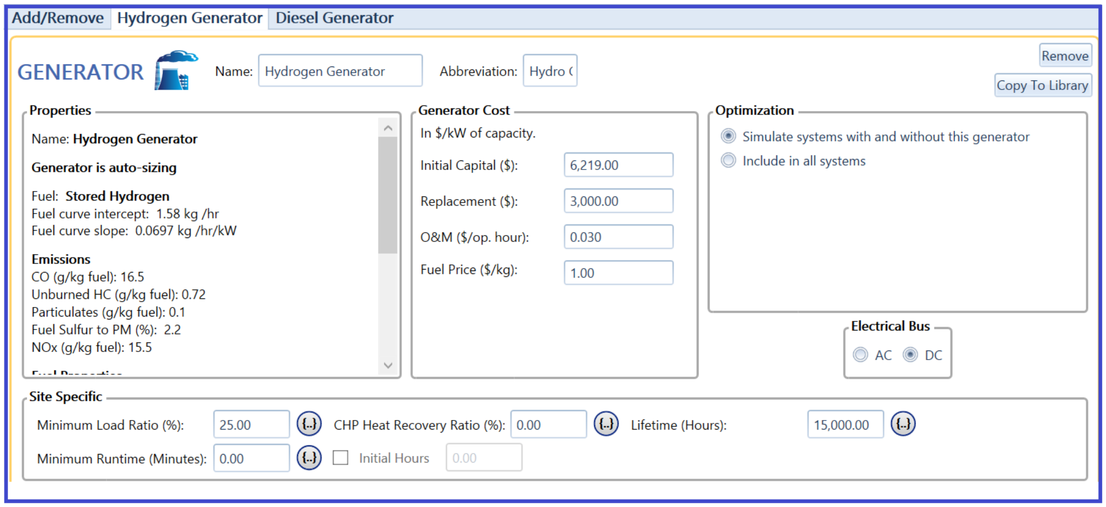
Figure 3.7. *Converter Setup in HOMER*

Generator Setup: We anticipate that some load demand will be mitigated by the battery and the generator if the resources are not available. The battery and generator will supply and mitigate some load power when solar and wind resources are unavailable. Section 2.2.2 contains more information on the priority of load demand managemenent.

Two options are considered to create a generator as alternatives in the microgrid configurations (1) a hydrogen-fueled electric generator and (2) a diesel-fueled DC generator. The properties of each generator are setup as follows:

(1) We setup a DC generator that uses stored hydrogen. The new hydrogen fuel cell product line is the ideal alternative to the standard portable power generators, which use diesel or batteries. Easy to use and with a smart and compact design, G-HFCS-1kW36V hydrogen fuel cell system produces 1000 W of nominal power. The term "nominal power" refers to the average power rating of a device or system under normal conditions. The time frame for power consumption may vary depending on the context and the specific device being discussed. In some cases, the time frame for power consumption may be explicitly

specified. For example, if a device has a nominal power rating of 1000 W and it operates for one hour, the energy consumed would be 1000 watt-hours (Wh) or 1 kilowatt-hour (kWh). The setting of initial capital for this auto-size genset model is \$6,219 per kW of capacity [81], the Replacement cost, which is \$3,000 per kW of capacity — half of the capital due to some repair items can be reused during the replacement, the operation maintenance cost, which is \$0.030, and the fuel price, which is \$1 per kilogram in this location. The manufacturer includes the expected lifetime of the generator to be 15,000 hours. This generator automatically sizes itself to meet the load. The capacity of the generator will be the smallest that will produce no capacity shortage in all sensitivity cases and future years, and brings the full energy independence for various applications that require power in the range of 0-1000 Watts. For this scenario, we used total of 210 of these hydrogen-fueled generators that results with the total capital cost of \$1,305,990.00 (i.e. 210 * 6,219).



Name: Hydrogen Generator

Abbreviation: Hydro (

Properties

Name: **Hydrogen Generator**

Generator is auto-sizing

Fuel: **Stored Hydrogen**
Fuel curve intercept: 1.58 kg /hr
Fuel curve slope: 0.0697 kg /hr/kW

Emissions
CO (g/kg fuel): 16.5
Unburned HC (g/kg fuel): 0.72
Particulates (g/kg fuel): 0.1
Fuel Sulfur to PM (%): 2.2
NOx (g/kg fuel): 15.5

Generator Cost

In \$/kW of capacity.

Initial Capital (\$): 6,219.00
Replacement (\$): 3,000.00
O&M (\$/op. hour): 0.030
Fuel Price (\$/kg): 1.00

Optimization

● Simulate systems with and without this generator
○ Include in all systems

Electrical Bus

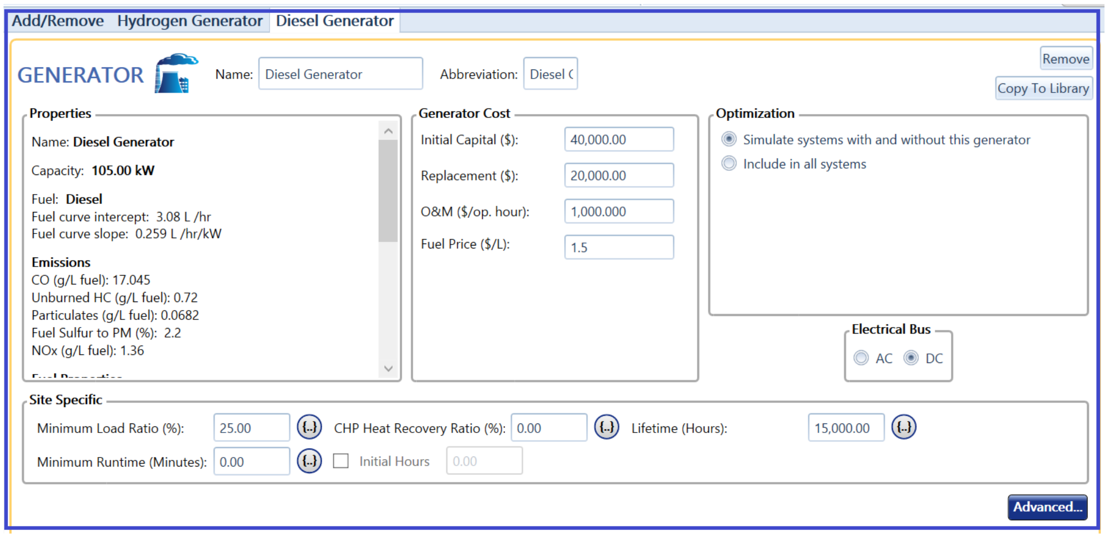
○ AC ● DC

Site Specific

Minimum Load Ratio (%): 25.00
CHP Heat Recovery Ratio (%): 0.00
Lifetime (Hours): 15,000.00
Minimum Runtime (Minutes): 0.00
☐ Initial Hours 0.00

Figure 3.8. *Hydrogen Generator Setup in HOMER*

(2) We setup a DC generator that uses diesel as fuel. The diesel-fueled generator is only considered in the traditional microgrid. The setup parameters in HOMER are shown in Fig. 3.9 for a 100 kW Prime Power Diesel Generator (120/240V Single Phase 60Hz). The initial capital for a diesel-fueled generator is $40,000 [48] and the replacement cost is $20,000 with around $1,000 operation cost. Minimum load ratio is entered as 25%. The total fixed capital cost of the diesel generator is $40,000.



Name: Diesel Generator
Abbreviation: Diesel (

Name: **Diesel Generator**
Capacity: **105.00 kW**
Fuel: **Diesel**
Fuel curve intercept: 3.08 L /hr
Fuel curve slope: 0.259 L /hr/kW

Emissions
CO (g/L fuel): 17.045
Unburned HC (g/L fuel): 0.72
Particulates (g/L fuel): 0.0682
Fuel Sulfur to PM (%): 2.2
NOx (g/L fuel): 1.36

Initial Capital ($): 40,000.00
Replacement ($): 20,000.00
O&M ($/op. hour): 1,000.000
Fuel Price ($/L): 1.5

● Simulate systems with and without this generator
○ Include in all systems

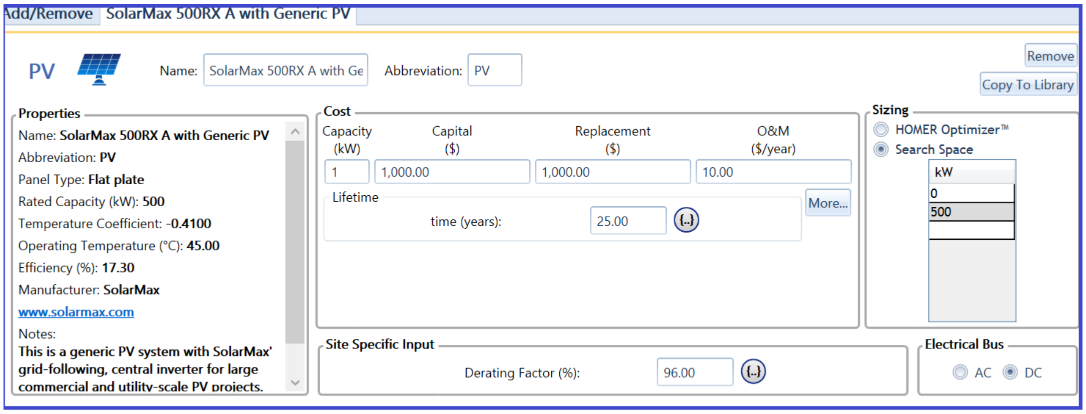
○ AC ● DC

Minimum Load Ratio (%): 25.00
CHP Heat Recovery Ratio (%): 0.00
Lifetime (Hours): 15,000.00
Minimum Runtime (Minutes): 0.00
☐ Initial Hours 0.00

Figure 3.9. *Diesel Generator Setup in HOMER*

Photovoltic Panels: There is a variety of models of photovoltic panels available in the complete catalog shown in HOMER Pro. In this study, a production model from a Manufacturer — SolarMax 500RX A with Generic PV is chosen randomly (see Fig. 3.10). This PV model functions at 500kW capacity which is desired to take care of 995,161 MWh annual load demand [86]. This is a generic PV system with SolarMax' grid-following, central inverter for large commercial and utility-scale PV projects. PV generation is connected to a

DC bus. The default prices from HOMER are used for this model.



Name: SolarMax 500RX A with Ge
Abbreviation: PV

Properties
Name: **SolarMax 500RX A with Generic PV**
Abbreviation: **PV**
Panel Type: **Flat plate**
Rated Capacity (kW): **500**
Temperature Coefficient: **-0.4100**
Operating Temperature (°C): **45.00**
Efficiency (%): **17.30**
Manufacturer: **SolarMax**
www.solarmax.com
Notes:
This is a generic PV system with SolarMax' grid-following, central inverter for large commercial and utility-scale PV projects.

Capacity (kW)	Capital ($)	Replacement ($)	O&M ($/year)
1	1,000.00	1,000.00	10.00

Lifetime time (years): 25.00

Sizing
○ HOMER Optimizer™
● Search Space

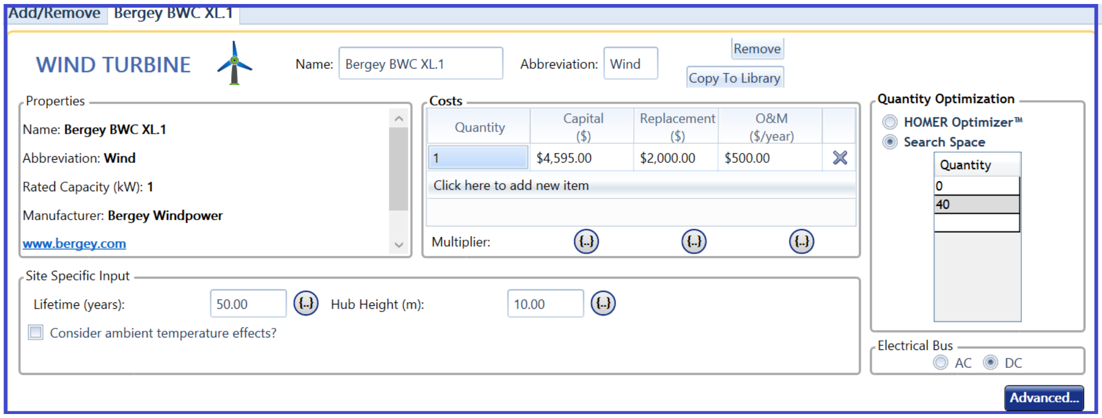
kW
0
500

Site Specific Input
Derating Factor (%): 96.00

Electrical Bus
○ AC ● DC

Figure 3.10. *Photovoltic Setup in HOMER*

Wind Turbine: For this simulation study, data is taken from a public database at a 10-meter height [47] as a standard height of the wind turbine. After that, we assume the data entry is representative for 10m. We enter the capital cost \$4,595 per a wind turbine [16], replacement cost at \$2,000 per a wind turbine, and operation and maintenance cost at \$500 (see Fig. 3.11). Since, the only DC renewables are considered for this study, we choose a DC bus as our transmission mode. Approximately, 40 wind turbines are considered that gives the total capital cost of $\$183,800$.



Name: Bergey BWC XL.1

Abbreviation: Wind

Properties

Name: **Bergey BWC XL.1**

Abbreviation: **Wind**

Rated Capacity (kW): **1**

Manufacturer: **Bergey Windpower**

www.bergey.com

Costs

Quantity	Capital ($)	Replacement ($)	O&M ($/year)
1	$4,595.00	$2,000.00	$500.00

Click here to add new item

Multiplier: {..} {..} {..}

Site Specific Input

Lifetime (years): 50.00

Hub Height (m): 10.00

☐ Consider ambient temperature effects?

Quantity Optimization

○ HOMER Optimizer™

● Search Space

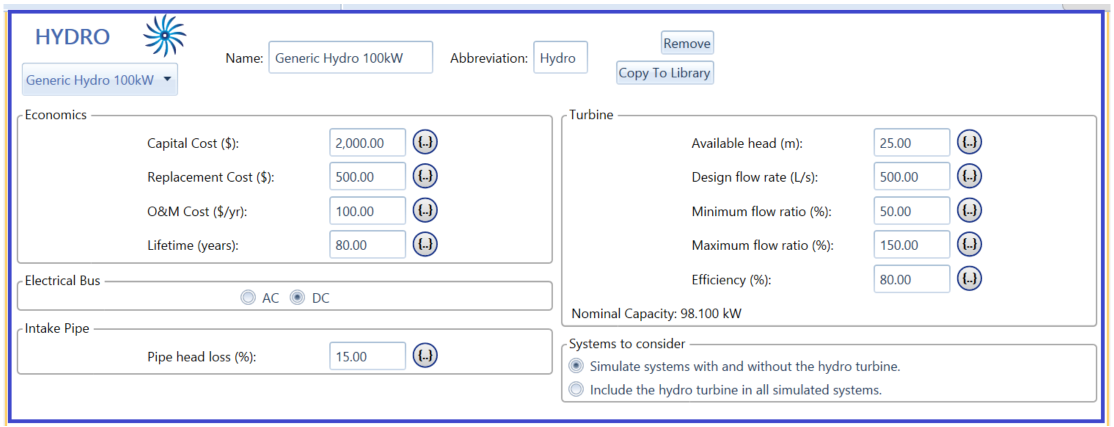
Quantity
0
40

Electrical Bus

○ AC ● DC

Figure 3.11. *Wind Turbine Setup in HOMER*

Hydro: The hydro power resources are not included in the HOMER Pro software but manual entry for a hydro resource is available. If there is a hydroelectric power plant available in the selected location then there is an opportunity to connect the hydroelectric power plant to the schematic structure. According to Ontario Hydro Network (OHN), located in Sarnia, daily hydrometric information, monthly average of stream flow data is 25.240 litres per second. This is the sector where we introduce Sarnia as a chosen location for this study. The information is manually entered in the Hydro Resources menu in HOMER for each month. The temperature, the amount of available head, and physical measurements such as distance between the water and the turbine in metres are used with default values (see Fig. 3.12).



Generic Hydro 100kW

Name: Generic Hydro 100kW

Abbreviation: Hydro

Economics
Capital Cost ($): 2,000.00
Replacement Cost ($): 500.00
O&M Cost ($/yr): 100.00
Lifetime (years): 80.00

Electrical Bus
○ AC ● DC

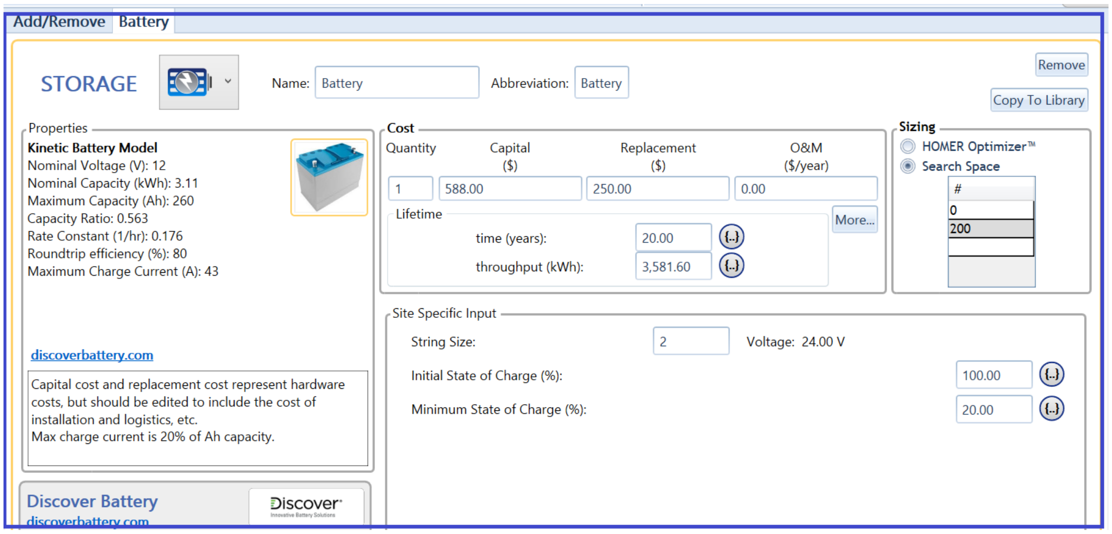
Intake Pipe
Pipe head loss (%): 15.00

Turbine
Available head (m): 25.00
Design flow rate (L/s): 500.00
Minimum flow ratio (%): 50.00
Maximum flow ratio (%): 150.00
Efficiency (%): 80.00
Nominal Capacity: 98.100 kW

Systems to consider
● Simulate systems with and without the hydro turbine.
○ Include the hydro turbine in all simulated systems.

Figure 3.12. *Hydro Setup in HOMER*

Batteries: The solar and wind turbines will not be always available when needed. As a result, the storage battery is extremely important. We always refer to a 12V battery when we talk about batteries. We randomly chose the “Discover 12VRE-3000TF” (Dis12V) model (see Fig. 3.13) and used the price given in [78]. We require some basic information before we can enter site-specific input and cost information. Batteries are connected to the DC bus. When the battery is plugged in, it will receive power from the source and then send power to the load (it is two way). When the battery is discharged, it uses available sources in the bus to power itself.



Name: Battery
Abbreviation: Battery

Properties
Kinetic Battery Model
Nominal Voltage (V): 12
Nominal Capacity (kWh): 3.11
Maximum Capacity (Ah): 260
Capacity Ratio: 0.563
Rate Constant (1/hr): 0.176
Roundtrip efficiency (%): 80
Maximum Charge Current (A): 43

discoverbattery.com

Capital cost and replacement cost represent hardware costs, but should be edited to include the cost of installation and logistics, etc.
Max charge current is 20% of Ah capacity.

Cost

Quantity	Capital ($)	Replacement ($)	O&M ($/year)
1	588.00	250.00	0.00

Lifetime
time (years): 20.00
throughput (kWh): 3,581.60

Sizing
○ HOMER Optimizer™
● Search Space

#
0
200

Site Specific Input
String Size: 2
Voltage: 24.00 V
Initial State of Charge (%): 100.00
Minimum State of Charge (%): 20.00

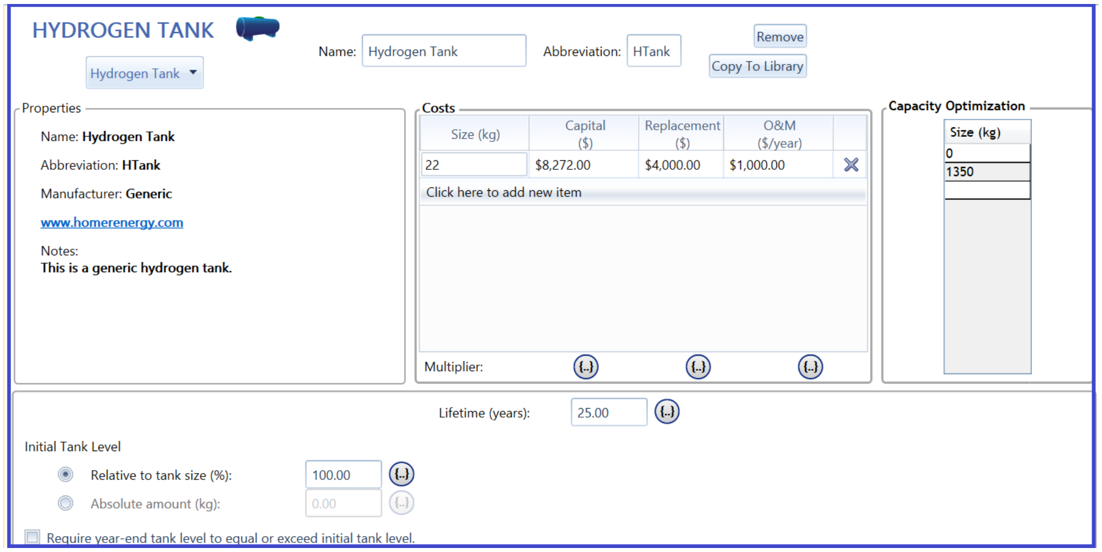
Figure 3.13. *Battery Storage Setup in HOMER*

The output voltage needs to be the same for both PV and the battery because the devices are connected to the same bus. The battery is 2 string size since PV is running at 24V. And since that's the case, we can set the initial state of charge to 100% and the minimum state of charge to 20%. HOMER preset value for the throughput is fixed at 3,581.60 kWh. In HOMER, 200 of these batteries are utilized in the search space to satisfy the objective function explained in Section 2.2.3.2. The total cost for batteries results as $200 * 588 * 2 = \$235,200$.

Hydrogen Tank Setup: Hydrogen and fuel cells are being proposed as a means of supplementing the primary grid. Renewable energy is converted to electrical energy first, and then used to electrolyze water to generate hydrogen for energy storage. When electrical energy demand peaks, hydrogen is used by fuel cells to convert back to electricity. The initial tank level is taken as 100% relative to tank size and it is chosen to require year-end tank level to equal or exceed initial tank level. The capacity of the hydrogen tank is determined based on the hydrogen tank used for the first hybrid power plant at Prenzlau, Brandenburg in Germany [27] which is a 42 bar (1 $kg/cm^2\ to\ bar\ =\ 0.98067\ bar$) hydrogen storage tank with a capacity of 1350 kg (Fig. 3.14) and the capital cost of a $16,690.

Figure 3.14. *Hydrogen Tank at Prenzlau, Brandenburg in Germany [27]*

Therefore, we used HOMER's default assumption that the cost of a tank with a capacity of 22 kg is $8,272 (see Fig. 3.15) based on the retail price in the fuel cell store [82] — (i.e. $\$8,272\ per\ \$22kg\ /\ cm^2$).



Name: Hydrogen Tank
Abbreviation: HTank

Properties

Name: Hydrogen Tank
Abbreviation: HTank
Manufacturer: Generic
www.homerenergy.com
Notes:
This is a generic hydrogen tank.

Costs

Size (kg)	Capital ($)	Replacement ($)	O&M ($/year)
22	$8,272.00	$4,000.00	$1,000.00

Multiplier:

Capacity Optimization

Size (kg)
0
1350

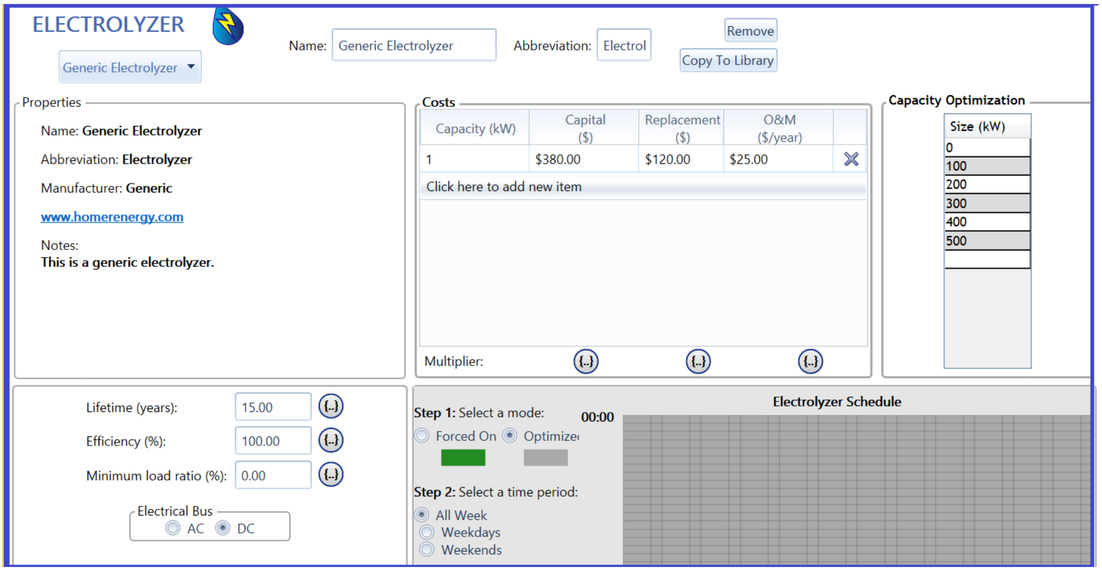
Lifetime (years): 25.00

Initial Tank Level
● Relative to tank size (%): 100.00
○ Absolute amount (kg): 0.00
☐ Require year-end tank level to equal or exceed initial tank level.

Figure 3.15. *Hydrogen Tank Setup in HOMER*

The replacement cost and operation and maintenance costs per 22kg are assumed to be $4,000 and $1,000 per year, respectively [40]. To broaden the scope of the search for a cost-effective configuration, a 1,350 kg hydrogen tank is considered. Meaning the total capital cost of this hydrogen tank is $1,350 * 8,272/22 = \$507,600$.

Electrolyzer: Modeling the electrolyzer is an easy process using HOMER. For example, it assumes that a given quantity of electricity will provide a certain amount of hydrogen. So if your Electrolyzer can only handle 75 percent of its capacity, you can set the minimum load level at 75 percent. To supply the hydrogen load or to power a generator, the Electrolyzer will demand electricity. Generally the Electrolyzer receives only excess electricity (or surplus electricity). The lifetime of an electrolyzer is from 10 to 20 years [37]. We assumed that the number of years the electrolyzer is expected to last is 15 years. Capacity of 100kW is chosen as the optimum value within the range of 100kW — 500kW in HOMER search optimization (see Fig. 3.16). The capital cost per kW is $380 that results with the total cost of $3,800 for a 100kW electrolyzer.



ELECTROLYZER

Generic Electrolyzer

Name: Generic Electrolyzer

Abbreviation: Electrol

Properties

Name: **Generic Electrolyzer**

Abbreviation: **Electrolyzer**

Manufacturer: **Generic**

www.homerenergy.com

Notes:

This is a generic electrolyzer.

Costs

Capacity (kW)	Capital ($)	Replacement ($)	O&M ($/year)
1	$380.00	$120.00	$25.00
Click here to add new item			
Multiplier:	{..}	{..}	{..}

Capacity Optimization

Size (kW)
0
100
200
300
400
500

Lifetime (years): 15.00

Efficiency (%): 100.00

Minimum load ratio (%): 0.00

Electrical Bus: ○ AC ● DC

Electrolyzer Schedule

Step 1: Select a mode: ○ Forced On ● Optimize

00:00

Step 2: Select a time period:

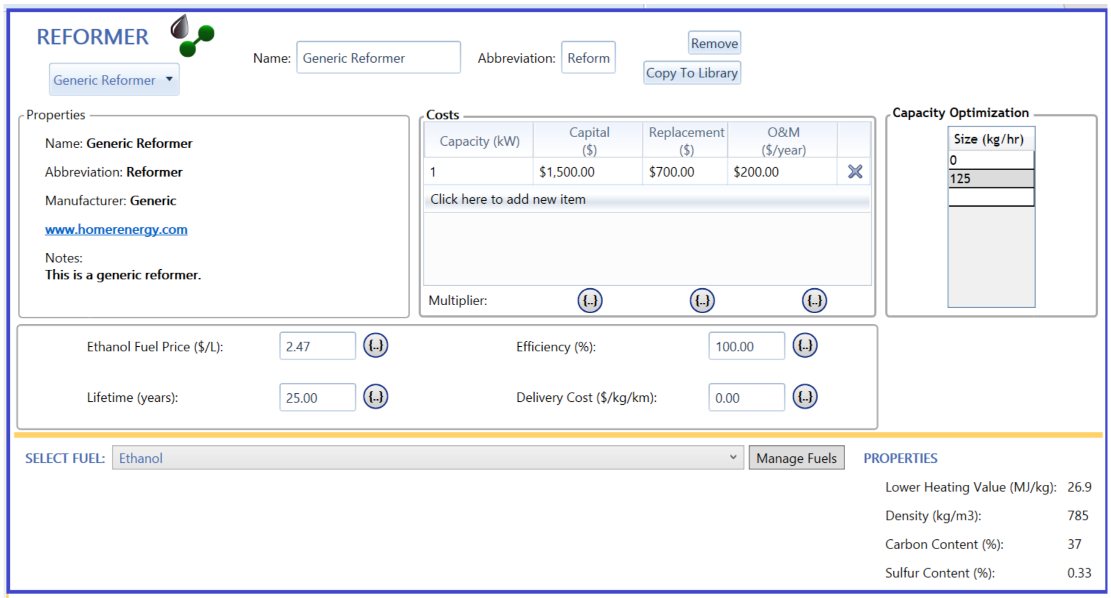
● All Week

○ Weekdays

○ Weekends

Figure 3.16. *Electrolyzer Setup in HOMER*

Reformer: A reformer generates hydrogen by reforming a hydrocarbon, typically natural gas. HOMER cannot simulate a system where a reformer provides hydrogen to a fuel cell. The reformer's sole function is to provide hydrogen for a hydrogen load. We assume a reformer of 1KW capacity cost is $1,500 [33] with replacement cost $700 and operation and management cost of $200 per year (see Fig. 3.17). We assumed 125kW capacity therefore needs total capital cost of $125 * 1,500 = \$187,500$.



Name: Generic Reformer

Abbreviation: Reform

Properties

Name: **Generic Reformer**

Abbreviation: **Reformer**

Manufacturer: **Generic**

www.homerenergy.com

Notes:
This is a generic reformer.

Costs

Capacity (kW)	Capital ($)	Replacement ($)	O&M ($/year)
1	$1,500.00	$700.00	$200.00

Click here to add new item

Multiplier: {..} {..} {..}

Capacity Optimization

Size (kg/hr)
0
125

Ethanol Fuel Price ($/L): 2.47

Efficiency (%): 100.00

Lifetime (years): 25.00

Delivery Cost ($/kg/km): 0.00

SELECT FUEL: Ethanol

PROPERTIES

Lower Heating Value (MJ/kg):	26.9
Density (kg/m3):	785
Carbon Content (%):	37
Sulfur Content (%):	0.33

Figure 3.17. *Reformer Setup in HOMER*

Fuel Cell: A fuel cell (FC) is a trio set consist of DC hydrogen generator, an electrolyzer and a hydrogen tank. The FC can switch to use reformed natural gas, so the FC inputs are set to both the FC and the reformer. In other words, the fuel curve should show electricity output versus fuel input.

The setup parameters of each component in the schema are summarized in Table 3.2.

Table 3.2. *Initial Unit Cost Parameters of the Selected Components in HOMER*

Component	**Unit**	**Capital ($)**	**Replacement($)**	**O& M** ($/*year*)	**Capacity**
Hydrogen Tank	size (kg)	8,272	4,000	1,000 (/*year*)	1,350*kg*
Generic Electrolyzer	capacity (kW)	380	120	25 ($/*year*)	100 kW
Generic Reformer	capacity (kW)	1,500	700	200 ($/*year*)	125kW
Autosize Genset (Stored Hydrogen)	capacity (kW)	6,219	3,000	0.03 ($/op.hour)	Autosize
Generator Kohler 105kW Standby (Diesel)	quantity	40,000	20,000	1,000 ($/op.hour)	105kW
Bergey BWC XL.1	quantity	4,595	2,000	500 ($/*year*)	40
SolarMax 500RX	capacity (kW)	1,000	1,000	10 ($/*year*)	500kW
Generic Hydro 100kW	quantity	2,000	500	100 ($/*year*)	1
System Converter	capacity (kW)	200	67	26 ($/*year*)	700
Discover 12VRE-3000TF	quantity	588	250	–	200

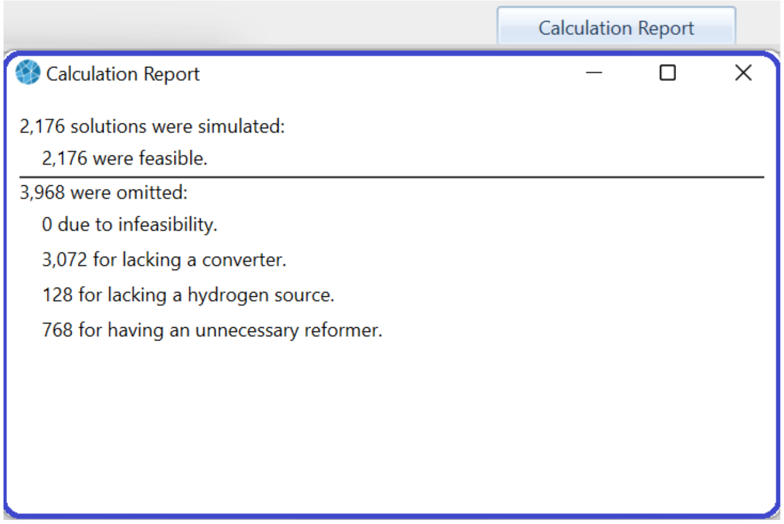
Referencing to the Table 3.2, the total capital cost (multiplication of the capital by the capacity) is given in the results section later in Section 3.3. In-depth cost calculations are out of scope of this study and left to the reader to further explore the economical formulations in HOMER.

3.3. Results

After designing the proposed hydrogen hybrid microgrid as described in Sections 3.1 and 3.2, HOMER Pro generates a variety of simulation results that are optimised based on the mathematical formulations presented in Section 2.2.3. The calculation report of the simulated solutions is provided in Section 3.3.1. The optimization results categorized by the schematic architecture are reported in Section 3.3.2 and the sensitivity analysis is covered in Section 3.3.3. In Section 3.3.4, the economics of the traditional microgrid and the proposed hydrogen hybrid microgrid are reported in details. The proposal of the new hydrogen hybrid microgrid is summarized in Section 3.3.2.

3.3.1. Simulation

The HOMER software compares energy demand and supply and calculates the energy flow for each microgrid system configuration. It determines whether or not a system configuration is feasible and then repeats the optimization results for various decision variables.



2,176 solutions were simulated:
2,176 were feasible.

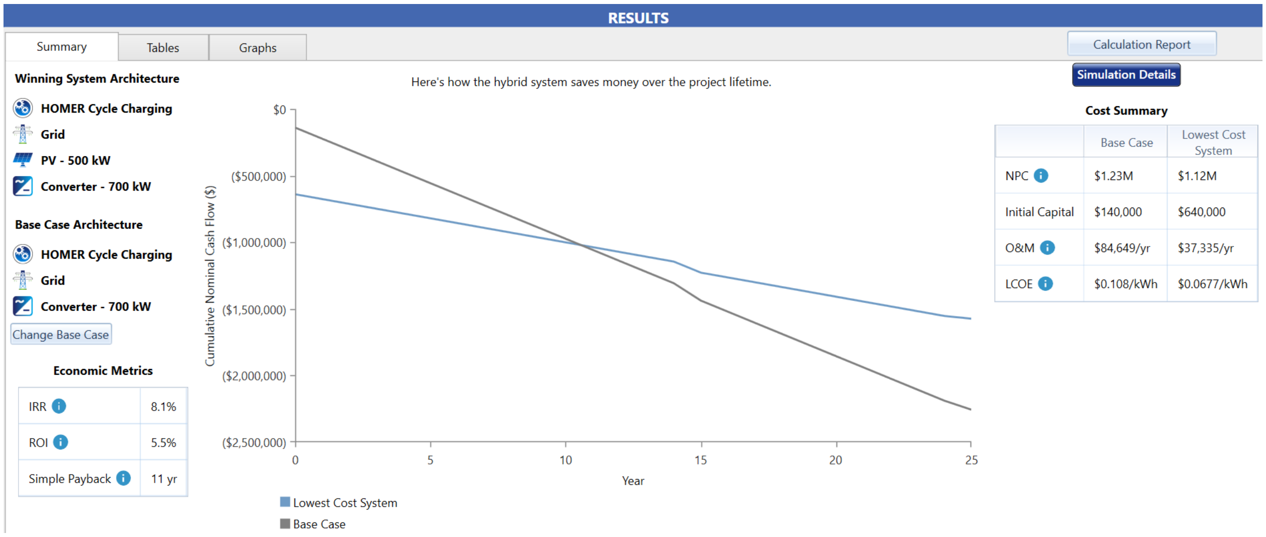
3,968 were omitted:
0 due to infeasibility.
3,072 for lacking a converter.
128 for lacking a hydrogen source.
768 for having an unnecessary reformer.

Figure 3.18. *Calculation Report of HOMER Simulation*

This study's calculation report, obtained from HOMER Pro, is shown in Fig. 3.18. According to this report, the total number of solutions simulated and found feasible for this study is 2,176, which includes various combinations of the configurations of the components in the designed schema (see Table 3.2). 3,968 computer simulated hybrid systems were omitted due to lacking a converter (3,072), lacking a hydrogen source (128) or having an unnecessary reformer (768). Only three feasible solutions map to the traditional microgrid while more than half of feasible solutions (1,188) included a hydrogen tank.

3.3.2. Optimization Results

Using the findings of the optimization, we can determine the feasible hybrid microgrid design based on the lowest NPC or lowest COE. This is defined as the ability to deliver electricity without a deficit by utilising existing renewable energy resources. First of all, we analyzed the default summary results. When looking at the overall optimization findings, the top-ranked system configuration based on total NPC is called the winning system architecture. The default microgrid in HOMER Pro is the grid only model and the winning system is defined as the top-ranked system configuration based on the lowest total NPC.



Winning System Architecture

- HOMER Cycle Charging
- Grid
- PV - 500 kW
- Converter - 700 kW

Base Case Architecture

- HOMER Cycle Charging
- Grid
- Converter - 700 kW

Here's how the hybrid system saves money over the project lifetime.

Cost Summary

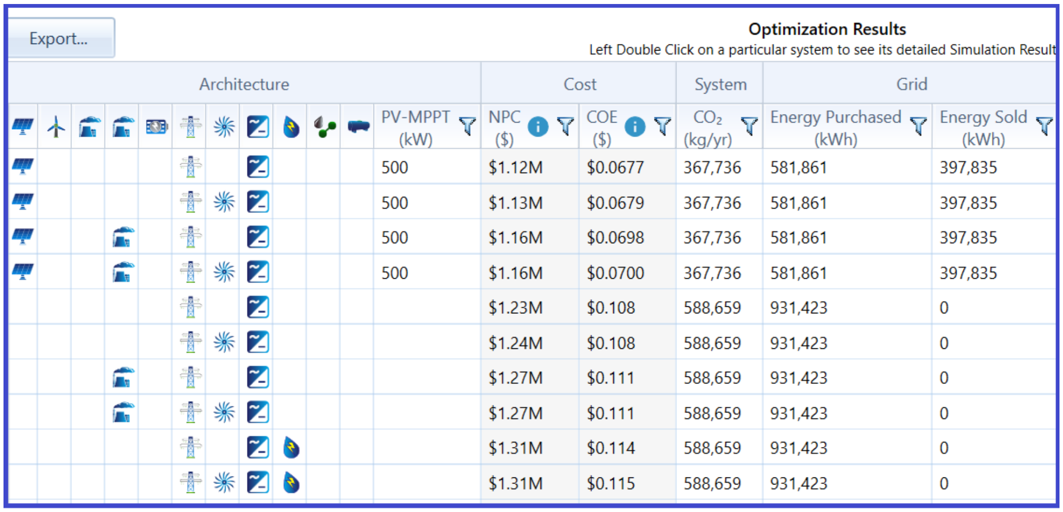
	Base Case	Lowest Cost System
NPC	$1.23M	$1.12M
Initial Capital	$140,000	$640,000
O&M	$84,649/yr	$37,335/yr
LCOE	$0.108/kWh	$0.0677/kWh

Economic Metrics

IRR	8.1%
ROI	5.5%
Simple Payback	11 yr

Figure 3.19. *Winning Hybrid Microgrid Architecture in HOMER Pro., with one non-conventional energy source (i.e. PV)*

According to Fig. 3.19, in this case, hybrid microgrid incorporating just one renewable energy component, such as photovoltaic panels, outperforms the grid-only traditional microgrid. That is, it is the least expensive system when compared to all other possible configurations, with a 5.5 percent return on investment in 11 years. The hybrid microgrid with a hydro and a PV component is the next cheapest.



Export...

Optimization Results

Left Double Click on a particular system to see its detailed Simulation Result

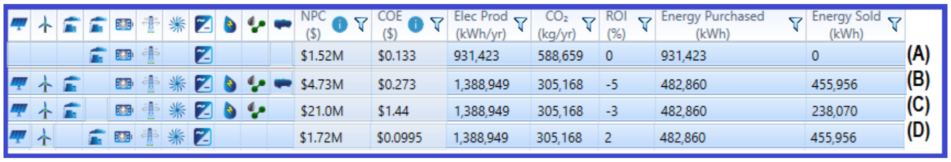
Architecture												Cost		System	Grid	
											PV-MPPT (kW)	NPC ($)	COE ($)	CO₂ (kg/yr)	Energy Purchased (kWh)	Energy Sold (kWh)
●					●		●				500	$1.12M	$0.0677	367,736	581,861	397,835
●					●	●	●				500	$1.13M	$0.0679	367,736	581,861	397,835
●			●		●		●				500	$1.16M	$0.0698	367,736	581,861	397,835
●			●		●	●	●				500	$1.16M	$0.0700	367,736	581,861	397,835
					●		●					$1.23M	$0.108	588,659	931,423	0
					●	●	●					$1.24M	$0.108	588,659	931,423	0
			●		●		●					$1.27M	$0.111	588,659	931,423	0
			●		●	●	●					$1.27M	$0.111	588,659	931,423	0
					●		●	●				$1.31M	$0.114	588,659	931,423	0
					●	●	●	●				$1.31M	$0.115	588,659	931,423	0

Figure 3.20. *Top 10 Optimization Results in HOMER Pro.*

With this project study's goals in mind, in the following Section 3.3.3, we changed the base system shown in Fig. 3.19 to a traditional microgrid consist of a diesel-fueled generator and batteries for storage and treated the hydrogen hybrid microgrid as a winning architecture in order to observe the changes in the net present cost. Then we present the sensitivity analysis in which we include and remove the components of the hydrogen technology that were discussed in Section 2.1.6.

3.3.3. Sensitivity Analysis

To begin, we altered the base system to present an on-grid traditional microgrid (System Architecture A), and we compared it to the proposed hydrogen hybrid microgrid that we have developed, which includes all hydrogen production technologies and an attachment for a hydrogen tank (System Architecture B). To carry out the sensitivity analysis we created two additional system architectures C and D. The first sensitivity strategy was to calculate the impact of the hydrogen tank on the amount of energy sold by removing the hydrogen tank from the model (System Architecture C), and then second sensitivity strategy was to remove all technologies that produce hydrogen from the model altogether (System Architecture D).



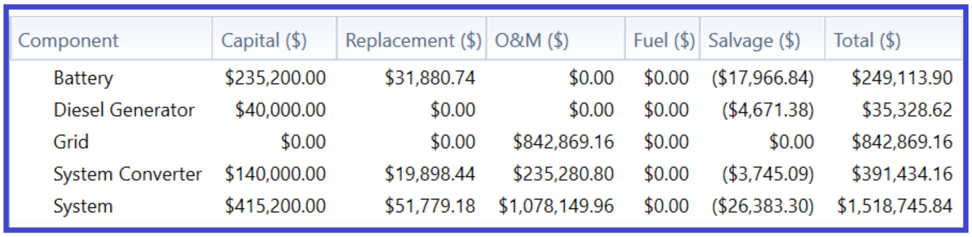
NPC ($)	COE ($)	Elec Prod (kWh/yr)	CO_2 (kg/yr)	ROI (%)	Energy Purchased (kWh)	Energy Sold (kWh)	
$1.52M	$0.133	931,423	588,659	0	931,423	0	(A)
$4.73M	$0.273	1,388,949	305,168	-5	482,860	455,956	(B)
$21.0M	$1.44	1,388,949	305,168	-3	482,860	238,070	(C)
$1.72M	$0.0995	1,388,949	305,168	2	482,860	455,956	(D)

Figure 3.21. *Categorized optimization results from HOMER. (A) Traditional Microgrid (B) Hydrogen Hybrid Microgrid (with hydrogen tank) (C) Hydrogen Hybrid Microgrid (without hydrogen tank) (D) Hybrid Microgrid (without any hydrogen component)*

.

Comparing the microgrid architectures in Fig. 3.21, we observe that the carbon dioxide emission (CO_2) is significantly lower, at 305,168 kg per year in the hydrogen hybrid microgrid (B), compared to 588,659 kg per year in the traditional microgrid (A). Furthermore, 455,956 kWh of energy was sold back to the grid in the hydrogen hybrid microgrid (B) while none in the traditional microgrid (A). The absence of a hydrogen tank (C) reduces the energy purchases from the grid by half compared to (B). The hydrogen hybrid microgrid (B) requires additional $3 million investment compare to original hybrid microgrid (D) leading to at least 645 kg (CO_2) reduction by its own (i.e. compare to off-grid hydrogen hybrid microgrid).

Fig. 3.22 presents the HOMER output of the cost summary for traditional microgrid (architecture (A) in Fig. 3.21). Total cost of the traditional microgrid is $1,518,745.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Battery	$235,200.00	$31,880.74	$0.00	$0.00	($17,966.84)	$249,113.90
Diesel Generator	$40,000.00	$0.00	$0.00	$0.00	($4,671.38)	$35,328.62
Grid	$0.00	$0.00	$842,869.16	$0.00	$0.00	$842,869.16
System Converter	$140,000.00	$19,898.44	$235,280.80	$0.00	($3,745.09)	$391,434.16
System	$415,200.00	$51,779.18	$1,078,149.96	$0.00	($26,383.30)	$1,518,745.84

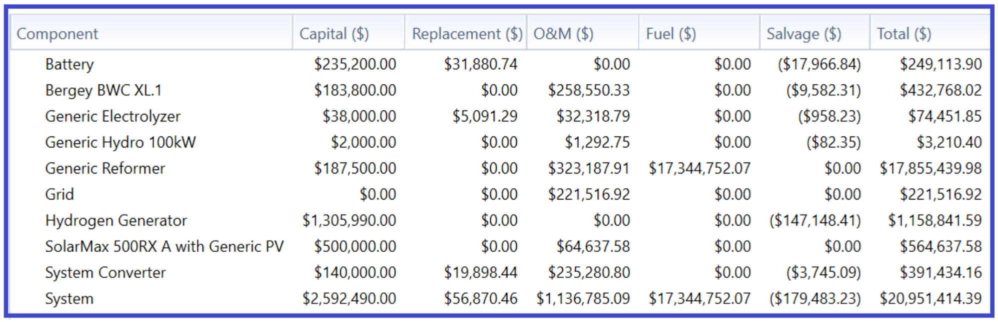
Figure 3.22. *Cost Summary Output of the Base System*

Fig. 3.23 presents the cost summary of the proposed hydrogen hybrid microgrid and Fig. 3.24 presents the cost summary excluding the hydrogen tank. The total cost of the hydrogen hybrid microgrid dramatically increases from $6.7 million to $20.6 million in case of the hydrogen tank exclusion. This is because, in the absence of the hydrogen tank, the reformer operates faster to meet the required energy in a short period of time for hydrogen generation, resulting in a significant cost increase by approximately $17 million dollars, whereas the hydrogen tank was storing the hydrogen produced by the reformer slowly for cheaper during daily operation.

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Battery	$235,200.00	$31,880.74	$0.00	$0.00	($17,966.84)	$249,113.90
Bergey BWC XL.1	$183,800.00	$0.00	$258,550.33	$0.00	($9,582.31)	$432,768.02
Generic Electrolyzer	$38,000.00	$5,091.29	$32,318.79	$0.00	($958.23)	$74,451.85
Generic Hydro 100kW	$2,000.00	$0.00	$1,292.75	$0.00	($82.35)	$3,210.40
Generic Reformer	$187,500.00	$0.00	$323,187.91	$0.00	$0.00	$510,687.91
Grid	$0.00	$0.00	$48,400.99	$0.00	$0.00	$48,400.99
Hydrogen Generator	$1,305,990.00	$0.00	$0.00	$0.00	($147,148.41)	$1,158,841.59
Hydrogen Tank	$507,600.00	$0.00	$793,279.42	$0.00	$0.00	$1,300,879.42
SolarMax 500RX A with Generic PV	$500,000.00	$0.00	$64,637.58	$0.00	$0.00	$564,637.58
System Converter	$140,000.00	$19,898.44	$235,280.80	$0.00	($3,745.09)	$391,434.16
System	$3,100,090.00	$56,870.46	$1,756,948.58	$0.00	($179,483.23)	$4,734,425.82

Figure 3.23. *Cost Summary Output of the Proposed System with a Hydrogen Tank*

In other words, this outcome of the comparison is not surprising due to the greater cost of hydrogen fuel in the absence of a hydrogen tank. On the other hand, operation and management cost of the grid increases by $173,116 in the absence of hydrogen tank.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Battery	$235,200.00	$31,880.74	$0.00	$0.00	($17,966.84)	$249,113.90
Bergey BWC XL.1	$183,800.00	$0.00	$258,550.33	$0.00	($9,582.31)	$432,768.02
Generic Electrolyzer	$38,000.00	$5,091.29	$32,318.79	$0.00	($958.23)	$74,451.85
Generic Hydro 100kW	$2,000.00	$0.00	$1,292.75	$0.00	($82.35)	$3,210.40
Generic Reformer	$187,500.00	$0.00	$323,187.91	$17,344,752.07	$0.00	$17,855,439.98
Grid	$0.00	$0.00	$221,516.92	$0.00	$0.00	$221,516.92
Hydrogen Generator	$1,305,990.00	$0.00	$0.00	$0.00	($147,148.41)	$1,158,841.59
SolarMax 500RX A with Generic PV	$500,000.00	$0.00	$64,637.58	$0.00	$0.00	$564,637.58
System Converter	$140,000.00	$19,898.44	$235,280.80	$0.00	($3,745.09)	$391,434.16
System	$2,592,490.00	$56,870.46	$1,136,785.09	$17,344,752.07	($179,483.23)	$20,951,414.39

Figure 3.24. *Cost Summary Output of the Proposed System without a Hydrogen Tank*

3.3.4. Economics Results

In this section, we compile the comparison of the economics based on the system architecture discussed in Section 3.3.3. The economics results of (A) the traditional microgrid, (B) the hydrogen hybrid microgrid (with hydrogen tank), (C) hydrogen hybrid microgrid (without hydrogen tank) and (D) hybrid microgrid (without hydrogen component) is given in Table 3.3. The return on investment calculation is determined by Eq. 2.12 in Section 2.2.3.3.

Table 3.3. *Economic analyisis results from HOMER simulation of the various microgrids*

Metric	**(A)**	**(B)**	**(C)**	**(D)**
Present worth ($)	$284,443	$3,215,680	$19,432,670	$206,148
Annual worth ($)	$22,003	$248,747	$1,503,202	$15,946
Total NPC ($)	$1,518,746	$4,734,426	$20,951,410	$1,724,894
Levelized COE ($)	$0.1328	$0.2731	$1.4400	$0.0995
Operating Cost ($)	$85,364	$126,423	$1,420,143	$48,260
Return on investment (%)	-4.1%	-5.0%	-3.1%	1.5%

According to Table 3.3 B, the hydrogen hybrid microgrid, gives lower COE and lower operating cost. The hydrogen tank accounts for $16.3M savings (e.g. the difference between the present worth of C and B) in for the net present cost, which corresponds to a 5% decrease in return on investment.

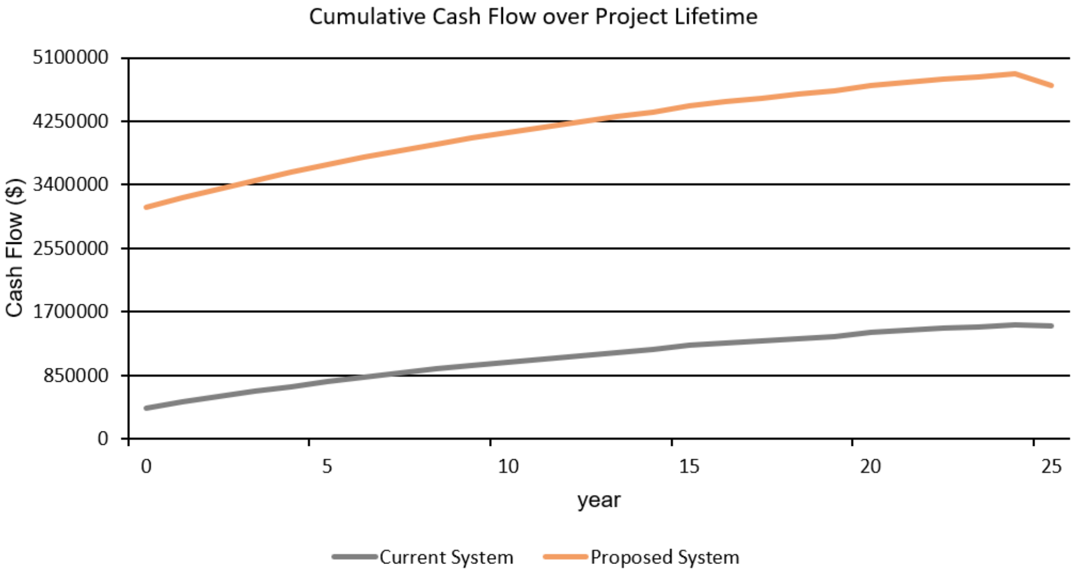
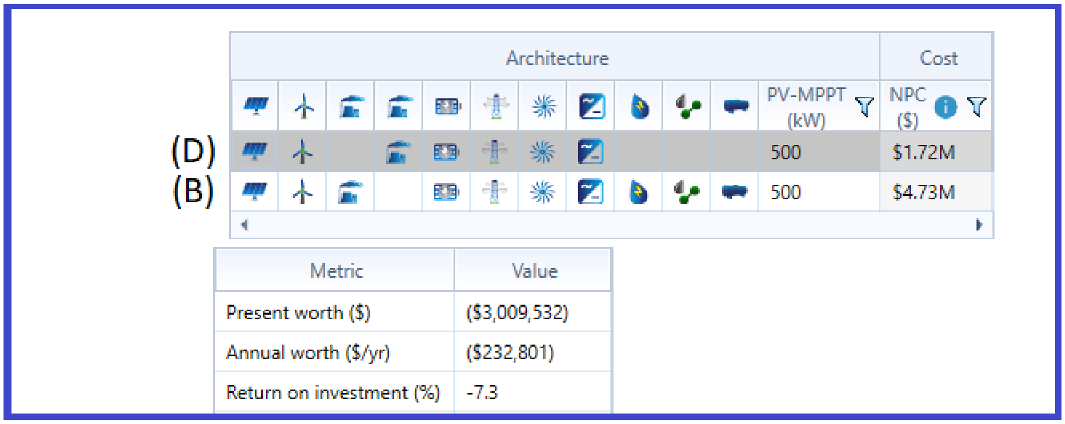


Figure 3.25. *Cumulative Cash Flow over Project Lifetime*

To calculate the return on investment of base system (A), we compared the base system to the grid only system. We observed that attaching a diesel generator and a battery to the base system, actually results in a 5% loss in the investment. However, it has many advantages compared to the grid-only system. For example, it covers the real-life emergency situations such as power outages or the absence of power. If we switch from conventional system (A) to a non-conventional system (D), the return on investment increase to 1.5% (see Table 3.3) and there is 283,491 kg CO_2 reduction per year. Furthermore, the microgrid system with hydrogen tank attached (B) has much higher cumulative cash flow (see Fig. 3.25) over the project lifetime (i.e. next 25 years).

In Fig. 3.26, we compare (D) hybrid microgrid (without hydrogen component) to (B) the hydrogen hybrid microgrid, we observe that adding hydrogen technologies to the existing hybrid microgrid (B) costs $3M more but results in higher cumulative cash flow in the long run.



	Architecture	Cost
	PV-MPPT (kW)	NPC ($)
(D)	500	$1.72M
(B)	500	$4.73M

Metric	Value
Present worth ($)	($3,009,532)
Annual worth ($/yr)	($232,801)
Return on investment (%)	-7.3

Figure 3.26. *Impact of adding hydrogen technologies*

Overall considering 5% loss in the return on investment which can be covered by potential government's programs as discussed in Chapter 1, we proceed by proposing the hydrogen hybrid microgrid architecture (B) which includes all hydrogen production technologies and an attachment for a hydrogen tank. Nevertheless, like numerous softwares, there exist noteworthy limits. The caveats, which might be used in future studies to improve this proposal, are covered in the next Section 3.3.5.

3.3.5. The Proposed System

Based on our research, we recommend that a hydrogen technologies as part of a hybrid microgrid setup — so called hydrogen hybrid microgrid. For modelling and simulations, we used HOMER Pro. We ran into a variety of challenges throughout the analysis itself.

When it comes to designing setups for non-conventional energy sources, HOMER is the leading choice because of the ease with which it allows for such designs to be implemented and the speed with which simulation results are generated. This functionality of the software allows us to propose the hydrogen hybrid microgrid as a better alternative to the current hybrid microgrid in Sarnia as of 2023. The electric needs of a hypothetical data center located at 2331 *Churchill Line, Sarnia, ON N7T 7H3, Canada* are met with $500kW$ of PV, $105kW$ of generator capacity, $1,246kWh$ of battery capacity, $40kW$ of wind generation capacity and $98kW$ of hydro generation capacity. The operating costs for energy are currently $\$85,364$ per year. We propose adding $105kW$ of generator capacity. This would increase the operating costs to $\$126,423/yr$.

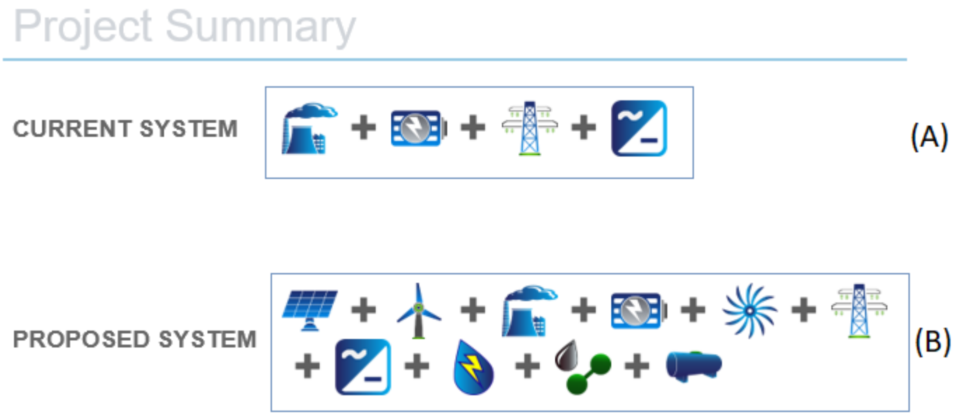


Figure 3.27. *Summary Current System versus Proposed Hybrid Microgrid System with Hydrogen Tank*

The biggest disadvantage of HOMER during this project study is that the functionality for integrating multiple microgrids schema does not exist. For example, if we have variation of microgrids then it is not possible to create interconnection between those microgrids. HOMER allows only a single objective function for minimizing the NPC as such multi-objective problems cannot be formulated. After the optimization process HOMER makes charts for the optimized system configurations based on NPC and does not rank the hybrid systems as per levelized cost of energy.

Chapter 4

Conclusion

We propose a hydrogen hybrid microgrid that accounts for primary load, the grid, non-conventional energy sources, and hydrogen production technologies and hydrogen storage to meet computing power demand for a hypothetical data centre in Sarnia, Ontario, Canada.

The overarching purpose of this project was to develop a hydrogen hybrid microgrid to reduce energy consumption costs by employing an optimal energy management strategy compared to a traditional microgrid while keeping system constraints and operating reserves in mind. Using the background foundations in the field of hybrid microgrid introduced in Section 2, the suggested frameworks was developed via HOMER.

This study provides solid evidence of the feasibility of developing hydrogen hybrid microgrid in Sarnia, Ontario. Model elements, assumptions, and results sensitivity are all described in depth. When compared to traditional microgrids, the hydrogen hybrid microgrid reduces CO_2 emissions by $283,491$ kg per year and the operating costs increases by 48% per year with a 5% loss in return on investment.

The HOMER application in this study is one of only a few publications undertaken for

Ontario in Canada, and the first of its kind that considers a potential data centre in rural Sarnia.

The HOMER software is not appropriate for integrating multiple microgrids in a centralized place. The software has only been used for single hybrid microgrid design. Findings from this study should be used for future work as follows:

- Insights to develop adequate management system for designing/managing multiple interconnected microgrids that consists of different type of microgrids sharing the same distribution system and operated as regions to achieve the smart grid operation concept (read more for future directions in [68]).
- Evaluating its applicability to system development in the real world calls for subject matter expert advice from a wide range of scientific fields such as engineering, economics, chemistry and mathematics.
- Because HOMER Pro is a commercial product (rather than open source code), there is a knowledge transfer gap when academics request more transparent mathematical formulations on optimisation problem structure and cost economics interpretations.
- Further research must be carried out to determine the functionality of the hydrogen tank and the green linkage between the hydrogen production technologies and the load satisfaction.

Overall, the findings presented in Section 3 of this project show the investment in integrating hydrogen technology with hybrid microgrid gains in the long run given the assumption that government rebate programs or investment funds in the future to support green technology (eg. [20]).

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